

Alex's Anthology of Algorithms
Common Code for Contests in Concise C++
(Draft, December 2015)

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Preface

Note: Visit <http://github.com/Alextrovert/Algorithms-Anthology> for the most up-to-date digital version of this codebook. The version you are reading is currently undergoing review.

0.1 Introduction

This anthology started as a personal project to implement common algorithms in the most concise and "vanilla" way possible so that they're easily adaptable for use in algorithm competitions. To that end, several properties of the algorithm implementations should be satisfied, not limited to the following:

- Implementations must be clear. There is no time to write rigorous documentation within contests. This makes it all the more important to make class and variable names reflexive of what they represent. Clarity must also be carefully balanced with not making them too long-winded, since it can be just as time-consuming to type out long identifiers.
- Implementations must be generic. The more code that must be changed during the contest, the more room there is for mistakes. Thus, it should be easy to apply implementations to different purposes. C++ templates are often used to accomplish this at the slight cost of readability.
- Implementations must be portable. Different contest environments use different versions of C++ (though almost all of them use GCC), so in order to make programs as compatible as possible, non-standard features should be avoided. This is also why no features from C++0x or above are used, since many contest systems remain stuck on older versions of the language. Refer to the "Portability" section below for more information.
- Implementations must be efficient. The code cannot simply demonstrate an idea, it should also have the correct running time and a reasonably low constant overhead. This is sometimes challenging if concision is to be preserved. However, contest problem setters will often be understanding and set time limits liberally. If an implementation from here does not pass in time, chances are you are choosing the wrong algorithm.
- Implementations must be concise. During timed contests, code chunks are often moved around the file. To minimize the amount of scrolling, code design and formatting conventions should ensure as much code fits on the screen as possible (while not excessively sacrificing readability). It's a given that each algorithm should be placed within singleton files. Nearly all contest environments demand submissions to be contained within a single file.

A good trade-off between clarity, genericness, portability, efficiency, and concision is what comprises the ultimate goal of adaptability.

0.2 Portability

All programs are tested with version 4.7.3 of the GNU Compiler Collection (GCC) compiled for a 32-bit target system.

That means the following assumptions are made:

- bool and char are 8-bit
- int and float are 32-bit
- double and long long are 64-bit
- long double is 96-bit

Programs are highly portable (ISO C++ 1998 compliant), **except** in the following regards:

- Usage of long long and related features [`-Wlong-long`] (such as `LLONG_MIN` in `<climits>`), which are compliant in C99/C++0x or later. 64-bit integers are a must for many programming contest problems, so it is necessary to include these.
- Usage of variable sized arrays [`-Wvla`] (an easy fix using vectors, but I chose to keep it because it is simpler and because dynamic memory is generally good to avoid in contests)
- Usage of GCC's built-in functions like `__builtin_popcount()` and `__builtin_clz()`. These can be extremely convenient, and are easily implemented if they're not available. See here for a reference: <https://gcc.gnu.org/onlinedocs/gcc/Other-Builtins.html>
- Usage of compound-literals, e.g. `vec.push_back(mystruct){a, b, c}`. This is used in the anthology because it makes code much more concise by not having to define a constructor (which is trivial to do).
- Ad-hoc cases where bitwise hacks are intentionally used, such as functions for getting the signbit with type-punned pointers. If you are looking for these features, chances are you don't care about portability anyway.

0.3 Usage Notes

The primary purpose of this project is not to better your understanding of algorithms. To take advantage of this anthology, you must have prior understanding of the algorithms in question. In each source code file, you will find brief descriptions and simple examples to clarify how the functions and classes should be used (not so much how they work). This is why if you actually want to learn algorithms, you are better off researching the idea and trying to implement it independently. Directly using the code found here should be considered a last resort during the pressures of an actual contest.

All information from the comments (descriptions, complexities, etc.) come from Wikipedia and other online sources. Some programs here are direct implementations of pseudocode found online, while others are adapted and translated from informatics books and journals. If references for a program are not listed in its comments, you may assume that I have written them from scratch. You are free to use, modify, and distribute these programs in accordance to the license, but please first examine any corresponding references of each program for more details on usage and authorship.

Cheers and hope you enjoy!

— Alex Li

December, 2015

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Chapter 1

Elementary Algorithms

1.1 Array Transformations

1.1.1 Sorting Algorithms

```
1  /*
2
3  1.1.1 - Sorting Algorithms
4
5  The following functions are to be used like std::sort(), taking two
6  RandomAccessIterators as the range to be sorted, and optionally a
7  comparison function object to replace the default < operator.
8
9  They are not intended to compete with the standard library sorting
10 functions in terms of speed, but are merely demonstrations of how to
11 implement common sorting algorithms concisely in C++.
12
13 */
14
15 #include <algorithm> /* std::copy(), std::swap() */
16 #include <functional> /* std::less */
17 #include <iterator> /* std::iterator_traits */
18
19 /*
20
21 Quicksort
22
23 Time Complexity (Best):  $O(n \log n)$ 
24 Time Complexity (Average):  $O(n \log n)$ 
25 Time Complexity (Worst):  $O(n^2)$ 
26 Space Complexity:  $O(\log n)$  auxiliary.
27 Stable?: No
28
29 Quicksort repeatedly selects a pivot and "partitions" the range so that
30 all values comparing less than the pivot come before it, and all values
31 comparing greater comes after it. Divide and conquer is then applied to
32 both sides of the pivot until the original range is sorted. Despite
33 having a worst case of  $O(n^2)$ , quicksort is faster in practice than
34 merge sort and heapsort, which each has a worst case of  $O(n \log n)$ .
35
```

```

36 The pivot chosen in this implementation is always the middle element
37 of the range to be sorted. To reduce the likelihood of encountering the
38 worst case, the algorithm should be modified to select a random pivot,
39 or use the "median of three" method.
40
41 */
42
43 template<class It, class Compare>
44 void quicksort(It lo, It hi, Compare cmp) {
45     if (hi - lo < 2) return;
46     typedef typename std::iterator_traits<It>::value_type T;
47     T pivot = *(lo + (hi - lo) / 2);
48     It i, j;
49     for (i = lo, j = hi - 1; ; ++i, --j) {
50         while (cmp(*i, pivot)) ++i;
51         while (cmp(pivot, *j)) --j;
52         if (i >= j) break;
53         std::swap(*i, *j);
54     }
55     quicksort(lo, i, cmp);
56     quicksort(i, hi, cmp);
57 }
58
59 template<class It> void quicksort(It lo, It hi) {
60     typedef typename std::iterator_traits<It>::value_type T;
61     quicksort(lo, hi, std::less<T>());
62 }
63
64 /*
65
66 Merge Sort
67
68 Time Complexity (Best):  $O(n \log n)$ 
69 Time Complexity (Average):  $O(n \log n)$ 
70 Time Complexity (Worst):  $O(n \log n)$ 
71 Space Complexity:  $O(n)$  auxiliary.
72 Stable?: Yes
73
74 Merge sort works by first dividing a list into  $n$  sublists, each with
75 one element, then recursively merging sublists to produce new sorted
76 sublists until only a single sorted sublist remains. Merge sort has a
77 better worst case than quicksort, and is also stable, meaning that it
78 will preserve the relative ordering of elements considered equal by
79 the < operator or comparator ( $a < b$  and  $b < a$  both return false).
80
81 While std::stable_sort() is a corresponding function in the standard
82 library, the implementation below differs in that it will simply fail
83 if extra memory is not available. Meanwhile, std::stable_sort() will
84 not fail, but instead fall back to a time complexity of  $O(n \log^2 n)$ .
85
86 */
87
88 template<class It, class Compare>
89 void mergesort(It lo, It hi, Compare cmp) {
90     if (hi - lo < 2) return;
91     It mid = lo + (hi - lo - 1) / 2, a = lo, c = mid + 1;
92     mergesort(lo, mid + 1, cmp);
93     mergesort(mid + 1, hi, cmp);
94     typedef typename std::iterator_traits<It>::value_type T;

```

```

95     T *buf = new T[hi - lo], *b = buf;
96     while (a <= mid && c < hi)
97         *(b++) = cmp(*c, *a) ? *(c++) : *(a++);
98     if (a > mid)
99         for (It k = c; k < hi; k++) *(b++) = *k;
100    else
101        for (It k = a; k <= mid; k++) *(b++) = *k;
102    for (int i = hi - lo - 1; i >= 0; i--)
103        *(lo + i) = buf[i];
104    delete[] buf;
105 }
106
107 template<class It> void mergesort(It lo, It hi) {
108     typedef typename std::iterator_traits<It>::value_type T;
109     mergesort(lo, hi, std::less<T>());
110 }
111
112 /*
113
114 Heapsort
115
116 Time Complexity (Best): O(n log n)
117 Time Complexity (Average): O(n log n)
118 Time Complexity (Worst): O(n log n)
119 Space Complexity: O(1) auxiliary.
120 Stable?: No
121
122 Heapsort first rearranges an array to satisfy the heap property, and
123 then the max element of the heap is repeatedly removed and added to the
124 end of the resulting sorted list. A heapified array has the root node
125 at index 0. The two children of the node at index n are respectively
126 located at indices 2n + 1 and 2n + 2. Each node is greater than both
127 of its children. This leads to a structure that takes O(log n) to
128 insert any element or remove the max element. Heapsort has a better
129 worst case complexity than quicksort, but a better space complexity
130 complexity than merge sort.
131
132 The standard library equivalent is calling std::make_heap(), followed
133 by std::sort_heap() on the input range.
134
135 */
136
137 template<class It, class Compare>
138 void heapsort(It lo, It hi, Compare cmp) {
139     typename std::iterator_traits<It>::value_type t;
140     It i = lo + (hi - lo) / 2, j = hi, parent, child;
141     for (;;) {
142         if (i <= lo) {
143             if (--j == lo) return;
144             t = *j;
145             *j = *lo;
146         } else {
147             t = *(--i);
148         }
149         parent = i;
150         child = lo + 2 * (i - lo) + 1;
151         while (child < j) {
152             if (child + 1 < j && cmp(*child, *(child + 1))) child++;
153             if (!cmp(t, *child)) break;

```

```

154     *parent = *child;
155     parent = child;
156     child = lo + 2 * (parent - lo) + 1;
157 }
158 *(lo + (parent - lo)) = t;
159 }
160 }
161
162 template<class It> void heapsort(It lo, It hi) {
163     typedef typename std::iterator_traits<It>::value_type T;
164     heapsort(lo, hi, std::less<T>());
165 }
166
167 /*
168
169 Comb Sort
170
171 Time Complexity (Best):  $O(n)$ 
172 Time Complexity (Average):  $O(n^2 / 2^p)$  for  $p$  increments.
173 Time Complexity (Worst):  $O(n^2)$ 
174 Space Complexity:  $O(1)$  auxiliary.
175 Stable?: No
176
177 Comb sort is an improved bubble sort. While bubble sort increases the
178 gap between swapped elements for every inner loop iteration, comb sort
179 uses a fixed gap for the inner loop and decreases the gap size by a
180 shrink factor for every iteration of the outer loop.
181
182 Even though the average time complexity is theoretically  $O(n^2)$ , if the
183 increments (gap sizes) are relatively prime and the shrink factor is
184 sensible (1.3 is empirically determined to be the best), then it will
185 require astronomically large  $n$  to make the algorithm exceed  $O(n \log n)$ 
186 steps. In practice, comb sort is only 2-3 times slower than merge sort.
187
188 */
189
190 template<class It, class Compare>
191 void combsort(It lo, It hi, Compare cmp) {
192     int gap = hi - lo;
193     bool swapped = true;
194     while (gap > 1 || swapped) {
195         if (gap > 1) gap = (int)((float)gap / 1.3f);
196         swapped = false;
197         for (It i = lo; i + gap < hi; i++)
198             if (cmp(*(i + gap), *i)) {
199                 std::swap(*i, *(i + gap));
200                 swapped = true;
201             }
202     }
203 }
204
205 template<class It> void combsort(It lo, It hi) {
206     typedef typename std::iterator_traits<It>::value_type T;
207     combsort(lo, hi, std::less<T>());
208 }
209
210 /*
211
212 Radix Sort

```

```

213
214 Time Complexity:  $O(n * w)$  for  $n$  integers of  $w$  bits.
215 Space Complexity:  $O(n + w)$  auxiliary.
216 Stable?: Yes
217
218 Radix sort can be used to sort integer keys with a constant number of
219 bits in linear time. The keys are grouped by the individual digits of
220 a particular base which share the same significant position and value.
221
222 The implementation below only works on ranges pointing to unsigned
223 integer primitives (but can be modified to also work on signed values).
224 Note that the input range need not strictly be "unsigned" types, as
225 long as the values are all technically non-negative. A power of two is
226 chosen to be the base of the sort since bitwise operations may be used
227 to extract digits (instead of modulus and powers, which are much less
228 efficient). In practice, it's been demonstrated that  $2^8$  is the best
229 choice for sorting 32-bit integers (roughly 5 times faster than using
230 std::sort and 2 to 4 times faster than any other chosen power of two).
231
232 This implementation was adapted from: http://qr.ae/RbdDTa
233 Explanation of base  $2^8$  choice: http://qr.ae/RbdDcG
234
235 */
236
237 template<class UnsignedIt>
238 void radix_sort(UnsignedIt lo, UnsignedIt hi) {
239     if (hi - lo < 2) return;
240     const int radix_bits = 8;
241     const int radix_base = 1 << radix_bits; //e.g.  $2^8 = 256$ 
242     const int radix_mask = radix_base - 1; //e.g.  $2^8 - 1 = 0xFF$ 
243     int num_bits = 8 * sizeof(*lo); //8 bits per byte
244     typedef typename std::iterator_traits<UnsignedIt>::value_type T;
245     T *l = new T[hi - lo];
246     for (int pos = 0; pos < num_bits; pos += radix_bits) {
247         int count[radix_base] = {0};
248         for (UnsignedIt it = lo; it != hi; it++)
249             count[( *it >> pos) & radix_mask]++;
250         T *bucket[radix_base], *curr = l;
251         for (int i = 0; i < radix_base; curr += count[i++])
252             bucket[i] = curr;
253         for (UnsignedIt it = lo; it != hi; it++)
254             *bucket[( *it >> pos) & radix_mask]++ = *it;
255         std::copy(l, l + (hi - lo), lo);
256     }
257     delete[] l;
258 }
259
260 /** Example Usage
261
262 Sample Output:
263
264 mergesort() with default comparisons: 1.32 1.41 1.62 1.73 2.58 2.72 3.14 4.67
265 mergesort() with 'compare_as_ints()': 1.41 1.73 1.32 1.62 2.72 2.58 3.14 4.67
266 -----
267 Sorting five million integers...
268 std::sort(): 0.429s
269 quicksort(): 0.498s
270 mergesort(): 1.437s
271 heapsort(): 1.179s

```

```

272 combsort(): 1.023s
273 radix_sort(): 0.078s
274
275 */
276
277 #include <cassert>
278 #include <cstdlib>
279 #include <ctime>
280 #include <iomanip>
281 #include <iostream>
282 #include <vector>
283 using namespace std;
284
285 template<class It> void print_range(It lo, It hi) {
286     while (lo != hi)
287         cout << *(lo++) << " ";
288     cout << "\n";
289 }
290
291 template<class It> bool is_sorted(It lo, It hi) {
292     while (++lo != hi)
293         if (*(lo - 1) > *lo) return false;
294     return true;
295 }
296
297 bool compare_as_ints(double i, double j) {
298     return (int)i < (int)j;
299 }
300
301 int main () {
302     { //can be used to sort arrays like std::sort()
303       int a[] = {32, 71, 12, 45, 26, 80, 53, 33};
304       quicksort(a, a + 8);
305       assert(is_sorted(a, a + 8));
306     }
307     { //STL containers work too
308       int a[] = {32, 71, 12, 45, 26, 80, 53, 33};
309       vector<int> v(a, a + 8);
310       quicksort(v.begin(), v.end());
311       assert(is_sorted(v.begin(), v.end()));
312     }
313     { //reverse iterators work as expected
314       int a[] = {32, 71, 12, 45, 26, 80, 53, 33};
315       vector<int> v(a, a + 8);
316       heapsort(v.rbegin(), v.rend());
317       assert(is_sorted(v.rbegin(), v.rend()));
318     }
319     { //doubles are also fine
320       double a[] = {1.1, -5.0, 6.23, 4.123, 155.2};
321       vector<double> v(a, a + 5);
322       combsort(v.begin(), v.end());
323       assert(is_sorted(v.begin(), v.end()));
324     }
325     { //only unsigned ints work for radix_sort (but reverse works!)
326       int a[] = {32, 71, 12, 45, 26, 80, 53, 33};
327       vector<int> v(a, a + 8);
328       radix_sort(v.rbegin(), v.rend());
329       assert(is_sorted(v.rbegin(), v.rend()));
330     }

```



```

331
332 //example from http://www.cplusplus.com/reference/algorithm/stable_sort
333 double a[] = {3.14, 1.41, 2.72, 4.67, 1.73, 1.32, 1.62, 2.58};
334 {
335     vector<double> v(a, a + 8);
336     cout << "mergesort() with default comparisons:";
337     mergesort(v.begin(), v.end());
338     print_range(v.begin(), v.end());
339 }
340 {
341     vector<double> v(a, a + 8);
342     cout << "mergesort() with 'compare_as_ints()':";
343     mergesort(v.begin(), v.end(), compare_as_ints);
344     print_range(v.begin(), v.end());
345 }
346 cout << "-----" << endl;
347
348 vector<int> v, v2;
349 for (int i = 0; i < 5000000; i++)
350     v.push_back((rand() & 0x7fff) | ((rand() & 0x7fff) << 15));
351 v2 = v;
352 cout << "Sorting five million integers..." << endl;
353 cout.precision(3);
354
355 #define test(sortfunc) { \
356     clock_t start = clock(); \
357     sortfunc(v.begin(), v.end()); \
358     double t = (double)(clock() - start) / CLOCKS_PER_SEC; \
359     cout << setw(14) << left << #sortfunc "():"; \
360     cout << fixed << t << "s" << endl; \
361     assert(is_sorted(v.begin(), v.end())); \
362     v = v2; \
363 }
364
365 test(std::sort);
366 test(quicksort);
367 test(mergesort);
368 test(heap sort);
369 test(combsort);
370 test(radix_sort);
371
372 return 0;
373 }

```

1.1.2 Array Rotation

```

1  /*
2
3  1.1.2 - Array Rotation
4
5  The following functions are equivalent to std::rotate(), taking three
6  iterators lo, mid, hi, and swapping the elements in the range [lo, hi)
7  in such a way that the element at mid becomes the first element of the
8  new range and the element at mid - 1 becomes the last element.
9
10 All three versions achieve the same result using no temporary arrays.
11 Version 1 uses a straightforward swapping algorithm listed on many C++

```

```

12 reference sites, requiring only forward iterators. Version 2 requires
13 bidirectional iterators, employing the well-known technique of three
14 simple reversals. Version 3 applies a "juggling" algorithm which first
15 divides the range into gcd(n, k) sets (n = hi - lo and k = mid - lo)
16 and then rotates the corresponding elements in each set. This version
17 requires random access iterators.
18
19 Time Complexity: O(n) on the distance between lo and hi.
20 Space Complexity: O(1) auxiliary.
21
22 */
23
24 #include <algorithm> /* std::reverse(), std::rotate(), std::swap() */
25
26 template<class It> void rotate1(It lo, It mid, It hi) {
27     It next = mid;
28     while (lo != next) {
29         std::swap(*lo++, *next++);
30         if (next == hi)
31             next = mid;
32         else if (lo == mid)
33             mid = next;
34     }
35 }
36
37 template<class It> void rotate2(It lo, It mid, It hi) {
38     std::reverse(lo, mid);
39     std::reverse(mid, hi);
40     std::reverse(lo, hi);
41 }
42
43 int gcd(int a, int b) {
44     return b == 0 ? a : gcd(b, a % b);
45 }
46
47 template<class It> void rotate3(It lo, It mid, It hi) {
48     int n = hi - lo, jump = mid - lo;
49     int g = gcd(jump, n), cycle = n / g;
50     for (int i = 0; i < g; i++) {
51         int curr = i, next;
52         for (int j = 0; j < cycle - 1; j++) {
53             next = curr + jump;
54             if (next >= n) next -= n;
55             std::swap(*(lo + curr), *(lo + next));
56             curr = next;
57         }
58     }
59 }
60
61 /** Example Usage
62
63 Sample Output:
64
65 before sort:  2 4 2 0 5 10 7 3 7 1
66 after sort:   0 1 2 2 3 4 5 7 7 10
67 rotate left:  1 2 2 3 4 5 7 7 10 0
68 rotate right: 0 1 2 2 3 4 5 7 7 10
69
70 */

```

```

71
72 #include <algorithm>
73 #include <cassert>
74 #include <iostream>
75 #include <vector>
76 using namespace std;
77
78 int main() {
79     std::vector<int> v0, v1, v2, v3;
80     for (int i = 0; i < 10000; i++) v0.push_back(i);
81     v1 = v2 = v3 = v0;
82     int mid = 5678;
83     std::rotate(v0.begin(), v0.begin() + mid, v0.end());
84     rotate1(v1.begin(), v1.begin() + mid, v1.end());
85     rotate2(v2.begin(), v2.begin() + mid, v2.end());
86     rotate3(v3.begin(), v3.begin() + mid, v3.end());
87     assert(v0 == v1 && v0 == v2 && v0 == v3);
88
89     //example from: http://en.cppreference.com/w/cpp/algorithm/rotate
90     int a[] = {2, 4, 2, 0, 5, 10, 7, 3, 7, 1};
91     vector<int> v(a, a + 10);
92     cout << "before_sort:\n";
93     for (int i = 0; i < (int)v.size(); i++)
94         cout << v[i] << ' ';
95     cout << endl;
96     //insertion sort
97     for (vector<int>::iterator i = v.begin(); i != v.end(); ++i)
98         rotate1(std::upper_bound(v.begin(), i, *i), i, i + 1);
99     cout << "after_sort:\n";
100    for (int i = 0; i < (int)v.size(); i++)
101        cout << v[i] << ' ';
102    cout << endl;
103    //simple rotation to the left
104    rotate2(v.begin(), v.begin() + 1, v.end());
105    cout << "rotate_left:\n";
106    for (int i = 0; i < (int)v.size(); i++)
107        cout << v[i] << ' ';
108    cout << endl;
109    //simple rotation to the right
110    rotate3(v.rbegin(), v.rbegin() + 1, v.rend());
111    cout << "rotate_right:\n";
112    for (int i = 0; i < (int)v.size(); i++)
113        cout << v[i] << ' ';
114    cout << endl;
115    return 0;
116 }

```

1.1.3 Counting Inversions

```

1  /*
2
3  1.1.3 - Counting Inversions
4
5  The number of inversions in an array a[] is the number of ordered pairs
6  (i, j) such that i < j and a[i] > a[j]. This is roughly how "close" an
7  array is to being sorted, but is not the same as the minimum number
8  of swaps required to sort the array. If the array is sorted then the

```

```

9 inversion count is 0. If the array is sorted in decreasing order, then
10 the inversion count is maximal. The following are two methods of
11 efficiently counting the number of inversions.
12
13 */
14
15 #include <iterator> /* std::iterator_traits */
16
17 /*
18
19 Version 1: Merge sort
20
21 The input range [lo, hi) will become sorted after the function call,
22 and then the number of inversions will be returned. The iterator's
23 value type must have the less than < operator defined appropriately.
24
25 Explanation: http://www.geeksforgeeks.org/counting-inversions
26
27 Time Complexity:  $O(n \log n)$  on the distance between lo and hi.
28 Space Complexity:  $O(n)$  auxiliary.
29
30 */
31
32 template<class It> long long inversions(It lo, It hi) {
33     if (hi - lo < 2) return 0;
34     It mid = lo + (hi - lo - 1) / 2, a = lo, c = mid + 1;
35     long long res = 0;
36     res += inversions(lo, mid + 1);
37     res += inversions(mid + 1, hi);
38     typedef typename std::iterator_traits<It>::value_type T;
39     T *buf = new T[hi - lo], *ptr = buf;
40     while (a <= mid && c < hi) {
41         if (*c < *a) {
42             *(ptr++) = *(c++);
43             res += (mid - a) + 1;
44         } else {
45             *(ptr++) = *(a++);
46         }
47     }
48     if (a > mid)
49         for (It k = c; k < hi; k++) *(ptr++) = *k;
50     else
51         for (It k = a; k <= mid; k++) *(ptr++) = *k;
52     for (int i = hi - lo - 1; i >= 0; i--)
53         *(lo + i) = buf[i];
54     delete[] buf;
55     return res;
56 }
57
58 /*
59
60 Version 2: Magic
61
62 The following magic is courtesy of misof, and works for any array of
63 nonnegative integers.
64
65 Explanation: http://codeforces.com/blog/entry/17881?comment=232099
66
67 The complexity depends on the magnitude of the maximum value in a[].
```

```

68 Coordinate compression should be applied on the values of a[] so that
69 they are strictly integers with magnitudes up to n for best results.
70 Note that after calling the function, a[] will be entirely set to 0.
71
72 Time Complexity:  $O(m \log m)$ , where m is maximum value in the array.
73 Space Complexity:  $O(m)$  auxiliary.
74
75 */
76
77 long long inversions(int n, int a[]) {
78     int mx = 0;
79     for (int i = 0; i < n; i++)
80         if (a[i] > mx) mx = a[i];
81     long long res = 0;
82     int *c = new int[mx];
83     while (mx > 0) {
84         for (int i = 0; i < mx; i++) c[i] = 0;
85         for (int i = 0; i < n; i++) {
86             if (a[i] % 2 == 0)
87                 res += c[a[i] / 2];
88             else
89                 c[a[i] / 2]++;
90         }
91         mx = 0;
92         for (int i = 0; i < n; i++)
93             if ((a[i] /= 2) > mx) mx = a[i];
94     }
95     delete[] c;
96     return res;
97 }
98
99 /** Example Usage **/
100
101 #include <cassert>
102
103 int main() {
104     {
105         int a[] = {6, 9, 1, 14, 8, 12, 3, 2};
106         assert(inversions(a, a + 8) == 16);
107     }
108     {
109         int a[] = {6, 9, 1, 14, 8, 12, 3, 2};
110         assert(inversions(8, a) == 16);
111     }
112     return 0;
113 }

```

1.1.4 Coordinate Compression

```

1  /*
2
3  1.1.4 - Coordinate Compression
4
5  Given an array a[] of size n, reassign integers to each value of a[]
6  such that the magnitude of each new value is no more than n, while the
7  relative order of each value as they were in the original array is
8  preserved. That is, if a[] is the original array and b[] is the result

```

```

9  array, then for every pair (i, j), the result of comparing a[i] < a[j]
10 will be exactly the same as the result of b[i] < b[j]. Furthermore,
11 no value of b[] will exceed the *number* of distinct values in a[].
12
13 In the following implementations, values in the range [lo, hi) will be
14 converted to integers in the range [0, d), where d is the number of
15 distinct values in the original range. lo and hi must be random access
16 iterators pointing to a numerical type that int can be assigned to.
17
18 Time Complexity: O(n log n) on the distance between lo and hi.
19 Space Complexity: O(n) auxiliary.
20
21 */
22
23 #include <algorithm> /* std::lower_bound(), std::sort(), std::unique() */
24 #include <iterator>  /* std::iterator_traits */
25 #include <map>
26
27 //version 1 - using std::sort(), std::unique() and std::lower_bound()
28 template<class It> void compress1(It lo, It hi) {
29     typedef typename std::iterator_traits<It>::value_type T;
30     T *a = new T[hi - lo];
31     int n = 0;
32     for (It it = lo; it != hi; ++it)
33         a[n++] = *it;
34     std::sort(a, a + n);
35     int n2 = std::unique(a, a + n) - a;
36     for (It it = lo; it != hi; ++it)
37         *it = (int)(std::lower_bound(a, a + n2, *it) - a);
38     delete[] a;
39 }
40
41 //version 2 - using std::map
42 template<class It> void compress2(It lo, It hi) {
43     typedef typename std::iterator_traits<It>::value_type T;
44     std::map<T, int> m;
45     for (It it = lo; it != hi; ++it)
46         m[*it] = 0;
47     typename std::map<T, int>::iterator x = m.begin();
48     for (int i = 0; x != m.end(); x++)
49         x->second = i++;
50     for (It it = lo; it != hi; ++it)
51         *it = m[*it];
52 }
53
54 /** Example Usage
55
56 Sample Output:
57
58 0 4 4 1 3 2 5 5
59 0 4 4 1 3 2 5 5
60 1 0 2 0 3 1
61
62 ***/
63
64 #include <iostream>
65 using namespace std;
66
67 template<class It> void print_range(It lo, It hi) {

```

```

68     while (lo != hi)
69         cout << *(lo++) << " ";
70     cout << "\n";
71 }
72
73 int main() {
74     {
75         int a[] = {1, 30, 30, 7, 9, 8, 99, 99};
76         compress1(a, a + 8);
77         print_range(a, a + 8);
78     }
79     {
80         int a[] = {1, 30, 30, 7, 9, 8, 99, 99};
81         compress2(a, a + 8);
82         print_range(a, a + 8);
83     }
84     { //works on doubles too
85         double a[] = {0.5, -1.0, 3, -1.0, 20, 0.5};
86         compress1(a, a + 6);
87         print_range(a, a + 6);
88     }
89     return 0;
90 }

```

1.1.5 Selection (Quickselect)

```

1  /*
2
3  1.1.5 - Selection (Quickselect)
4
5  Quickselect (also known as Hoare's algorithm) is a selection algorithm
6  which rearranges the elements in a sequence such that the element at
7  the nth position is the element that would be there if the sequence
8  were sorted. The other elements in the sequence are partitioned around
9  the nth element. That is, they are left in no particular order, except
10 that no element before the nth element is greater than it, and no
11 element after it is less.
12
13 The following implementation is equivalent to std::nth_element(),
14 taking in two random access iterators as the range and performing the
15 described operation in expected linear time.
16
17 Time Complexity (Average):  $O(n)$  on the distance between lo and hi.
18 Time Complexity (Worst):  $O(n^2)$ , although this almost never occurs.
19 Space Complexity:  $O(1)$  auxiliary.
20
21 */
22
23 #include <algorithm> /* std::swap() */
24 #include <cstdlib>   /* rand() */
25 #include <iterator>  /* std::iterator_traits */
26
27 int rand32(int n) {
28     return ((rand() & 0x7fff) | ((rand() & 0x7fff) << 15)) % n;
29 }
30
31 template<class It> It rand_partition(It lo, It hi) {

```

```

32     std::swap(*(lo + rand32(hi - lo)), *(hi - 1));
33     typename std::iterator_traits<It>::value_type mid = *(hi - 1);
34     It i = lo - 1;
35     for (It j = lo; j != hi; ++j)
36         if (*j <= mid)
37             std::swap(*(++i), *j);
38     return i;
39 }
40
41 template<class It> void nth_element2(It lo, It n, It hi) {
42     for (;;) {
43         It k = rand_partition(lo, hi);
44         if (n < k)
45             hi = k;
46         else if (n > k)
47             lo = k + 1;
48         else
49             return;
50     }
51 }
52
53 /** Example Usage
54
55 Sample Output:
56 2 3 1 5 4 6 8 7 9
57
58 */
59
60 #include <iostream>
61 using namespace std;
62
63 template<class It> void print_range(It lo, It hi) {
64     while (lo != hi)
65         cout << *(lo++) << " ";
66     cout << "\n";
67 }
68
69 int main () {
70     int a[] = {1, 2, 3, 4, 5, 6, 7, 8, 9};
71     random_shuffle(a, a + 9);
72     nth_element2(a, a + 5, a + 9);
73     print_range(a, a + 9);
74     return 0;
75 }

```

1.2 Array Queries

1.2.1 Longest Increasing Subsequence

```

1  /*
2
3  1.2.1 - Longest Increasing Subsequence
4
5  Find a subarray of a given array n such that the subarray's
6  elements are in sorted order, lowest to highest, and in which
7  the subsequence is as long as possible. This subsequence is not

```



```

8  necessarily contiguous, or unique, so the following function
9  will find one such sequence.
10
11  Time Complexity:  $O(n \log n)$  on the size of the array.
12  Space Complexity:  $O(n)$  auxiliary.
13
14  */
15
16  #include <vector>
17
18  int lower_bound(int a[], int tail[], int len, int key) {
19      int lo = -1, hi = len;
20      while (hi - lo > 1) {
21          int mid = (lo + hi) / 2;
22          if (a[tail[mid]] < key) lo = mid;
23          else hi = mid;
24      }
25      return hi;
26  }
27
28  template<class T> std::vector<T> lis(int n, T a[]) {
29      int tail[n], prev[n];
30      int len = 0;
31      for (int i = 0; i < n; i++) {
32          int pos = lower_bound(a, tail, len, a[i]);
33          if (len < pos + 1) len = pos + 1;
34          prev[i] = pos > 0 ? tail[pos - 1] : -1;
35          tail[pos] = i;
36      }
37      std::vector<T> res(len);
38      for (int i = tail[len - 1]; i != -1; i = prev[i])
39          res[--len] = a[i];
40      return res;
41  }
42
43  /** Example Usage */
44
45  #include <iostream>
46  using namespace std;
47
48  template<class It> void print(It lo, It hi) {
49      while (lo != hi) cout << *lo++ << " ";
50      cout << "\n";
51  }
52
53  int main () {
54      int a[] = {-2, -5, 1, 9, 10, 8, 11, 10, 13, 11};
55      vector<int> res = lis(10, a);
56      print(res.begin(), res.end()); // -5 1 9 10 11 13
57      return 0;
58  }

```

1.2.2 Maximal Subarray Sum (Kadane's)

```

1  /*
2
3  1.2.2 - Maximal Subarray Sum (Kadane's Algorithm)

```

```

4
5 Given an array of integers that may be negative, determine
6 the maximum sum of any contiguous subarray. Additionally,
7 do so optimally without using extra memory.
8
9 Time Complexity:  $O(n)$  on the size of the array
10 Space Complexity:  $O(1)$  auxiliary.
11
12 */
13
14 template<class It> int max_subarray_sum(It lo, It hi) {
15     int max_ending_here = 0, max_so_far = 0, max_overall;
16     for (max_overall = *lo; lo != hi; ++lo) {
17         max_ending_here += *lo;
18         if (max_overall < *lo) max_overall = *lo;
19         if (max_ending_here < 0) {
20             max_ending_here = 0;
21         } else if (max_so_far < max_ending_here) {
22             max_so_far = max_ending_here;
23         }
24     }
25     if (max_overall < 0) return max_overall; //all negative
26     return max_so_far;
27 }
28
29 /** Example Usage **/
30
31 #include <iostream>
32 using namespace std;
33
34 int main() {
35     int a[] = {-2, 1, -3, 4, -1, 2, 1, -5, 4};
36     //answer is 4 + (-1) + 2 + 1 = 6;
37     cout << max_subarray_sum(a, a + 9) << "\n";
38     return 0;
39 }

```

1.2.3 Majority Element (Boyer-Moore)

```

1 /*
2
3 1.2.3 - Majority Element (Boyer-Moore Algorithm)
4
5 Given an array of size n, the majority vote problem asks
6 to determine whether there exists a value with greater
7 occurrences than all the others, and if so, to determine
8 this value. In other words, a value must occur more than
9 floor(n/2) times to be the majority. Additionally, do so
10 optimally without using extra memory.
11
12 Time Complexity:  $O(n)$  on the size of the array.
13 Space Complexity:  $O(1)$  auxiliary space.
14
15 */
16
17 #include <iterator> /* std::iterator_traits */
18

```

```

19 //returns an iterator to the majority element in
20 //the range [lo, hi), or hi if none exists.
21 template<class It> It majority(It lo, It hi) {
22     int cnt = 0;
23     It candidate = lo;
24     for (It i = lo; i != hi; ++i) {
25         if (cnt == 0) {
26             candidate = i;
27             cnt = 1;
28         } else {
29             if (*i == *candidate) cnt++;
30             else cnt--;
31         }
32     }
33     cnt = 0;
34     for (It i = lo; i != hi; ++i)
35         if (*i == *candidate) cnt++;
36     if (cnt < (hi - lo + 1) / 2) return hi;
37     return candidate;
38 }
39
40 /** Example Usage */
41
42 #include <cassert>
43
44 int main() {
45     int a[] = {3, 2, 3, 1, 3};
46     int b[] = {2, 2, 3, 1, 3};
47     assert(*majority(a, a + 5) == 3);
48     assert(majority(b, b + 5) == b + 5);
49     return 0;
50 }

```

1.2.4 Subset Sum (Meet-in-the-Middle)

```

1  /*
2
3  1.2.4 - Subset Sum (Meet-in-the-Middle)
4
5  Given an unsorted array of integers and a value v, determine
6  the minimum sum of any subset of values in the array that is
7  not less than v. A meet-in-the-middle algorithm divides the
8  array in two equal parts. All possible sums are precomputed
9  and stored in a table and sorted by the sum. Finally, to
10 find the answer, the table is searched.
11
12 Time Complexity:  $O(n * 2^{(n / 2)})$  on the size of the array.
13 Space Complexity:  $O(n)$  auxiliary on the size of the array.
14
15 */
16
17 #include <algorithm> /* std::max(), std::sort() */
18 #include <climits> /* LLONG_MIN */
19
20 template<class It>
21 long long sum_lower_bound(It lo, It hi, long long v) {
22     int n = hi - lo;

```

```

23  int llen = 1 << (n / 2);
24  int rlen = 1 << (n - n / 2);
25  long long lsum[llen], rsum[rlen];
26  std::fill(lsum, lsum + llen, 0);
27  std::fill(rsum, rsum + rlen, 0);
28  for (int i = 0; i < llen; ++i)
29      for (int j = 0; j < n / 2; ++j)
30          if ((i & (1 << j)) > 0)
31              lsum[i] += *(lo + j);
32  for (int i = 0; i < rlen; ++i)
33      for (int j = 0; j < n - n / 2; ++j)
34          if ((i & (1 << j)) > 0)
35              rsum[i] += *(lo + j + n / 2);
36  std::sort(lsum, lsum + llen);
37  std::sort(rsum, rsum + llen);
38  int l = 0, r = rlen - 1;
39  long long cur = LLONG_MIN;
40  while (l < llen && r >= 0) {
41      if (lsum[l] + rsum[r] <= v) {
42          cur = std::max(cur, lsum[l] + rsum[r]);
43          l++;
44      } else {
45          r--;
46      }
47  }
48  return cur;
49 }
50
51 /** Example Usage **/
52
53 #include <iostream>
54 using namespace std;
55
56 int main() {
57     long long a[] = {9, 1, 5, 0, 1, 11, 5};
58     cout << sum_lower_bound(a, a + 7, 8) << "\n"; //7
59     return 0;
60 }

```

1.2.5 Maximal Zero Submatrix

```

1  /*
2
3  1.2.5 - Maximal Zero Submatrix
4
5  Given a rectangular matrix of 0's and 1's, determine the
6  area of the largest submatrix which contains only 0's.
7
8  Time Complexity:  $O(n * m)$ , where  $n$  is the number of rows
9  and  $m$  is the number of columns in the matrix.
10
11 Space Complexity:  $O(m)$  auxiliary on the number of columns.
12
13 */
14
15 #include <algorithm> /* std::max() */
16 #include <vector>

```

```

17
18 typedef std::vector<std::vector<bool> > matrix;
19
20 int max_zero_submatrix(const matrix & a) {
21     int n = a.size(), m = a[0].size(), res = 0;
22     std::vector<int> d(m, -1), d1(m), d2(m), st(m);
23     for (int r = 0; r < n; r++) {
24         for (int c = 0; c < m; c++)
25             if (a[r][c]) d[c] = r;
26         int sz = 0;
27         for (int c = 0; c < m; c++) {
28             while (sz > 0 && d[st[sz - 1]] <= d[c]) sz--;
29             d1[c] = sz == 0 ? -1 : st[sz - 1];
30             st[sz++] = c;
31         }
32         sz = 0;
33         for (int c = m - 1; c >= 0; c--) {
34             while (sz > 0 && d[st[sz - 1]] <= d[c]) sz--;
35             d2[c] = sz == 0 ? m : st[sz - 1];
36             st[sz++] = c;
37         }
38         for (int j = 0; j < m; j++)
39             res = std::max(res, (r - d[j]) * (d2[j] - d1[j] - 1));
40     }
41     return res;
42 }
43
44 /** Example Usage */
45
46 #include <iostream>
47 using namespace std;
48
49 int main() {
50     const int n = 5, m = 6;
51     bool a[n][m] = {{1, 0, 1, 1, 0, 0},
52                     {1, 0, 0, 1, 0, 0},
53                     {0, 0, 0, 0, 0, 1},
54                     {1, 0, 0, 1, 0, 0},
55                     {1, 0, 1, 0, 0, 1}};
56     matrix v(n);
57     for (int i = 0; i < 5; i++)
58         v[i] = vector<bool>(a[i], a[i] + m);
59     cout << max_zero_submatrix(v) << "\n";
60     return 0;
61 }

```

1.3 Searching

1.3.1 Discrete Binary Search

```

1  /*
2
3  1.3.1 - Discrete Binary Search
4
5  Not only can binary search be used on arrays, it can also be used
6  on monotonic functions. In this case we aren't restricted by

```

```

7  tangible quantities such as available memory, as is the case with
8  storing values explicitly in a sorted array.
9
10 binary_search_first_true() returns the smallest integer k in the
11 range [lo, hi) - (i.e. including lo, but excluding hi) for which
12 the boolean function query(k) is true. It can be used if and only
13 if there exists a constant k where the return value of query(x)
14 is false for all x < k and true for all x >= k.
15
16 binary_search_last_true() returns the greatest integer k in the
17 range [lo, hi) - (i.e. including lo, but excluding hi) for which
18 the boolean function query(k) is true. It can be used if and only
19 if there exists a constant k where the return value of query(x)
20 is true for all x <= k and false for all x > k.
21
22 Complexity: At most  $O(\log N)$  calls to query(), where N is the
23 search space (the distance between lo and hi).
24
25 fbinary_search() works like binary_search_first_true(), but on
26 floating point query functions. Since the set of reals numbers is
27 dense, it is clear that we cannot find the exact target. Instead,
28 fbinary_search() will return a value that is very close to the
29 border between false and true. Note that the number of iterations
30 performed depends on how precise we want the answer to be. Although
31 one can loop while (hi - lo > epsilon) until the distance between
32 lo and hi is really small, we can instead just keep it simple and
33 let the loop run for a few hundred iterations. In most contest
34 applications, 100 iterations is more than sufficient, reducing the
35 search space to  $10^{-30}$  times its original size.
36
37 */
38
39 //000[1]11
40 template<class Int, class BoolFunction>
41 Int binary_search_first_true(Int lo, Int hi, BoolFunction query) {
42     Int mid, _hi = hi;
43     while (lo < hi) {
44         mid = lo + (hi - lo) / 2;
45         if (query(mid)) hi = mid;
46         else lo = mid + 1;
47     }
48     if (!query(lo)) return _hi; //all [lo, hi) is false
49     return lo;
50 }
51
52 //11[1]000
53 template<class Int, class BoolFunction>
54 Int binary_search_last_true(Int lo, Int hi, BoolFunction query) {
55     Int mid, _hi = hi;
56     while (lo < hi) {
57         mid = lo + (hi - lo + 1) / 2;
58         if (query(mid)) lo = mid;
59         else hi = mid - 1;
60     }
61     if (!query(lo)) return _hi; //all [lo, hi) is true
62     return lo;
63 }
64
65 //000[1]11

```

```

66 template<class Double, class BoolFunction>
67 Double fbinary_search(Double lo, Double hi, BoolFunction query) {
68     Double mid;
69     for (int reps = 0; reps < 100; reps++) {
70         mid = (lo + hi) / 2.0;
71         //simply switch hi and lo in the line below to find last true
72         (query(mid) ? hi : lo) = mid;
73     }
74     return lo;
75 }
76
77 /** Example Usage */
78
79 #include <iostream>
80 using namespace std;
81
82 //Define your own black-box query function here. Simple examples:
83 bool query1(int x) { return x >= 3; }
84 bool query2(int x) { return false; }
85 bool query3(int x) { return x <= 5; }
86 bool query4(int x) { return true; }
87 bool query5(double x) { return x >= 1.2345; }
88
89 int main() {
90     cout << binary_search_first_true(0, 7, query1) << "\n"; //3
91     cout << binary_search_first_true(0, 7, query2) << "\n"; //7
92     cout << binary_search_last_true(0, 7, query3) << "\n"; //5
93     cout << binary_search_last_true(0, 7, query4) << "\n"; //7
94     cout << fbinary_search(-10.0, 10.0, query5) << "\n"; //1.2345
95     return 0;
96 }

```

1.3.2 Ternary Search

```

1  /*
2
3  1.3.2 - Ternary Search
4
5  Given a unimodal function f(x), find its maximum or minimum.
6
7  Assume we are looking for a maximum of f(x) and that we know
8  the maximum lies somewhere between A and B. For the algorithm
9  to be applicable, there must be some value x such that:
10 >>> for all a,b with A <= a < b <= x, we have f(a) < f(b); and
11 >>> for all a,b with x <= a < b <= B, we have f(a) > f(b).
12
13 In other words, for the graph of f(x) must look like a "valley"
14 with a single point at its trough (lowest point) and no flat
15 regions on the left side or right side for a ternary search to
16 be able to find its minimum point. Similarly the graph of f(x)
17 must look like a "hill" with a single peak for a ternary search
18 to be able to find its maximum point.
19
20 The answer for both functions will be really close to the peak
21 or trough by no further than +/-epsilon (0.00000001 by default).
22
23 */

```

```

24
25 template<class UnimodalFunction>
26 double ternary_search_min(double lo, double hi,
27                           UnimodalFunction f, double eps = 1e-8) {
28     double lthird, hthird;
29     while (hi - lo > eps) {
30         lthird = lo + (hi - lo) / 3;
31         hthird = hi - (hi - lo) / 3;
32         if (f(lthird) < f(hthird)) hi = hthird;
33         else lo = lthird;
34     }
35     return lo;
36 }
37
38 template<class UnimodalFunction>
39 double ternary_search_max(double lo, double hi,
40                           UnimodalFunction f, double eps = 1e-8) {
41     double lthird, hthird;
42     while (hi - lo > eps) {
43         lthird = lo + (hi - lo) / 3;
44         hthird = hi - (hi - lo) / 3;
45         if (f(lthird) < f(hthird)) lo = lthird;
46         else hi = hthird;
47     }
48     return lo;
49 }
50
51 /** Example Usage */
52
53 #include <iostream>
54 using namespace std;
55
56 //parabola opening up with vertex at (-2, -24)
57 double f1(double x) { return 3 * x * x + 12 * x - 12; }
58
59 //parabola opening down with vertex at (0.105, 88.1)
60 double f2(double x) { return -5.7 * x * x + 1.2 * x + 88; }
61
62 int main() {
63     cout << ternary_search_min(-99, 99, f1) << endl; //-2
64     cout << ternary_search_max(-99, 99, f2) << endl; //0.105263
65     return 0;
66 }

```

1.3.3 Hill Climbing

```

1  /*
2
3  1.3.3 - Hill Climbing
4
5  Hill climbing is an optimization technique which finds the
6  local extrema of a function. It is an iterative algorithm
7  that starts with an arbitrary solution, then attempts to
8  find a better solution by incrementally changing a single
9  element of the solution. If the change produces a better
10 solution, an incremental change is made to the new solution,
11 repeating until no further improvements can be found.

```



```

12
13 Complexity:  $O(\log \text{SIZE})$  where SIZE is the search space.
14
15 */
16
17 #include <cmath>
18 #include <iostream>
19 using namespace std;
20
21 template<class BinaryFunction>
22 double find_minimum(BinaryFunction f) {
23     static const double PI = acos(-1.0);
24     double x = 0, y = 0, res = f(x, y);
25     for (double step = 1e6; step > 1e-7; ) {
26         double best = res, bestx = x, besty = y;
27         bool found = false;
28         for (int i = 0; i < 6; i++) {
29             double a = 2.0 * PI * i / 6.0;
30             double nextx = x + step * cos(a);
31             double nexty = y + step * sin(a);
32             double next = f(nextx, nexty);
33             if (best > next) {
34                 bestx = nextx;
35                 besty = nexty;
36                 best = next;
37                 found = true;
38             }
39         }
40         if (!found) {
41             step /= 2.0;
42         } else {
43             x = bestx;
44             y = besty;
45             res = best;
46         }
47     }
48     cout << fixed << x << " " << y << "\n";
49     return res;
50 }
51
52 /** Example Usage */
53
54 //minimized at f(2, 3) = 0
55 double f(double x, double y) {
56     return (x - 2)*(x - 2) + (y - 3)*(y - 3);
57 }
58
59 int main() {
60     cout.precision(1);
61     cout << fixed << find_minimum(f) << "\n";
62     return 0;
63 }

```

1.3.4 Convex Hull Optimization

```

1 /*
2

```

```

3  1.3.4 - Convex Hull Optimization
4
5  Given a set of lines in the form  $y = mx + b$  process queries
6  of x-coordinates to find the minimum y-value for any of the
7  lines when evaluated at x. For the following implementation,
8  the lines must be added in order of descending slope (m),
9  and queries must be called in nondecreasing order of x.
10 See: http://wcipeg.com/wiki/Convex\_hull\_optimization
11
12 Time Complexity:  $O(n \log n)$  overall, where n is the number
13 of lines, for any number of calls to the two functions that
14 satisfy the preconditions.
15
16 Space Complexity:  $O(n)$  auxiliary on the number of lines.
17
18 */
19
20 #include <vector>
21
22 std::vector<long long> M, B;
23 int ptr = 0;
24
25 //precondition: m must be the minimum of all lines added so far
26 void add_line(long long m, long long b) {
27     int len = M.size();
28     while (len >= 2 && (B[len - 2] - B[len - 1]) * (m - M[len - 1]) >=
29             (B[len - 1] - b) * (M[len - 1] - M[len - 2])) {
30         len--;
31     }
32     M.resize(len);
33     B.resize(len);
34     M.push_back(m);
35     B.push_back(b);
36 }
37
38 //precondition: x must be the maximum of all x queried so far
39 long long min_y(long long x) {
40     if (ptr >= (int)M.size()) ptr = (int)M.size() - 1;
41     while (ptr + 1 < (int)M.size() && M[ptr + 1] * x + B[ptr + 1] <=
42             M[ptr] * x + B[ptr]) {
43         ptr++;
44     }
45     return M[ptr] * x + B[ptr];
46 }
47
48 /** Example Usage */
49
50 #include <cassert>
51
52 int main() {
53     add_line(3, 0);
54     add_line(2, 1);
55     add_line(3, 2);
56     add_line(0, 6);
57     assert(min_y(0) == 0);
58     assert(min_y(1) == 3);
59     assert(min_y(2) == 5);
60     assert(min_y(3) == 6);
61     return 0;

```

62 }

1.4 Cycle Detection

1.4.1 Floyd's Algorithm

```

1  /*
2
3  1.4.1 - Cycle Detection (Floyd's Algorithm)
4
5  For a function f which maps a finite set S to itself and any
6  initial value x0 in S, the sequence of iterated values:
7
8  x_0, x_1 = f(x_0), x_2 = f(x_1), ... x_i = f(x_{i-1})
9
10 must eventually use the same value twice: there must be some
11 i <> j such that x_i = x_j. Once this happens, the sequence
12 must continue periodically, by repeating the same sequence
13 of values from x_i to x_{j1}. Cycle detection asks to find
14 i and j, given the function f(x) and x_0.
15
16 Floyd's cycle-finding algorithm, a.k.a. the "tortoise and
17 the hare algorithm", is a pointer algorithm that uses only
18 2 pointers, moving through the sequence at different speeds.
19
20 Time Complexity: O(lambda + mu), where lambda is the length
21 of the cycle and mu is the first index of x for which the
22 cycle starts to occur.
23
24 Space Complexity: O(1) auxiliary.
25
26 */
27
28 #include <utility> /* std::pair */
29
30 //returns pair<mu, lambda> (as described above)
31 template<class IntFunction>
32 std::pair<int, int> floyd(IntFunction f, int x0) {
33     int tortoise = f(x0), hare = f(f(x0));
34     while (tortoise != hare) {
35         tortoise = f(tortoise);
36         hare = f(f(hare));
37     }
38     int start = 0;
39     tortoise = x0;
40     while (tortoise != hare) {
41         tortoise = f(tortoise);
42         hare = f(hare);
43         start++;
44     }
45     int length = 1;
46     hare = f(tortoise);
47     while (tortoise != hare) {
48         hare = f(hare);
49         length++;
50     }

```

```

51     return std::make_pair(start, length);
52 }
53
54 /** Example Usage */
55
56 #include <cassert>
57 #include <iostream>
58 #include <set>
59 using namespace std;
60
61 int f(int x) {
62     return (123 * x * x + 4567890) % 1337;
63 }
64
65 void verify(int x0, int start, int length) {
66     set<int> s;
67     int x = x0;
68     for (int i = 0; i < start; i++) {
69         assert(!s.count(x));
70         s.insert(x);
71         x = f(x);
72     }
73     int startx = x;
74     s.clear();
75     for (int i = 0; i < length; i++) {
76         assert(!s.count(x));
77         s.insert(x);
78         x = f(x);
79     }
80     assert(startx == x);
81 }
82
83 int main () {
84     int x0 = 0;
85     pair<int, int> res = floyd(f, x0);
86     cout << "Found cycle of length " << res.second;
87     cout << " starting at x_ " << res.first << ".\n";
88     verify(x0, res.first, res.second);
89     return 0;
90 }

```

1.4.2 Brent's Algorithm

```

1  /*
2
3  1.4.2 - Cycle Detection (Brent's Algorithm)
4
5  For a function f which maps a finite set S to itself and any
6  initial value x0 in S, the sequence of iterated values:
7
8  x_0, x_1 = f(x_0), x_2 = f(x_1), ... x_i = f(x_{i-1})
9
10 must eventually use the same value twice: there must be some
11 i <> j such that x_i = x_j. Once this happens, the sequence
12 must continue periodically, by repeating the same sequence
13 of values from x_i to x_{j1}. Cycle detection asks to find
14 i and j, given the function f(x) and x_0.

```

```

15
16 Brent's cycle-finding algorithm is based on a different idea
17 than Floyd's: searching for the smallest power of two,  $2^i$ 
18 that is larger than both  $\lambda$  and  $\mu$ .
19
20 Time Complexity:  $O(\lambda + \mu)$ , where  $\lambda$  is the length
21 of the cycle and  $\mu$  is the first index of  $x$  for which the
22 cycle starts to occur. Brent claims that, on average, his
23 cycle finding algorithm runs around 36% more quickly than
24 Floyd's and that it speeds up the Pollard rho algorithm by
25 around 24% (see mathematics chapter).
26
27 Space Complexity:  $O(1)$  auxiliary.
28
29 */
30
31 #include <utility> /* std::pair */
32
33 //returns pair<mu, lambda> (as described above)
34 template<class IntFunction>
35 std::pair<int, int> brent(IntFunction f, int x0) {
36     int power = 1, length = 1;
37     int tortoise = x0, hare = f(x0);
38     while (tortoise != hare) {
39         if (power == length) {
40             tortoise = hare;
41             power *= 2;
42             length = 0;
43         }
44         hare = f(hare);
45         length++;
46     }
47     hare = x0;
48     for (int i = 0; i < length; i++)
49         hare = f(hare);
50     int start = 0;
51     tortoise = x0;
52     while (tortoise != hare) {
53         tortoise = f(tortoise);
54         hare = f(hare);
55         start++;
56     }
57     return std::make_pair(start, length);
58 }
59
60 /** Example Usage */
61
62 #include <cassert>
63 #include <iostream>
64 #include <set>
65 using namespace std;
66
67 int f(int x) {
68     return (123 * x * x + 4567890) % 1337;
69 }
70
71 void verify(int x0, int start, int length) {
72     set<int> s;
73     int x = x0;

```

```

74     for (int i = 0; i < start; i++) {
75         assert(!s.count(x));
76         s.insert(x);
77         x = f(x);
78     }
79     int startx = x;
80     s.clear();
81     for (int i = 0; i < length; i++) {
82         assert(!s.count(x));
83         s.insert(x);
84         x = f(x);
85     }
86     assert(startx == x);
87 }
88
89 int main () {
90     int x0 = 0;
91     pair<int, int> res = brent(f, x0);
92     cout << "Found cycle of length" << res.second;
93     cout << " starting at x_" << res.first << ".\n";
94     verify(x0, res.first, res.second);
95     return 0;
96 }

```

1.5 Binary Exponentiation

```

1  /*
2
3  1.5.1 - Binary Exponentiation
4
5  Exponentiation by squaring is a general method for fast
6  computation of large positive integer powers of a number.
7  This method is also known as "square-and-multiply." The
8  following version computes  $x^n$  modulo  $m$ . Remove the "% m"
9  if you do not want the answer to be modded - but as this
10 causes overflow, you should switch to a bigger data type.
11
12 Complexity:  $O(\log n)$  on the exponent of the computation.
13
14 */
15
16 #include <stdint.h>
17
18 uint64_t mulmod(uint64_t a, uint64_t b, uint64_t m) {
19     uint64_t x = 0, y = a % m;
20     for (; b > 0; b >>= 1) {
21         if (b & 1) x = (x + y) % m;
22         y = (y << 1) % m;
23     }
24     return x % m;
25 }
26
27 uint64_t powmod(uint64_t a, uint64_t b, uint64_t m) {
28     uint64_t x = 1, y = a;
29     for (; b > 0; b >>= 1) {
30         if (b & 1) x = mulmod(x, y, m);

```

```
31     y = mulmod(y, y, m);
32 }
33 return x % m;
34 }
35
36 /** Example Usage */
37
38 #include <cassert>
39
40 int main() {
41     assert(powmod(2, 10, 1000000007) == 1024);
42     return 0;
43 }
```

Chapter 2

Graph Theory

2.1 Depth-First Search

2.1.1 Depth-First Search

```
1  /*
2
3  2.1.1 - Depth First Search
4
5  Description: Given an unweighted graph, traverse all reachable
6  nodes from a source node. Each branch is explored as deep as
7  possible before more branches are visited. DFS only uses as
8  much space as the length of the longest branch. When DFS'ing
9  recursively, the internal call-stack could overflow, so
10 sometimes it is safer to use an explicit stack data structure.
11
12 Complexity:  $O(V+E)$  on the number of vertices and edges for
13 explicit graphs traversed without repetition.  $O(b^d)$  for
14 implicit graphs with a branch factor of  $b$ , searched to depth  $d$ .
15
16 ~=~=~= Sample Input ~=~=~=
17 12 11 0
18 0 1
19 0 6
20 0 7
21 1 2
22 1 5
23 2 3
24 2 4
25 7 8
26 7 11
27 8 9
28 8 10
29
30 ~=~=~= Sample Output ~=~=~=
31 Nodes visited: 0 1 2 3 4 5 6 7 8 9 10 11
32
33 */
34
35 #include <iostream>
```



```

36 #include <vector>
37 using namespace std;
38
39 const int MAXN = 100;
40 vector<bool> vis(MAXN);
41 vector<int> adj[MAXN];
42
43 void dfs(int u) {
44     vis[u] = true;
45     cout << "└─" << u;
46     for (int j = 0; j < (int)adj[u].size(); j++)
47         if (!vis[adj[u][j]])
48             dfs(adj[u][j]);
49 }
50
51 int main() {
52     int nodes, edges, start, u, v;
53     cin >> nodes >> edges >> start;
54     for (int i = 0; i < edges; i++) {
55         cin >> u >> v;
56         adj[u].push_back(v);
57     }
58     cout << "Nodes└─visited:";
59     dfs(start);
60     cout << "\n";
61     return 0;
62 }

```

2.1.2 Floodfill

```

1  /*
2
3  2.1.2 - Floodfill (DFS)
4
5  Description: Given a directed graph and a source node,
6  traverse to all reachable nodes from the source and determine
7  the total area traveled. Conceptually, the order that nodes
8  are visited in a "flooding" of the graph should resemble a
9  BFS ordering. However, if the objective is simply to visit
10 all reachable nodes without regard for the order (as is the
11 case with most applications of floodfill in contests), it is
12 much simpler to DFS because an extra queue is not needed.
13 The input graph is stored in an adjacency list.
14
15 Complexity:  $O(V+E)$  on the number of vertices and edges.
16
17 ~=~=~= Sample Input ~=~=~=
18 8 8 0
19 0 1
20 0 5
21 1 2
22 1 3
23 3 2
24 4 0
25 4 3
26 6 7
27

```

```

28  ~~~~ Sample Output ~~~~
29  Visited 5 nodes starting from 0
30
31  */
32
33  #include <iostream>
34  #include <vector>
35  using namespace std;
36
37  const int MAXN = 100;
38  vector<bool> vis(MAXN);
39  vector<int> adj[MAXN];
40
41  int dfs(int u) {
42      vis[u] = true;
43      int area = 1;
44      for (int j = 0; j < (int)adj[u].size(); j++)
45          if (!vis[adj[u][j]])
46              area += dfs(adj[u][j]);
47      return area;
48  }
49
50  int main() {
51      int nodes, edges, start, u, v;
52      cin >> nodes >> edges >> start;
53      for (int i = 0; i < edges; i++) {
54          cin >> u >> v;
55          adj[u].push_back(v);
56      }
57      cout << "Visited_" << dfs(start) << "_nodes";
58      cout << "_starting_from_" << start << "\n";
59      return 0;
60  }

```

2.1.3 Topological Sorting

```

1  /*
2
3  2.1.3 - Topological Sorting (DFS)
4
5  Description: Given a directed acyclic graph (DAG), order the nodes
6  such that for every edge from a to b, a precedes b in the ordering.
7  Usually, there is more than one possible valid ordering. The
8  following program uses DFS to produce one possible ordering.
9  This can also be used to detect whether the graph is a DAG.
10 Note that the DFS algorithm here produces a reversed topological
11 ordering, so the output must be printed backwards. The graph is
12 stored in an adjacency list.
13
14 Complexity:  $O(V+E)$  on the number of vertices and edges.
15
16 ~~~~ Sample Input ~~~~
17 8 9
18 0 3
19 0 4
20 1 3
21 2 4

```

```

22  2 7
23  3 5
24  3 6
25  3 7
26  4 6
27
28  ~=~=~= Sample Output ~=~=~=
29  The topological order: 2 1 0 4 3 7 6 5
30
31  */
32
33  #include <algorithm> /* std::fill(), std::reverse() */
34  #include <iostream>
35  #include <stdexcept> /* std::runtime_error() */
36  #include <vector>
37  using namespace std;
38
39  const int MAXN = 100;
40  vector<bool> vis(MAXN), done(MAXN);
41  vector<int> adj[MAXN], sorted;
42
43  void dfs(int u) {
44      if (vis[u])
45          throw std::runtime_error("Not_a_DAG.");
46      if (done[u]) return;
47      vis[u] = true;
48      for (int j = 0; j < (int)adj[u].size(); j++)
49          dfs(adj[u][j]);
50      vis[u] = false;
51      done[u] = true;
52      sorted.push_back(u);
53  }
54
55  void toposort(int nodes) {
56      fill(vis.begin(), vis.end(), false);
57      fill(done.begin(), done.end(), false);
58      sorted.clear();
59      for (int i = 0; i < nodes; i++)
60          if (!done[i]) dfs(i);
61      reverse(sorted.begin(), sorted.end());
62  }
63
64  int main() {
65      int nodes, edges, u, v;
66      cin >> nodes >> edges;
67      for (int i = 0; i < edges; i++) {
68          cin >> u >> v;
69          adj[u].push_back(v);
70      }
71      toposort(nodes);
72      cout << "The_topological_order:";
73      for (int i = 0; i < (int)sorted.size(); i++)
74          cout << " " << sorted[i];
75      cout << "\n";
76      return 0;
77  }

```

2.1.4 Eulerian Cycles

```

1  /*
2
3  2.1.4 - Eulerian Cycles (DFS)
4
5  Description: A Eulerian trail is a trail in a graph which
6  visits every edge exactly once. Similarly, an Eulerian circuit
7  or Eulerian cycle is an Eulerian trail which starts and ends
8  on the same vertex.
9
10 An undirected graph has an Eulerian cycle if and only if every
11 vertex has even degree, and all of its vertices with nonzero
12 degree belong to a single connected component.
13
14 A directed graph has an Eulerian cycle if and only if every
15 vertex has equal in degree and out degree, and all of its
16 vertices with nonzero degree belong to a single strongly
17 connected component.
18
19 Complexity:  $O(V+E)$  on the number of vertices and edges.
20
21 ~=~=~= Sample Input ~=~=~=
22 5 6
23 0 1
24 1 2
25 2 0
26 1 3
27 3 4
28 4 1
29
30 ~=~=~= Sample Output ~=~=~=
31 Eulerian cycle from 0 (directed): 0 1 3 4 1 2 0
32 Eulerian cycle from 2 (undirected): 2 1 3 4 1 0 2
33
34 */
35
36 #include <algorithm> /* std::reverse() */
37 #include <iostream>
38 #include <vector>
39 using namespace std;
40
41 const int MAXN = 100;
42
43 vector<int> euler_cycle_directed(vector<int> adj[], int u) {
44     vector<int> stack, res, cur_edge(MAXN);
45     stack.push_back(u);
46     while (!stack.empty()) {
47         u = stack.back();
48         stack.pop_back();
49         while (cur_edge[u] < (int)adj[u].size()) {
50             stack.push_back(u);
51             u = adj[u][cur_edge[u]++];
52         }
53         res.push_back(u);
54     }
55     reverse(res.begin(), res.end());
56     return res;

```

```

57 }
58
59 vector<int> euler_cycle_undirected(vector<int> adj[], int u) {
60     vector<vector<bool>> > used(MAXN, vector<bool>(MAXN, false));
61     vector<int> stack, res, cur_edge(MAXN);
62     stack.push_back(u);
63     while (!stack.empty()) {
64         u = stack.back();
65         stack.pop_back();
66         while (cur_edge[u] < (int)adj[u].size()) {
67             int v = adj[u][cur_edge[u]++];
68             if (!used[min(u, v)][max(u, v)]) {
69                 used[min(u, v)][max(u, v)] = 1;
70                 stack.push_back(u);
71                 u = v;
72             }
73         }
74         res.push_back(u);
75     }
76     reverse(res.begin(), res.end());
77     return res;
78 }
79
80 int main() {
81     int nodes, edges, u, v;
82     vector<int> g1[5], g2[5], cycle;
83
84     cin >> nodes >> edges;
85     for (int i = 0; i < edges; i++) {
86         cin >> u >> v;
87         g1[u].push_back(v);
88         g2[u].push_back(v);
89         g2[v].push_back(u);
90     }
91
92     cycle = euler_cycle_directed(g1, 0);
93     cout << "Eulerian cycle from 0 (directed):";
94     for (int i = 0; i < (int)cycle.size(); i++)
95         cout << " " << cycle[i];
96     cout << "\n";
97
98     cycle = euler_cycle_undirected(g2, 2);
99     cout << "Eulerian cycle from 2 (undirected):";
100     for (int i = 0; i < (int)cycle.size(); i++)
101         cout << " " << cycle[i];
102     cout << "\n";
103     return 0;
104 }

```

2.1.5 Unweighted Tree Centers

```

1  /*
2
3  2.1.5 - Unweighted Tree Centers, Centroid, and Diameter
4
5  The following applies to unweighted, undirected trees only.
6

```

```

7  find_centers(): Returns 1 or 2 tree centers. The center
8  (or Jordan center) of a graph is the set of all vertices of
9  minimum eccentricity, that is, the set of all vertices A
10 where the max distance d(A,B) to other vertices B is minimal.
11
12 find_centroid(): Returns a vertex where all of its subtrees
13 have size <= N/2, where N is the number of nodes in the tree.
14
15 diameter(): The diameter of a tree is the greatest distance
16 d(A,B) between any two of the nodes in the tree.
17
18 Complexity: All three functions are O(V) on the number of
19 vertices in the tree.
20
21 ~=~=~= Sample Input ~=~=~=
22 6
23 0 1
24 1 2
25 1 4
26 3 4
27 4 5
28
29 ~=~=~= Sample Output ~=~=~=
30 Center(s): 1 4
31 Centroid: 4
32 Diameter: 3
33
34 */
35
36 #include <iostream>
37 #include <vector>
38 using namespace std;
39
40 const int MAXN = 100;
41 vector<int> adj[MAXN];
42
43 vector<int> find_centers(int n) {
44     vector<int> leaves, degree(n);
45     for (int i = 0; i < n; i++) {
46         degree[i] = adj[i].size();
47         if (degree[i] <= 1) leaves.push_back(i);
48     }
49     int removed = leaves.size();
50     while (removed < n) {
51         vector<int> nleaves;
52         for (int i = 0; i < (int)leaves.size(); i++) {
53             int u = leaves[i];
54             for (int j = 0; j < (int)adj[u].size(); j++) {
55                 int v = adj[u][j];
56                 if (--degree[v] == 1)
57                     nleaves.push_back(v);
58             }
59         }
60         leaves = nleaves;
61         removed += leaves.size();
62     }
63     return leaves;
64 }
65

```

```

66 int find_centroid(int n, int u = 0, int p = -1) {
67     int cnt = 1, v;
68     bool good_center = true;
69     for (int j = 0; j < (int)adj[u].size(); j++) {
70         if ((v = adj[u][j]) == p) continue;
71         int res = find_centroid(n, v, u);
72         if (res >= 0) return res;
73         int size = -res;
74         good_center &= (size <= n / 2);
75         cnt += size;
76     }
77     good_center &= (n - cnt <= n / 2);
78     return good_center ? u : -cnt;
79 }
80
81 pair<int, int> dfs(int u, int p, int depth) {
82     pair<int, int> res = make_pair(depth, u);
83     for (int j = 0; j < (int)adj[u].size(); j++)
84         if (adj[u][j] != p)
85             res = max(res, dfs(adj[u][j], u, depth + 1));
86     return res;
87 }
88
89 int diameter() {
90     int furthest_vertex = dfs(0, -1, 0).second;
91     return dfs(furthest_vertex, -1, 0).first;
92 }
93
94 int main() {
95     int nodes, u, v;
96     cin >> nodes;
97     for (int i = 0; i < nodes - 1; i++) {
98         cin >> u >> v;
99         adj[u].push_back(v);
100        adj[v].push_back(u);
101    }
102    vector<int> centers = find_centers(nodes);
103    cout << "Center(s):";
104    for (int i = 0; i < (int)centers.size(); i++)
105        cout << "␣" << centers[i];
106    cout << "\nCentroid:␣" << find_centroid(nodes);
107    cout << "\nDiameter:␣" << diameter() << "\n";
108    return 0;
109 }

```

2.2 Shortest Paths

2.2.1 Breadth First Search

```

1  /*
2
3  2.2.1 - Shortest Path (Breadth First Search)
4
5  Description: Given an unweighted graph, traverse all reachable
6  nodes from a source node and determine the shortest path.
7

```

```

8 Complexity:  $O(V+E)$  on the number of vertices and edges.
9
10 Note: The line "for (q.push(start); !q.empty(); q.pop())"
11 is simply a mnemonic for looping a BFS with a FIFO queue.
12 This will not work as intended with a priority queue, such as in
13 Dijkstra's algorithm for solving weighted shortest paths
14
15 ~=~=~= Sample Input ~=~=~=
16 4 5
17 0 1
18 0 3
19 1 2
20 1 3
21 2 3
22 0 3
23
24 ~=~=~= Sample Output ~=~=~=
25 The shortest distance from 0 to 3 is 2.
26 Take the path: 0->1->3.
27
28 */
29
30 #include <iostream>
31 #include <queue>
32 #include <vector>
33 using namespace std;
34
35 const int MAXN = 100, INF = 0x3f3f3f3f;
36 int dist[MAXN], pred[MAXN];
37 vector<int> adj[MAXN];
38
39 void bfs(int nodes, int start) {
40     vector<bool> vis(nodes, false);
41     for (int i = 0; i < nodes; i++) {
42         dist[i] = INF;
43         pred[i] = -1;
44     }
45     int u, v, d;
46     queue<pair<int, int> > q;
47     q.push(make_pair(start, 0));
48     while (!q.empty()) {
49         u = q.front().first;
50         d = q.front().second;
51         q.pop();
52         vis[u] = true;
53         for (int j = 0; j < (int)adj[u].size(); j++) {
54             if (vis[v = adj[u][j]]) continue;
55             dist[v] = d + 1;
56             pred[v] = u;
57             q.push(make_pair(v, d + 1));
58         }
59     }
60 }
61
62 //Use the precomputed pred[] array to print the path
63 void print_path(int dest) {
64     int i = 0, j = dest, path[MAXN];
65     while (pred[j] != -1) j = path[++i] = pred[j];
66     cout << "Take the path: ";

```



```

67 while (i > 0) cout << path[i--] << "->";
68 cout << dest << ".\n";
69 }
70
71 int main() {
72     int nodes, edges, u, v, start, dest;
73     cin >> nodes >> edges;
74     for (int i = 0; i < edges; i++) {
75         cin >> u >> v;
76         adj[u].push_back(v);
77     }
78     cin >> start >> dest;
79     bfs(nodes, start);
80     cout << "The shortest distance from " << start;
81     cout << " to " << dest << " is " << dist[dest] << ".\n";
82     print_path(dest);
83     return 0;
84 }

```

2.2.2 Dijkstra's Algorithm

```

1  /*
2
3  2.2.2 - Dijkstra's Algorithm (Single Source Shortest Path)
4
5  Description: Given a directed graph with positive weights only, find
6  the shortest distance to all nodes from a single starting node.
7
8  Implementation Notes: The graph is stored using an adjacency list.
9  This implementation negates distances before adding them to the
10 priority queue, since the container is a max-heap by default. This
11 method is suggested in contests because it is easier than defining
12 special comparators. An alternative would be declaring the queue
13 with template parameters (clearly, this way is very verbose and ugly):
14     priority_queue< pair<int, int>, vector<pair<int, int> >,
15                   greater<pair<int, int> > > pq;
16 If only the path between a single pair of nodes is needed, for speed,
17 we may break out of the loop as soon as the destination is reached
18 by inserting the line "if (a == dest) break;" after the line "pq.pop();"
19
20 Complexity: This version uses an adjacency list and priority queue
21 (internally a binary heap) and has a complexity of  $O((E+V) \log V) =$ 
22  $O(E \log V)$ . The priority queue and adjacency list improves the
23 simplest  $O(V^2)$  version of the algorithm, which uses looping and
24 an adjacency matrix. If the priority queue is implemented as a more
25 sophisticated Fibonacci heap, the complexity becomes  $O(E + V \log V)$ .
26
27 Modification to Shortest Path Faster Algorithm: The code for Dijkstra's
28 algorithm here can be easily modified to become the Shortest Path Faster
29 Algorithm (SPFA) by simply commenting out "visit[a] = true;" and changing
30 the priority queue to a FIFO queue like in BFS. SPFA is a faster version
31 of the Bellman-Ford algorithm, working on negative path lengths (whereas
32 Dijkstra's cannot). Certain graphs can be constructed to make SPFA slow.
33
34 ~=~=~= Sample Input ~=~=~=
35 4 5
36 0 1 2

```

```

37 0 3 8
38 1 2 2
39 1 3 4
40 2 3 1
41 0 3
42
43 ~=~=~= Sample Output ~=~=~=
44 The shortest distance from 0 to 3 is 5.
45 Take the path: 0->1->2->3.
46
47 */
48
49 #include <iostream>
50 #include <queue>
51 #include <vector>
52 using namespace std;
53
54 const int MAXN = 100, INF = 0x3f3f3f3f;
55 int dist[MAXN], pred[MAXN];
56 vector<pair<int, int> > adj[MAXN];
57
58 void dijkstra(int nodes, int start) {
59     vector<bool> vis(nodes, false);
60     for (int i = 0; i < nodes; i++) {
61         dist[i] = INF;
62         pred[i] = -1;
63     }
64     int u, v;
65     dist[start] = 0;
66     priority_queue<pair<int, int> > pq;
67     pq.push(make_pair(0, start));
68     while (!pq.empty()) {
69         u = pq.top().second;
70         pq.pop();
71         vis[u] = true;
72         for (int j = 0; j < (int)adj[u].size(); j++) {
73             if (vis[v = adj[u][j].first]) continue;
74             if (dist[v] > dist[u] + adj[u][j].second) {
75                 dist[v] = dist[u] + adj[u][j].second;
76                 pred[v] = u;
77                 pq.push(make_pair(-dist[v], v));
78             }
79         }
80     }
81 }
82
83 //Use the precomputed pred[] array to print the path
84 void print_path(int dest) {
85     int i = 0, j = dest, path[MAXN];
86     while (pred[j] != -1) j = path[++i] = pred[j];
87     cout << "Take the path: ";
88     while (i > 0) cout << path[i--] << "->";
89     cout << dest << ".\n";
90 }
91
92 int main() {
93     int nodes, edges, u, v, w, start, dest;
94     cin >> nodes >> edges;
95     for (int i = 0; i < edges; i++) {

```

```

96     cin >> u >> v >> w;
97     adj[u].push_back(make_pair(v, w));
98 }
99 cin >> start >> dest;
100 dijkstra(nodes, start);
101 cout << "The shortest distance from " << start;
102 cout << " to " << dest << " is " << dist[dest] << ".\n";
103 print_path(dest);
104 return 0;
105 }

```

2.2.3 Bellman-Ford Algorithm

```

1  /*
2
3  2.2.3 - Bellman-Ford Algorithm (Single-Source Shortest Path)
4
5  Description: Given a directed graph with positive or negative weights
6  but no negative cycles, find the shortest distance to all nodes from
7  a single starting node. The input graph is stored using an edge list.
8
9  Complexity:  $O(V \cdot E)$  on the number of vertices and edges, respectively.
10
11  ~=~=~= Sample Input ~=~=~=
12  3 3
13  0 1 1
14  1 2 2
15  0 2 5
16  0 2
17
18  ~=~=~= Sample Output ~=~=~=
19  The shortest distance from 0 to 2 is 3.
20  Take the path: 0->1->2.
21
22  */
23
24  #include <iostream>
25  #include <stdexcept>
26  #include <vector>
27  using namespace std;
28
29  struct edge { int u, v, w; };
30
31  const int MAXN = 100, INF = 0x3f3f3f3f;
32  int dist[MAXN], pred[MAXN];
33  vector<edge> e;
34
35  void bellman_ford(int nodes, int start) {
36      for (int i = 0; i < nodes; i++) {
37          dist[i] = INF;
38          pred[i] = -1;
39      }
40      dist[start] = 0;
41      for (int i = 0; i < nodes; i++) {
42          for (int j = 0; j < (int)e.size(); j++) {
43              if (dist[e[j].v] > dist[e[j].u] + e[j].w) {
44                  dist[e[j].v] = dist[e[j].u] + e[j].w;

```

```

45     pred[e[j].v] = e[j].u;
46 }
47 }
48 }
49 //optional: report negative-weight cycles
50 for (int i = 0; i < (int)e.size(); i++)
51     if (dist[e[i].v] > dist[e[i].u] + e[i].w)
52         throw std::runtime_error("Negative-weight found");
53 }
54
55 //Use the precomputed pred[] array to print the path
56 void print_path(int dest) {
57     int i = 0, j = dest, path[MAXN];
58     while (pred[j] != -1) j = path[++i] = pred[j];
59     cout << "Take the path: ";
60     while (i > 0) cout << path[i--] << "->";
61     cout << dest << ".\n";
62 }
63
64 int main() {
65     int nodes, edges, u, v, w, start, dest;
66     cin >> nodes >> edges;
67     for (int i = 0; i < edges; i++) {
68         cin >> u >> v >> w;
69         e.push_back((edge){u, v, w});
70     }
71     cin >> start >> dest;
72     bellman_ford(nodes, start);
73     cout << "The shortest distance from " << start;
74     cout << " to " << dest << " is " << dist[dest] << ".\n";
75     print_path(dest);
76     return 0;
77 }

```

2.2.4 Floyd-Warshall Algorithm

```

1  /*
2
3  2.2.4 - Floyd-Warshall Algorithm (All-Pairs Shortest Path)
4
5  Description: Given a directed graph with positive or negative
6  weights but no negative cycles, find the shortest distance
7  between all pairs of nodes. The input graph is stored using
8  an adjacency matrix. Note that the input adjacency matrix
9  is converted to the distance matrix afterwards. If you still
10 need the adjacencies afterwards, back it up at the beginning.
11
12 Complexity:  $O(V^3)$  on the number of vertices.
13
14 ~=~=~= Sample Input ~=~=~=
15 3 3
16 0 1 1
17 1 2 2
18 0 2 5
19 0 2
20
21 ~=~=~= Sample Output ~=~=~=

```

```

22 The shortest distance from 0 to 2 is 3.
23 Take the path: 0->1->2.
24
25 */
26
27 #include <iostream>
28 using namespace std;
29
30 const int MAXN = 100, INF = 0x3f3f3f3f;
31 int dist[MAXN][MAXN], next[MAXN][MAXN];
32
33 void initialize(int nodes) {
34     for (int i = 0; i < nodes; i++)
35         for (int j = 0; j < nodes; j++) {
36             dist[i][j] = (i == j) ? 0 : INF;
37             next[i][j] = -1;
38         }
39 }
40
41 void floyd_warshall(int nodes) {
42     for (int k = 0; k < nodes; k++)
43         for (int i = 0; i < nodes; i++)
44             for (int j = 0; j < nodes; j++)
45                 if (dist[i][j] > dist[i][k] + dist[k][j]) {
46                     dist[i][j] = dist[i][k] + dist[k][j];
47                     next[i][j] = k;
48                 }
49 }
50
51 void print_path(int u, int v) {
52     if (next[u][v] != -1) {
53         print_path(u, next[u][v]);
54         cout << next[u][v];
55         print_path(next[u][v], v);
56     } else cout << "->";
57 }
58
59 int main() {
60     int nodes, edges, u, v, w, start, dest;
61     cin >> nodes >> edges;
62     initialize(nodes);
63     for (int i = 0; i < edges; i++) {
64         cin >> u >> v >> w;
65         dist[u][v] = w;
66     }
67     cin >> start >> dest;
68     floyd_warshall(nodes);
69     cout << "The shortest distance from " << start;
70     cout << " to " << dest << " is ";
71     cout << dist[start][dest] << ".\n";
72
73     //Use next[][] to recursively print the path
74     cout << "Take the path " << start;
75     print_path(start, dest);
76     cout << dest << ".\n";
77     return 0;
78 }

```

2.3 Connectivity

2.3.1 Strongly Connected Components (Kosaraju's Algorithm)

```

1  /*
2
3  2.3.1 - Strongly Connected Components (Kosaraju's Algorithm)
4
5  Description: Determines the strongly connected components (SCC)
6  from a given directed graph. Given a directed graph, its SCCs
7  are its maximal strongly connected sub-graphs. A graph is
8  strongly connected if there is a path from each node to every
9  other node. Condensing the strongly connected components of a
10 graph into single nodes will result in a directed acyclic graph.
11 The input is stored in an adjacency list.
12
13 Complexity:  $O(V+E)$  on the number of vertices and edges.
14
15 Comparison with other SCC algorithms:
16 The strongly connected components of a graph can be efficiently
17 computed using Kosaraju's algorithm, Tarjan's algorithm, or the
18 path-based strong component algorithm. Tarjan's algorithm can
19 be seen as an improved version of Kosaraju's because it performs
20 a single DFS rather than two. Though they both have the same
21 complexity, Tarjan's algorithm is much more efficient in
22 practice. However, Kosaraju's algorithm is conceptually simpler.
23
24 ~=~=~= Sample Input ~=~=~=
25 8 14
26 0 1
27 1 2
28 1 4
29 1 5
30 2 3
31 2 6
32 3 2
33 3 7
34 4 0
35 4 5
36 5 6
37 6 5
38 7 3
39 7 6
40
41 ~=~=~= Sample Output ~=~=~=
42 Component: 1 4 0
43 Component: 7 3 2
44 Component: 5 6
45
46 */
47
48 #include <algorithm> /* std::fill(), std::reverse() */
49 #include <iostream>
50 #include <vector>
51 using namespace std;
52
53 const int MAXN = 100;

```

```

54 vector<bool> vis(MAXN);
55 vector<int> adj[MAXN], order;
56 vector<vector<int> > scc;
57
58 void dfs(vector<int> graph[], vector<int> & res, int u) {
59     vis[u] = true;
60     for (int j = 0; j < (int)graph[u].size(); j++)
61         if (!vis[graph[u][j]])
62             dfs(graph, res, graph[u][j]);
63     res.push_back(u);
64 }
65
66 void kosaraju(int nodes) {
67     scc.clear();
68     order.clear();
69     vector<int> rev[nodes];
70     fill(vis.begin(), vis.end(), false);
71     for (int i = 0; i < nodes; i++)
72         if (!vis[i]) dfs(adj, order, i);
73     for (int i = 0; i < nodes; i++)
74         for (int j = 0; j < (int)adj[i].size(); j++)
75             rev[adj[i][j]].push_back(i);
76     fill(vis.begin(), vis.end(), false);
77     reverse(order.begin(), order.end());
78     for (int i = 0; i < (int)order.size(); i++) {
79         if (vis[order[i]]) continue;
80         vector<int> component;
81         dfs(rev, component, order[i]);
82         scc.push_back(component);
83     }
84 }
85
86 int main() {
87     int nodes, edges, u, v;
88     cin >> nodes >> edges;
89     for (int i = 0; i < edges; i++) {
90         cin >> u >> v;
91         adj[u].push_back(v);
92     }
93     kosaraju(nodes);
94     for (int i = 0; i < (int)scc.size(); i++) {
95         cout << "Component:";
96         for (int j = 0; j < (int)scc[i].size(); j++)
97             cout << "□" << scc[i][j];
98         cout << "\n";
99     }
100     return 0;
101 }

```

2.3.2 Strongly Connected Components (Tarjan's Algorithm)

```

1  /*
2
3  2.3.2 - Strongly Connected Components (Tarjan's Algorithm)
4
5  Description: Determines the strongly connected components (SCC)
6  from a given directed graph. Given a directed graph, its SCCs

```

7 are its maximal strongly connected sub-graphs. A graph is
 8 strongly connected if there is a path from each node to every
 9 other node. Condensing the strongly connected components of a
 10 graph into single nodes will result in a directed acyclic graph.
 11 The input is stored in an adjacency list.

12
 13 In this implementation, a vector is used to emulate a stack
 14 for the sake of simplicity. One useful property of Tarjan's
 15 algorithm is that, while there is nothing special about the
 16 ordering of nodes within each component, the resulting DAG
 17 is produced in reverse topological order.

18
 19 Complexity: $O(V+E)$ on the number of vertices and edges.
 20

21 Comparison with other SCC algorithms:

22 The strongly connected components of a graph can be efficiently
 23 computed using Kosaraju's algorithm, Tarjan's algorithm, or the
 24 path-based strong component algorithm. Tarjan's algorithm can
 25 be seen as an improved version of Kosaraju's because it performs
 26 a single DFS rather than two. Though they both have the same
 27 complexity, Tarjan's algorithm is much more efficient in
 28 practice. However, Kosaraju's algorithm is conceptually simpler.

29
 30 ~=~=~= Sample Input ~=~=~=

31 8 14
 32 0 1
 33 1 2
 34 1 4
 35 1 5
 36 2 3
 37 2 6
 38 3 2
 39 3 7
 40 4 0
 41 4 5
 42 5 6
 43 6 5
 44 7 3
 45 7 6

46
 47 ~=~=~= Sample Output ~=~=~=

48 Component 1: 5 6
 49 Component 2: 7 3 2
 50 Component 3: 4 1 0

51
 52 */
 53
 54 #include <algorithm> /* std::fill() */
 55 #include <iostream>
 56 #include <vector>
 57 using namespace std;
 58
 59 const int MAXN = 100, INF = 0x3f3f3f3f;
 60 int timer, lowlink[MAXN];
 61 vector<bool> vis(MAXN);
 62 vector<int> adj[MAXN], stack;
 63 vector<vector<int>> > scc;
 64
 65 void dfs(int u) {


```

66     lowlink[u] = timer++;
67     vis[u] = true;
68     stack.push_back(u);
69     bool is_component_root = true;
70     int v;
71     for (int j = 0; j < (int)adj[u].size(); j++) {
72         if (!vis[v = adj[u][j]]) dfs(v);
73         if (lowlink[u] > lowlink[v]) {
74             lowlink[u] = lowlink[v];
75             is_component_root = false;
76         }
77     }
78     if (!is_component_root) return;
79     vector<int> component;
80     do {
81         vis[v = stack.back()] = true;
82         stack.pop_back();
83         lowlink[v] = INF;
84         component.push_back(v);
85     } while (u != v);
86     scc.push_back(component);
87 }
88
89 void tarjan(int nodes) {
90     scc.clear();
91     stack.clear();
92     fill(lowlink, lowlink + nodes, 0);
93     fill(vis.begin(), vis.end(), false);
94     timer = 0;
95     for (int i = 0; i < nodes; i++)
96         if (!vis[i]) dfs(i);
97 }
98
99 int main() {
100     int nodes, edges, u, v;
101     cin >> nodes >> edges;
102     for (int i = 0; i < edges; i++) {
103         cin >> u >> v;
104         adj[u].push_back(v);
105     }
106     tarjan(nodes);
107     for (int i = 0; i < (int)scc.size(); i++) {
108         cout << "Component:";
109         for (int j = 0; j < (int)scc[i].size(); j++)
110             cout << "␣" << scc[i][j];
111         cout << "\n";
112     }
113     return 0;
114 }

```

2.3.3 Bridges, Cut-points, and Biconnectivity

```

1  /*
2
3  2.3.3 - Bridges, Cut-points, and Biconnectivity (Tarjan's)
4
5  Description: The following operations apply to undirected graphs.

```

```

6
7 A bridge is an edge, when deleted, increases the number of
8 connected components. An edge is a bridge if and only if it is not
9 contained in any cycle.
10
11 A cut-point (i.e. cut-vertex or articulation point) is any vertex
12 whose removal increases the number of connected components.
13
14 A biconnected component of a graph is a maximally biconnected
15 subgraph. A biconnected graph is a connected and "nonseparable"
16 graph, meaning that if any vertex were to be removed, the graph
17 will remain connected. Therefore, a biconnected graph has no
18 articulation vertices.
19
20 Any connected graph decomposes into a tree of biconnected
21 components called the "block tree" of the graph. An unconnected
22 graph will thus decompose into a "block forest."
23
24 See: http://en.wikipedia.org/wiki/Biconnected\_component
25
26 Complexity:  $O(V+E)$  on the number of vertices and edges.
27
28 ~=~=~= Sample Input ~=~=~=
29 8 6
30 0 1
31 0 5
32 1 2
33 1 5
34 3 7
35 4 5
36
37 ~=~=~= Sample Output ~=~=~=
38 Cut Points: 5 1
39 Bridges:
40 1 2
41 5 4
42 3 7
43 Edge-Biconnected Components:
44 Component 1: 2
45 Component 2: 4
46 Component 3: 5 1 0
47 Component 4: 7
48 Component 5: 3
49 Component 6: 6
50 Adjacency List for Block Forest:
51 0 => 2
52 1 => 2
53 2 => 0 1
54 3 => 4
55 4 => 3
56 5 =>
57
58 */
59
60 #include <algorithm> /* std::fill(), std::min() */
61 #include <iostream>
62 #include <vector>
63 using namespace std;
64

```

```

65  const int MAXN = 100;
66  int timer, lowlink[MAXN], tin[MAXN], comp[MAXN];
67  vector<bool> vis(MAXN);
68  vector<int> adj[MAXN], bcc_forest[MAXN];
69  vector<int> stack, cutpoints;
70  vector<vector<int>> bcc;
71  vector<pair<int, int>> bridges;
72
73  void dfs(int u, int p) {
74      vis[u] = true;
75      lowlink[u] = tin[u] = timer++;
76      stack.push_back(u);
77      int v, children = 0;
78      bool cutpoint = false;
79      for (int j = 0; j < (int)adj[u].size(); j++) {
80          if ((v = adj[u][j]) == p) continue;
81          if (vis[v]) {
82              //lowlink[u] = min(lowlink[u], lowlink[v]);
83              lowlink[u] = min(lowlink[u], tin[v]);
84          } else {
85              dfs(v, u);
86              lowlink[u] = min(lowlink[u], lowlink[v]);
87              cutpoint |= (lowlink[v] >= tin[u]);
88              if (lowlink[v] > tin[u])
89                  bridges.push_back(make_pair(u, v));
90              children++;
91          }
92      }
93      if (p == -1) cutpoint = (children >= 2);
94      if (cutpoint) cutpoints.push_back(u);
95      if (lowlink[u] == tin[u]) {
96          vector<int> component;
97          do {
98              v = stack.back();
99              stack.pop_back();
100             component.push_back(v);
101         } while (u != v);
102         bcc.push_back(component);
103     }
104 }
105
106 void tarjan(int nodes) {
107     bcc.clear();
108     bridges.clear();
109     cutpoints.clear();
110     stack.clear();
111     fill(lowlink, lowlink + nodes, 0);
112     fill(tin, tin + nodes, 0);
113     fill(vis.begin(), vis.end(), false);
114     timer = 0;
115     for (int i = 0; i < nodes; i++)
116         if (!vis[i]) dfs(i, -1);
117 }
118
119 //condenses each bcc to a node and generates a tree
120 //global variables adj and bcc must be set beforehand
121 void get_block_tree(int nodes) {
122     fill(comp, comp + nodes, 0);
123     for (int i = 0; i < nodes; i++) bcc_forest[i].clear();

```

```

124     for (int i = 0; i < (int)bcc.size(); i++)
125         for (int j = 0; j < (int)bcc[i].size(); j++)
126             comp[bcc[i][j]] = i;
127     for (int i = 0; i < nodes; i++)
128         for (int j = 0; j < (int)adj[i].size(); j++)
129             if (comp[i] != comp[adj[i][j]])
130                 bcc_forest[comp[i]].push_back(comp[adj[i][j]]);
131 }
132
133 int main() {
134     int nodes, edges, u, v;
135     cin >> nodes >> edges;
136     for (int i = 0; i < edges; i++) {
137         cin >> u >> v;
138         adj[u].push_back(v);
139         adj[v].push_back(u);
140     }
141     tarjan(nodes);
142     cout << "Cut-points:";
143     for (int i = 0; i < (int)cutpoints.size(); i++)
144         cout << " " << cutpoints[i];
145     cout << "\nBridges:\n";
146     for (int i = 0; i < (int)bridges.size(); i++)
147         cout << bridges[i].first << " " << bridges[i].second << "\n";
148     cout << "Edge-Biconnected Components:\n";
149     for (int i = 0; i < (int)bcc.size(); i++) {
150         cout << "Component:";
151         for (int j = 0; j < (int)bcc[i].size(); j++)
152             cout << " " << bcc[i][j];
153         cout << "\n";
154     }
155     get_block_tree(nodes);
156     cout << "Adjacency List for Block Forest:\n";
157     for (int i = 0; i < (int)bcc.size(); i++) {
158         cout << i << "=>";
159         for (int j = 0; j < (int)bcc_forest[i].size(); j++)
160             cout << " " << bcc_forest[i][j];
161         cout << "\n";
162     }
163     return 0;
164 }

```

2.4 Minimal Spanning Trees

2.4.1 Prim's Algorithm

```

1  /*
2
3  2.4.1 - Minimum Spanning Tree (Prim's Algorithm)
4
5  Description: Given an undirected graph, its minimum spanning
6  tree (MST) is a tree connecting all nodes with a subset of its
7  edges such that their total weight is minimized. Prim's algorithm
8  greedily selects edges from a priority queue, and is similar to
9  Dijkstra's algorithm, where instead of processing nodes, we
10 process individual edges. If the graph is not connected, Prim's

```

```

11 algorithm will produce the minimum spanning forest. The input
12 graph is stored in an adjacency list.
13
14 Note that the concept of the minimum spanning tree makes Prim's
15 algorithm work with negative weights. In fact, a big positive
16 constant added to all of the edge weights of the graph will not
17 change the resulting spanning tree.
18
19 Implementation Notes: Similar to the implementation of Dijkstra's
20 algorithm in the previous section, weights are negated before they
21 are added to the priority queue (and negated once again when they
22 are retrieved). To find the maximum spanning tree, simply skip the
23 two negation steps and the max weighted edges will be prioritized.
24
25 Complexity: This version uses an adjacency list and priority queue
26 (internally a binary heap) and has a complexity of  $O((E+V) \log V) =$ 
27  $O(E \log V)$ . The priority queue and adjacency list improves the
28 simplest  $O(V^2)$  version of the algorithm, which uses looping and
29 an adjacency matrix. If the priority queue is implemented as a more
30 sophisticated Fibonacci heap, the complexity becomes  $O(E + V \log V)$ .
31
32 ~=~=~= Sample Input ~=~=~=
33 7 7
34 0 1 4
35 1 2 6
36 2 0 3
37 3 4 1
38 4 5 2
39 5 6 3
40 6 4 4
41
42 ~=~=~= Sample Output ~=~=~=
43 Total distance: 13
44 0<->2
45 0<->1
46 3<->4
47 4<->5
48 5<->6
49
50 */
51
52 #include <algorithm> /* std::fill() */
53 #include <iostream>
54 #include <queue>
55 #include <vector>
56 using namespace std;
57
58 const int MAXN = 100;
59 vector<pair<int, int> > adj[MAXN], mst;
60
61 int prim(int nodes) {
62     mst.clear();
63     vector<bool> vis(nodes);
64     int u, v, w, total_dist = 0;
65     for (int i = 0; i < nodes; i++) {
66         if (vis[i]) continue;
67         vis[i] = true;
68         priority_queue<pair<int, pair<int, int> > > pq;
69         for (int j = 0; j < (int)adj[i].size(); j++)

```

```

70     pq.push(make_pair(-adj[i][j].second,
71                     make_pair(i, adj[i][j].first)));
72     while (!pq.empty()) {
73         w = -pq.top().first;
74         u = pq.top().second.first;
75         v = pq.top().second.second;
76         pq.pop();
77         if (vis[u] && !vis[v]) {
78             vis[v] = true;
79             if (v != i) {
80                 mst.push_back(make_pair(u, v));
81                 total_dist += w;
82             }
83             for (int j = 0; j < (int)adj[v].size(); j++)
84                 pq.push(make_pair(-adj[v][j].second,
85                                 make_pair(v, adj[v][j].first)));
86         }
87     }
88 }
89 return total_dist;
90 }
91
92 int main() {
93     int nodes, edges, u, v, w;
94     cin >> nodes >> edges;
95     for (int i = 0; i < edges; i++) {
96         cin >> u >> v >> w;
97         adj[u].push_back(make_pair(v, w));
98         adj[v].push_back(make_pair(u, w));
99     }
100     cout << "Total_distance:␣" << prim(nodes) << "\n";
101     for (int i = 0; i < (int)mst.size(); i++)
102         cout << mst[i].first << "<->" << mst[i].second << "\n";
103     return 0;
104 }

```

2.4.2 Kruskal's Algorithm

```

1  /*
2
3  2.4.2 - Minimum Spanning Tree (Kruskal's Algorithm)
4
5  Description: Given an undirected graph, its minimum spanning
6  tree (MST) is a tree connecting all nodes with a subset of its
7  edges such that their total weight is minimized. If the graph
8  is not connected, Kruskal's algorithm will produce the minimum
9  spanning forest. The input graph is stored in an edge list.
10
11 Complexity:  $O(E \log V)$  on the number of edges and vertices.
12
13 ~=~=~= Sample Input ~=~=~=
14 7 7
15 0 1 4
16 1 2 6
17 2 0 3
18 3 4 1
19 4 5 2

```

```

20 5 6 3
21 6 4 4
22
23 ~=~=~= Sample Output ~=~=~=
24 Total distance: 13
25 3<->4
26 4<->5
27 2<->0
28 5<->6
29 0<->1
30
31 Note: If you already have a disjoint set data structure,
32 then the middle section of the program can be replaced by:
33
34 disjoint_set_forest<int> dsf;
35 for (int i = 0; i < nodes; i++) dsf.make_set(i);
36 for (int i = 0; i < E.size(); i++) {
37     a = E[i].second.first;
38     b = E[i].second.second;
39     if (!dsf.is_united(a, b)) {
40         ...
41         dsf.unite(a, b);
42     }
43 }
44
45 */
46
47 #include <algorithm> /* std::sort() */
48 #include <iostream>
49 #include <vector>
50 using namespace std;
51
52 const int MAXN = 100;
53 int root[MAXN];
54 vector<pair<int, pair<int, int> > > E;
55 vector<pair<int, int> > mst;
56
57 int find_root(int x) {
58     if (root[x] != x)
59         root[x] = find_root(root[x]);
60     return root[x];
61 }
62
63 int kruskal(int nodes) {
64     mst.clear();
65     sort(E.begin(), E.end());
66     int u, v, total_dist = 0;
67     for (int i = 0; i < nodes; i++) root[i] = i;
68     for (int i = 0; i < (int)E.size(); i++) {
69         u = find_root(E[i].second.first);
70         v = find_root(E[i].second.second);
71         if (u != v) {
72             mst.push_back(E[i].second);
73             total_dist += E[i].first;
74             root[u] = root[v];
75         }
76     }
77     return total_dist;
78 }

```

```

79
80 int main() {
81     int nodes, edges, u, v, w;
82     cin >> nodes >> edges;
83     for (int i = 0; i < edges; i++) {
84         cin >> u >> v >> w;
85         E.push_back(make_pair(w, make_pair(u, v)));
86     }
87     cout << "Total_distance:_" << kruskal(nodes) << "\n";
88     for (int i = 0; i < (int)mst.size(); i++)
89         cout << mst[i].first << "<->" << mst[i].second << "\n";
90     return 0;
91 }

```

2.5 Maximum Flow

2.5.1 Ford-Fulkerson Algorithm

```

1  /*
2
3  2.5.1 - Maximum Flow (Ford-Fulkerson Algorithm)
4
5  Description: Given a flow network, find a flow from a single
6  source node to a single sink node that is maximized. Note
7  that in this implementation, the adjacency matrix cap[][]
8  will be modified by the function ford_fulkerson() after it's
9  been called. Make a back-up if you require it afterwards.
10
11 Complexity:  $O(V^2 \cdot |F|)$ , where V is the number of
12 vertices and |F| is the magnitude of the max flow.
13
14 Real-valued capacities:
15 The Ford-Fulkerson algorithm is only optimal on graphs with
16 integer capacities; there exists certain real capacity inputs
17 for which it will never terminate. The Edmonds-Karp algorithm
18 is an improvement using BFS, supporting real number capacities.
19
20 ~=~=~= Sample Input ~=~=~=
21 6 8
22 0 1 3
23 0 2 3
24 1 2 2
25 1 3 3
26 2 4 2
27 3 4 1
28 3 5 2
29 4 5 3
30 0 5
31
32 ~=~=~= Sample Output ~=~=~=
33 5
34
35 */
36
37 #include <algorithm> /* std::fill() */
38 #include <iostream>

```



```

39 #include <vector>
40 using namespace std;
41
42 const int MAXN = 100, INF = 0x3f3f3f3f;
43 int nodes, source, sink, cap[MAXN][MAXN];
44 vector<bool> vis(MAXN);
45
46 int dfs(int u, int f) {
47     if (u == sink) return f;
48     vis[u] = true;
49     for (int v = 0; v < nodes; v++) {
50         if (!vis[v] && cap[u][v] > 0) {
51             int df = dfs(v, min(f, cap[u][v]));
52             if (df > 0) {
53                 cap[u][v] -= df;
54                 cap[v][u] += df;
55                 return df;
56             }
57         }
58     }
59     return 0;
60 }
61
62 int ford_fulkerson() {
63     int max_flow = 0;
64     for (;;) {
65         fill(vis.begin(), vis.end(), false);
66         int df = dfs(source, INF);
67         if (df == 0) break;
68         max_flow += df;
69     }
70     return max_flow;
71 }
72
73 int main() {
74     int edges, u, v, capacity;
75     cin >> nodes >> edges;
76     for (int i = 0; i < edges; i++) {
77         cin >> u >> v >> capacity;
78         cap[u][v] = capacity;
79     }
80     cin >> source >> sink;
81     cout << ford_fulkerson() << "\n";
82     return 0;
83 }

```

2.5.2 Edmonds-Karp Algorithm

```

1  /*
2
3  2.5.2 - Maximum Flow (Edmonds-Karp Algorithm)
4
5  Description: Given a flow network, find a flow from a single
6  source node to a single sink node that is maximized. Note
7  that in this implementation, the adjacency list adj[] will
8  be modified by the function edmonds_karp() after it's been called.
9

```

```

10 Complexity:  $O(\min(V \cdot E^2, E \cdot |F|))$ , where  $V$  is the number of
11 vertices,  $E$  is the number of edges, and  $|F|$  is the magnitude of
12 the max flow. This improves the original Ford-Fulkerson algorithm,
13 which runs in  $O(E \cdot |F|)$ . As the Edmonds-Karp algorithm is also
14 bounded by  $O(E \cdot |F|)$ , it is guaranteed to be at least as fast as
15 Ford-Fulkerson. For an even faster algorithm, see Dinic's
16 algorithm in the next section, which runs in  $O(V^2 \cdot E)$ .
17
18 Real-valued capacities:
19 Although the Ford-Fulkerson algorithm is only optimal on graphs
20 with integer capacities, the Edmonds-Karp algorithm also works
21 correctly on real-valued capacities.
22
23 ~=~=~= Sample Input ~=~=~=
24 6 8
25 0 1 3
26 0 2 3
27 1 2 2
28 1 3 3
29 2 4 2
30 3 4 1
31 3 5 2
32 4 5 3
33 0 5
34
35 ~=~=~= Sample Output ~=~=~=
36 5
37
38 */
39
40 #include <algorithm> /* std::fill(), std::min() */
41 #include <iostream>
42 #include <vector>
43 using namespace std;
44
45 struct edge { int s, t, rev, cap, f; };
46
47 const int MAXN = 100, INF = 0x3f3f3f3f;
48 vector<edge> adj[MAXN];
49
50 void add_edge(int s, int t, int cap) {
51     adj[s].push_back((edge){s, t, (int)adj[t].size(), cap, 0});
52     adj[t].push_back((edge){t, s, (int)adj[s].size() - 1, 0, 0});
53 }
54
55 int edmonds_karp(int nodes, int source, int sink) {
56     static int q[MAXN];
57     int max_flow = 0;
58     for (;;) {
59         int qt = 0;
60         q[qt++] = source;
61         edge * pred[nodes];
62         fill(pred, pred + nodes, (edge*)0);
63         for (int qh = 0; qh < qt && !pred[sink]; qh++) {
64             int u = q[qh];
65             for (int j = 0; j < (int)adj[u].size(); j++) {
66                 edge * e = &adj[u][j];
67                 if (!pred[e->t] && e->cap > e->f) {
68                     pred[e->t] = e;

```

```

69         q[qt++] = e->t;
70     }
71 }
72 }
73 if (!pred[sink]) break;
74 int df = INF;
75 for (int u = sink; u != source; u = pred[u]->s)
76     df = min(df, pred[u]->cap - pred[u]->f);
77 for (int u = sink; u != source; u = pred[u]->s) {
78     pred[u]->f += df;
79     adj[pred[u]->t][pred[u]->rev].f -= df;
80 }
81 max_flow += df;
82 }
83 return max_flow;
84 }
85
86 int main() {
87     int nodes, edges, u, v, capacity, source, sink;
88     cin >> nodes >> edges;
89     for (int i = 0; i < edges; i++) {
90         cin >> u >> v >> capacity;
91         add_edge(u, v, capacity);
92     }
93     cin >> source >> sink;
94     cout << edmonds_karp(nodes, source, sink) << "\n";
95     return 0;
96 }

```

2.5.3 Dinic's Algorithm

```

1  /*
2
3  2.5.3 - Maximum Flow (Dinic's Blocking Flow Algorithm)
4
5  Description: Given a flow network, find a flow from a single
6  source node to a single sink node that is maximized. Note
7  that in this implementation, the adjacency list adj[] will
8  be modified by the function dinic() after it's been called.
9
10 Complexity:  $O(V^2 \cdot E)$  on the number of vertices and edges.
11
12 Comparison with Edmonds-Karp Algorithm:
13 Dinic's is similar to the Edmonds-Karp algorithm in that it
14 uses the shortest augmenting path. The introduction of the
15 concepts of the level graph and blocking flow enable Dinic's
16 algorithm to achieve its better performance. Hence, Dinic's
17 algorithm is also called Dinic's blocking flow algorithm.
18
19 ~=~=~= Sample Input ~=~=~=
20 6 8
21 0 1 3
22 0 2 3
23 1 2 2
24 1 3 3
25 2 4 2
26 3 4 1

```

```

27 3 5 2
28 4 5 3
29 0 5
30
31 ~=~=~= Sample Output ~=~=~=
32 5
33
34 */
35
36 #include <algorithm> /* std::fill(), std::min() */
37 #include <iostream>
38 #include <vector>
39 using namespace std;
40
41 struct edge { int to, rev, cap, f; };
42
43 const int MAXN = 100, INF = 0x3f3f3f3f;
44 int dist[MAXN], ptr[MAXN];
45 vector<edge> adj[MAXN];
46
47 void add_edge(int s, int t, int cap) {
48     adj[s].push_back((edge){t, (int)adj[t].size(), cap, 0});
49     adj[t].push_back((edge){s, (int)adj[s].size() - 1, 0, 0});
50 }
51
52 bool dinic_bfs(int nodes, int source, int sink) {
53     fill(dist, dist + nodes, -1);
54     dist[source] = 0;
55     int q[nodes], qh = 0, qt = 0;
56     q[qt++] = source;
57     while (qh < qt) {
58         int u = q[qh++];
59         for (int j = 0; j < (int)adj[u].size(); j++) {
60             edge & e = adj[u][j];
61             if (dist[e.to] < 0 && e.f < e.cap) {
62                 dist[e.to] = dist[u] + 1;
63                 q[qt++] = e.to;
64             }
65         }
66     }
67     return dist[sink] >= 0;
68 }
69
70 int dinic_dfs(int u, int f, int sink) {
71     if (u == sink) return f;
72     for (; ptr[u] < (int)adj[u].size(); ptr[u]++) {
73         edge & e = adj[u][ptr[u]];
74         if (dist[e.to] == dist[u] + 1 && e.f < e.cap) {
75             int df = dinic_dfs(e.to, min(f, e.cap - e.f), sink);
76             if (df > 0) {
77                 e.f += df;
78                 adj[e.to][e.rev].f -= df;
79                 return df;
80             }
81         }
82     }
83     return 0;
84 }
85

```

```

86 int dinic(int nodes, int source, int sink) {
87     int max_flow = 0, delta;
88     while (dinic_bfs(nodes, source, sink)) {
89         fill(ptr, ptr + nodes, 0);
90         while ((delta = dinic_dfs(source, INF, sink)) != 0)
91             max_flow += delta;
92     }
93     return max_flow;
94 }
95
96 int main() {
97     int nodes, edges, u, v, capacity, source, sink;
98     cin >> nodes >> edges;
99     for (int i = 0; i < edges; i++) {
100         cin >> u >> v >> capacity;
101         add_edge(u, v, capacity);
102     }
103     cin >> source >> sink;
104     cout << dinic(nodes, source, sink) << "\n";
105     return 0;
106 }

```

2.5.4 Push-Relabel Algorithm

```

1  /*
2
3  2.5.4 - Max Flow (Push-Relabel Algorithm)
4
5  Description: Given a flow network, find a flow from a single
6  source node to a single sink node that is maximized. The push-
7  relabel algorithm is considered one of the most efficient
8  maximum flow algorithms. However, unlike the Ford-Fulkerson or
9  Edmonds-Karp algorithms, it cannot take advantage of the fact
10 if max flow itself has a small magnitude.
11
12 Complexity:  $O(V^3)$  on the number of vertices.
13
14 ~=~=~= Sample Input ~=~=~=
15 6 8
16 0 1 3
17 0 2 3
18 1 2 2
19 1 3 3
20 2 4 2
21 3 4 1
22 3 5 2
23 4 5 3
24 0 5
25
26 ~=~=~= Sample Output ~=~=~=
27 5
28
29 */
30
31 #include <algorithm> /* std::fill(), std::min() */
32 #include <iostream>
33 using namespace std;

```

```

34
35 const int MAXN = 100, INF = 0x3F3F3F3F;
36 int cap[MAXN][MAXN], f[MAXN][MAXN];
37
38 int push_relabel(int nodes, int source, int sink) {
39     int e[nodes], h[nodes], maxh[nodes];
40     fill(e, e + nodes, 0);
41     fill(h, h + nodes, 0);
42     fill(maxh, maxh + nodes, 0);
43     for (int i = 0; i < nodes; i++)
44         fill(f[i], f[i] + nodes, 0);
45     h[source] = nodes - 1;
46     for (int i = 0; i < nodes; i++) {
47         f[source][i] = cap[source][i];
48         f[i][source] = -f[source][i];
49         e[i] = cap[source][i];
50     }
51     int sz = 0;
52     for (;;) {
53         if (sz == 0) {
54             for (int i = 0; i < nodes; i++)
55                 if (i != source && i != sink && e[i] > 0) {
56                     if (sz != 0 && h[i] > h[maxh[0]]) sz = 0;
57                     maxh[sz++] = i;
58                 }
59         }
60         if (sz == 0) break;
61         while (sz != 0) {
62             int i = maxh[sz - 1];
63             bool pushed = false;
64             for (int j = 0; j < nodes && e[i] != 0; j++) {
65                 if (h[i] == h[j] + 1 && cap[i][j] - f[i][j] > 0) {
66                     int df = min(cap[i][j] - f[i][j], e[i]);
67                     f[i][j] += df;
68                     f[j][i] -= df;
69                     e[i] -= df;
70                     e[j] += df;
71                     if (e[i] == 0) sz--;
72                     pushed = true;
73                 }
74             }
75             if (!pushed) {
76                 h[i] = INF;
77                 for (int j = 0; j < nodes; j++)
78                     if (h[i] > h[j] + 1 && cap[i][j] - f[i][j] > 0)
79                         h[i] = h[j] + 1;
80                 if (h[i] > h[maxh[0]]) {
81                     sz = 0;
82                     break;
83                 }
84             }
85         }
86     }
87     int max_flow = 0;
88     for (int i = 0; i < nodes; i++)
89         max_flow += f[source][i];
90     return max_flow;
91 }
92

```

```

93 int main() {
94     int nodes, edges, u, v, capacity, source, sink;
95     cin >> nodes >> edges;
96     for (int i = 0; i < edges; i++) {
97         cin >> u >> v >> capacity;
98         cap[u][v] = capacity;
99     }
100    cin >> source >> sink;
101    cout << push_relabel(nodes, source, sink) << "\n";
102    return 0;
103 }

```

2.6 Backtracking

2.6.1 Max Clique (Bron-Kerbosch Algorithm)

```

1  /*
2
3  2.6.1 - Backtracking: Maximum Clique (Bron-Kerbosch Algorithm)
4
5  Description: Given an undirected graph, determine a subset of
6  the graph's vertices such that every pair of vertices in the
7  subset are connected by an edge, and that the subset is as
8  large as possible. For the weighted version, each vertex is
9  assigned a weight and the objective is to find the clique in
10 the graph that has maximum total weight.
11
12 Complexity:  $O(3^{(V/3)})$  where V is the number of vertices.
13
14 ~=~=~= Sample Input ~=~=~=
15 5 8
16 0 1
17 0 2
18 0 3
19 1 2
20 1 3
21 2 3
22 3 4
23 4 2
24 10 20 30 40 50
25
26 ~=~=~= Sample Output ~=~=~=
27 Max unweighted clique: 4
28 Max weighted clique: 120
29
30 */
31
32 #include <algorithm> /* std::fill(), std::max() */
33 #include <bitset>
34 #include <iostream>
35 #include <vector>
36 using namespace std;
37
38 const int MAXN = 35;
39 typedef bitset<MAXN> bits;
40 typedef unsigned long long ull;

```

```

41
42 int w[MAXN];
43 bool adj[MAXN][MAXN];
44
45 int rec(int nodes, bits & curr, bits & pool, bits & excl) {
46     if (pool.none() && excl.none()) return curr.count();
47     int ans = 0, u = 0;
48     for (int v = 0; v < nodes; v++)
49         if (pool[v] || excl[v]) u = v;
50     for (int v = 0; v < nodes; v++) {
51         if (!pool[v] || adj[u][v]) continue;
52         bits ncurr, npool, nexcl;
53         for (int i = 0; i < nodes; i++) ncurr[i] = curr[i];
54         ncurr[v] = true;
55         for (int j = 0; j < nodes; j++) {
56             npool[j] = pool[j] && adj[v][j];
57             nexcl[j] = excl[j] && adj[v][j];
58         }
59         ans = max(ans, rec(nodes, ncurr, npool, nexcl));
60         pool[v] = false;
61         excl[v] = true;
62     }
63     return ans;
64 }
65
66 int bron_kerbosch(int nodes) {
67     bits curr, excl, pool;
68     pool.flip();
69     return rec(nodes, curr, pool, excl);
70 }
71
72 //This is a fast implementation using bitmasks.
73 //Precondition: the number of nodes must be less than 64.
74 int bron_kerbosch_weighted(int nodes, ull g[], ull curr, ull pool, ull excl) {
75     if (pool == 0 && excl == 0) {
76         int res = 0, u = __builtin_ctzll(curr);
77         while (u < nodes) {
78             res += w[u];
79             u += __builtin_ctzll(curr >> (u + 1)) + 1;
80         }
81         return res;
82     }
83     if (pool == 0) return -1;
84     int res = -1, pivot = __builtin_ctzll(pool | excl);
85     ull z = pool & ~g[pivot];
86     int u = __builtin_ctzll(z);
87     while (u < nodes) {
88         res = max(res, bron_kerbosch_weighted(nodes, g, curr | (1LL << u),
89                                             pool & g[u], excl & g[u]));
90         pool ^= 1LL << u;
91         excl |= 1LL << u;
92         u += __builtin_ctzll(z >> (u + 1)) + 1;
93     }
94     return res;
95 }
96
97 int bron_kerbosch_weighted(int nodes) {
98     ull g[nodes];
99     for (int i = 0; i < nodes; i++) {

```



```

100     g[i] = 0;
101     for (int j = 0; j < nodes; j++)
102         if (adj[i][j]) g[i] |= 1LL << j;
103 }
104 return bron_kerbosch_weighted(nodes, g, 0, (1LL << nodes) - 1, 0);
105 }
106
107 int main() {
108     int nodes, edges, u, v;
109     cin >> nodes >> edges;
110     for (int i = 0; i < edges; i++) {
111         cin >> u >> v;
112         adj[u][v] = adj[v][u] = true;
113     }
114     for (int i = 0; i < nodes; i++) cin >> w[i];
115     cout << "Max_unweighted_clique: ";
116     cout << bron_kerbosch(nodes) << "\n";
117     cout << "Max_weighted_clique: ";
118     cout << bron_kerbosch_weighted(nodes) << "\n";
119     return 0;
120 }

```

2.6.2 Graph Coloring

```

1  /*
2
3  2.6.2 - Backtracking - Graph Coloring
4
5  Description: Given an undirected graph, assign colors to each
6  of the vertices such that no pair of adjacent vertices have the
7  same color. Furthermore, do so using the minimum # of colors.
8
9  Complexity: Exponential on the number of vertices. The exact
10 running time is difficult to calculate due to several pruning
11 optimizations used here.
12
13 ~=~=~= Sample Input ~=~=~=
14 5 7
15 0 1
16 0 4
17 1 3
18 1 4
19 2 3
20 2 4
21 3 4
22
23 ~=~=~= Sample Output ~=~=~=
24 Colored using 3 color(s). The colorings are:
25 Color 1: 0 3
26 Color 2: 1 2
27 Color 3: 4
28
29 */
30
31 #include <algorithm> /* std::fill(), std::max() */
32 #include <iostream>
33 #include <vector>

```

```

34 using namespace std;
35
36 const int MAXN = 30;
37 int cols[MAXN], adj[MAXN][MAXN];
38 int id[MAXN + 1], deg[MAXN + 1];
39 int min_cols, best_cols[MAXN];
40
41 void dfs(int from, int to, int cur, int used_cols) {
42     if (used_cols >= min_cols) return;
43     if (cur == to) {
44         for (int i = from; i < to; i++)
45             best_cols[id[i]] = cols[i];
46         min_cols = used_cols;
47         return;
48     }
49     vector<bool> used(used_cols + 1);
50     for (int i = 0; i < cur; i++)
51         if (adj[id[cur]][id[i]]) used[cols[i]] = true;
52     for (int i = 0; i <= used_cols; i++) {
53         if (!used[i]) {
54             int tmp = cols[cur];
55             cols[cur] = i;
56             dfs(from, to, cur + 1, max(used_cols, i + 1));
57             cols[cur] = tmp;
58         }
59     }
60 }
61
62 int color_graph(int nodes) {
63     for (int i = 0; i <= nodes; i++) {
64         id[i] = i;
65         deg[i] = 0;
66     }
67     int res = 1;
68     for (int from = 0, to = 1; to <= nodes; to++) {
69         int best = to;
70         for (int i = to; i < nodes; i++) {
71             if (adj[id[to - 1]][id[i]]) deg[id[i]]++;
72             if (deg[id[best]] < deg[id[i]]) best = i;
73         }
74         int tmp = id[to];
75         id[to] = id[best];
76         id[best] = tmp;
77         if (deg[id[to]] == 0) {
78             min_cols = nodes + 1;
79             fill(cols, cols + nodes, 0);
80             dfs(from, to, from, 0);
81             from = to;
82             res = max(res, min_cols);
83         }
84     }
85     return res;
86 }
87
88 int main() {
89     int nodes, edges, u, v;
90     cin >> nodes >> edges;
91     for (int i = 0; i < edges; i++) {
92         cin >> u >> v;

```

```

93     adj[u][v] = adj[v][u] = true;
94 }
95 cout << "Colored using " << color_graph(nodes);
96 cout << "color(s). The colorings are:\n";
97 for (int i = 0; i < min_cols; i++) {
98     cout << "Color " << i + 1 << ": ";
99     for (int j = 0; j < nodes; j++)
100         if (best_cols[j] == i) cout << " " << j;
101     cout << "\n";
102 }
103 return 0;
104 }

```

2.7 Maximum Matching

2.7.1 Maximum Bipartite Matching (Kuhn's Algorithm)

```

1  /*
2
3  2.7.1 - Maximum Bipartite Matching (Kuhn's Algorithm)
4
5  Description: Given two sets of vertices A = {0, 1, ..., n1}
6  and B = {0, 1, ..., n2} as well as a set of edges E mapping
7  nodes from set A to set B, determine the largest possible
8  subset of E such that no pair of edges in the subset share
9  a common vertex. Precondition: n2 >= n1.
10
11 Complexity: O(V*E) on the number of vertices and edges.
12
13 ~=~=~= Sample Input ~=~=~=
14 3 4 6
15 0 1
16 1 0
17 1 1
18 1 2
19 2 2
20 2 3
21
22 ~=~=~= Sample Output ~=~=~=
23 Matched 3 pairs. Matchings are:
24 1 0
25 0 1
26 2 2
27
28 */
29
30 #include <algorithm> /* std::fill() */
31 #include <iostream>
32 #include <vector>
33 using namespace std;
34
35 const int MAXN = 100;
36 int match[MAXN];
37 vector<bool> vis(MAXN);
38 vector<int> adj[MAXN];
39

```

```

40 bool dfs(int u) {
41     vis[u] = true;
42     for (int j = 0; j < (int)adj[u].size(); j++) {
43         int v = match[adj[u][j]];
44         if (v == -1 || (!vis[v] && dfs(v))) {
45             match[adj[u][j]] = u;
46             return true;
47         }
48     }
49     return false;
50 }
51
52 int kuhn(int n1, int n2) {
53     fill(vis.begin(), vis.end(), false);
54     fill(match, match + n2, -1);
55     int matches = 0;
56     for (int i = 0; i < n1; i++) {
57         for (int j = 0; j < n1; j++) vis[j] = 0;
58         if (dfs(i)) matches++;
59     }
60     return matches;
61 }
62
63 int main() {
64     int n1, n2, edges, u, v;
65     cin >> n1 >> n2 >> edges;
66     for (int i = 0; i < edges; i++) {
67         cin >> u >> v;
68         adj[u].push_back(v);
69     }
70     cout << "Matched_" << kuhn(n1, n2);
71     cout << "_pair(s)_Matchings_are:\n";
72     for (int i = 0; i < n2; i++) {
73         if (match[i] == -1) continue;
74         cout << match[i] << "_" << i << "\n";
75     }
76     return 0;
77 }

```

2.7.2 Maximum Bipartite Matching (Hopcroft-Karp Algorithm)

```

1  /*
2
3  2.7.2 - Maximum Bipartite Matching (Hopcroft-Karp Algorithm)
4
5  Description: Given two sets of vertices A = {0, 1, ..., n1}
6  and B = {0, 1, ..., n2} as well as a set of edges E mapping
7  nodes from set A to set B, determine the largest possible
8  subset of E such that no pair of edges in the subset share
9  a common vertex. Precondition: n2 >= n1.
10
11 Complexity: O(E sqrt V) on the number of edges and vertices.
12
13 ~=~=~= Sample Input ~=~=~=
14 3 4 6
15 0 1
16 1 0

```

```

17  1 1
18  1 2
19  2 2
20  2 3
21
22  ~=~=~= Sample Output ~=~=~=
23  Matched 3 pairs. Matchings are:
24  1 0
25  0 1
26  2 2
27
28  */
29
30  #include <algorithm> /* std::fill() */
31  #include <iostream>
32  #include <vector>
33  using namespace std;
34
35  const int MAXN = 100;
36  int match[MAXN], dist[MAXN];
37  vector<bool> used(MAXN), vis(MAXN);
38  vector<int> adj[MAXN];
39
40  void bfs(int n1, int n2) {
41      fill(dist, dist + n1, -1);
42      int q[n2], qb = 0;
43      for (int u = 0; u < n1; ++u) {
44          if (!used[u]) {
45              q[qb++] = u;
46              dist[u] = 0;
47          }
48      }
49      for (int i = 0; i < qb; i++) {
50          int u = q[i];
51          for (int j = 0; j < (int)adj[u].size(); j++) {
52              int v = match[adj[u][j]];
53              if (v >= 0 && dist[v] < 0) {
54                  dist[v] = dist[u] + 1;
55                  q[qb++] = v;
56              }
57          }
58      }
59  }
60
61  bool dfs(int u) {
62      vis[u] = true;
63      for (int j = 0; j < (int)adj[u].size(); j++) {
64          int v = match[adj[u][j]];
65          if (v < 0 || (!vis[v] && dist[v] == dist[u] + 1 && dfs(v))) {
66              match[adj[u][j]] = u;
67              used[u] = true;
68              return true;
69          }
70      }
71      return false;
72  }
73
74  int hopcroft_karp(int n1, int n2) {
75      fill(match, match + n2, -1);

```

```

76  fill(used.begin(), used.end(), false);
77  int res = 0;
78  for (;;) {
79      bfs(n1, n2);
80      fill(vis.begin(), vis.end(), false);
81      int f = 0;
82      for (int u = 0; u < n1; ++u)
83          if (!used[u] && dfs(u)) f++;
84      if (!f) return res;
85      res += f;
86  }
87  return res;
88 }
89
90 int main() {
91     int n1, n2, edges, u, v;
92     cin >> n1 >> n2 >> edges;
93     for (int i = 0; i < edges; i++) {
94         cin >> u >> v;
95         adj[u].push_back(v);
96     }
97     cout << "Matched_" << hopcroft_karp(n1, n2);
98     cout << "_pair(s)._Matchings_are:\n";
99     for (int i = 0; i < n2; i++) {
100         if (match[i] == -1) continue;
101         cout << match[i] << "_" << i << "\n";
102     }
103     return 0;
104 }

```

2.7.3 Maximum Graph Matching (Edmonds's Algorithm)

```

1  /*
2
3  2.7.3 - Maximum Matching for General Graphs (Edmonds's Algorithm)
4
5  Description: Given a general directed graph, determine a maximal
6  subset of the edges such that no vertex is repeated in the subset.
7
8  Complexity:  $O(V^3)$  on the number of vertices.
9
10  ~=~=~= Sample Input ~=~=~=
11  4 8
12  0 1
13  1 0
14  1 2
15  2 1
16  2 3
17  3 2
18  3 0
19  0 3
20
21  ~=~=~= Sample Output ~=~=~=
22  Matched 2 pair(s). Matchings are:
23  0 1
24  2 3
25

```

```

26  */
27
28  #include <iostream>
29  #include <vector>
30  using namespace std;
31
32  const int MAXN = 100;
33  int p[MAXN], base[MAXN], match[MAXN];
34  vector<int> adj[MAXN];
35
36  int lca(int nodes, int a, int b) {
37      vector<bool> used(nodes);
38      for (;;) {
39          a = base[a];
40          used[a] = true;
41          if (match[a] == -1) break;
42          a = p[match[a]];
43      }
44      for (;;) {
45          b = base[b];
46          if (used[b]) return b;
47          b = p[match[b]];
48      }
49  }
50
51  void mark_path(vector<bool> & blossom, int v, int b, int children) {
52      for (; base[v] != b; v = p[match[v]]) {
53          blossom[base[v]] = blossom[base[match[v]]] = true;
54          p[v] = children;
55          children = match[v];
56      }
57  }
58
59  int find_path(int nodes, int root) {
60      vector<bool> used(nodes);
61      for (int i = 0; i < nodes; ++i) {
62          p[i] = -1;
63          base[i] = i;
64      }
65      used[root] = true;
66      int q[nodes], qh = 0, qt = 0;
67      q[qt++] = root;
68      while (qh < qt) {
69          int v = q[qh++];
70          for (int j = 0, to; j < (int)adj[v].size(); j++) {
71              to = adj[v][j];
72              if (base[v] == base[to] || match[v] == to) continue;
73              if (to == root || (match[to] != -1 && p[match[to]] != -1)) {
74                  int curbase = lca(nodes, v, to);
75                  vector<bool> blossom(nodes);
76                  mark_path(blossom, v, curbase, to);
77                  mark_path(blossom, to, curbase, v);
78                  for (int i = 0; i < nodes; i++)
79                      if (blossom[base[i]]) {
80                          base[i] = curbase;
81                          if (!used[i]) {
82                              used[i] = true;
83                              q[qt++] = i;
84                          }
85                      }
86              }
87          }
88      }
89  }

```

```

85     }
86   } else if (p[to] == -1) {
87     p[to] = v;
88     if (match[to] == -1) return to;
89     to = match[to];
90     used[to] = true;
91     q[qt++] = to;
92   }
93 }
94 }
95 return -1;
96 }
97
98 int edmonds(int nodes) {
99   for (int i = 0; i < nodes; i++) match[i] = -1;
100  for (int i = 0; i < nodes; i++) {
101    if (match[i] == -1) {
102      int v, pv, ppv;
103      for (v = find_path(nodes, i); v != -1; v = ppv) {
104        ppv = match[pv = p[v]];
105        match[v] = pv;
106        match[pv] = v;
107      }
108    }
109  }
110  int matches = 0;
111  for (int i = 0; i < nodes; i++)
112    if (match[i] != -1) matches++;
113  return matches / 2;
114 }
115
116 int main() {
117   int nodes, edges, u, v;
118   cin >> nodes >> edges;
119   for (int i = 0; i < edges; i++) {
120     cin >> u >> v;
121     adj[u].push_back(v);
122   }
123   cout << "Matched_" << edmonds(nodes);
124   cout << "_pair(s)._Matchings_are:\n";
125   for (int i = 0; i < nodes; i++) {
126     if (match[i] != -1 && i < match[i])
127       cout << i << "_" << match[i] << "\n";
128   }
129   return 0;
130 }

```

2.8 Hamiltonian Path and Cycle

2.8.1 Shortest Hamiltonian Cycle (Travelling Salesman)

```

1  /*
2
3  2.8.1 - Shortest Hamiltonian Cycle (TSP)
4
5  Description: Given a weighted, directed graph, the shortest

```



```

6  hamiltonian cycle is a cycle of minimum distance that visits
7  each vertex exactly once and returns to the original vertex.
8  This is also known as the traveling salesman problem (TSP).
9  Since this is a bitmasking solution with 32-bit integers,
10 the number of vertices must be less than 32.
11
12 Complexity:  $O(2^V * V^2)$  on the number of vertices.
13
14 ~=~=~= Sample Input ~=~=~=
15 5 10
16 0 1 1
17 0 2 10
18 0 3 1
19 0 4 10
20 1 2 10
21 1 3 10
22 1 4 1
23 2 3 1
24 2 4 1
25 3 4 10
26
27 ~=~=~= Sample Output ~=~=~=
28 The shortest hamiltonian cycle has length 5.
29 Take the path: 0->3->2->4->1->0
30
31 */
32
33 #include <algorithm> /* std::fill(), std::min() */
34 #include <iostream>
35 using namespace std;
36
37 const int MAXN = 20, INF = 0x3f3f3f3f;
38 int adj[MAXN][MAXN], order[MAXN];
39
40 int shortest_hamiltonian_cycle(int nodes) {
41     int dp[1 << nodes][nodes];
42     for (int i = 0; i < (1 << nodes); i++)
43         fill(dp[i], dp[i] + nodes, INF);
44     dp[1][0] = 0;
45     for (int mask = 1; mask < (1 << nodes); mask += 2) {
46         for (int i = 1; i < nodes; i++)
47             if ((mask & 1 << i) != 0)
48                 for (int j = 0; j < nodes; j++)
49                     if ((mask & 1 << j) != 0)
50                         dp[mask][i] = min(dp[mask][i], dp[mask ^ (1 << i)][j] + adj[j][i]);
51     }
52     int res = INF + INF;
53     for (int i = 1; i < nodes; i++)
54         res = min(res, dp[(1 << nodes) - 1][i] + adj[i][0]);
55     int cur = (1 << nodes) - 1, last = 0;
56     for (int i = nodes - 1; i >= 1; i--) {
57         int bj = -1;
58         for (int j = 1; j < nodes; j++) {
59             if ((cur & 1 << j) != 0 && (bj == -1 ||
60                 dp[cur][bj] + adj[bj][last] > dp[cur][j] + adj[j][last])) {
61                 bj = j;
62             }
63         }
64         order[i] = bj;

```

```

65     cur ^= 1 << bj;
66     last = bj;
67 }
68 return res;
69 }
70
71 int main() {
72     int nodes, edges, u, v, w;
73     cin >> nodes >> edges;
74     for (int i = 0; i < edges; i++) {
75         cin >> u >> v >> w;
76         adj[u][v] = adj[v][u] = w; //only set adj[u][v] if directed edges
77     }
78     cout << "The shortest hamiltonian cycle has length ";
79     cout << shortest_hamiltonian_cycle(nodes) << ".\n";
80     cout << "Take the path: ";
81     for (int i = 0; i < nodes; i++) cout << order[i] << "->";
82     cout << order[0] << "\n";
83     return 0;
84 }

```

2.8.2 Shortest Hamiltonian Path

```

1  /*
2
3  2.8.2 - Shortest Hamiltonian Path
4
5  Description: Given a weighted, directed graph, the shortest
6  hamiltonian path is a path of minimum distance that visits
7  each vertex exactly once. Unlike the travelling salesman
8  problem, we don't have to return to the starting vertex.
9  Since this is a bitmasking solution with 32-bit integers,
10 the number of vertices must be less than 32.
11
12 Complexity:  $O(2^V * V^2)$  on the number of vertices.
13
14 ~=~=~=~= Sample Input ~=~=~=~=
15 3 6
16 0 1 1
17 0 2 1
18 1 0 7
19 1 2 2
20 2 0 3
21 2 1 5
22
23 ~=~=~=~= Sample Output ~=~=~=~=
24 The shortest hamiltonian path has length 3.
25 Take the path: 0->1->2
26
27 */
28
29 #include <algorithm> /* std::fill(), std::min() */
30 #include <iostream>
31 using namespace std;
32
33 const int MAXN = 20, INF = 0x3f3f3f3f;
34

```

```

35 int adj[MAXN][MAXN], order[MAXN];
36
37 int shortest_hamiltonian_path(int nodes) {
38     int dp[1 << nodes][nodes];
39     for (int i = 0; i < (1 << nodes); i++)
40         fill(dp[i], dp[i] + nodes, INF);
41     for (int i = 0; i < nodes; i++) dp[1 << i][i] = 0;
42     for (int mask = 1; mask < (1 << nodes); mask += 2) {
43         for (int i = 0; i < nodes; i++)
44             if ((mask & 1 << i) != 0)
45                 for (int j = 0; j < nodes; j++)
46                     if ((mask & 1 << j) != 0)
47                         dp[mask][i] = min(dp[mask][i], dp[mask ^ (1 << i)][j] + adj[j][i]);
48     }
49     int res = INF + INF;
50     for (int i = 1; i < nodes; i++)
51         res = min(res, dp[(1 << nodes) - 1][i]);
52     int cur = (1 << nodes) - 1, last = -1;
53     for (int i = nodes - 1; i >= 0; i--) {
54         int bj = -1;
55         for (int j = 0; j < nodes; j++) {
56             if ((cur & 1 << j) != 0 && (bj == -1 ||
57                 dp[cur][bj] + (last == -1 ? 0 : adj[bj][last]) >
58                 dp[cur][j] + (last == -1 ? 0 : adj[j][last]))) {
59                 bj = j;
60             }
61         }
62         order[i] = bj;
63         cur ^= 1 << bj;
64         last = bj;
65     }
66     return res;
67 }
68
69 int main() {
70     int nodes, edges, u, v, w;
71     cin >> nodes >> edges;
72     for (int i = 0; i < edges; i++) {
73         cin >> u >> v >> w;
74         adj[u][v] = w;
75     }
76     cout << "The shortest hamiltonian path has length ";
77     cout << shortest_hamiltonian_path(nodes) << ".\n";
78     cout << "Take the path: ";
79     for (int i = 1; i < nodes; i++) cout << "->" << order[i];
80     return 0;
81 }

```

Chapter 3

Data Structures

3.1 Disjoint Sets

3.1.1 Disjoint Set Forest (Simple)

```
1  /*
2
3  3.1.1 - Disjoint Set Forest (Simple)
4
5  Description: This data structure dynamically keeps track
6  of items partitioned into non-overlapping sets (a disjoint
7  set forest). It is also known as a union-find data structure.
8
9  Time Complexity: Every function below is  $O(a(N))$  amortized
10 on the number of items in the set due to the optimizations
11 of union by rank and path compression. Here,  $a(N)$  is the
12 extremely slow growing inverse of the Ackermann function.
13 For all practical values of  $n$ ,  $a(n)$  is less than 5.
14
15 Space Complexity:  $O(N)$  total.
16
17 */
18
19 const int MAXN = 1000;
20 int num_sets = 0, root[MAXN+1], rank[MAXN+1];
21
22 int find_root(int x) {
23     if (root[x] != x) root[x] = find_root(root[x]);
24     return root[x];
25 }
26
27 void make_set(int x) {
28     root[x] = x;
29     rank[x] = 0;
30     num_sets++;
31 }
32
33 bool is_united(int x, int y) {
34     return find_root(x) == find_root(y);
35 }
```

```

36
37 void unite(int x, int y) {
38     int X = find_root(x), Y = find_root(y);
39     if (X == Y) return;
40     num_sets--;
41     if (rank[X] < rank[Y]) root[X] = Y;
42     else if (rank[X] > rank[Y]) root[Y] = X;
43     else rank[root[Y] = X]++;
44 }
45
46 /** Example Usage **/
47
48 #include <cassert>
49 #include <iostream>
50 using namespace std;
51
52 int main() {
53     for (char c = 'a'; c <= 'g'; c++) make_set(c);
54     unite('a', 'b');
55     unite('b', 'f');
56     unite('d', 'e');
57     unite('e', 'g');
58     assert(num_sets == 3);
59     assert(is_united('a', 'b'));
60     assert(!is_united('a', 'c'));
61     assert(!is_united('b', 'g'));
62     assert(is_united('d', 'g'));
63     return 0;
64 }

```

3.1.2 Disjoint Set Forest

```

1  /*
2
3  3.1.2 - Disjoint Set Forest
4
5  Description: This data structure dynamically keeps track
6  of items partitioned into non-overlapping sets (a disjoint
7  set forest). It is also known as a union-find data structure.
8  This particular templated version employs an std::map for
9  built in storage and coordinate compression. That is, the
10 magnitude of values inserted is not limited.
11
12 Time Complexity: make_set(), unite() and is_united() are
13  $O(a(N) + \log N) = O(\log N)$  on the number of elements in the
14 disjoint set forest. get_all_sets() is  $O(N)$ . find() is is
15  $O(a(N))$  amortized on the number of items in the set due to
16 the optimizations of union by rank and path compression.
17 Here,  $a(N)$  is the extremely slow growing inverse of the
18 Ackermann function. For all practical values of  $n$ ,  $a(n)$  is
19 less than 5.
20
21 Space Complexity:  $O(N)$  storage and auxiliary.
22
23 ~=~=~= Sample Output ~=~=~=
24 Elements: 7, Sets: 3
25 [[a,b,f],[c],[d,e,g]]

```

```

26
27 */
28
29 #include <map>
30 #include <vector>
31
32 template<class T> class disjoint_set_forest {
33     int num_elements, num_sets;
34     std::map<T, int> ID;
35     std::vector<int> root, rank;
36
37     int find_root(int x) {
38         if (root[x] != x) root[x] = find_root(root[x]);
39         return root[x];
40     }
41
42 public:
43     disjoint_set_forest(): num_elements(0), num_sets(0) {}
44     int elements() { return num_elements; }
45     int sets() { return num_sets; }
46
47     bool is_united(const T & x, const T & y) {
48         return find_root(ID[x]) == find_root(ID[y]);
49     }
50
51     void make_set(const T & x) {
52         if (ID.find(x) != ID.end()) return;
53         root.push_back(ID[x] = num_elements++);
54         rank.push_back(0);
55         num_sets++;
56     }
57
58     void unite(const T & x, const T & y) {
59         int X = find_root(ID[x]), Y = find_root(ID[y]);
60         if (X == Y) return;
61         num_sets--;
62         if (rank[X] < rank[Y]) root[X] = Y;
63         else if (rank[X] > rank[Y]) root[Y] = X;
64         else rank[root[Y] = X]++;
65     }
66
67     std::vector<std::vector<T> > get_all_sets() {
68         std::map<int, std::vector<T> > tmp;
69         for (typename std::map<T, int>::iterator
70             it = ID.begin(); it != ID.end(); it++)
71             tmp[find_root(it->second)].push_back(it->first);
72         std::vector<std::vector<T> > ret;
73         for (typename std::map<int, std::vector<T> >::
74             iterator it = tmp.begin(); it != tmp.end(); it++)
75             ret.push_back(it->second);
76         return ret;
77     }
78 };
79
80 /** Example Usage */
81
82 #include <iostream>
83 using namespace std;
84

```

```

85 int main() {
86     disjoint_set_forest<char> d;
87     for (char c = 'a'; c <= 'g'; c++) d.make_set(c);
88     d.unite('a', 'b');
89     d.unite('b', 'f');
90     d.unite('d', 'e');
91     d.unite('e', 'g');
92     cout << "Elements:␣" << d.elements();
93     cout << ",␣Sets:␣" << d.sets() << endl;
94     vector<vector<char>> > s = d.get_all_sets();
95     cout << "[";
96     for (int i = 0; i < (int)s.size(); i++) {
97         cout << (i > 0 ? ",[" : "[";
98         for (int j = 0; j < (int)s[i].size(); j++)
99             cout << (j > 0 ? ", " : "") << s[i][j];
100         cout << "]";
101     }
102     cout << "]\n";
103     return 0;
104 }

```

3.2 Fenwick Trees

3.2.1 Simple Fenwick Tree

```

1  /*
2
3  3.2.1 - Fenwick Tree (Simple)
4
5  Description: A Fenwick tree (a.k.a. binary indexed tree) is a
6  data structure that allows for the sum of an arbitrary range
7  of values in an array to be dynamically queried in logarithmic
8  time. Note that unlike the object-oriented versions of this
9  data structure found in later sections, the operations here
10 work on 1-based indices (i.e. between 1 and MAXN, inclusive).
11 The array a[] is always synchronized with the bit[] array and
12 should not be modified outside of the functions below.
13
14 Time Complexity: All functions are O(log MAXN).
15 Space Complexity: O(MAXN) storage and auxiliary.
16
17 */
18
19 const int MAXN = 1000;
20 int a[MAXN + 1], bit[MAXN + 1];
21
22 //a[i] += v
23 void add(int i, int v) {
24     a[i] += v;
25     for (; i <= MAXN; i += i & -i)
26         bit[i] += v;
27 }
28
29 //a[i] = v
30 void set(int i, int v) {
31     int inc = v - a[i];

```

```

32     add(i, inc);
33 }
34
35 //returns sum(a[i] for i = 1..hi inclusive)
36 int sum(int hi) {
37     int ret = 0;
38     for (; hi > 0; hi -= hi & -hi)
39         ret += bit[hi];
40     return ret;
41 }
42
43 //returns sum(a[i] for i = lo..hi inclusive)
44 int sum(int lo, int hi) {
45     return sum(hi) - sum(lo - 1);
46 }
47
48 /** Example Usage */
49
50 #include <iostream>
51 using namespace std;
52
53 int main() {
54     for (int i = 1; i <= 5; i++) set(i, i);
55     add(4, -5);
56     cout << "BIT values: ";
57     for (int i = 1; i <= 5; i++)
58         cout << a[i] << " "; //1 2 3 -1 5
59     cout << "\nSum of range [1,3] is ";
60     cout << sum(1, 3) << ".\n"; //6
61     return 0;
62 }

```

3.2.2 Fenwick Tree

```

1  /*
2
3  3.2.2 - Fenwick Tree (Point Update, Range Query)
4
5  Description: A Fenwick tree (a.k.a. binary indexed tree) is a
6  data structure that allows for the sum of an arbitrary range
7  of values in an array to be dynamically queried in logarithmic
8  time. All methods below work on 0-based indices (i.e. indices
9  in the range from 0 to size() - 1, inclusive, are valid).
10
11 Time Complexity: add(), set(), and sum() are all O(log N) on
12 the length of the array. size() and at() are O(1).
13
14 Space Complexity: O(N) storage and O(N) auxiliary on size().
15
16 */
17
18 #include <vector>
19
20 template<class T> class fenwick_tree {
21     int len;
22     std::vector<int> a, bit;
23

```



```

24 public:
25     fenwick_tree(int n): len(n),
26         a(n + 1), bit(n + 1) {}
27
28     //a[i] += v
29     void add(int i, const T & v) {
30         a[++i] += v;
31         for (; i <= len; i += i & -i)
32             bit[i] += v;
33     }
34
35     //a[i] = v
36     void set(int i, const T & v) {
37         T inc = v - a[i + 1];
38         add(i, inc);
39     }
40
41     //returns sum(a[i] for i = 1..hi inclusive)
42     T sum(int hi) {
43         T res = 0;
44         for (hi++; hi > 0; hi -= hi & -hi)
45             res += bit[hi];
46         return res;
47     }
48
49     //returns sum(a[i] for i = lo..hi inclusive)
50     T sum(int lo, int hi) {
51         return sum(hi) - sum(lo - 1);
52     }
53
54     inline int size() { return len; }
55     inline T at(int i) { return a[i + 1]; }
56 };
57
58 /** Example Usage **/
59
60 #include <iostream>
61 using namespace std;
62
63 int main() {
64     int a[] = {10, 1, 2, 3, 4};
65     fenwick_tree<int> t(5);
66     for (int i = 0; i < 5; i++) t.set(i, a[i]);
67     t.add(0, -5);
68     cout << "BIT values:\n";
69     for (int i = 0; i < t.size(); i++)
70         cout << t.at(i) << "\n"; //5 1 2 3 4
71     cout << "\nSum of range [1,3] is\n";
72     cout << t.sum(1, 3) << ".\n"; //6
73     return 0;
74 }

```

3.2.3 Fenwick Tree (Point Query)

```

1  /*
2
3  3.2.3 - Fenwick Tree (Range Update, Point Query)

```

```

4
5 Description: A Fenwick tree (a.k.a. binary indexed tree) is a
6 data structure that allows for the sum of an arbitrary range
7 of values in an array to be dynamically queried in logarithmic
8 time. Range updating in a Fenwick tree can only increment
9 values in a range, not set them all to the same value. This
10 version is a very concise version if only point queries are
11 needed. The functions below work on 1-based indices (between
12 1 and MAXN, inclusive).
13
14 Time Complexity: add() and at() are  $O(\log \text{MAXN})$ .
15 Space Complexity:  $O(N)$ .
16
17 */
18
19 const int MAXN = 1000;
20 int bit[MAXN + 1];
21
22 //a[i] += v
23 void add(int i, int v) {
24     for (i++; i <= MAXN; i += i & -i) bit[i] += v;
25 }
26
27 //a[i] += v for i = lo..hi, inclusive
28 void add(int lo, int hi, int v) {
29     add(lo, v);
30     add(hi + 1, -v);
31 }
32
33 //returns a[i]
34 int at(int i) {
35     int sum = 0;
36     for (i++; i > 0; i -= i & -i) sum += bit[i];
37     return sum;
38 }
39
40 /** Example Usage */
41
42 #include <iostream>
43 using namespace std;
44
45 int main() {
46     add(1, 2, 5);
47     add(2, 3, 5);
48     add(3, 5, 10);
49     cout << "BIT values: "; //5 10 15 10 10
50     for (int i = 1; i <= 5; i++)
51         cout << at(i) << " ";
52     cout << "\n";
53     return 0;
54 }

```

3.2.4 Fenwick Tree (Range Update)

```

1 /*
2
3 3.2.4 - Fenwick Tree (Range Update/Query)

```

```

4
5 Description: Using two arrays, a Fenwick tree can be made to
6 support range updates and range queries simultaneously. However,
7 the range updates can only be used to add an increment to all
8 values in a range, not set them to the same value. The latter
9 problem may be solved using a segment tree + lazy propagation.
10 All methods below operate 0-based indices (i.e. indices in the
11 range from 0 to size() - 1, inclusive, are valid).
12
13 Time Complexity: add(), set(), at(), and sum() are all  $O(\log N)$ 
14 on the length of the array. size() is  $O(1)$ .
15
16 Space Complexity:  $O(N)$  storage and auxiliary.
17
18 ~=~=~= Sample Output ~=~=~=
19 BIT values: 15 6 7 -5 4
20 Sum of range [0, 4] is 27.
21
22 */
23
24 #include <vector>
25
26 template<class T> class fenwick_tree {
27     int len;
28     std::vector<T> b1, b2;
29
30     T sum(const std::vector<T> & b, int i) {
31         T res = 0;
32         for (; i != 0; i -= i & -i) res += b[i];
33         return res;
34     }
35
36     void add(std::vector<T> & b, int i, const T & v) {
37         for (; i <= len; i += i & -i) b[i] += v;
38     }
39
40 public:
41     fenwick_tree(int n):
42         len(n + 1), b1(n + 2), b2(n + 2) {}
43
44     //a[i] += v for i = lo..hi, inclusive
45     void add(int lo, int hi, const T & v) {
46         lo++, hi++;
47         add(b1, lo, v);
48         add(b1, hi + 1, -v);
49         add(b2, lo, v * (lo - 1));
50         add(b2, hi + 1, -v * hi);
51     }
52
53     //a[i] = v
54     void set(int i, const T & v) { add(i, i, v - at(i)); }
55
56     //returns sum(a[i] for i = 1..hi inclusive)
57     T sum(int hi) { return sum(b1, hi)*hi - sum(b2, hi); }
58
59     //returns sum(a[i] for i = lo..hi inclusive)
60     T sum(int lo, int hi) { return sum(hi + 1) - sum(lo); }
61
62     inline int size() const { return len - 1; }

```

```

63     inline T at(int i) { return sum(i, i); }
64 };
65
66 /** Example Usage */
67
68 #include <iostream>
69 using namespace std;
70
71 int main() {
72     int a[] = {10, 1, 2, 3, 4};
73     fenwick_tree<int> t(5);
74     for (int i = 0; i < 5; i++) t.set(i, a[i]);
75     t.add(0, 2, 5); //15 6 7 3 4
76     t.set(3, -5);   //15 6 7 -5 4
77     cout << "BIT values:\n";
78     for (int i = 0; i < t.size(); i++)
79         cout << t.at(i) << "\n";
80     cout << "\nSum of range [0,4] is\n";
81     cout << t.sum(0, 4) << ".\n"; //27
82     return 0;
83 }

```

3.2.5 Fenwick Tree (Map)

```

1  /*
2
3  3.2.5 - Fenwick Tree (Range Updates and Range Query
4           with Co-ordinate Compression)
5
6  Description: Using two std::maps to represent the Fenwick tree,
7  there no longer needs to be a restriction on the magnitude of
8  queried indices. All indices in range [0, MAXN] are valid.
9
10 Time Complexity: All functions are  $O(\log^2 \text{MAXN})$ . If the
11 std::map is replaced with an std::unordered_map, then the
12 running time will become  $O(\log \text{MAXN})$  amortized.
13
14 Space Complexity:  $O(n)$  on the number of indices accessed.
15
16 */
17
18 #include <map>
19
20 const int MAXN = 1000000000;
21 std::map<int, int> tmul, tadd;
22
23 void _add(int at, int mul, int add) {
24     for (int i = at; i <= MAXN; i = (i | (i+1))) {
25         tmul[i] += mul;
26         tadd[i] += add;
27     }
28 }
29
30 //a[i] += v for all i = lo..hi, inclusive
31 void add(int lo, int hi, int v) {
32     _add(lo, v, -v * (lo - 1));
33     _add(hi, -v, v * hi);

```

```

34 }
35
36 //returns sum(a[i] for i = 1..hi inclusive)
37 int sum(int hi) {
38     int mul = 0, add = 0, start = hi;
39     for (int i = hi; i >= 0; i = (i & (i + 1)) - 1) {
40         if (tmul.find(i) != tmul.end())
41             mul += tmul[i];
42         if (tadd.find(i) != tadd.end())
43             add += tadd[i];
44     }
45     return mul*start + add;
46 }
47
48 //returns sum(a[i] for i = lo..hi inclusive)
49 int sum(int lo, int hi) {
50     return sum(hi) - sum(lo - 1);
51 }
52
53 //a[i] = v
54 void set(int i, int v) {
55     add(i, i, v - sum(i, i));
56 }
57
58 /** Example Usage */
59
60 #include <iostream>
61 using namespace std;
62
63 int main() {
64     add(500000001, 500000010, 3);
65     add(500000011, 500000015, 5);
66     set(500000000, 10);
67     cout << sum(500000000, 500000015) << "\n"; //65
68     return 0;
69 }

```

3.2.6 2D Fenwick Tree

```

1  /*
2
3  3.2.6 - 2D Fenwick Tree (Point Update, Range Query)
4
5  Description: A 2D Fenwick tree is abstractly a 2D array which also
6  supports efficient queries for the sum of values in the rectangle
7  with top-left (1, 1) and bottom-right (r, c). The implementation
8  below has indices accessible in the range [1...xmax][1...ymax].
9
10 Time Complexity: All functions are O(log(xmax)*log(ymax)).
11 Space Complexity: O(xmax*ymax) storage and auxiliary.
12
13 */
14
15 const int xmax = 100, ymax = 100;
16
17 int a[xmax+1][ymax+1], bit[xmax+1][ymax+1];
18

```

```

19 //a[x][y] += v
20 void add(int x, int y, int v) {
21     a[x][y] += v;
22     for (int i = x; i <= xmax; i += i & -i)
23         for (int j = y; j <= ymax; j += j & -j)
24             bit[i][j] += v;
25 }
26
27 //a[x][y] = v
28 void set(int x, int y, int v) {
29     int inc = v - a[x][y];
30     add(x, y, inc);
31 }
32
33 //returns sum(data[1..x][1..y], all inclusive)
34 int sum(int x, int y) {
35     int ret = 0;
36     for (int i = x; i > 0; i -= i & -i)
37         for (int j = y; j > 0; j -= j & -j)
38             ret += bit[i][j];
39     return ret;
40 }
41
42 //returns sum(data[x1..x2][y1..y2], all inclusive)
43 int sum(int x1, int y1, int x2, int y2) {
44     return sum(x2, y2) + sum(x1 - 1, y1 - 1) -
45         sum(x1 - 1, y2) - sum(x2, y1 - 1);
46 }
47
48 /** Example Usage */
49
50 #include <cassert>
51 #include <iostream>
52 using namespace std;
53
54 int main() {
55     set(1, 1, 5);
56     set(1, 2, 6);
57     set(2, 1, 7);
58     add(3, 3, 9);
59     add(2, 1, -4);
60     /*
61     5 6 0
62     3 0 0
63     0 0 9
64     */
65     cout << "2D_BIT values:\n";
66     for (int i = 1; i <= 3; i++) {
67         for (int j = 1; j <= 3; j++)
68             cout << a[i][j] << " ";
69         cout << "\n";
70     }
71     assert(sum(1, 1, 1, 2) == 11);
72     assert(sum(1, 1, 2, 1) == 8);
73     assert(sum(1, 1, 3, 3) == 23);
74     return 0;
75 }

```

3.2.7 2D Fenwick Tree (Range Update)

```

1  /*
2
3  3.2.7 - 2D Fenwick Tree (Range Update, Range Query,
4              with Coordinate Compression)
5
6  Description: A 2D Fenwick tree is abstractly a 2D array which also
7  supports efficient queries for the sum of values in the rectangle
8  with top-left (1, 1) and bottom-right (r, c). The implementation
9  below has indices accessible in the range [0..xmax][0..ymax].
10
11 Time Complexity: All functions are  $O(\log(xmax) * \log(ymax) * \log(N))$ 
12 where N is the number of indices operated on so far. Use an array
13 or an unordered_map instead of a map to remove the  $\log(N)$  factor.
14
15 Space Complexity:  $O(xmax * ymax)$  storage and auxiliary.
16
17 */
18
19 #include <map>
20 #include <utility>
21
22 template<class T> class fenwick_tree_2d {
23     static const int xmax = 1000000000;
24     static const int ymax = 1000000000;
25
26     std::map<std::pair<int, int>, T> t1, t2, t3, t4;
27
28     template<class Tree>
29     void add(Tree & t, int x, int y, const T & v) {
30         for (int i = x; i <= xmax; i += i & -i)
31             for (int j = y; j <= ymax; j += j & -j)
32                 t[std::make_pair(i, j)] += v;
33     }
34
35     //a[i][j] += v for i = [1,x], j = [1,y]
36     void add_pre(int x, int y, const T & v) {
37         add(t1, 1, 1, v);
38
39         add(t1, 1, y + 1, -v);
40         add(t2, 1, y + 1, v * y);
41
42         add(t1, x + 1, 1, -v);
43         add(t3, x + 1, 1, v * x);
44
45         add(t1, x + 1, y + 1, v);
46         add(t2, x + 1, y + 1, -v * y);
47         add(t3, x + 1, y + 1, -v * x);
48         add(t4, x + 1, y + 1, v * x * y);
49     }
50
51 public:
52     //a[i][j] += v for i = [x1,x2], j = [y1,y2]
53     void add(int x1, int y1, int x2, int y2, const T & v) {
54         x1++; y1++; x2++; y2++;
55         add_pre(x2, y2, v);
56         add_pre(x1 - 1, y2, -v);

```

```

57     add_pre(x2, y1 - 1, -v);
58     add_pre(x1 - 1, y1 - 1, v);
59 }
60
61 //a[x][y] += v
62 void add(int x, int y, const T & v) {
63     add(x, y, x, y, v);
64 }
65
66 //a[x][y] = v
67 void set(int x, int y, const T & v) {
68     add(x, y, v - at(x, y));
69 }
70
71 //returns sum(a[i][j] for i = [1,x], j = [1,y])
72 T sum(int x, int y) {
73     x++; y++;
74     T s1 = 0, s2 = 0, s3 = 0, s4 = 0;
75     for (int i = x; i > 0; i -= i & -i)
76         for (int j = y; j > 0; j -= j & -j) {
77             s1 += t1[std::make_pair(i, j)];
78             s2 += t2[std::make_pair(i, j)];
79             s3 += t3[std::make_pair(i, j)];
80             s4 += t4[std::make_pair(i, j)];
81         }
82     return s1 * x * y + s2 * x + s3 * y + s4;
83 }
84
85 //returns sum(a[i][j] for i = [x1,x2], j = [y1,y2])
86 T sum(int x1, int y1, int x2, int y2) {
87     return sum(x2, y2) + sum(x1 - 1, y1 - 1) -
88         sum(x1 - 1, y2) - sum(x2, y1 - 1);
89 }
90
91 T at(int x, int y) { return sum(x, y, x, y); }
92 };
93
94 /** Example Usage */
95
96 #include <cassert>
97 #include <iostream>
98 using namespace std;
99
100 int main() {
101     fenwick_tree_2d<long long> t;
102     t.set(0, 0, 5);
103     t.set(0, 1, 6);
104     t.set(1, 0, 7);
105     t.add(2, 2, 9);
106     t.add(1, 0, -4);
107     t.add(1, 1, 2, 2, 5);
108     /*
109     5 6 0
110     3 5 5
111     0 5 14
112     */
113     cout << "2D_BIT_values:\n";
114     for (int i = 0; i < 3; i++) {
115         for (int j = 0; j < 3; j++)

```



```

116         cout << t.at(i, j) << "␣";
117         cout << "\n";
118     }
119     assert(t.sum(0, 0, 0, 1) == 11);
120     assert(t.sum(0, 0, 1, 0) == 8);
121     assert(t.sum(1, 1, 2, 2) == 29);
122     return 0;
123 }

```

3.3 1D Range Queries

3.3.1 Simple Segment Tree

```

1  /*
2
3  3.3.1 - 1D Segment Tree (Simple Version for ints)
4
5  Description: A segment tree is a data structure used for
6  solving the dynamic range query problem, which asks to
7  determine the minimum (or maximum) value in any given
8  range in an array that is constantly being updated.
9
10 Time Complexity: Assuming merge() is O(1), build is O(n)
11 while query() and update() are O(log n). If merge() is
12 not O(1), then all running times are multiplied by a
13 factor of whatever complexity merge() runs in.
14
15 Space Complexity: O(MAXN). Note that a segment tree with
16 N leaves requires  $2^{(\log_2(N) - 1)} = 4*N$  total nodes.
17
18 Note: This implementation is 0-based, meaning that all
19 indices from 0 to MAXN - 1, inclusive, are accessible.
20
21 ~=~=~= Sample Input ~=~=~=
22 5 10
23 35232
24 390942
25 649675
26 224475
27 18709
28 Q 1 3
29 M 4 475689
30 Q 2 3
31 Q 1 3
32 Q 1 2
33 Q 3 3
34 Q 2 3
35 M 2 645514
36 M 2 680746
37 Q 0 4
38
39 ~=~=~= Sample Output ~=~=~=
40 224475
41 224475
42 224475
43 390942

```

```

44 224475
45 224475
46 35232
47
48 */
49
50 const int MAXN = 100000;
51 int N, M, a[MAXN], t[4*MAXN];
52
53 //define your custom nullv and merge() below.
54 //merge(x, nullv) must return x for all x
55
56 const int nullv = 1 << 30;
57
58 inline int merge(int a, int b) { return a < b ? a : b; }
59
60 void build(int n, int lo, int hi) {
61     if (lo == hi) {
62         t[n] = a[lo];
63         return;
64     }
65     build(2*n + 1, lo, (lo + hi)/2);
66     build(2*n + 2, (lo + hi)/2 + 1, hi);
67     t[n] = merge(t[2*n + 1], t[2*n + 2]);
68 }
69
70 //x and y must be manually set before each call to the
71 //functions below. For query(), [x, y] is the range to
72 //be considered. For update(), a[x] is to be set to y.
73 int x, y;
74
75 //merge(a[i] for i = x..y, inclusive)
76 int query(int n, int lo, int hi) {
77     if (hi < x || lo > y) return nullv;
78     if (lo >= x && hi <= y) return t[n];
79     return merge(query(2*n + 1, lo, (lo + hi) / 2),
80                 query(2*n + 2, (lo + hi) / 2 + 1, hi));
81 }
82
83 //a[x] = y
84 void update(int n, int lo, int hi) {
85     if (hi < x || lo > x) return;
86     if (lo == hi) {
87         t[n] = y;
88         return;
89     }
90     update(2*n + 1, lo, (lo + hi)/2);
91     update(2*n + 2, (lo + hi)/2 + 1, hi);
92     t[n] = merge(t[2*n + 1], t[2*n + 2]);
93 }
94
95 /** Example Usage (wcipeg.com/problem/segtree) */
96
97 #include <stdio>
98
99 int main() {
100     scanf("%d%d", &N, &M);
101     for (int i = 0; i < N; i++) scanf("%d", &a[i]);
102     build(0, 0, N - 1);

```

```

103 char op;
104 for (int i = 0; i < M; i++) {
105     scanf("%c%d", &op, &x, &y);
106     if (op == 'Q') {
107         printf("%d\n", query(0, 0, N - 1));
108     } else if (op == 'M') {
109         update(0, 0, N - 1);
110     }
111 }
112 return 0;
113 }

```

3.3.2 Segment Tree

```

1  /*
2
3  3.3.2 - 1D Segment Tree Class
4
5  Description: A segment tree is a data structure used for
6  solving the dynamic range query problem, which asks to
7  determine the minimum (or maximum) value in any given
8  range in an array that is constantly being updated.
9
10 Time Complexity: Assuming merge() is O(1), query(),
11 update(), and at() are O(log N). size() is O(1). If
12 merge() is not O(1), then all logarithmic running times
13 are multiplied by a factor of the complexity of merge().
14
15 Space Complexity: O(MAXN). Note that a segment tree with
16 N leaves requires  $2^{(\log_2(N) - 1)} = 4*N$  total nodes.
17
18 Note: This implementation is 0-based, meaning that all
19 indices from 0 to N - 1, inclusive, are accessible.
20
21 */
22
23 #include <limits> /* std::numeric_limits<T>::min() */
24 #include <vector>
25
26 template<class T> class segment_tree {
27     int len, x, y;
28     std::vector<T> t;
29     T val, *init;
30
31     //define the following yourself. merge(x, nullv) must return x for all x
32     static inline T nullv() { return std::numeric_limits<T>::min(); }
33     static inline T merge(const T & a, const T & b) { return a > b ? a : b; }
34
35     void build(int n, int lo, int hi) {
36         if (lo == hi) {
37             t[n] = init[lo];
38             return;
39         }
40         build(n * 2 + 1, lo, (lo + hi) / 2);
41         build(n * 2 + 2, (lo + hi) / 2 + 1, hi);
42         t[n] = merge(t[n * 2 + 1], t[n * 2 + 2]);
43     }

```

```

44
45 void update(int n, int lo, int hi) {
46     if (x < lo || x > hi) return;
47     if (lo == hi) {
48         t[n] = val;
49         return;
50     }
51     update(n * 2 + 1, lo, (lo + hi) / 2);
52     update(n * 2 + 2, (lo + hi) / 2 + 1, hi);
53     t[n] = merge(t[n * 2 + 1], t[n * 2 + 2]);
54 }
55
56 T query(int n, int lo, int hi) {
57     if (hi < x || lo > y) return nullv();
58     if (lo >= x && hi <= y) return t[n];
59     return merge(query(n * 2 + 1, lo, (lo + hi) / 2),
60                 query(n * 2 + 2, (lo + hi) / 2 + 1, hi));
61 }
62
63 public:
64 segment_tree(int n, T * a = 0): len(n), t(4 * n, nullv()) {
65     if (a != 0) {
66         init = a;
67         build(0, 0, len - 1);
68     }
69 }
70
71 //a[i] = v
72 void update(int i, const T & v) {
73     x = i;
74     val = v;
75     update(0, 0, len - 1);
76 }
77
78 //merge(a[i] for i = lo..hi, inclusive)
79 T query(int lo, int hi) {
80     x = lo;
81     y = hi;
82     return query(0, 0, len - 1);
83 }
84
85 inline int size() { return len; }
86 inline T at(int i) { return query(i, i); }
87 };
88
89 /** Example Usage */
90
91 #include <iostream>
92 using namespace std;
93
94 int main() {
95     int arr[5] = {6, -2, 1, 8, 10};
96     segment_tree<int> T(5, arr);
97     T.update(1, 4);
98     cout << "Array contains:";
99     for (int i = 0; i < T.size(); i++)
100         cout << " " << T.at(i);
101     cout << "\nThe max value in the range [0,3] is ";
102     cout << T.query(0, 3) << ".\n"; //8

```

```

103     return 0;
104 }

```

3.3.3 Segment Tree (Range Updates)

```

1  /*
2
3  3.3.3 - 1D Segment Tree with Range Updates
4
5  Description: A segment tree is a data structure used for
6  solving the dynamic range query problem, which asks to
7  determine the minimum (or maximum) value in any given
8  range in an array that is constantly being updated.
9  Lazy propagation is a technique applied to segment trees that
10 allows range updates to be carried out in  $O(\log N)$  time. The
11 range updating mechanism is less versatile than the one
12 implemented in the next section.
13
14 Time Complexity: Assuming merge() is  $O(1)$ , query(), update(),
15 at() are  $O(\log(N))$ . If merge() is not constant time, then all
16 running times are multiplied by whatever complexity the merge
17 function runs in.
18
19 Space Complexity:  $O(N)$  on the size of the array. A segment
20 tree for an array of size  $N$  needs  $2^{(\log_2(N)-1)} = 4N$  nodes.
21
22 Note: This implementation is 0-based, meaning that all
23 indices from 0 to size() - 1, inclusive, are accessible.
24
25 */
26
27 #include <limits> /* std::numeric_limits<T>::min() */
28 #include <vector>
29
30 template<class T> class segment_tree {
31     int len, x, y;
32     std::vector<T> tree, lazy;
33     T val, *init;
34
35     //define the following yourself. merge(x, nullv) must return x for all valid x
36     static inline T nullv() { return std::numeric_limits<T>::min(); }
37     static inline T merge(const T & a, const T & b) { return a > b ? a : b; }
38
39     void build(int n, int lo, int hi) {
40         if (lo == hi) {
41             tree[n] = init[lo];
42             return;
43         }
44         build(n * 2 + 1, lo, (lo + hi) / 2);
45         build(n * 2 + 2, (lo + hi) / 2 + 1, hi);
46         tree[n] = merge(tree[n * 2 + 1], tree[n * 2 + 2]);
47     }
48
49     T query(int n, int lo, int hi) {
50         if (x > hi || y < lo) return nullv();
51         if (x <= lo && hi <= y) {
52             if (lazy[n] == nullv()) return tree[n];

```

```

53     return tree[n] = lazy[n];
54 }
55 int lchild = n * 2 + 1, rchild = n * 2 + 2;
56 if (lazy[n] != nullv()) {
57     lazy[lchild] = lazy[rchild] = lazy[n];
58     lazy[n] = nullv();
59 }
60 return merge(query(lchild, lo, (lo + hi)/2),
61             query(rchild, (lo + hi)/2 + 1, hi));
62 }
63
64 void _update(int n, int lo, int hi) {
65     if (x > hi || y < lo) return;
66     if (lo == hi) {
67         tree[n] = val;
68         return;
69     }
70     if (x <= lo && hi <= y) {
71         tree[n] = lazy[n] = merge(lazy[n], val);
72         return;
73     }
74     int lchild = n * 2 + 1, rchild = n * 2 + 2;
75     if (lazy[n] != nullv()) {
76         lazy[lchild] = lazy[rchild] = lazy[n];
77         lazy[n] = nullv();
78     }
79     _update(lchild, lo, (lo + hi) / 2);
80     _update(rchild, (lo + hi) / 2 + 1, hi);
81     tree[n] = merge(tree[lchild], tree[rchild]);
82 }
83
84 public:
85 segment_tree(int n, T * a = 0):
86     len(n), tree(4 * n, nullv()), lazy(4 * n, nullv()) {
87     if (a != 0) {
88         init = a;
89         build(0, 0, len - 1);
90     }
91 }
92
93 void update(int i, const T & v) {
94     x = y = i;
95     val = v;
96     _update(0, 0, len - 1);
97 }
98
99 //a[i] = v for i = lo..hi, inclusive
100 void update(int lo, int hi, const T & v) {
101     x = lo; y = hi;
102     val = v;
103     _update(0, 0, len - 1);
104 }
105
106 //returns merge(a[i] for i = lo..hi, inclusive)
107 T query(int lo, int hi) {
108     x = lo;
109     y = hi;
110     return query(0, 0, len - 1);
111 }

```

```

112
113     inline int size() { return len; }
114     inline T at(int i) { return query(i, i); }
115 };
116
117 /** Example Usage */
118
119 #include <iostream>
120 using namespace std;
121
122 int main() {
123     int arr[5] = {6, 4, 1, 8, 10};
124     segment_tree<int> T(5, arr);
125     cout << "Array_contains:"; //6 4 1 8 10
126     for (int i = 0; i < T.size(); i++)
127         cout << " " << T.at(i);
128     cout << "\n";
129     T.update(2, 4, 12);
130     cout << "Array_contains:"; //6 4 12 12 12
131     for (int i = 0; i < T.size(); i++)
132         cout << " " << T.at(i);
133     cout << "\nThe_max_value_in_the_range[0,3] is ";
134     cout << T.query(0, 3) << ".\n"; //12
135     return 0;
136 }

```

3.3.4 Segment Tree (Fast, Non-recursive)

```

1  /*
2
3  3.3.4 - 1D Segment Tree with Range Updates (Fast, No Recursion)
4
5  Description: A segment tree is a data structure used for
6  solving the dynamic range query problem, which asks to
7  determine the minimum (or maximum) value in any given
8  range in an array that is constantly being updated.
9  Lazy propagation is a technique applied to segment trees that
10 allows range updates to be carried out in  $O(\log N)$  time.
11
12 Time Complexity: Assuming merge() is  $O(1)$ , query(), update(),
13 at() are  $O(\log(N))$ . If merge() is not constant time, then all
14 running times are multiplied by whatever complexity the merge
15 function runs in.
16
17 Space Complexity:  $O(N)$  on the size of the array.
18
19 Note: This implementation is 0-based, meaning that all
20 indices from 0 to T.size() - 1, inclusive, are accessible.
21
22 */
23
24 #include <algorithm> /* std::fill(), std::max() */
25 #include <stdexcept> /* std::runtime_error */
26 #include <vector>
27
28 template<class T> class segment_tree {
29     //Modify the following 5 methods to implement your custom

```

```

30 //operations on the tree. This implements the Add/Max operations.
31 //Operations like Add/Sum, Set/Max can also be implemented.
32 static inline T modify_op(const T & x, const T & y) {
33     return x + y;
34 }
35
36 static inline T query_op(const T & x, const T & y) {
37     return std::max(x, y);
38 }
39
40 static inline T delta_on_segment(const T & delta, int seglen) {
41     if (delta == nullv()) return nullv();
42     //Here you must write a fast equivalent of following slow code:
43     // T result = delta;
44     // for (int i = 1; i < seglen; i++) result = query_op(result, delta);
45     // return result;
46     return delta;
47 }
48
49 static inline T nullv() { return 0; }
50 static inline T initv() { return 0; }
51
52 int length;
53 std::vector<T> value, delta;
54 std::vector<int> len;
55
56 static T join_value_with_delta(const T & val, const T & delta) {
57     return delta == nullv() ? val : modify_op(val, delta);
58 }
59
60 static T join_deltas(const T & delta1, const T & delta2) {
61     if (delta1 == nullv()) return delta2;
62     if (delta2 == nullv()) return delta1;
63     return modify_op(delta1, delta2);
64 }
65
66 T join_value_with_delta(int i) {
67     return join_value_with_delta(value[i], delta_on_segment(delta[i], len[i]));
68 }
69
70 void push_delta(int i) {
71     int d = 0;
72     while ((i >> d) > 0) d++;
73     for (d -= 2; d >= 0; d--) {
74         int x = i >> d;
75         value[x >> 1] = join_value_with_delta(x >> 1);
76         delta[x] = join_deltas(delta[x], delta[x >> 1]);
77         delta[x ^ 1] = join_deltas(delta[x ^ 1], delta[x >> 1]);
78         delta[x >> 1] = nullv();
79     }
80 }
81
82 public:
83 segment_tree(int n):
84     length(n), value(2 * n), delta(2 * n, nullv()), len(2 * n) {
85     std::fill(len.begin() + n, len.end(), 1);
86     for (int i = 0; i < n; i++) value[i + n] = initv();
87     for (int i = 2 * n - 1; i > 1; i -= 2) {
88         value[i >> 1] = query_op(value[i], value[i ^ 1]);

```



```

89     len[i >> 1] = len[i] + len[i ^ 1];
90 }
91 }
92
93 T query(int lo, int hi) {
94     if (lo < 0 || hi >= length || lo > hi)
95         throw std::runtime_error("Invalid_query_range.");
96     push_delta(lo += length);
97     push_delta(hi += length);
98     T res = 0;
99     bool found = false;
100    for (; lo <= hi; lo = (lo + 1) >> 1, hi = (hi - 1) >> 1) {
101        if ((lo & 1) != 0) {
102            res = found ? query_op(res, join_value_with_delta(lo)) :
103                        join_value_with_delta(lo);
104            found = true;
105        }
106        if ((hi & 1) == 0) {
107            res = found ? query_op(res, join_value_with_delta(hi)) :
108                        join_value_with_delta(hi);
109            found = true;
110        }
111    }
112    if (!found) throw std::runtime_error("Not_found.");
113    return res;
114 }
115
116 void modify(int lo, int hi, const T & delta) {
117     if (lo < 0 || hi >= length || lo > hi)
118         throw std::runtime_error("Invalid_modify_range.");
119     push_delta(lo += length);
120     push_delta(hi += length);
121     int ta = -1, tb = -1;
122     for (; lo <= hi; lo = (lo + 1) >> 1, hi = (hi - 1) >> 1) {
123         if ((lo & 1) != 0) {
124             this->delta[lo] = join_deltas(this->delta[lo], delta);
125             if (ta == -1) ta = lo;
126         }
127         if ((hi & 1) == 0) {
128             this->delta[hi] = join_deltas(this->delta[hi], delta);
129             if (tb == -1) tb = hi;
130         }
131     }
132     for (int i = ta; i > 1; i >>= 1)
133         value[i >> 1] = query_op(join_value_with_delta(i),
134                                 join_value_with_delta(i ^ 1));
135     for (int i = tb; i > 1; i >>= 1)
136         value[i >> 1] = query_op(join_value_with_delta(i),
137                                 join_value_with_delta(i ^ 1));
138 }
139
140 inline int size() { return length; }
141 inline T at(int i) { return query(i, i); }
142 };
143
144 /** Example Usage */
145
146 #include <iostream>
147 using namespace std;

```

```

148
149 int main() {
150     segment_tree<int> T(10);
151     T.modify(0, 0, 10);
152     T.modify(1, 1, 5);
153     T.modify(1, 1, 4);
154     T.modify(2, 2, 7);
155     T.modify(3, 3, 8);
156     cout << T.query(0, 3) << "\n"; //10
157     cout << T.query(1, 3) << "\n"; //9
158     T.modify(0, 9, 5);
159     cout << T.query(0, 9) << "\n"; //15
160     cout << "Array contains: "; //15 14 12 13 5 5 5 5 5
161     for (int i = 0; i < T.size(); i++)
162         cout << " " << T.at(i);
163     cout << "\n";
164     return 0;
165 }

```

3.3.5 Implicit Treap

```

1  /*
2
3  3.3.5 - Implicit Treap for Range Operations
4
5  Description: A treap is a self-balancing binary search tree that
6  uses randomization to maintain a low height. In this version,
7  it is used emulate the operations of an std::vector with a tradeoff
8  of increasing the running time of push_back() and at() from  $O(1)$  to
9   $O(\log N)$ , while decreasing the running time of insert() and erase()
10 from  $O(N)$  to  $O(\log N)$ . Furthermore, this version supports the same
11 operations as a segment tree with lazy propagation, allowing range
12 updates and queries to be performed in  $O(\log N)$ .
13
14 Time Complexity: Assuming the join functions have constant complexity:
15 insert(), push_back(), erase(), at(), modify(), and query() are all
16  $O(\log N)$ , while walk() is  $O(N)$ .
17
18 Space Complexity:  $O(N)$  on the size of the array.
19
20 Note: This implementation is 0-based, meaning that all
21 indices from 0 to size() - 1, inclusive, are accessible.
22
23 */
24
25 #include <climits> /* INT_MIN */
26 #include <cstdlib> /* srand(), rand() */
27 #include <ctime> /* time() */
28
29 template<class T> class implicit_treap {
30     //Modify the following 5 functions to implement your custom
31     //operations on the tree. This implements the Add/Max operations.
32     //Operations like Add/Sum, Set/Max can also be implemented.
33     static inline T join_values(const T & a, const T & b) {
34         return a > b ? a : b;
35     }
36

```

```

37 static inline T join_deltas(const T & d1, const T & d2) {
38     return d1 + d2;
39 }
40
41 static inline T join_value_with_delta(const T & v, const T & d, int len) {
42     return v + d;
43 }
44
45 static inline T null_delta() { return 0; }
46 static inline T null_value() { return INT_MIN; }
47
48 struct node_t {
49     static inline int rand32() {
50         return (rand() & 0x7fff) | ((rand() & 0x7fff) << 15);
51     }
52
53     T value, subtree_value, delta;
54     int count, priority;
55     node_t *L, *R;
56
57     node_t(const T & val) {
58         value = subtree_value = val;
59         delta = null_delta();
60         count = 1;
61         L = R = 0;
62         priority = rand32();
63     }
64 } *root;
65
66 static int count(node_t * n) {
67     return n ? n->count : 0;
68 }
69
70 static T subtree_value(node_t * n) {
71     return n ? n->subtree_value : null_value();
72 }
73
74 static void update(node_t * n) {
75     if (n == 0) return;
76     n->subtree_value = join_values(join_values(subtree_value(n->L), n->value),
77                                     subtree_value(n->R));
78     n->count = 1 + count(n->L) + count(n->R);
79 }
80
81 static void apply_delta(node_t * n, const T & delta) {
82     if (n == 0) return;
83     n->delta = join_deltas(n->delta, delta);
84     n->value = join_value_with_delta(n->value, delta, 1);
85     n->subtree_value = join_value_with_delta(n->subtree_value, delta, n->count);
86 }
87
88 static void push_delta(node_t * n) {
89     if (n == 0) return;
90     apply_delta(n->L, n->delta);
91     apply_delta(n->R, n->delta);
92     n->delta = null_delta();
93 }
94
95 static void merge(node_t *& n, node_t * L, node_t * R) {

```

```

96     push_delta(L);
97     push_delta(R);
98     if (L == 0) n = R;
99     else if (R == 0) n = L;
100    else if (L->priority < R->priority)
101        merge(L->R, L->R, R), n = L;
102    else
103        merge(R->L, L, R->L), n = R;
104    update(n);
105 }
106
107 static void split(node_t * n, node_t *& L, node_t *& R, int key) {
108     push_delta(n);
109     if (n == 0) L = R = 0;
110     else if (key <= count(n->L))
111         split(n->L, L, n->L, key), R = n;
112     else
113         split(n->R, n->R, R, key - count(n->L) - 1), L = n;
114     update(n);
115 }
116
117 static void insert(node_t *& n, node_t * item, int idx) {
118     push_delta(n);
119     if (n == 0) n = item;
120     else if (item->priority < n->priority)
121         split(n, item->L, item->R, idx), n = item;
122     else if (idx <= count(n->L))
123         insert(n->L, item, idx);
124     else
125         insert(n->R, item, idx - count(n->L) - 1);
126     update(n);
127 }
128
129 static T get(node_t * n, int idx) {
130     push_delta(n);
131     if (idx < count(n->L))
132         return get(n->L, idx);
133     else if (idx > count(n->L))
134         return get(n->R, idx - count(n->L) - 1);
135     return n->value;
136 }
137
138 static void erase(node_t *& n, int idx) {
139     push_delta(n);
140     if (idx == count(n->L)) {
141         delete n;
142         merge(n, n->L, n->R);
143     } else if (idx < count(n->L)) {
144         erase(n->L, idx);
145     } else {
146         erase(n->R, idx - count(n->L) - 1);
147     }
148 }
149
150 template<class UnaryFunction>
151 void walk(node_t * n, UnaryFunction f) {
152     if (n == 0) return;
153     push_delta(n);
154     if (n->L) walk(n->L, f);

```

```

155     f(n->value);
156     if (n->R) walk(n->R, f);
157 }
158
159 void clean_up(node_t *& n) {
160     if (n == 0) return;
161     clean_up(n->L);
162     clean_up(n->R);
163     delete n;
164 }
165
166 public:
167 implicit_treap(): root(0) { srand(time(0)); }
168 ~implicit_treap() { clean_up(root); }
169
170 int size() const { return count(root); }
171 bool empty() const { return root == 0; }
172
173 //list.insert(list.begin() + idx, val)
174 void insert(int idx, const T & val) {
175     if (idx < 0 || idx > size()) return;
176     node_t * item = new node_t(val);
177     insert(root, item, idx);
178 }
179
180 void push_back(const T & val) {
181     insert(size(), val);
182 }
183
184 //list.erase(list.begin() + idx)
185 void erase(int idx) {
186     if (idx < 0 || idx >= size()) return;
187     erase(root, idx);
188 }
189
190 T at(int idx) {
191     if (root == 0 || idx < 0 || idx >= size())
192         return null_value();
193     return get(root, idx);
194 }
195
196 template<class UnaryFunction> void walk(UnaryFunction f) {
197     walk(root, f);
198 }
199
200 //for (i = a; i <= b; i++)
201 // list[i] = join_value_with_delta(list[i], delta)
202 void modify(int a, int b, const T & delta) {
203     if (a < 0 || b < 0 || a >= size() || b >= size() || a > b)
204         return;
205     node_t *l1, *r1;
206     split(root, l1, r1, b + 1);
207     node_t *l2, *r2;
208     split(l1, l2, r2, a);
209     apply_delta(r2, delta);
210     node_t *t;
211     merge(t, l2, r2);
212     merge(root, t, r1);
213 }

```

```

214
215 //return join_values(list[a..b])
216 T query(int a, int b) {
217     if (a < 0 || b < 0 || a >= size() || b >= size() || a > b)
218         return null_value();
219     node_t *l1, *r1;
220     split(root, l1, r1, b + 1);
221     node_t *l2, *r2;
222     split(l1, l2, r2, a);
223     int res = subtree_value(r2);
224     node_t *t;
225     merge(t, l2, r2);
226     merge(root, t, r1);
227     return res;
228 }
229 };
230
231 /** Example Usage */
232
233 #include <iostream>
234 using namespace std;
235
236 void print(int x) { cout << x << " "; }
237
238 int main() {
239     implicit_treap<int> T;
240     T.push_back(7);
241     T.push_back(8);
242     T.push_back(9);
243     T.insert(1, 5);
244     T.erase(3);
245     T.walk(print); cout << "\n"; //7 5 8
246     T.modify(0, 2, 2);
247     T.walk(print); cout << "\n"; //9 7 10
248     cout << T.at(1) << "\n"; //7
249     cout << T.query(0, 2) << "\n"; //10
250     cout << T.size() << "\n"; //3
251     return 0;
252 }

```

3.3.6 Sparse Table

```

1  /*
2
3  3.3.6 - Range Minimum Query using a Sparse Table
4
5  Description: The static range minimum query problem can be solved
6  using a sparse table data structure. The RMQ for sub arrays of
7  length  $2^k$  is pre-processed using dynamic programming with formula:
8
9   $dp[i][j] = dp[i][j-1]$ , if  $A[dp[i][j-1]] \leq A[dp[i+2^{j-1}-1][j-1]]$ 
10      $dp[i+2^{j-1}-1][j-1]$ , otherwise
11
12  where  $dp[i][j]$  is the index of the minimum value in the sub array
13  starting at  $i$  having length  $2^j$ .
14
15  Time Complexity:  $O(N \log N)$  for build() and  $O(1)$  for min_idx()

```

```

16 Space Complexity:  $O(N \log N)$  on the size of the array.
17
18 Note: This implementation is 0-based, meaning that all
19 indices from 0 to  $N - 1$ , inclusive, are valid.
20
21 */
22
23 #include <vector>
24
25 const int MAXN = 100;
26 std::vector<int> logtable, dp[MAXN];
27
28 void build(int n, int a[]) {
29     logtable.resize(n + 1);
30     for (int i = 2; i <= n; i++)
31         logtable[i] = logtable[i >> 1] + 1;
32     for (int i = 0; i < n; i++) {
33         dp[i].resize(logtable[n] + 1);
34         dp[i][0] = i;
35     }
36     for (int k = 1; (1 << k) < n; k++) {
37         for (int i = 0; i + (1 << k) <= n; i++) {
38             int x = dp[i][k - 1];
39             int y = dp[i + (1 << (k - 1))][k - 1];
40             dp[i][k] = a[x] <= a[y] ? x : y;
41         }
42     }
43 }
44
45 //returns index of min element in [lo, hi]
46 int min_idx(int a[], int lo, int hi) {
47     int k = logtable[hi - lo];
48     int x = dp[lo][k];
49     int y = dp[hi - (1 << k) + 1][k];
50     return a[x] <= a[y] ? x : y;
51 }
52
53 /** Example Usage */
54
55 #include <iostream>
56 using namespace std;
57
58 int main() {
59     int a[] = {7, -10, 5, 20};
60     build(4, a);
61     cout << min_idx(a, 0, 3) << "\n"; //1
62     return 0;
63 }

```

3.3.7 Square Root Decomposition

```

1  /*
2
3  3.3.7 - Square Root Decomposition
4
5  Description: To solve the dynamic range query problem using
6  square root decomposition, we split an array of size N into

```

```

7  sqrt(N) buckets, each bucket of size sqrt(N). As a result,
8  each query and update operation will be sqrt(N) in running time.
9
10 Time Complexity:  $O(N \cdot \sqrt{N})$  to construct the initial
11 decomposition. After, query() and update() are  $O(\sqrt{N})$ /call.
12
13 Space Complexity:  $O(N)$  for the array.  $O(\sqrt{N})$  for the buckets.
14
15 Note: This implementation is 0-based, meaning that all
16 indices from 0 to  $N - 1$ , inclusive, are accessible.
17
18 ~=~=~= Sample Input ~=~=~=
19 5 10
20 35232
21 390942
22 649675
23 224475
24 18709
25 Q 1 3
26 M 4 475689
27 Q 2 3
28 Q 1 3
29 Q 1 2
30 Q 3 3
31 Q 2 3
32 M 2 645514
33 M 2 680746
34 Q 0 4
35
36 ~=~=~= Sample Output ~=~=~=
37 224475
38 224475
39 224475
40 390942
41 224475
42 224475
43 35232
44
45 */
46
47 #include <cmath> /* sqrt() */
48 #include <limits> /* std::numeric_limits<T>::max() */
49 #include <vector>
50
51 template<class T> class sqrt_decomp {
52     //define the following yourself. merge(x, nullv) must return x for all x
53     static inline T nullv() { return std::numeric_limits<T>::max(); }
54     static inline T merge(const T & a, const T & b) { return a < b ? a : b; }
55
56     int len, blocklen, blocks;
57     std::vector<T> array, block;
58
59 public:
60     sqrt_decomp(int n, T * a = 0): len(n), array(n) {
61         blocklen = (int)sqrt(n);
62         blocks = (n + blocklen - 1) / blocklen;
63         block.resize(blocks);
64         for (int i = 0; i < n; i++)
65             array[i] = a ? a[i] : nullv();

```



```

66     for (int i = 0; i < blocks; i++) {
67         int h = (i + 1) * blocklen;
68         if (h > n) h = n;
69         block[i] = nullv();
70         for (int j = i * blocklen; j < h; j++)
71             block[i] = merge(block[i], array[j]);
72     }
73 }
74
75 void update(int idx, const T & val) {
76     array[idx] = val;
77     int b = idx / blocklen;
78     int h = (b + 1) * blocklen;
79     if (h > len) h = len;
80     block[b] = nullv();
81     for (int i = b * blocklen; i < h; i++)
82         block[b] = merge(block[b], array[i]);
83 }
84
85 T query(int lo, int hi) {
86     T ret = nullv();
87     int lb = ceil((double)lo / blocklen);
88     int hb = (hi + 1) / blocklen - 1;
89     if (lb > hb) {
90         for (int i = lo; i <= hi; i++)
91             ret = merge(ret, array[i]);
92     } else {
93         int l = lb * blocklen - 1;
94         int h = (hb + 1) * blocklen;
95         for (int i = lo; i <= l; i++)
96             ret = merge(ret, array[i]);
97         for (int i = lb; i <= hb; i++)
98             ret = merge(ret, block[i]);
99         for (int i = h; i <= hi; i++)
100             ret = merge(ret, array[i]);
101     }
102     return ret;
103 }
104
105 inline int size() { return len; }
106 inline int at(int idx) { return array[idx]; }
107 };
108
109 /** Example Usage (wcipeg.com/problem/segtree) */
110
111 #include <cstdio>
112
113 int N, M, A, B, init[100005];
114
115 int main() {
116     scanf("%d%d", &N, &M);
117     for (int i = 0; i < N; i++) scanf("%d", &init[i]);
118     sqrt_decomp<int> a(N, init);
119     char op;
120     for (int i = 0; i < M; i++) {
121         scanf("%c%d%d", &op, &A, &B);
122         if (op == 'Q') {
123             printf("%d\n", a.query(A, B));
124         } else if (op == 'M') {

```

```

125     a.update(A, B);
126 }
127 }
128 return 0;
129 }

```

3.3.8 Interval Tree (Augmented Treap)

```

1  /*
2
3  3.3.8 - 1D Interval Tree (Augmented Treap)
4
5  Description: An interval tree is structure used to store and efficiently
6  query intervals. An interval may be dynamically inserted, and range
7  queries of [lo, hi] may be performed to have the tree report all intervals
8  that intersect with the queried interval. Augmented trees, described in
9  CLRS (2009, Section 14.3: pp. 348354), is one way to represent these
10 intervals. This implementation uses a treap to maintain balance.
11 See: http://en.wikipedia.org/wiki/Interval\_tree#Augmented\_tree
12
13 Time Complexity: On average  $O(\log N)$  for insert() and  $O(k)$  for query(),
14 where  $N$  is the number of intervals in the tree and  $k$  is the number of
15 intervals that will be reported by each query().
16
17 Space Complexity:  $O(N)$  on the number of intervals in the tree.
18
19 */
20
21 #include <cstdlib>    /* srand() */
22 #include <ctime>      /* time() */
23 #include <utility>    /* std::pair */
24
25 class interval_tree {
26     typedef std::pair<int, int> interval;
27
28     static bool overlap(const interval & a, const interval & b) {
29         return a.first <= b.second && b.first <= a.second;
30     }
31
32     struct node_t {
33         static inline int rand32() {
34             return (rand() & 0x7fff) | ((rand() & 0x7fff) << 15);
35         }
36
37         interval i;
38         int maxh, priority;
39         node_t *L, *R;
40
41         node_t(const interval & i) {
42             this->i = i;
43             maxh = i.second;
44             L = R = 0;
45             priority = rand32();
46         }
47
48         void update() {
49             maxh = i.second;

```

```

50     if (L != 0 && L->maxh > maxh) maxh = L->maxh;
51     if (R != 0 && R->maxh > maxh) maxh = R->maxh;
52 }
53 } *root;
54
55 static void rotate_l(node_t *& k2) {
56     node_t *k1 = k2->R;
57     k2->R = k1->L;
58     k1->L = k2;
59     k2 = k1;
60     k2->update();
61     k1->update();
62 }
63
64 static void rotate_r(node_t *& k2) {
65     node_t *k1 = k2->L;
66     k2->L = k1->R;
67     k1->R = k2;
68     k2 = k1;
69     k2->update();
70     k1->update();
71 }
72
73 interval i; //temporary
74
75 void insert(node_t *& n) {
76     if (n == 0) { n = new node_t(i); return; }
77     if (i.first < (n->i).first) {
78         insert(n->L);
79         if (n->L->priority < n->priority) rotate_r(n);
80     } else {
81         insert(n->R);
82         if (n->R->priority < n->priority) rotate_l(n);
83     }
84     n->update();
85 }
86
87 template<class ReportFunction>
88 void query(node_t * n, ReportFunction f) {
89     if (n == 0 || n->maxh < i.first) return;
90     if (overlap(n->i, i)) f(n->i.first, n->i.second);
91     query(n->L, f);
92     query(n->R, f);
93 }
94
95 static void clean_up(node_t * n) {
96     if (n == 0) return;
97     clean_up(n->L);
98     clean_up(n->R);
99     delete n;
100 }
101
102 public:
103 interval_tree(): root(0) { srand(time(0)); }
104 ~interval_tree() { clean_up(root); }
105
106 void insert(int lo, int hi) {
107     i = interval(lo, hi);
108     insert(root);

```

```

109     }
110
111     template<class ReportFunction>
112     void query(int lo, int hi, ReportFunction f) {
113         i = interval(lo, hi);
114         query(root, f);
115     }
116 };
117
118 /** Example Usage */
119
120 #include <cassert>
121 #include <iostream>
122 using namespace std;
123
124 void print(int lo, int hi) {
125     cout << "[" << lo << "," << hi << "]\n";
126 }
127
128 int cnt;
129 void count(int lo, int hi) { cnt++; }
130
131 int main() {
132     int N = 6;
133     int intv[6][2] = {{15, 20}, {10, 30}, {17, 19}, {5, 20}, {12, 15}, {30, 40}};
134     interval_tree T;
135     for (int i = 0; i < N; i++) {
136         T.insert(intv[i][0], intv[i][1]);
137     }
138     T.query(10, 20, print); cout << "\n"; //[15,20] [10,30] [5,20] [12,15] [17,19]
139     T.query(0, 5, print); cout << "\n";  //[5,20]
140     T.query(25, 45, print); cout << "\n"; //[10,30] [30,40]
141     //check correctness
142     for (int l = 0; l <= 50; l++) {
143         for (int h = l; h <= 50; h++) {
144             cnt = 0;
145             T.query(l, h, count);
146             int cnt2 = 0;
147             for (int i = 0; i < N; i++)
148                 if (intv[i][0] <= h && l <= intv[i][1])
149                     cnt2++;
150             assert(cnt == cnt2);
151         }
152     }
153     return 0;
154 }

```

3.4 2D Range Queries

3.4.1 Quadtree (Simple)

```

1  /*
2
3  3.4.1 - Quadtree (Simple)
4
5  Description: A quadtree can be used to dynamically query values

```

```

6 of rectangles in a 2D array. In a quadtree, every node has exactly
7 4 children. The following uses a statically allocated array to
8 store the nodes. This is less efficient than a 2D segment tree.
9
10 Time Complexity: For update(), query() and at():  $O(\log(N*M))$  on
11 average and  $O(\sqrt{N*M})$  in the worst case, where N is the number
12 of rows and M is the number of columns in the 2D array.
13
14 Space Complexity:  $O(N*M)$ 
15
16 Note: This implementation is 0-based. Valid indices for
17 all operations are  $[0..xmax][0..ymax]$ 
18
19 */
20
21 #include <climits> /* INT_MIN */
22
23 const int xmax = 100, ymax = 100;
24 int tree[4 * xmax * ymax];
25 int X, Y, X1, X2, Y1, Y2, V; //temporary value to speed up recursion
26
27 //define the following yourself. merge(x, nullv) must return x for all valid x
28 inline int nullv() { return INT_MIN; }
29 inline int merge(int a, int b) { return a > b ? a : b; }
30
31 void update(int n, int x1, int x2, int y1, int y2) {
32     if (X < x1 || X > x2 || Y < y1 || Y > y2) return;
33     if (x1 == x2 && y1 == y2) {
34         tree[n] = V;
35         return;
36     }
37     update(n * 4 + 1, x1, (x1 + x2) / 2, y1, (y1 + y2) / 2);
38     update(n * 4 + 2, x1, (x1 + x2) / 2, (y1 + y2) / 2 + 1, y2);
39     update(n * 4 + 3, (x1 + x2) / 2 + 1, x2, y1, (y1 + y2) / 2);
40     update(n * 4 + 4, (x1 + x2) / 2 + 1, x2, (y1 + y2) / 2 + 1, y2);
41     tree[n] = merge(merge(tree[n * 4 + 1], tree[n * 4 + 2]),
42                     merge(tree[n * 4 + 3], tree[n * 4 + 4]));
43 }
44
45 void query(int n, int x1, int x2, int y1, int y2) {
46     if (x1 > X2 || x2 < X1 || y2 < Y1 || y1 > Y2 || merge(tree[n], V) == V)
47         return;
48     if (x1 >= X1 && x2 <= X2 && y1 >= Y1 && y2 <= Y2) {
49         V = merge(tree[n], V);
50         return;
51     }
52     query(n * 4 + 1, x1, (x1 + x2) / 2, y1, (y1 + y2) / 2);
53     query(n * 4 + 2, x1, (x1 + x2) / 2, (y1 + y2) / 2 + 1, y2);
54     query(n * 4 + 3, (x1 + x2) / 2 + 1, x2, y1, (y1 + y2) / 2);
55     query(n * 4 + 4, (x1 + x2) / 2 + 1, x2, (y1 + y2) / 2 + 1, y2);
56 }
57
58 void update(int x, int y, int v) {
59     X = x;
60     Y = y;
61     V = v;
62     update(0, 0, xmax - 1, 0, ymax - 1);
63 }
64

```

```

65 int query(int x1, int y1, int x2, int y2) {
66     X1 = x1;
67     X2 = x2;
68     Y1 = y1;
69     Y2 = y2;
70     V = nullv();
71     query(0, 0, xmax - 1, 0, ymax - 1);
72     return V;
73 }
74
75 /** Example Usage **/
76
77 #include <iostream>
78 using namespace std;
79
80 int main() {
81     int arr[5][5] = {{1, 2, 3, 4, 5},
82                     {5, 4, 3, 2, 1},
83                     {6, 7, 8, 0, 0},
84                     {0, 1, 2, 3, 4},
85                     {5, 9, 9, 1, 2}};
86     for (int r = 0; r < 5; r++)
87         for (int c = 0; c < 5; c++)
88             update(r, c, arr[r][c]);
89     cout << "The maximum value in the rectangle with ";
90     cout << "upper left (0,2) and lower right (3,4) is ";
91     cout << query(0, 2, 3, 4) << ".\n"; //8
92     return 0;
93 }

```

3.4.2 Quadtree

```

1  /*
2
3  3.4.2 - Quadtree with Compression
4
5  Description: A quadtree can be used to dynamically query values
6  of rectangles in a 2D array. In a quadtree, every node has exactly
7  4 children. The following uses dynamically allocated memory to
8  store the nodes, which allows arbitrarily large indices to exist
9  without affecting the performance of operations.
10
11 Time Complexity: For update(), query() and at():  $O(\log(N*M))$  on
12 average and  $O(\sqrt{N*M})$  in the worst case, where N is the number
13 of rows and M is the number of columns in the 2D array.
14
15 Space Complexity:  $O(N*M)$ 
16
17 Note: This implementation is 0-based. Valid indices for
18 all operations are [0..XMAX][0..YMAX]
19
20 */
21
22 #include <algorithm> /* std::max(), std::min() */
23 #include <limits> /* std::numeric_limits<T>::min() */
24
25 template<class T> class quadtree {

```

```

26 //these can be set to large values without affecting your memory usage!
27 static const int xmax = 1000000000;
28 static const int ymax = 1000000000;
29
30 //define the following yourself. merge(x, nullv) must return x for all valid x
31 static inline T nullv() { return std::numeric_limits<T>::min(); }
32 static inline T merge(const T & a, const T & b) { return a > b ? a : b; }
33
34 int X, Y, X1, X2, Y1, Y2; T V; //temp vals for speed
35
36 struct node_t {
37     node_t * child[4];
38     int x1, x2, y1, y2;
39     T value;
40
41     node_t(int x, int y) {
42         x1 = x2 = x;
43         y1 = y2 = y;
44         child[0] = child[1] = child[2] = child[3] = 0;
45         value = nullv();
46     }
47 } *root;
48
49 void update(node_t *& n, int x1, int x2, int y1, int y2) {
50     if (X < x1 || X > x2 || Y < y1 || Y > y2) return;
51     if (n == 0) n = new node_t(X, Y);
52     if (x1 == x2 && y1 == y2) {
53         n->value = V;
54         return;
55     }
56     int xmid = (x1 + x2)/2, ymid = (y1 + y2)/2;
57     update(n->child[0], x1, xmid, y1, ymid);
58     update(n->child[1], xmid + 1, x2, y1, ymid);
59     update(n->child[2], x1, xmid, ymid + 1, y2);
60     update(n->child[3], xmid + 1, x2, ymid + 1, y2);
61     for (int i = 0; i < 4; i++) {
62         if (!n->child[i] || n->child[i]->value == nullv()) continue;
63         n->x1 = std::min(n->x1, n->child[i]->x1);
64         n->x2 = std::max(n->x2, n->child[i]->x2);
65         n->y1 = std::min(n->y1, n->child[i]->y1);
66         n->y2 = std::max(n->y2, n->child[i]->y2);
67         n->value = merge(n->value, n->child[i]->value);
68     }
69 }
70
71 void query(node_t * n) {
72     if (n == 0 || n->x1 > X2 || n->x2 < X1 || n->y2 < Y1 || n->y1 > Y2 ||
73         merge(n->value, V) == V)
74         return;
75     if (n->x1 >= X1 && n->y1 >= Y1 && n->x2 <= X2 && n->y2 <= Y2) {
76         V = merge(V, n->value);
77         return;
78     }
79     for (int i = 0; i < 4; i++) query(n->child[i]);
80 }
81
82 static void clean_up(node_t * n) {
83     if (n == 0) return;
84     for (int i = 0; i < 4; i++) clean_up(n->child[i]);

```

```

85     delete n;
86 }
87
88 public:
89     quadtree() { root = 0; }
90     ~quadtree() { clean_up(root); }
91
92     void update(int x, int y, const T & v) {
93         X = x;
94         Y = y;
95         V = v;
96         update(root, 0, xmax - 1, 0, ymax - 1);
97     }
98
99     T query(int x1, int y1, int x2, int y2) {
100         X1 = x1;
101         X2 = x2;
102         Y1 = y1;
103         Y2 = y2;
104         V = nullv();
105         query(root);
106         return V;
107     }
108
109     T at(int x, int y) {
110         return query(x, y, x, y);
111     }
112 };
113
114 /** Example Usage */
115
116 #include <iostream>
117 using namespace std;
118
119 int main() {
120     int arr[5][5] = {{1, 2, 3, 4, 5},
121                     {5, 4, 3, 2, 1},
122                     {6, 7, 8, 0, 0},
123                     {0, 1, 2, 3, 4},
124                     {5, 9, 9, 1, 2}};
125     quadtree<int> T;
126     for (int r = 0; r < 5; r++)
127         for (int c = 0; c < 5; c++)
128             T.update(r, c, arr[r][c]);
129     cout << "The maximum value in the rectangle with ";
130     cout << "upper_left(0,2) and lower_right(3,4) is ";
131     cout << T.query(0, 2, 3, 4) << ".\n"; //8
132     return 0;
133 }

```

3.4.3 2D Segment Tree

```

1  /*
2
3  3.4.3 - 2D Segment Tree
4
5  Description: A quadtree is a segment tree but with 4 children

```



```

6  per node, making its running time proportional to the square
7  root of the number of leaves. However, a 2D segment tree is a
8  segment tree of segment trees, making its running time
9  proportional to the log of its size. The following implementation
10 is a highly optimized implementation with features such as
11 coordinate compression and path compression.
12
13 Time Complexity:  $O(\log(x_{\max}) \cdot \log(y_{\max}))$  for update(), query(),
14 and at() operations. size() is  $O(1)$ .
15
16 Space Complexity: Left as an exercise for the reader.
17
18 Note: This implementation is 0-based. Valid indices for
19 all operations are [0..xmax][0..ymax]
20
21 */
22
23 #include <limits> /* std::numeric_limits<T>::min() */
24
25 template<class T> class segment_tree_2d {
26     //these can be set to large values without affecting your memory usage!
27     static const int xmax = 1000000000;
28     static const int ymax = 1000000000;
29
30     //define the following yourself. merge(x, nullv) must return x for all valid x
31     static inline T nullv() { return std::numeric_limits<T>::min(); }
32     static inline T merge(const T & a, const T & b) { return a > b ? a : b; }
33
34     struct layer2_node {
35         int lo, hi;
36         layer2_node *L, *R;
37         T value;
38         layer2_node(int l, int h) : lo(l), hi(h), L(0), R(0) {}
39     };
40
41     struct layer1_node {
42         layer1_node *L, *R;
43         layer2_node l2;
44         layer1_node() : L(0), R(0), l2(0, ymax) {}
45     } *root;
46
47     void update2(layer2_node * node, int Q, const T & v) {
48         int lo = node->lo, hi = node->hi, mid = (lo + hi)/2;
49         if (lo + 1 == hi) {
50             node->value = v;
51             return;
52         }
53         layer2_node *& tgt = Q < mid ? node->L : node->R;
54         if (tgt == 0) {
55             tgt = new layer2_node(Q, Q + 1);
56             tgt->value = v;
57         } else if (tgt->lo <= Q && Q < tgt->hi) {
58             update2(tgt, Q, v);
59         } else {
60             do {
61                 (Q < mid ? hi : lo) = mid;
62                 mid = (lo + hi)/2;
63             } while ((Q < mid) == (tgt->lo < mid));
64             layer2_node *nnode = new layer2_node(lo, hi);

```

```

65     (tgt->lo < mid ? nnode->L : nnode->R) = tgt;
66     tgt = nnode;
67     update2(nnode, Q, v);
68 }
69 node->value = merge(node->L ? node->L->value : nullv(),
70                   node->R ? node->R->value : nullv());
71 }
72
73 T query2(layer2_node * nd, int A, int B) {
74     if (nd == 0 || B <= nd->lo || nd->hi <= A) return nullv();
75     if (A <= nd->lo && nd->hi <= B) return nd->value;
76     return merge(query2(nd->L, A, B), query2(nd->R, A, B));
77 }
78
79 void update1(layer1_node * node, int lo, int hi, int x, int y, const T & v) {
80     if (lo + 1 == hi) update2(&node->l2, y, v);
81     else {
82         int mid = (lo + hi)/2;
83         layer1_node *& nnode = x < mid ? node->L : node->R;
84         (x < mid ? hi : lo) = mid;
85         if (nnode == 0) nnode = new layer1_node();
86         update1(nnode, lo, hi, x, y, v);
87         update2(&node->l2, y, merge(
88             node->L ? query2(&node->L->l2, y, y + 1) : nullv(),
89             node->R ? query2(&node->R->l2, y, y + 1) : nullv()
90         ));
91     }
92 }
93
94 T query1(layer1_node * nd, int lo, int hi, int A1, int B1, int A2, int B2) {
95     if (nd == 0 || B1 <= lo || hi <= A1) return nullv();
96     if (A1 <= lo && hi <= B1) return query2(&nd->l2, A2, B2);
97     int mid = (lo + hi) / 2;
98     return merge(query1(nd->L, lo, mid, A1, B1, A2, B2),
99                 query1(nd->R, mid, hi, A1, B1, A2, B2));
100 }
101
102 void clean_up2(layer2_node * n) {
103     if (n == 0) return;
104     clean_up2(n->L);
105     clean_up2(n->R);
106     delete n;
107 }
108
109 void clean_up1(layer1_node * n) {
110     if (n == 0) return;
111     clean_up2(n->l2.L);
112     clean_up2(n->l2.R);
113     clean_up1(n->L);
114     clean_up1(n->R);
115     delete n;
116 }
117
118 public:
119 segment_tree_2d() { root = new layer1_node(); }
120 ~segment_tree_2d() { clean_up1(root); }
121
122 void update(int x, int y, const T & v) {
123     update1(root, 0, xmax, x, y, v);

```

```

124     }
125
126     T query(int x1, int y1, int x2, int y2) {
127         return query1(root, 0, xmax, x1, x2 + 1, y1, y2 + 1);
128     }
129
130     T at(int x, int y) {
131         return query(x, y, x, y);
132     }
133 };
134
135 /** Example Usage **/
136
137 #include <iostream>
138 using namespace std;
139
140 int main() {
141     int arr[5][5] = {{1, 2, 3, 4, 5},
142                     {5, 4, 3, 2, 1},
143                     {6, 7, 8, 0, 0},
144                     {0, 1, 2, 3, 4},
145                     {5, 9, 9, 1, 2}};
146     segment_tree_2d<int> T;
147     for (int r = 0; r < 5; r++)
148         for (int c = 0; c < 5; c++)
149             T.update(r, c, arr[r][c]);
150     cout << "The maximum value in the rectangle with "
151     cout << "upper left (0,2) and lower right (3,4) is ";
152     cout << T.query(0, 2, 3, 4) << ".\n"; //8
153     return 0;
154 }

```

3.4.4 K-d Tree (2D Range Query)

```

1  /*
2
3  3.4.4 - K-d Tree for 2D Rectangular Queries
4
5  Description: k-d tree (short for k-dimensional tree) is a space-
6  partitioning data structure for organizing points in a k-
7  dimensional space. The following implementation supports
8  counting the number of points in rectangular ranges after the
9  tree has been build.
10
11 Time Complexity: O(N log N) for build(), where N is the number
12 of points in the tree. count() is O(sqrt N).
13
14 Space Complexity: O(N) on the number of points.
15
16 */
17
18 #include <algorithm> /* nth_element(), max(), min() */
19 #include <climits>   /* INT_MIN, INT_MAX */
20 #include <utility>    /* std::pair */
21 #include <vector>
22
23 class kd_tree {

```

```

24     typedef std::pair<int, int> point;
25
26     static inline bool cmp_x(const point & a, const point & b) {
27         return a.first < b.first;
28     }
29
30     static inline bool cmp_y(const point & a, const point & b) {
31         return a.second < b.second;
32     }
33
34     std::vector<int> tx, ty, cnt, minx, miny, maxx, maxy;
35     int x1, y1, x2, y2; //temporary values to speed up recursion
36
37     void build(int lo, int hi, bool div_x, point P[]) {
38         if (lo >= hi) return;
39         int mid = (lo + hi) >> 1;
40         std::nth_element(P + lo, P + mid, P + hi, div_x ? cmp_x : cmp_y);
41         tx[mid] = P[mid].first;
42         ty[mid] = P[mid].second;
43         cnt[mid] = hi - lo;
44         minx[mid] = INT_MAX; miny[mid] = INT_MAX;
45         maxx[mid] = INT_MIN; maxy[mid] = INT_MIN;
46         for (int i = lo; i < hi; i++) {
47             minx[mid] = std::min(minx[mid], P[i].first);
48             maxx[mid] = std::max(maxx[mid], P[i].first);
49             miny[mid] = std::min(miny[mid], P[i].second);
50             maxy[mid] = std::max(maxy[mid], P[i].second);
51         }
52         build(lo, mid, !div_x, P);
53         build(mid + 1, hi, !div_x, P);
54     }
55
56     int count(int lo, int hi) {
57         if (lo >= hi) return 0;
58         int mid = (lo + hi) >> 1;
59         int ax = minx[mid], ay = miny[mid];
60         int bx = maxx[mid], by = maxy[mid];
61         if (ax > x2 || x1 > bx || ay > y2 || y1 > by) return 0;
62         if (x1 <= ax && bx <= x2 && y1 <= ay && by <= y2) return cnt[mid];
63         int res = count(lo, mid) + count(mid + 1, hi);
64         res += (x1 <= tx[mid] && tx[mid] <= x2 && y1 <= ty[mid] && ty[mid] <= y2);
65         return res;
66     }
67
68     public:
69     kd_tree(int n, point P[]): tx(n), ty(n), cnt(n),
70         minx(n), miny(n), maxx(n), maxy(n) {
71         build(0, n, true, P);
72     }
73
74     int count(int x1, int y1, int x2, int y2) {
75         this->x1 = x1;
76         this->y1 = y1;
77         this->x2 = x2;
78         this->y2 = y2;
79         return count(0, tx.size());
80     }
81 };
82

```

```

83  /** Example Usage **/
84
85  #include <cassert>
86  using namespace std;
87
88  int main() {
89      pair<int, int> P[4];
90      P[0] = make_pair(0, 0);
91      P[1] = make_pair(10, 10);
92      P[2] = make_pair(0, 10);
93      P[3] = make_pair(10, 0);
94      kd_tree t(4, P);
95      assert(t.count(0, 0, 10, 9) == 2);
96      assert(t.count(0, 0, 10, 10) == 4);
97      return 0;
98  }

```

3.4.5 K-d Tree (Nearest Neighbor)

```

1  /*
2
3  3.4.5 - K-d Tree for Nearest Neighbour Queries
4
5  Description: k-d tree (short for k-dimensional tree) is a space-
6  partitioning data structure for organizing points in a k-
7  dimensional space. The following implementation supports
8  querying the nearest neighboring point to (x, y) in terms of
9  Euclidean distance after the tree has been build. Note that
10 a point is not considered its own neighbour if it already exists
11 in the tree.
12
13 Time Complexity:  $O(N \log N)$  for build(), where N is the number of
14 points in the tree. nearest_neighbor_id() is  $O(\log(N))$  on average.
15
16 Space Complexity:  $O(N)$  on the number of points.
17
18 */
19
20 #include <algorithm> /* nth_element(), max(), min(), swap() */
21 #include <climits> /* INT_MIN, INT_MAX */
22 #include <utility>
23 #include <vector>
24
25 class kd_tree {
26     typedef std::pair<int, int> point;
27
28     static inline bool cmp_x(const point & a, const point & b) {
29         return a.first < b.first;
30     }
31
32     static inline bool cmp_y(const point & a, const point & b) {
33         return a.second < b.second;
34     }
35
36     std::vector<int> tx, ty;
37     std::vector<bool> div_x;
38

```

```

39 void build(int lo, int hi, point P[]) {
40     if (lo >= hi) return;
41     int mid = (lo + hi) >> 1;
42     int minx = INT_MAX, maxx = INT_MIN;
43     int miny = INT_MAX, maxy = INT_MIN;
44     for (int i = lo; i < hi; i++) {
45         minx = std::min(minx, P[i].first);
46         maxx = std::max(maxx, P[i].first);
47         miny = std::min(miny, P[i].second);
48         maxy = std::max(maxy, P[i].second);
49     }
50     div_x[mid] = (maxx - minx) >= (maxy - miny);
51     std::nth_element(P + lo, P + mid, P + hi, div_x[mid] ? cmp_x : cmp_y);
52     tx[mid] = P[mid].first;
53     ty[mid] = P[mid].second;
54     if (lo + 1 == hi) return;
55     build(lo, mid, P);
56     build(mid + 1, hi, P);
57 }
58
59 long long min_dist;
60 int min_dist_id, x, y;
61
62 void nearest_neighbor(int lo, int hi) {
63     if (lo >= hi) return;
64     int mid = (lo + hi) >> 1;
65     int dx = x - tx[mid], dy = y - ty[mid];
66     long long d = dx*(long long)dx + dy*(long long)dy;
67     if (min_dist > d && d) {
68         min_dist = d;
69         min_dist_id = mid;
70     }
71     if (lo + 1 == hi) return;
72     int delta = div_x[mid] ? dx : dy;
73     long long delta2 = delta*(long long)delta;
74     int l1 = lo, r1 = mid, l2 = mid + 1, r2 = hi;
75     if (delta > 0) std::swap(l1, l2), std::swap(r1, r2);
76     nearest_neighbor(l1, r1);
77     if (delta2 < min_dist) nearest_neighbor(l2, r2);
78 }
79
80 public:
81 kd_tree(int N, point P[]) {
82     tx.resize(N);
83     ty.resize(N);
84     div_x.resize(N);
85     build(0, N, P);
86 }
87
88 int nearest_neighbor_id(int x, int y) {
89     this->x = x; this->y = y;
90     min_dist = LLONG_MAX;
91     nearest_neighbor(0, tx.size());
92     return min_dist_id;
93 }
94 };
95
96 /** Example Usage */
97

```

```

98 #include <iostream>
99 using namespace std;
100
101 int main() {
102     pair<int, int> P[3];
103     P[0] = make_pair(0, 2);
104     P[1] = make_pair(0, 3);
105     P[2] = make_pair(-1, 0);
106     kd_tree T(3, P);
107     int res = T.nearest_neighbor_id(0, 0);
108     cout << P[res].first << "□" << P[res].second << "\n"; //-1, 0
109     return 0;
110 }

```

3.4.6 R-Tree (Nearest Segment)

```

1  /*
2
3  3.4.6 - R-Tree for Nearest Neighbouring Line Segment Queries
4
5  Description: R-trees are tree data structures used for spatial
6  access methods, i.e., for indexing multi-dimensional information
7  such as geographical coordinates, rectangles or polygons. The
8  following implementation supports querying of the nearing line
9  segment to a point after a tree of line segments have been built.
10
11 Time Complexity:  $O(N \log N)$  for build(), where N is the number of
12 points in the tree. nearest_neighbor_id() is  $O(\log(N))$  on average.
13
14 Space Complexity:  $O(N)$  on the number of points.
15
16 */
17
18 #include <algorithm> /* nth_element(), max(), min(), swap() */
19 #include <cfloat> /* DBL_MAX */
20 #include <climits> /* INT_MIN, INT_MAX */
21 #include <vector>
22
23 struct segment { int x1, y1, x2, y2; };
24
25 class r_tree {
26
27     static inline bool cmp_x(const segment & a, const segment & b) {
28         return a.x1 + a.x2 < b.x1 + b.x2;
29     }
30
31     static inline bool cmp_y(const segment & a, const segment & b) {
32         return a.y1 + a.y2 < b.y1 + b.y2;
33     }
34
35     std::vector<segment> s;
36     std::vector<int> minx, maxx, miny, maxy;
37
38     void build(int lo, int hi, bool div_x, segment s[]) {
39         if (lo >= hi) return;
40         int mid = (lo + hi) >> 1;
41         std::nth_element(s + lo, s + mid, s + hi, div_x ? cmp_x : cmp_y);

```

```

42     this->s[mid] = s[mid];
43     for (int i = lo; i < hi; i++) {
44         minx[mid] = std::min(minx[mid], std::min(s[i].x1, s[i].x2));
45         miny[mid] = std::min(miny[mid], std::min(s[i].y1, s[i].y2));
46         maxx[mid] = std::max(maxx[mid], std::max(s[i].x1, s[i].x2));
47         maxy[mid] = std::max(maxy[mid], std::max(s[i].y1, s[i].y2));
48     }
49     build(lo, mid, !div_x, s);
50     build(mid + 1, hi, !div_x, s);
51 }
52
53 double min_dist;
54 int min_dist_id, x, y;
55
56 void nearest_neighbor(int lo, int hi, bool div_x) {
57     if (lo >= hi) return;
58     int mid = (lo + hi) >> 1;
59     double pdist = point_to_segment_squared(x, y, s[mid]);
60     if (min_dist > pdist) {
61         min_dist = pdist;
62         min_dist_id = mid;
63     }
64     long long delta = div_x ? 2*x - s[mid].x1 - s[mid].x2 :
65                         2*y - s[mid].y1 - s[mid].y2;
66     if (delta <= 0) {
67         nearest_neighbor(lo, mid, !div_x);
68         if (mid + 1 < hi) {
69             int mid1 = (mid + hi + 1) >> 1;
70             long long dist = div_x ? seg_dist(x, minx[mid1], maxx[mid1]) :
71                                 seg_dist(y, miny[mid1], maxy[mid1]);
72             if (dist*dist < min_dist) nearest_neighbor(mid + 1, hi, !div_x);
73         }
74     } else {
75         nearest_neighbor(mid + 1, hi, !div_x);
76         if (lo < mid) {
77             int mid1 = (lo + mid) >> 1;
78             long long dist = div_x ? seg_dist(x, minx[mid1], maxx[mid1]) :
79                                 seg_dist(y, miny[mid1], maxy[mid1]);
80             if (dist*dist < min_dist) nearest_neighbor(lo, mid, !div_x);
81         }
82     }
83 }
84
85 static double point_to_segment_squared(int x, int y, const segment & s) {
86     long long dx = s.x2 - s.x1, dy = s.y2 - s.y1;
87     long long px = x - s.x1, py = y - s.y1;
88     long long square_dist = dx*dx + dy*dy;
89     long long dot_product = dx*px + dy*py;
90     if (dot_product <= 0 || square_dist == 0) return px*px + py*py;
91     if (dot_product >= square_dist)
92         return (px - dx)*(px - dx) + (py - dy)*(py - dy);
93     double q = (double)dot_product/square_dist;
94     return (px - q*dx)*(px - q*dx) + (py - q*dy)*(py - q*dy);
95 }
96
97 static inline int seg_dist(int v, int lo, int hi) {
98     return v <= lo ? lo - v : (v >= hi ? v - hi : 0);
99 }

```



```

101 public:
102     r_tree(int N, segment s[]) {
103         this->s.resize(N);
104         minx.assign(N, INT_MAX);
105         maxx.assign(N, INT_MIN);
106         miny.assign(N, INT_MAX);
107         maxy.assign(N, INT_MIN);
108         build(0, N, true, s);
109     }
110
111     int nearest_neighbor_id(int x, int y) {
112         min_dist = DBL_MAX;
113         this->x = x; this->y = y;
114         nearest_neighbor(0, s.size(), true);
115         return min_dist_id;
116     }
117 };
118
119 /** Example Usage */
120
121 #include <iostream>
122 using namespace std;
123
124 int main() {
125     segment s[4];
126     s[0] = (segment){0, 0, 0, 4};
127     s[1] = (segment){0, 4, 4, 4};
128     s[2] = (segment){4, 4, 4, 0};
129     s[3] = (segment){4, 0, 0, 0};
130     r_tree t(4, s);
131     int id = t.nearest_neighbor_id(-1, 2);
132     cout << s[id].x1 << " " << s[id].y1 << " " <<
133           s[id].x2 << " " << s[id].y2 << "\n"; //0 0 0 4
134     return 0;
135 }

```

3.4.7 2D Range Tree

```

1  /*
2
3  3.4.7 - 2D Range Tree for Rectangular Queries
4
5  Description: A range tree is an ordered tree data structure to
6  hold a list of points. It allows all points within a given range
7  to be reported efficiently. Specifically, for a given query, a
8  range tree will report *all* points that lie in the given range.
9  Note that the initial array passed to construct the tree will be
10 sorted, and all resulting query reports will pertain to the
11 indices of points in the sorted array.
12
13 Time Complexity: A range tree can build() in  $O(N \log^{d-1}(N))$ 
14 and query() in  $O(\log^d(n) + k)$ , where  $N$  is the number of points
15 stored in the tree,  $d$  is the dimension of each point and  $k$  is the
16 number of points reported by a given query. Thus for this 2D case
17 build() is  $O(N \log N)$  and query() is  $O(\log^2(N) + k)$ .
18
19 Space Complexity:  $O(N \log^{d-1}(N))$  for a  $d$ -dimensional range tree.

```

```

20 Thus for this 2D case, the space complexity is  $O(N \log N)$ .
21
22 */
23
24 #include <algorithm> /* lower_bound(), merge(), sort() */
25 #include <utility>   /* std::pair */
26 #include <vector>
27
28 class range_tree_2d {
29     typedef std::pair<int, int> point;
30
31     std::vector<point> P;
32     std::vector<std::vector<point> > seg;
33
34     static inline bool comp1(const point & a, const point & b) {
35         return a.second < b.second;
36     }
37
38     static inline bool comp2(const point & a, int v) {
39         return a.second < v;
40     }
41
42     void build(int n, int lo, int hi) {
43         if (P[lo].first == P[hi].first) {
44             for (int i = lo; i <= hi; i++)
45                 seg[n].push_back(point(i, P[i].second));
46             return;
47         }
48         int l = n * 2 + 1, r = n * 2 + 2;
49         build(l, lo, (lo + hi)/2);
50         build(r, (lo + hi)/2 + 1, hi);
51         seg[n].resize(seg[l].size() + seg[r].size());
52         std::merge(seg[l].begin(), seg[l].end(), seg[r].begin(), seg[r].end(),
53                   seg[n].begin(), comp1);
54     }
55
56     int xl, xh, yl, yh;
57
58     template<class ReportFunction>
59     void query(int n, int lo, int hi, ReportFunction f) {
60         if (P[hi].first < xl || P[lo].first > xh) return;
61         if (xl <= P[lo].first && P[hi].first <= xh) {
62             if (!seg[n].empty() && yh >= yl) {
63                 std::vector<point>::iterator it;
64                 it = std::lower_bound(seg[n].begin(), seg[n].end(), yl, comp2);
65                 for (; it != seg[n].end(); ++it) {
66                     if (it->second > yh) break;
67                     f(it->first); //or report P[it->first], the actual point
68                 }
69             }
70             else if (lo != hi) {
71                 query(n * 2 + 1, lo, (lo + hi) / 2, f);
72                 query(n * 2 + 2, (lo + hi) / 2 + 1, hi, f);
73             }
74         }
75
76     public:
77         range_tree_2d(int n, point init[]): seg(4 * n + 1) {
78             std::sort(init, init + n);

```

```

79     P = std::vector<point>(init, init + n);
80     build(0, 0, n - 1);
81 }
82
83 template<class ReportFunction>
84 void query(int x1, int y1, int x2, int y2, ReportFunction f) {
85     xl = x1; xh = x2;
86     yl = y1; yh = y2;
87     query(0, 0, P.size() - 1, f);
88 }
89 };
90
91 /** Example Usage (wcipeg.com/problem/box1) */
92
93 #include <bitset>
94 #include <cstdio>
95 using namespace std;
96
97 int N, M; bitset<200005> b;
98 pair<int, int> pts[200005];
99 int x1[200005], y1[200005];
100 int x2[200005], y2[200005];
101
102 void mark(int i) {
103     b[i] = true;
104 }
105
106 int main() {
107     scanf("%d%d", &N, &M);
108     for (int i = 0; i < N; i++)
109         scanf("%d%d%d", x1 + i, y1 + i, x2 + i, y2 + i);
110     for (int i = 0; i < M; i++)
111         scanf("%d%d", &pts[i].first, &pts[i].second);
112     range_tree_2d t(M, pts);
113     for (int i = 0; i < N; i++)
114         t.query(x1[i], y1[i], x2[i], y2[i], mark);
115     printf("%d\n", b.count());
116     return 0;
117 }

```

3.5 Search Trees and Alternatives

3.5.1 Binary Search Tree

```

1  /*
2
3  3.5.1 - Binary Search Tree
4
5  Description: A binary search tree (BST) is a node-based binary tree data
6  structure where the left sub-tree of every node has keys less than the
7  node's key and the right sub-tree of every node has keys greater than the
8  node's key. A BST may be come degenerate like a linked list resulting in
9  an O(N) running time per operation. A self-balancing binary search tree
10 such as a randomized treap prevents the occurrence of this known worst case.
11
12 Note: The following implementation is used similar to an std::map. In order

```

```

13  to make it behave like an std::set, modify the code to remove the value
14  associated with each node. In order to make it behave like an std::multiset
15  or std::multimap, make appropriate changes with key comparisons (e.g.
16  change (k < n->key) to (k <= n->key) in search conditions).
17
18  Time Complexity: insert(), erase() and find() are  $O(\log(N))$  on average,
19  but  $O(N)$  at worst if the tree becomes degenerate. Speed can be improved
20  by randomizing insertion order if it doesn't matter. walk() is  $O(N)$ .
21
22  Space Complexity:  $O(N)$  on the number of nodes.
23
24  */
25
26  template<class key_t, class val_t> class binary_search_tree {
27      struct node_t {
28          key_t key;
29          val_t val;
30          node_t *L, *R;
31
32          node_t(const key_t & k, const val_t & v) {
33              key = k;
34              val = v;
35              L = R = 0;
36          }
37      } *root;
38
39      int num_nodes;
40
41      static bool insert(node_t *& n, const key_t & k, const val_t & v) {
42          if (n == 0) {
43              n = new node_t(k, v);
44              return true;
45          }
46          if (k < n->key) return insert(n->L, k, v);
47          if (n->key < k) return insert(n->R, k, v);
48          return false; //already exists
49      }
50
51      static bool erase(node_t *& n, const key_t & key) {
52          if (n == 0) return false;
53          if (key < n->key) return erase(n->L, key);
54          if (n->key < key) return erase(n->R, key);
55          if (n->L == 0) {
56              node_t *temp = n->R;
57              delete n;
58              n = temp;
59          } else if (n->R == 0) {
60              node_t *temp = n->L;
61              delete n;
62              n = temp;
63          } else {
64              node_t *temp = n->R, *parent = 0;
65              while (temp->L != 0) {
66                  parent = temp;
67                  temp = temp->L;
68              }
69              n->key = temp->key;
70              n->val = temp->val;
71              if (parent != 0)

```

```

72         return erase(parent->L, parent->L->key);
73     return erase(n->R, n->R->key);
74 }
75 return true;
76 }
77
78 template<class BinaryFunction>
79 static void walk(node_t * n, BinaryFunction f) {
80     if (n == 0) return;
81     walk(n->L, f);
82     f(n->key, n->val);
83     walk(n->R, f);
84 }
85
86 static void clean_up(node_t * n) {
87     if (n == 0) return;
88     clean_up(n->L);
89     clean_up(n->R);
90     delete n;
91 }
92
93 public:
94     binary_search_tree(): root(0), num_nodes(0) {}
95     ~binary_search_tree() { clean_up(root); }
96     int size() const { return num_nodes; }
97     bool empty() const { return root == 0; }
98
99     bool insert(const key_t & key, const val_t & val) {
100         if (insert(root, key, val)) {
101             num_nodes++;
102             return true;
103         }
104         return false;
105     }
106
107     bool erase(const key_t & key) {
108         if (erase(root, key)) {
109             num_nodes--;
110             return true;
111         }
112         return false;
113     }
114
115     template<class BinaryFunction> void walk(BinaryFunction f) {
116         walk(root, f);
117     }
118
119     val_t * find(const key_t & key) {
120         for (node_t *n = root; n != 0; ) {
121             if (n->key == key) return &(n->val);
122             n = (key < n->key ? n->L : n->R);
123         }
124         return 0; //key not found
125     }
126 };
127
128 /** Example Usage */
129
130 #include <iostream>

```

```

131 using namespace std;
132
133 void printch(int k, char v) { cout << v; }
134
135 int main() {
136     binary_search_tree<int, char> T;
137     T.insert(2, 'b');
138     T.insert(1, 'a');
139     T.insert(3, 'c');
140     T.insert(5, 'e');
141     T.insert(4, 'x');
142     *T.find(4) = 'd';
143     cout << "In-order: ";
144     T.walk(printch); //abcde
145     cout << "\nRemoving node with key 3...";
146     cout << (T.erase(3) ? "Success!" : "Failed");
147     cout << "\n";
148     return 0;
149 }

```

3.5.2 Treap

```

1  /*
2
3  3.5.2 - Treap
4
5  Description: A binary search tree (BST) is a node-based binary tree data
6  structure where the left sub-tree of every node has keys less than the
7  node's key and the right sub-tree of every node has keys greater than the
8  node's key. A BST may become degenerate like a linked list resulting in
9  an  $O(N)$  running time per operation. A self-balancing binary search tree
10 such as a randomized treap prevents the occurrence of this known worst case.
11
12 Treaps use randomly generated priorities to reduce the height of the
13 tree. We assume that the rand() function in <cstdlib> is 16-bits, and
14 call it twice to generate a 32-bit number. For the treap to be
15 effective, the range of the randomly generated numbers should be
16 between 0 and around the number of elements in the treap.
17
18 Note: The following implementation is used similar to an std::map. In order
19 to make it behave like an std::set, modify the code to remove the value
20 associated with each node. In order to make it behave like an std::multiset
21 or std::multimap, make appropriate changes with key comparisons (e.g.
22 change (k < n->key) to (k <= n->key) in search conditions).
23
24 Time Complexity: insert(), erase(), and find() are  $O(\log(N))$  on average
25 and  $O(N)$  in the worst case. Despite the technically  $O(N)$  worst case,
26 such cases are still extremely difficult to trigger, making treaps
27 very practice in many programming contest applications. walk() is  $O(N)$ .
28
29 Space Complexity:  $O(N)$  on the number of nodes.
30
31 */
32
33 #include <cstdlib> /* srand(), rand() */
34 #include <ctime>   /* time() */
35

```

```

36 template<class key_t, class val_t> class treap {
37     struct node_t {
38         static inline int rand32() {
39             return (rand() & 0x7fff) | ((rand() & 0x7fff) << 15);
40         }
41
42         key_t key;
43         val_t val;
44         int priority;
45         node_t *L, *R;
46
47         node_t(const key_t & k, const val_t & v): key(k), val(v), L(0), R(0) {
48             priority = rand32();
49         }
50     } *root;
51
52     int num_nodes;
53
54     static void rotate_l(node_t *& k2) {
55         node_t *k1 = k2->R;
56         k2->R = k1->L;
57         k1->L = k2;
58         k2 = k1;
59     }
60
61     static void rotate_r(node_t *& k2) {
62         node_t *k1 = k2->L;
63         k2->L = k1->R;
64         k1->R = k2;
65         k2 = k1;
66     }
67
68     static bool insert(node_t *& n, const key_t & k, const val_t & v) {
69         if (n == 0) {
70             n = new node_t(k, v);
71             return true;
72         }
73         if (k < n->key && insert(n->L, k, v)) {
74             if (n->L->priority < n->priority) rotate_r(n);
75             return true;
76         } else if (n->key < k && insert(n->R, k, v)) {
77             if (n->R->priority < n->priority) rotate_l(n);
78             return true;
79         }
80         return false;
81     }
82
83     static bool erase(node_t *& n, const key_t & k) {
84         if (n == 0) return false;
85         if (k < n->key) return erase(n->L, k);
86         if (k > n->key) return erase(n->R, k);
87         if (n->L == 0 || n->R == 0) {
88             node_t *temp = n;
89             n = (n->L != 0) ? n->L : n->R;
90             delete temp;
91             return true;
92         }
93         if (n->L->priority < n->R->priority) {
94             rotate_r(n);

```

```

95     return erase(n->R, k);
96 }
97 rotate_l(n);
98 return erase(n->L, k);
99 }
100
101 template<class BinaryFunction>
102 static void walk(node_t * n, BinaryFunction f) {
103     if (n == 0) return;
104     walk(n->L, f);
105     f(n->key, n->val);
106     walk(n->R, f);
107 }
108
109 static void clean_up(node_t * n) {
110     if (n == 0) return;
111     clean_up(n->L);
112     clean_up(n->R);
113     delete n;
114 }
115
116 public:
117     treap(): root(0), num_nodes(0) { srand(time(0)); }
118     ~treap() { clean_up(root); }
119     int size() const { return num_nodes; }
120     bool empty() const { return root == 0; }
121
122     bool insert(const key_t & key, const val_t & val) {
123         if (insert(root, key, val)) {
124             num_nodes++;
125             return true;
126         }
127         return false;
128     }
129
130     bool erase(const key_t & key) {
131         if (erase(root, key)) {
132             num_nodes--;
133             return true;
134         }
135         return false;
136     }
137
138     template<class BinaryFunction> void walk(BinaryFunction f) {
139         walk(root, f);
140     }
141
142     val_t * find(const key_t & key) {
143         for (node_t *n = root; n != 0; ) {
144             if (n->key == key) return &(n->val);
145             n = (key < n->key ? n->L : n->R);
146         }
147         return 0; //key not found
148     }
149 };
150
151 /** Example Usage */
152
153 #include <cassert>

```



```

154 #include <iostream>
155 using namespace std;
156
157 void printch(int k, char v) { cout << v; }
158
159 int main() {
160     treap<int, char> T;
161     T.insert(2, 'b');
162     T.insert(1, 'a');
163     T.insert(3, 'c');
164     T.insert(5, 'e');
165     T.insert(4, 'x');
166     *T.find(4) = 'd';
167     cout << "In-order: ";
168     T.walk(printch); //abcde
169     cout << "\nRemoving node with key 3...";
170     cout << (T.erase(3) ? "Success!" : "Failed");
171     cout << "\n";
172
173     //stress test - runs in <0.5 seconds
174     //insert keys in an order that would break a normal BST
175     treap<int, int> T2;
176     for (int i = 0; i < 1000000; i++)
177         T2.insert(i, i*1337);
178     for (int i = 0; i < 1000000; i++)
179         assert(*T2.find(i) == i*1337);
180     return 0;
181 }

```

3.5.3 Size Balanced Tree (Order Statistics)

```

1  /*
2
3  3.5.3 - Size Balanced Tree with Order Statistics
4
5  Description: A binary search tree (BST) is a node-based binary tree data
6  structure where the left sub-tree of every node has keys less than the
7  node's key and the right sub-tree of every node has keys greater than the
8  node's key. A BST may become degenerate like a linked list resulting in
9  an O(N) running time per operation. A self-balancing binary search tree
10 such as a randomized treap prevents the occurrence of this known worst case.
11
12 The size balanced tree is a data structure first published in 2007 by
13 Chinese student Chen Qifeng. The tree is rebalanced by examining the sizes
14 of each node's subtrees. It is popular amongst Chinese OI competitors due
15 to its speed, simplicity to implement, and ability to double up as an
16 ordered statistics tree if necessary.
17 For more info, see: http://wcipeg.com/wiki/Size\_Balanced\_Tree
18
19 An ordered statistics tree is a BST that supports additional operations:
20 - Select(i): find the i-th smallest element stored in the tree
21 - Rank(x): find the rank of element x in the tree,
22           i.e. its index in the sorted list of elements of the tree
23 For more info, see: http://en.wikipedia.org/wiki/Order\_statistic\_tree
24
25 Note: The following implementation is used similar to an std::map. In order
26 to make it behave like an std::set, modify the code to remove the value

```

```

27 associated with each node. Making a size balanced tree behave like an
28 std::multiset or std::multimap is a more complex issue. Refer to the
29 articles above and determine the correct way to preserve the binary search
30 tree property with maintain() if equivalent keys are allowed.
31
32 Time Complexity: insert(), erase(), find(), select() and rank() are
33  $O(\log N)$  on the number of elements in the tree. walk() is  $O(N)$ .
34
35 Space Complexity:  $O(N)$  on the number of nodes in the tree.
36
37 */
38
39 #include <stdexcept> /* std::runtime_error */
40 #include <utility>    /* pair */
41
42 template<class key_t, class val_t> class size_balanced_tree {
43     struct node_t {
44         key_t key;
45         val_t val;
46         int size;
47         node_t * c[2];
48
49         node_t(const key_t & k, const val_t & v) {
50             key = k, val = v;
51             size = 1;
52             c[0] = c[1] = 0;
53         }
54
55         void update() {
56             size = 1;
57             if (c[0]) size += c[0]->size;
58             if (c[1]) size += c[1]->size;
59         }
60     } *root;
61
62     static inline int size(node_t * n) {
63         return n ? n->size : 0;
64     }
65
66     static void rotate(node_t *& n, bool d) {
67         node_t * p = n->c[d];
68         n->c[d] = p->c[!d];
69         p->c[!d] = n;
70         n->update();
71         p->update();
72         n = p;
73     }
74
75     static void maintain(node_t *& n, bool d) {
76         if (n == 0 || n->c[d] == 0) return;
77         node_t *& p = n->c[d];
78         if (size(p->c[d]) > size(n->c[!d])) {
79             rotate(n, d);
80         } else if (size(p->c[!d]) > size(n->c[!d])) {
81             rotate(p, !d);
82             rotate(n, d);
83         } else return;
84         maintain(n->c[0], 0);
85         maintain(n->c[1], 1);

```

```

86     maintain(n, 0);
87     maintain(n, 1);
88 }
89
90 static void insert(node_t *&n, const key_t &k, const val_t &v) {
91     if (n == 0) {
92         n = new node_t(k, v);
93         return;
94     }
95     if (k < n->key) {
96         insert(n->c[0], k, v);
97         maintain(n, 0);
98     } else if (n->key < k) {
99         insert(n->c[1], k, v);
100        maintain(n, 1);
101    } else return;
102    n->update();
103 }
104
105 static void erase(node_t *&n, const key_t &k) {
106     if (n == 0) return;
107     bool d = k < n->key;
108     if (k < n->key) {
109         erase(n->c[0], k);
110     } else if (n->key < k) {
111         erase(n->c[1], k);
112     } else {
113         if (n->c[1] == 0 || n->c[0] == 0) {
114             delete n;
115             n = n->c[1] == 0 ? n->c[0] : n->c[1];
116             return;
117         }
118         node_t * p = n->c[1];
119         while (p->c[0] != 0) p = p->c[0];
120         n->key = p->key;
121         erase(n->c[1], p->key);
122     }
123     maintain(n, d);
124     n->update();
125 }
126
127 template<class BinaryFunction>
128 static void walk(node_t * n, BinaryFunction f) {
129     if (n == 0) return;
130     walk(n->c[0], f);
131     f(n->key, n->val);
132     walk(n->c[1], f);
133 }
134
135 static std::pair<key_t, val_t> select(node_t *&n, int k) {
136     int r = size(n->c[0]);
137     if (k < r) return select(n->c[0], k);
138     if (k > r) return select(n->c[1], k - r - 1);
139     return std::make_pair(n->key, n->val);
140 }
141
142 static int rank(node_t * n, const key_t &k) {
143     if (n == 0)
144         throw std::runtime_error("Cannot rank key not in tree.");

```

```

145     int r = size(n->c[0]);
146     if (k < n->key) return rank(n->c[0], k);
147     if (n->key < k) return rank(n->c[1], k) + r + 1;
148     return r;
149 }
150
151 static void clean_up(node_t * n) {
152     if (n == 0) return;
153     clean_up(n->c[0]);
154     clean_up(n->c[1]);
155     delete n;
156 }
157
158 public:
159     size_balanced_tree() : root(0) {}
160     ~size_balanced_tree() { clean_up(root); }
161     int size() { return size(root); }
162     bool empty() const { return root == 0; }
163
164     void insert(const key_t & key, const val_t & val) {
165         insert(root, key, val);
166     }
167
168     void erase(const key_t & key) {
169         erase(root, key);
170     }
171
172     template<class BinaryFunction> void walk(BinaryFunction f) {
173         walk(root, f);
174     }
175
176     val_t * find(const key_t & key) {
177         for (node_t *n = root; n != 0; ) {
178             if (n->key == key) return &(n->val);
179             n = (key < n->key ? n->c[0] : n->c[1]);
180         }
181         return 0; //key not found
182     }
183
184     std::pair<key_t, val_t> select(int k) {
185         if (k >= size(root))
186             throw std::runtime_error("k must be smaller size of tree.");
187         return select(root, k);
188     }
189
190     int rank(const key_t & key) {
191         return rank(root, key);
192     }
193 };
194
195 /** Example Usage */
196
197 #include <cassert>
198 #include <iostream>
199 using namespace std;
200
201 void printch(int k, char v) { cout << v; }
202
203 int main() {

```

```

204 size_balanced_tree<int, char> T;
205 T.insert(2, 'b');
206 T.insert(1, 'a');
207 T.insert(3, 'c');
208 T.insert(5, 'e');
209 T.insert(4, 'x');
210 *T.find(4) = 'd';
211 cout << "In-order:\n";
212 T.walk(printch); //abcde
213 T.erase(3);
214 cout << "\nRank_of_2:\n" << T.rank(2); //1
215 cout << "\nRank_of_5:\n" << T.rank(5); //3
216 cout << "\nValue_of_3rd_smallest_key:\n";
217 cout << T.select(2).second; //d
218 cout << "\n";
219
220 //stress test - runs in <1 second
221 //insert keys in an order that would break a normal BST
222 size_balanced_tree<int, int> T2;
223 for (int i = 0; i < 1000000; i++)
224     T2.insert(i, i*1337);
225 for (int i = 0; i < 1000000; i++)
226     assert(*T2.find(i) == i*1337);
227 return 0;
228 }

```

3.5.4 Hashmap (Chaining)

```

1  /*
2
3  3.5.4 - Hashmap (Chaining)
4
5  Description: A hashmap (std::unordered_map in C++11) is an
6  alternative to a binary search tree. Hashmaps use more memory than
7  BSTs, but are usually more efficient. The following implementation
8  uses the chaining method to handle collisions. You can use the
9  hash algorithms provided in the example, or define your own.
10
11 Time Complexity: insert(), remove(), find(), are O(1) amortized.
12 rehash() is O(N).
13
14 Space Complexity: O(N) on the number of entries.
15
16 */
17
18 #include <list>
19
20 template<class key_t, class val_t, class Hash> class hashmap {
21     struct entry_t {
22         key_t key;
23         val_t val;
24         entry_t(const key_t & k, const val_t & v): key(k), val(v) {}
25     };
26
27     std::list<entry_t> * table;
28     int table_size, map_size;
29

```

```

30  /**
31   * This doubles the table size, then rehashes every entry.
32   * Rehashing is expensive; it is strongly suggested for the
33   * table to be constructed with a large size to avoid rehashing.
34   */
35  void rehash() {
36      std::list<entry_t> * old = table;
37      int old_size = table_size;
38      table_size = 2*table_size;
39      table = new std::list<entry_t>[table_size];
40      map_size = 0;
41      typename std::list<entry_t>::iterator it;
42      for (int i = 0; i < old_size; i++)
43          for (it = old[i].begin(); it != old[i].end(); ++it)
44              insert(it->key, it->val);
45      delete[] old;
46  }
47
48  public:
49  hashmap(int size = 1024): table_size(size), map_size(0) {
50      table = new std::list<entry_t>[table_size];
51  }
52
53  ~hashmap() { delete[] table; }
54  int size() const { return map_size; }
55
56  void insert(const key_t & key, const val_t & val) {
57      if (find(key) != 0) return;
58      if (map_size >= table_size) rehash();
59      unsigned int i = Hash()(key) % table_size;
60      table[i].push_back(entry_t(key, val));
61      map_size++;
62  }
63
64  void remove(const key_t & key) {
65      unsigned int i = Hash()(key) % table_size;
66      typename std::list<entry_t>::iterator it = table[i].begin();
67      while (it != table[i].end() && it->key != key) ++it;
68      if (it == table[i].end()) return;
69      table[i].erase(it);
70      map_size--;
71  }
72
73  val_t * find(const key_t & key) {
74      unsigned int i = Hash()(key) % table_size;
75      typename std::list<entry_t>::iterator it = table[i].begin();
76      while (it != table[i].end() && it->key != key) ++it;
77      if (it == table[i].end()) return 0;
78      return &(it->val);
79  }
80
81  val_t & operator [] (const key_t & key) {
82      val_t * ret = find(key);
83      if (ret != 0) return *ret;
84      insert(key, val_t());
85      return *find(key);
86  }
87 };
88

```

```

89  /*** Examples of Hash Algorithm Definitions ***/
90
91  #include <string>
92
93  struct class_hash {
94      unsigned int operator () (int key) {
95          return class_hash()((unsigned int)key);
96      }
97
98      unsigned int operator () (long long key) {
99          return class_hash()((unsigned long long)key);
100     }
101
102     //Knuth's multiplicative method (one-to-one)
103     unsigned int operator () (unsigned int key) {
104         return key * 2654435761u; //or just return key
105     }
106
107     //Jenkins's 64-bit hash
108     unsigned int operator () (unsigned long long key) {
109         key += ~(key << 32); key ^= (key >> 22);
110         key += ~(key << 13); key ^= (key >> 8);
111         key += (key << 3); key ^= (key >> 15);
112         key += ~(key << 27); key ^= (key >> 31);
113         return key;
114     }
115
116     //Jenkins's one-at-a-time hash
117     unsigned int operator () (const std::string & key) {
118         unsigned int hash = 0;
119         for (unsigned int i = 0; i < key.size(); i++) {
120             hash += ((hash += key[i]) << 10);
121             hash ^= (hash >> 6);
122         }
123         hash ^= ((hash += (hash << 3)) >> 11);
124         return hash + (hash << 15);
125     }
126 };
127
128 /*** Example Usage ***/
129
130 #include <iostream>
131 using namespace std;
132
133 int main() {
134     hashmap<string, int, class_hash> M;
135     M["foo"] = 1;
136     M.insert("bar", 2);
137     cout << M["foo"] << M["bar"] << endl; //prints 12
138     cout << M["baz"] << M["qux"] << endl; //prints 00
139     M.remove("foo");
140     cout << M.size() << endl; //prints 3
141     cout << M["foo"] << M["bar"] << endl; //prints 02
142     return 0;
143 }

```

3.5.5 Skip List (Probabilistic)

```

1  /*
2
3  3.5.5 - Skip List (Probabilistic)
4
5  Description: A skip list is an alternative to binary search trees.
6  Fast search is made possible by maintaining a linked hierarchy of
7  subsequences, each skipping over fewer elements. Searching starts
8  in the sparsest subsequence until two consecutive elements have
9  been found, one smaller and one larger than the element searched for.
10 Skip lists are generally slower than binary search trees, but can
11 be easier to implement. The following version uses randomized levels.
12
13 Time Complexity: insert(), erase(), count() and find() are  $O(\log(N))$ 
14 on average, but  $O(N)$  in the worst case. walk() is  $O(N)$ .
15
16 Space Complexity:  $O(N)$  on the number of elements inserted on average,
17 but  $O(N \log N)$  in the worst case.
18
19 */
20
21 #include <cmath>    /* log() */
22 #include <cstdlib> /* rand(), srand() */
23 #include <cstring> /* memset() */
24 #include <ctime>   /* time() */
25
26 template<class key_t, class val_t> struct skip_list {
27     static const int MAX_LEVEL = 32; //~ log2(max # of keys)
28
29     static int random_level() { //geometric distribution
30         static const float P = 0.5;
31         int lvl = log((float)rand()/RAND_MAX)/log(1.0 - P);
32         return lvl < MAX_LEVEL ? lvl : MAX_LEVEL;
33     }
34
35     struct node_t {
36         key_t key;
37         val_t val;
38         node_t **next;
39
40         node_t(int level, const key_t & k, const val_t & v) {
41             next = new node_t * [level + 1];
42             memset(next, 0, sizeof(node_t)*(level + 1));
43             key = k;
44             val = v;
45         }
46
47         ~node_t() { delete[] next; }
48     } *head, *update[MAX_LEVEL + 1];
49
50     int level, num_nodes;
51
52     skip_list() {
53         srand(time(0));
54         head = new node_t(MAX_LEVEL, key_t(), val_t());
55         level = num_nodes = 0;
56     }
57
58     ~skip_list() { delete head; }
59     int size() { return num_nodes; }

```



```

60  bool empty() { return num_nodes == 0; }
61  int count(const key_t & k) { return find(k) != 0; }
62
63  void insert(const key_t & k, const val_t & v) {
64      node_t * n = head;
65      memset(update, 0, sizeof(node_t)*(MAX_LEVEL + 1));
66      for (int i = level; i >= 0; i--) {
67          while (n->next[i] && n->next[i]->key < k) n = n->next[i];
68          update[i] = n;
69      }
70      n = n->next[0];
71      if (!n || n->key != k) {
72          int lvl = random_level();
73          if (lvl > level) {
74              for (int i = level + 1; i <= lvl; i++) update[i] = head;
75              level = lvl;
76          }
77          n = new node_t(lvl, k, v);
78          num_nodes++;
79          for (int i = 0; i <= lvl; i++) {
80              n->next[i] = update[i]->next[i];
81              update[i]->next[i] = n;
82          }
83      } else if (n && n->key == k && n->val != v) {
84          n->val = v;
85      }
86  }
87
88  void erase(const key_t & k) {
89      node_t * n = head;
90      memset(update, 0, sizeof(node_t)*(MAX_LEVEL + 1));
91      for (int i = level; i >= 0; i--) {
92          while (n->next[i] && n->next[i]->key < k) n = n->next[i];
93          update[i] = n;
94      }
95      n = n->next[0];
96      if (n->key == k) {
97          for (int i = 0; i <= level; i++) {
98              if (update[i]->next[i] != n) break;
99              update[i]->next[i] = n->next[i];
100          }
101          delete n;
102          num_nodes--;
103          while (level > 0 && !head->next[level]) level--;
104      }
105  }
106
107  val_t * find(const key_t & k) {
108      node_t * n = head;
109      for (int i = level; i >= 0; i--)
110          while (n->next[i] && n->next[i]->key < k)
111              n = n->next[i];
112      n = n->next[0];
113      if (n && n->key == k) return &(n->val);
114      return 0; //not found
115  }
116
117  template<class BinaryFunction> void walk(BinaryFunction f) {
118      node_t *n = head->next[0];

```

```

119     while (n) {
120         f(n->key, n->val);
121         n = n->next[0];
122     }
123 }
124 };
125
126 /** Example Usage: Random Tests */
127
128 #include <cassert>
129 #include <iostream>
130 #include <map>
131 using namespace std;
132
133 int main() {
134     map<int, int> m;
135     skip_list<int, int> s;
136     for (int i = 0; i < 50000; i++) {
137         int op = rand() % 3;
138         int val1 = rand(), val2 = rand();
139         if (op == 0) {
140             m[val1] = val2;
141             s.insert(val1, val2);
142         } else if (op == 1) {
143             if (!m.count(val1)) continue;
144             m.erase(val1);
145             s.erase(val1);
146         } else if (op == 2) {
147             assert(s.count(val1) == (int)m.count(val1));
148             if (m.count(val1)) {
149                 assert(m[val1] == *s.find(val1));
150             }
151         }
152     }
153     return 0;
154 }

```

3.6 Tree Data Structures

3.6.1 Heavy-Light Decomposition

```

1  /*
2
3  3.6.1 - Heavy-Light Decomposition for Dynamic Path Queries
4
5  Description: Given an undirected, connected graph that is a tree, the
6  heavy-light decomposition (HLD) on the graph is a partitioning of the
7  vertices into disjoint paths to later support dynamic modification and
8  querying of values on paths between pairs of vertices.
9  See: http://wcipeg.com/wiki/Heavy-light\_decomposition
10 and: http://blog.anudeep2011.com/heavy-light-decomposition/
11 To support dynamic adding and removal of edges, see link/cut tree.
12
13 Note: The adjacency list tree[] that is passed to the constructor must
14 not be changed afterwards in order for modify() and query() to work.
15

```

```

16 Time Complexity:  $O(N)$  for the constructor and  $O(\log N)$  in the worst
17 case for both modify() and query(), where  $N$  is the number of vertices.
18
19 Space Complexity:  $O(N)$  on the number of vertices in the tree.
20
21 */
22
23 #include <algorithm> /* std::max(), std::min() */
24 #include <climits> /* INT_MIN */
25 #include <vector>
26
27 template<class T> class heavy_light {
28     //true if you want values on edges, false if you want values on vertices
29     static const bool VALUES_ON_EDGES = true;
30
31     //Modify the following 6 functions to implement your custom
32     //operations on the tree. This implements the Add/Max operations.
33     //Operations like Add/Sum, Set/Max can also be implemented.
34     static inline T modify_op(const T & x, const T & y) {
35         return x + y;
36     }
37
38     static inline T query_op(const T & x, const T & y) {
39         return std::max(x, y);
40     }
41
42     static inline T delta_on_segment(const T & delta, int seglen) {
43         if (delta == null_delta()) return null_delta();
44         //Here you must write a fast equivalent of following slow code:
45         // T result = delta;
46         // for (int i = 1; i < seglen; i++) result = query_op(result, delta);
47         // return result;
48         return delta;
49     }
50
51     static inline T init_value() { return 0; }
52     static inline T null_delta() { return 0; }
53     static inline T null_value() { return INT_MIN; }
54
55     static inline T join_value_with_delta(const T & v, const T & delta) {
56         return delta == null_delta() ? v : modify_op(v, delta);
57     }
58
59     static T join_deltas(const T & delta1, const T & delta2) {
60         if (delta1 == null_delta()) return delta2;
61         if (delta2 == null_delta()) return delta1;
62         return modify_op(delta1, delta2);
63     }
64
65     int counter, paths;
66     std::vector<int> *adj;
67     std::vector<std::vector<T> > value, delta;
68     std::vector<std::vector<int> > len;
69     std::vector<int> size, parent, tin, tout;
70     std::vector<int> path, pathlen, pathpos, pathroot;
71
72     void precompute_dfs(int u, int p) {
73         tin[u] = counter++;
74         parent[u] = p;

```

```

75     size[u] = 1;
76     for (int j = 0, v; j < (int)adj[u].size(); j++) {
77         if ((v = adj[u][j]) == p) continue;
78         precompute_dfs(v, u);
79         size[u] += size[v];
80     }
81     tout[u] = counter++;
82 }
83
84 int new_path(int u) {
85     pathroot[paths] = u;
86     return paths++;
87 }
88
89 void build_paths(int u, int path) {
90     this->path[u] = path;
91     pathpos[u] = pathlen[path]++;
92     for (int j = 0, v; j < (int)adj[u].size(); j++) {
93         if ((v = adj[u][j]) == parent[u]) continue;
94         build_paths(v, 2*size[v] >= size[u] ? path : new_path(v));
95     }
96 }
97
98 inline T join_value_with_delta0(int path, int i) {
99     return join_value_with_delta(value[path][i],
100         delta_on_segment(delta[path][i], len[path][i]));
101 }
102
103 void push_delta(int path, int i) {
104     int d = 0;
105     while ((i >> d) > 0) d++;
106     for (d -= 2; d >= 0; d--) {
107         int x = i >> d;
108         value[path][x >> 1] = join_value_with_delta0(path, x >> 1);
109         delta[path][x] = join_deltas(delta[path][x], delta[path][x >> 1]);
110         delta[path][x ^ 1] = join_deltas(delta[path][x ^ 1], delta[path][x >> 1]);
111         delta[path][x >> 1] = null_delta();
112     }
113 }
114
115 T query(int path, int a, int b) {
116     push_delta(path, a += value[path].size() >> 1);
117     push_delta(path, b += value[path].size() >> 1);
118     T res = null_value();
119     for (; a <= b; a = (a + 1) >> 1, b = (b - 1) >> 1) {
120         if ((a & 1) != 0)
121             res = query_op(res, join_value_with_delta0(path, a));
122         if ((b & 1) == 0)
123             res = query_op(res, join_value_with_delta0(path, b));
124     }
125     return res;
126 }
127
128 void modify(int path, int a, int b, const T & delta) {
129     push_delta(path, a += value[path].size() >> 1);
130     push_delta(path, b += value[path].size() >> 1);
131     int ta = -1, tb = -1;
132     for (; a <= b; a = (a + 1) >> 1, b = (b - 1) >> 1) {
133         if ((a & 1) != 0) {

```

```

134         this->delta[path][a] = join_deltas(this->delta[path][a], delta);
135         if (ta == -1) ta = a;
136     }
137     if ((b & 1) == 0) {
138         this->delta[path][b] = join_deltas(this->delta[path][b], delta);
139         if (tb == -1) tb = b;
140     }
141 }
142 for (int i = ta; i > 1; i >= 1)
143     value[path][i >> 1] = query_op(join_value_with_delta0(path, i),
144                                     join_value_with_delta0(path, i ^ 1));
145 for (int i = tb; i > 1; i >= 1)
146     value[path][i >> 1] = query_op(join_value_with_delta0(path, i),
147                                     join_value_with_delta0(path, i ^ 1));
148 }
149
150 inline bool is_ancestor(int p, int ch) {
151     return tin[p] <= tin[ch] && tout[ch] <= tout[p];
152 }
153
154 public:
155 heavy_light(int N, std::vector<int> tree[]): size(N), parent(N),
156 tin(N), tout(N), path(N), pathlen(N), pathpos(N), pathroot(N) {
157     adj = tree;
158     counter = paths = 0;
159     precompute_dfs(0, -1);
160     build_paths(0, new_path(0));
161     value.resize(paths);
162     delta.resize(paths);
163     len.resize(paths);
164     for (int i = 0; i < paths; i++) {
165         int m = pathlen[i];
166         value[i].assign(2*m, init_value());
167         delta[i].assign(2*m, null_delta());
168         len[i].assign(2*m, 1);
169         for (int j = 2*m - 1; j > 1; j -= 2) {
170             value[i][j >> 1] = query_op(value[i][j], value[i][j ^ 1]);
171             len[i][j >> 1] = len[i][j] + len[i][j ^ 1];
172         }
173     }
174 }
175
176 T query(int a, int b) {
177     T res = null_value();
178     for (int root; !is_ancestor(root = pathroot[path[a]], b); a = parent[root])
179         res = query_op(res, query(path[a], 0, pathpos[a]));
180     for (int root; !is_ancestor(root = pathroot[path[b]], a); b = parent[root])
181         res = query_op(res, query(path[b], 0, pathpos[b]));
182     if (VALUES_ON_EDGES && a == b) return res;
183     return query_op(res, query(path[a], std::min(pathpos[a], pathpos[b]) +
184                                     VALUES_ON_EDGES, std::max(pathpos[a], pathpos[b])));
185 }
186
187 void modify(int a, int b, const T & delta) {
188     for (int root; !is_ancestor(root = pathroot[path[a]], b); a = parent[root])
189         modify(path[a], 0, pathpos[a], delta);
190     for (int root; !is_ancestor(root = pathroot[path[b]], a); b = parent[root])
191         modify(path[b], 0, pathpos[b], delta);
192     if (VALUES_ON_EDGES && a == b) return;

```

```

193     modify(path[a], std::min(pathpos[a], pathpos[b]) + VALUES_ON_EDGES,
194             std::max(pathpos[a], pathpos[b]), delta);
195 }
196 };
197
198 /** Example Usage */
199
200 #include <iostream>
201 using namespace std;
202
203 const int MAXN = 1000;
204 vector<int> adj[MAXN];
205
206 /*
207     w=10      w=20      w=40
208     0-----1-----2-----3
209                       \
210                       -----4
211                           w=30
212 */
213 int main() {
214     adj[0].push_back(1);
215     adj[1].push_back(0);
216     adj[1].push_back(2);
217     adj[2].push_back(1);
218     adj[2].push_back(3);
219     adj[3].push_back(2);
220     adj[2].push_back(4);
221     adj[4].push_back(2);
222     heavy_light<int> hld(5, adj);
223     hld.modify(0, 1, 10);
224     hld.modify(1, 2, 20);
225     hld.modify(2, 3, 40);
226     hld.modify(2, 4, 30);
227     cout << hld.query(0, 3) << "\n"; //40
228     cout << hld.query(2, 4) << "\n"; //30
229     hld.modify(3, 4, 50); //w[every edge from 3 to 4] += 50
230     cout << hld.query(1, 4) << "\n"; //80
231     return 0;
232 }

```

3.6.2 Link-Cut Tree

```

1  /*
2
3  3.6.2 - Link/Cut Tree for Dynamic Path Queries and Connectivity
4
5  Description: Given an unweighted forest of trees where each node
6  has an associated value, a link/cut tree can be used to dynamically
7  query and modify values on the path between pairs of nodes in a tree.
8  This problem can be solved using heavy-light decomposition, which
9  also supports having values stored on edges rather than the nodes.
10 However in a link/cut tree, nodes in different trees may be
11 dynamically linked, edges between nodes in the same tree may be
12 dynamically split, and connectivity between two nodes (whether they
13 are in the same tree) may be checked.
14

```

```

15 Time Complexity:  $O(\log N)$  amortized for make_root(), link(), cut(),
16 connected(), modify(), and query(), where N is the number of nodes
17 in the forest.
18
19 Space Complexity:  $O(N)$  on the number of nodes in the forest.
20
21 */
22
23 #include <algorithm> /* std::max(), std::swap() */
24 #include <climits> /* INT_MIN */
25 #include <map>
26 #include <stdexcept> /* std::runtime_error() */
27
28 template<class T> class linkcut_forest {
29     //Modify the following 5 functions to implement your custom
30     //operations on the tree. This implements the Add/Max operations.
31     //Operations like Add/Sum, Set/Max can also be implemented.
32     static inline T modify_op(const T & x, const T & y) {
33         return x + y;
34     }
35
36     static inline T query_op(const T & x, const T & y) {
37         return std::max(x, y);
38     }
39
40     static inline T delta_on_segment(const T & delta, int seglen) {
41         if (delta == null_delta()) return null_delta();
42         //Here you must write a fast equivalent of following slow code:
43         // T result = delta;
44         // for (int i = 1; i < seglen; i++) result = query_op(result, delta);
45         // return result;
46         return delta;
47     }
48
49     static inline T null_delta() { return 0; }
50     static inline T null_value() { return INT_MIN; }
51
52     static inline T join_value_with_delta(const T & v, const T & delta) {
53         return delta == null_delta() ? v : modify_op(v, delta);
54     }
55
56     static T join_deltas(const T & delta1, const T & delta2) {
57         if (delta1 == null_delta()) return delta2;
58         if (delta2 == null_delta()) return delta1;
59         return modify_op(delta1, delta2);
60     }
61
62     struct node_t {
63         T value, subtree_value, delta;
64         int size;
65         bool rev;
66         node_t *L, *R, *parent;
67
68         node_t(const T & v) {
69             value = subtree_value = v;
70             delta = null_delta();
71             size = 1;
72             rev = false;
73             L = R = parent = 0;

```

```

74     }
75
76     bool is_root() { //is this the root of a splay tree?
77         return parent == 0 || (parent->L != this && parent->R != this);
78     }
79
80     void push() {
81         if (rev) {
82             rev = false;
83             std::swap(L, R);
84             if (L != 0) L->rev = !L->rev;
85             if (R != 0) R->rev = !R->rev;
86         }
87         value = join_value_with_delta(value, delta);
88         subtree_value = join_value_with_delta(subtree_value,
89             delta_on_segment(delta, size));
90         if (L != 0) L->delta = join_deltas(L->delta, delta);
91         if (R != 0) R->delta = join_deltas(R->delta, delta);
92         delta = null_delta();
93     }
94
95     void update() {
96         subtree_value = query_op(query_op(get_subtree_value(L),
97             join_value_with_delta(value, delta)),
98             get_subtree_value(R));
99         size = 1 + get_size(L) + get_size(R);
100     }
101 };
102
103 static inline int get_size(node_t * n) {
104     return n == 0 ? 0 : n->size;
105 }
106
107 static inline int get_subtree_value(node_t * n) {
108     return n == 0 ? null_value() : join_value_with_delta(n->subtree_value,
109         delta_on_segment(n->delta, n->size));
110 }
111
112 static void connect(node_t * ch, node_t * p, char is_left) {
113     if (ch != 0) ch->parent = p;
114     if (is_left < 0) return;
115     (is_left ? p->L : p->R) = ch;
116 }
117
118 /** rotates edge (n, n.parent)
119 *
120 *      g          g
121 *     /          /
122 *    p          n
123 *   /\  -->  /\
124 *  n p.r  n.l p
125 * /\      /\
126 * n.l n.r  n.r p.r
127 */
128 static void rotate(node_t * n) {
129     node_t *p = n->parent, *g = p->parent;
130     bool is_rootp = p->is_root(), is_left = (n == p->L);
131     connect(is_left ? n->R : n->L, p, is_left);
132     connect(p, n, !is_left);
133     connect(n, g, is_rootp ? -1 : (p == g->L));

```



```

133     p->update();
134 }
135
136 /** brings n to the root, balancing tree
137  *
138  * zig-zig case:
139  *
140  *      g
141  *    / \
142  *   p   g.r  rot(p)
143  *  / \
144  * n   p.r
145  / \
146 n.l n.r
147
148      p
149    / \
150   n   g.r  rot(n)
151  / \
152 n.l n.r
153
154      g
155    / \
156   n   g.r  rot(n)
157  / \
158 n.l n.r
159
160      n
161    / \
162   p   g
163  / \
164 n.l n.r
165
166      p
167    / \
168   n   g
169  / \
170 n.l n.r
171
172      g
173    / \
174   p   g.r  rot(p)
175  / \
176 n   p.r
177
178      n
179    / \
180   p   g
181  / \
182 n.l n.r
183
184      g
185    / \
186   n   g.r  rot(n)
187  / \
188 n.l n.r
189
190      p
191    / \
192   n   g
193  / \
194 n.l n.r
195
196      g
197    / \
198   n   g.r  rot(n)
199  / \
200 n.l n.r
201
202      n
203    / \
204   p   g
205  / \
206 n.l n.r
207
208      p
209    / \
210   n   g
211  / \
212 n.l n.r
213
214      g
215    / \
216   n   g.r  rot(n)
217  / \
218 n.l n.r
219
220      n
221    / \
222   p   g
223  / \
224 n.l n.r
225
226      p
227    / \
228   n   g
229  / \
230 n.l n.r
231
232      g
233    / \
234   n   g.r  rot(n)
235  / \
236 n.l n.r
237
238      n
239    / \
240   p   g
241  / \
242 n.l n.r
243
244      p
245    / \
246   n   g
247  / \
248 n.l n.r
249
250      g
251    / \
252   n   g.r  rot(n)
253  / \
254 n.l n.r
255
256      n
257    / \
258   p   g
259  / \
260 n.l n.r
261
262      p
263    / \
264   n   g
265  / \
266 n.l n.r
267
268      g
269    / \
270   n   g.r  rot(n)
271  / \
272 n.l n.r
273
274      n
275    / \
276   p   g
277  / \
278 n.l n.r
279
280      p
281    / \
282   n   g
283  / \
284 n.l n.r
285
286      g
287    / \
288   n   g.r  rot(n)
289  / \
290 n.l n.r
291
292      n
293    / \
294   p   g
295  / \
296 n.l n.r
297
298      p
299    / \
300   n   g
301  / \
302 n.l n.r
303
304      g
305    / \
306   n   g.r  rot(n)
307  / \
308 n.l n.r
309
310      n
311    / \
312   p   g
313  / \
314 n.l n.r
315
316      p
317    / \
318   n   g
319  / \
320 n.l n.r
321
322      g
323    / \
324   n   g.r  rot(n)
325  / \
326 n.l n.r
327
328      n
329    / \
330   p   g
331  / \
332 n.l n.r
333
334      p
335    / \
336   n   g
337  / \
338 n.l n.r
339
340      g
341    / \
342   n   g.r  rot(n)
343  / \
344 n.l n.r
345
346      n
347    / \
348   p   g
349  / \
350 n.l n.r
351
352      p
353    / \
354   n   g
355  / \
356 n.l n.r
357
358      g
359    / \
360   n   g.r  rot(n)
361  / \
362 n.l n.r
363
364      n
365    / \
366   p   g
367  / \
368 n.l n.r
369
370      p
371    / \
372   n   g
373  / \
374 n.l n.r
375
376      g
377    / \
378   n   g.r  rot(n)
379  / \
380 n.l n.r
381
382      n
383    / \
384   p   g
385  / \
386 n.l n.r
387
388      p
389    / \
390   n   g
391  / \
392 n.l n.r
393
394      g
395    / \
396   n   g.r  rot(n)
397  / \
398 n.l n.r
399
400      n
401    / \
402   p   g
403  / \
404 n.l n.r
405
406      p
407    / \
408   n   g
409  / \
410 n.l n.r
411
412      g
413    / \
414   n   g.r  rot(n)
415  / \
416 n.l n.r
417
418      n
419    / \
420   p   g
421  / \
422 n.l n.r
423
424      p
425    / \
426   n   g
427  / \
428 n.l n.r
429
430      g
431    / \
432   n   g.r  rot(n)
433  / \
434 n.l n.r
435
436      n
437    / \
438   p   g
439  / \
440 n.l n.r
441
442      p
443    / \
444   n   g
445  / \
446 n.l n.r
447
448      g
449    / \
450   n   g.r  rot(n)
451  / \
452 n.l n.r
453
454      n
455    / \
456   p   g
457  / \
458 n.l n.r
459
460      p
461    / \
462   n   g
463  / \
464 n.l n.r
465
466      g
467    / \
468   n   g.r  rot(n)
469  / \
470 n.l n.r
471
472      n
473    / \
474   p   g
475  / \
476 n.l n.r
477
478      p
479    / \
480   n   g
481  / \
482 n.l n.r
483
484      g
485    / \
486   n   g.r  rot(n)
487  / \
488 n.l n.r
489
490      n
491    / \
492   p   g
493  / \
494 n.l n.r
495
496      p
497    / \
498   n   g
499  / \
500 n.l n.r
501
502      g
503    / \
504   n   g.r  rot(n)
505  / \
506 n.l n.r
507
508      n
509    / \
510   p   g
511  / \
512 n.l n.r
513
514      p
515    / \
516   n   g
517  / \
518 n.l n.r
519
520      g
521    / \
522   n   g.r  rot(n)
523  / \
524 n.l n.r
525
526      n
527    / \
528   p   g
529  / \
530 n.l n.r
531
532      p
533    / \
534   n   g
535  / \
536 n.l n.r
537
538      g
539    / \
540   n   g.r  rot(n)
541  / \
542 n.l n.r
543
544      n
545    / \
546   p   g
547  / \
548 n.l n.r
549
550      p
551    / \
552   n   g
553  / \
554 n.l n.r
555
556      g
557    / \
558   n   g.r  rot(n)
559  / \
560 n.l n.r
561
562      n
563    / \
564   p   g
565  / \
566 n.l n.r
567
568      p
569    / \
570   n   g
571  / \
572 n.l n.r
573
574      g
575    / \
576   n   g.r  rot(n)
577  / \
578 n.l n.r
579
580      n
581    / \
582   p   g
583  / \
584 n.l n.r
585
586      p
587    / \
588   n   g
589  / \
590 n.l n.r
591
592      g
593    / \
594   n   g.r  rot(n)
595  / \
596 n.l n.r
597
598      n
599    / \
600   p   g
601  / \
602 n.l n.r
603
604      p
605    / \
606   n   g
607  / \
608 n.l n.r
609
610      g
611    / \
612   n   g.r  rot(n)
613  / \
614 n.l n.r
615
616      n
617    / \
618   p   g
619  / \
620 n.l n.r
621
622      p
623    / \
624   n   g
625  / \
626 n.l n.r
627
628      g
629    / \
630   n   g.r  rot(n)
631  / \
632 n.l n.r
633
634      n
635    / \
636   p   g
637  / \
638 n.l n.r
639
640      p
641    / \
642   n   g
643  / \
644 n.l n.r
645
646      g
647    / \
648   n   g.r  rot(n)
649  / \
650 n.l n.r
651
652      n
653    / \
654   p   g
655  / \
656 n.l n.r
657
658      p
659    / \
660   n   g
661  / \
662 n.l n.r
663
664      g
665    / \
666   n   g.r  rot(n)
667  / \
668 n.l n.r
669
670      n
671    / \
672   p   g
673  / \
674 n.l n.r
675
676      p
677    / \
678   n   g
679  / \
680 n.l n.r
681
682      g
683    / \
684   n   g.r  rot(n)
685  / \
686 n.l n.r
687
688      n
689    / \
690   p   g
691  / \
692 n.l n.r
693
694      p
695    / \
696   n   g
697  / \
698 n.l n.r
699
700      g
701    / \
702   n   g.r  rot(n)
703  / \
704 n.l n.r
705
706      n
707    / \
708   p   g
709  / \
710 n.l n.r
711
712      p
713    / \
714   n   g
715  / \
716 n.l n.r
717
718      g
719    / \
720   n   g.r  rot(n)
721  / \
722 n.l n.r
723
724      n
725    / \
726   p   g
727  / \
728 n.l n.r
729
730      p
731    / \
732   n   g
733  / \
734 n.l n.r
735
736      g
737    / \
738   n   g.r  rot(n)
739  / \
740 n.l n.r
741
742      n
743    / \
744   p   g
745  / \
746 n.l n.r
747
748      p
749    / \
750   n   g
751  / \
752 n.l n.r
753
754      g
755    / \
756   n   g.r  rot(n)
757  / \
758 n.l n.r
759
760      n
761    / \
762   p   g
763  / \
764 n.l n.r
765
766      p
767    / \
768   n   g
769  / \
770 n.l n.r
771
772      g
773    / \
774   n   g.r  rot(n)
775  / \
776 n.l n.r
777
778      n
779    / \
780   p   g
781  / \
782 n.l n.r
783
784      p
785    / \
786   n   g
787  / \
788 n.l n.r
789
790      g
791    / \
792   n   g.r  rot(n)
793  / \
794 n.l n.r
795
796      n
797    / \
798   p   g
799  / \
800 n.l n.r
801
802      p
803    / \
804   n   g
805  / \
806 n.l n.r
807
808      g
809    / \
810   n   g.r  rot(n)
811  / \
812 n.l n.r
813
814      n
815    / \
816   p   g
817  / \
818 n.l n.r
819
820      p
821    / \
822   n   g
823  / \
824 n.l n.r
825
826      g
827    / \
828   n   g.r  rot(n)
829  / \
830 n.l n.r
831
832      n
833    / \
834   p   g
835  / \
836 n.l n.r
837
838      p
839    / \
840   n   g
841  / \
842 n.l n.r
843
844      g
845    / \
846   n   g.r  rot(n)
847  / \
848 n.l n.r
849
850      n
851    / \
852   p   g
853  / \
854 n.l n.r
855
856      p
857    / \
858   n   g
859  / \
860 n.l n.r
861
862      g
863    / \
864   n   g.r  rot(n)
865  / \
866 n.l n.r
867
868      n
869    / \
870   p   g
871  / \
872 n.l n.r
873
874      p
875    / \
876   n   g
877  / \
878 n.l n.r
879
880      g
881    / \
882   n   g.r  rot(n)
883  / \
884 n.l n.r
885
886      n
887    / \
888   p   g
889  / \
890 n.l n.r
891
892      p
893    / \
894   n   g
895  / \
896 n.l n.r
897
898      g
899    / \
900   n   g.r  rot(n)
901  / \
902 n.l n.r
903
904      n
905    / \
906   p   g
907  / \
908 n.l n.r
909
910      p
911    / \
912   n   g
913  / \
914 n.l n.r
915
916      g
917    / \
918   n   g.r  rot(n)
919  / \
920 n.l n.r
921
922      n
923    / \
924   p   g
925  / \
926 n.l n.r
927
928      p
929    / \
930   n   g
931  / \
932 n.l n.r
933
934      g
935    / \
936   n   g.r  rot(n)
937  / \
938 n.l n.r
939
940      n
941    / \
942   p   g
943  / \
944 n.l n.r
945
946      p
947    / \
948   n   g
949  / \
950 n.l n.r
951
952      g
953    / \
954   n   g.r  rot(n)
955  / \
956 n.l n.r
957
958      n
959    / \
960   p   g
961  / \
962 n.l n.r
963
964      p
965    / \
966   n   g
967  / \
968 n.l n.r
969
970      g
971    / \
972   n   g.r  rot(n)
973  / \
974 n.l n.r
975
976      n
977    / \
978   p   g
979  / \
980 n.l n.r
981
982      p
983    / \
984   n   g
985  / \
986 n.l n.r
987
988      g
989    / \
990   n   g.r  rot(n)
991  / \
992 n.l n.r
993
994      n
995    / \
996   p   g
997  / \
998 n.l n.r
999
1000     p->update();

```

```

192     u = it1->second;
193     v = it2->second;
194 }
195
196 public:
197 ~linkcut_forest() {
198     static typename std::map<int, node_t*>::iterator it;
199     for (it = nodes.begin(); it != nodes.end(); ++it)
200         delete it->second;
201 }
202
203 void make_root(int id, const T & initv) {
204     if (nodes.find(id) != nodes.end())
205         throw std::runtime_error("Cannot make_root(): ID already exists.");
206     node_t * n = new node_t(initv);
207     expose(n);
208     n->rev = !n->rev;
209     nodes[id] = n;
210 }
211
212 bool connected(int a, int b) {
213     get_uv(a, b);
214     if (a == b) return true;
215     expose(u);
216     expose(v);
217     return u->parent != 0;
218 }
219
220 void link(int a, int b) {
221     if (connected(a, b))
222         throw std::runtime_error("Error: a and b are already connected.");
223     get_uv(a, b);
224     expose(u);
225     u->rev = !u->rev;
226     u->parent = v;
227 }
228
229 void cut(int a, int b) {
230     get_uv(a, b);
231     expose(u);
232     u->rev = !u->rev;
233     expose(v);
234     if (v->R != u || u->L != 0)
235         throw std::runtime_error("Error: edge(a, b) does not exist.");
236     v->R->parent = 0;
237     v->R = 0;
238 }
239
240 T query(int a, int b) {
241     if (!connected(a, b))
242         throw std::runtime_error("Error: a and b are not connected.");
243     get_uv(a, b);
244     expose(u);
245     u->rev = !u->rev;
246     expose(v);
247     return get_subtree_value(v);
248 }
249
250 void modify(int a, int b, const T & delta) {

```

```

251     if (!connected(a, b))
252         throw std::runtime_error("Error: a and b are not connected.");
253     get_uv(a, b);
254     expose(u);
255     u->rev = !u->rev;
256     expose(v);
257     v->delta = join_deltas(v->delta, delta);
258 }
259 };
260
261 /** Example Usage */
262
263 #include <iostream>
264 using namespace std;
265
266 int main() {
267     linkcut_forest<int> F;
268     /*
269     v=10      v=40      v=20      v=10
270     0-----1-----2-----3
271                      \
272                      -----4
273                          v=30
274     */
275     F.make_root(0, 10);
276     F.make_root(1, 40);
277     F.make_root(2, 20);
278     F.make_root(3, 10);
279     F.make_root(4, 30);
280     F.link(0, 1);
281     F.link(1, 2);
282     F.link(2, 3);
283     F.link(2, 4);
284     cout << F.query(1, 4) << "\n"; //40
285     F.modify(1, 1, -10);
286     F.modify(3, 4, -10);
287     /*
288     v=10      v=30      v=10      v=0
289     0-----1-----2-----3
290                      \
291                      -----4
292                          v=20
293     */
294     cout << F.query(0, 4) << "\n"; //30
295     cout << F.query(3, 4) << "\n"; //20
296     F.cut(1, 2);
297     cout << F.connected(1, 2) << "\n"; //0
298     cout << F.connected(0, 4) << "\n"; //0
299     cout << F.connected(2, 3) << "\n"; //1
300     return 0;
301 }

```

3.7 Lowest Common Ancestor

3.7.1 Sparse Tables

```

1  /*
2
3  3.7.1 - Sparse Tables for Lowest Common Ancestor
4
5  Description: Given an undirected graph that is a tree, the
6  lowest common ancestor (LCA) of two nodes v and w is the
7  lowest (i.e. deepest) node that has both v and w as descendants,
8  where we define each node to be a descendant of itself (so if
9  v has a direct connection from w, w is the lowest common
10 ancestor). The following program uses sparse tables to solve
11 the problem on an unchanging graph.
12
13 Time Complexity:  $O(N \log N)$  for build() and  $O(\log N)$  for lca(),
14 where N is the number of nodes in the tree.
15
16 Space Complexity:  $O(N \log N)$ .
17
18 */
19
20 #include <vector>
21
22 const int MAXN = 1000;
23 int len, timer, tin[MAXN], tout[MAXN];
24 std::vector<int> adj[MAXN], dp[MAXN];
25
26 void dfs(int u, int p) {
27     tin[u] = timer++;
28     dp[u][0] = p;
29     for (int i = 1; i < len; i++)
30         dp[u][i] = dp[dp[u][i - 1]][i - 1];
31     for (int j = 0; j < (int)adj[u].size(); j++)
32         if ((v = adj[u][j]) != p)
33             dfs(v, u);
34     tout[u] = timer++;
35 }
36
37 void build(int nodes, int root) {
38     len = 1;
39     while ((1 << len) <= nodes) len++;
40     for (int i = 0; i < nodes; i++)
41         dp[i].resize(len);
42     timer = 0;
43     dfs(root, root);
44 }
45
46 inline bool is_parent(int parent, int child) {
47     return tin[parent] <= tin[child] && tout[child] <= tout[parent];
48 }
49
50 int lca(int a, int b) {
51     if (is_parent(a, b)) return a;
52     if (is_parent(b, a)) return b;
53     for (int i = len - 1; i >= 0; i--)
54         if (!is_parent(dp[a][i], b))
55             a = dp[a][i];
56     return dp[a][0];
57 }
58
59 /** Example Usage **/

```

```

60
61 #include <iostream>
62 using namespace std;
63
64 int main() {
65     adj[0].push_back(1);
66     adj[1].push_back(0);
67     adj[1].push_back(2);
68     adj[2].push_back(1);
69     adj[3].push_back(1);
70     adj[1].push_back(3);
71     adj[0].push_back(4);
72     adj[4].push_back(0);
73     build(5, 0);
74     cout << lca(3, 2) << "\n"; //1
75     cout << lca(2, 4) << "\n"; //0
76     return 0;
77 }

```

3.7.2 Segment Trees

```

1  /*
2
3  3.7.2 - Segment Trees for Lowest Common Ancestor
4
5  Description: Given a rooted tree, the lowest common ancestor (LCA)
6  of two nodes v and w is the lowest (i.e. deepest) node that has
7  both v and w as descendants, where we define each node to be a
8  descendant of itself (so if v has a direct connection from w, w
9  is the lowest common ancestor). This problem can be reduced to the
10 range minimum query problem using Eulerian tours.
11
12 Time Complexity:  $O(N \log N)$  for build() and  $O(\log N)$  for lca(),
13 where N is the number of nodes in the tree.
14
15 Space Complexity:  $O(N \log N)$ .
16
17 */
18
19 #include <algorithm> /* std::fill(), std::min(), std::max() */
20 #include <vector>
21
22 const int MAXN = 1000;
23 int len, counter;
24 int depth[MAXN], dfs_order[2*MAXN], first[MAXN], minpos[8*MAXN];
25 std::vector<int> adj[MAXN];
26
27 void dfs(int u, int d) {
28     depth[u] = d;
29     dfs_order[counter++] = u;
30     for (int j = 0, v; j < (int)adj[u].size(); j++) {
31         if (depth[v = adj[u][j]] == -1) {
32             dfs(v, d + 1);
33             dfs_order[counter++] = u;
34         }
35     }
36 }

```

```

37
38 void build_tree(int n, int l, int h) {
39     if (l == h) {
40         minpos[n] = dfs_order[l];
41         return;
42     }
43     int lchild = 2 * n + 1, rchild = 2 * n + 2;
44     build_tree(lchild, l, (l + h)/2);
45     build_tree(rchild, (l + h) / 2 + 1, h);
46     minpos[n] = depth[minpos[lchild]] < depth[minpos[rchild]] ?
47         minpos[lchild] : minpos[rchild];
48 }
49
50 void build(int nodes, int root) {
51     std::fill(depth, depth + nodes, -1);
52     std::fill(first, first + nodes, -1);
53     len = 2*nodes - 1;
54     counter = 0;
55     dfs(root, 0);
56     build_tree(0, 0, len - 1);
57     for (int i = 0; i < len; i++)
58         if (first[dfs_order[i]] == -1)
59             first[dfs_order[i]] = i;
60 }
61
62 int get_minpos(int a, int b, int n, int l, int h) {
63     if (a == l && b == h) return minpos[n];
64     int mid = (l + h) >> 1;
65     if (a <= mid && b > mid) {
66         int p1 = get_minpos(a, std::min(b, mid), 2 * n + 1, l, mid);
67         int p2 = get_minpos(std::max(a, mid + 1), b, 2 * n + 2, mid + 1, h);
68         return depth[p1] < depth[p2] ? p1 : p2;
69     }
70     if (a <= mid) return get_minpos(a, std::min(b, mid), 2 * n + 1, l, mid);
71     return get_minpos(std::max(a, mid + 1), b, 2 * n + 2, mid + 1, h);
72 }
73
74 int lca(int a, int b) {
75     return get_minpos(std::min(first[a], first[b]),
76         std::max(first[a], first[b]), 0, 0, len - 1);
77 }
78
79 /** Example Usage */
80
81 #include <iostream>
82 using namespace std;
83
84 int main() {
85     adj[0].push_back(1);
86     adj[1].push_back(0);
87     adj[1].push_back(2);
88     adj[2].push_back(1);
89     adj[3].push_back(1);
90     adj[1].push_back(3);
91     adj[0].push_back(4);
92     adj[4].push_back(0);
93     build(5, 0);
94     cout << lca(3, 2) << "\n"; //1
95     cout << lca(2, 4) << "\n"; //0

```

```
96     return 0;  
97 }
```

Chapter 4

Mathematics

4.1 Mathematics Toolbox

```
1  /*
2
3  4.1 - Mathematics Toolbox
4
5  Useful math definitions. Excludes geometry (see next chapter).
6
7  */
8
9  #include <algorithm> /* std::reverse() */
10 #include <cfloat>    /* DBL_MAX */
11 #include <cmath>     /* a lot of things */
12 #include <string>
13 #include <vector>
14
15 /* Definitions for Common Floating Point Constants */
16
17 const double PI = acos(-1.0), E = exp(1.0), root2 = sqrt(2.0);
18 const double phi = (1.0 + sqrt(5.0)) / 2.0; //golden ratio
19
20 //Sketchy but working definitions of +infinity, -infinity and quiet NaN
21 //A better way is using functions of std::numeric_limits<T> from <limits>
22 //See main() for identities involving the following special values.
23 const double posinf = 1.0 / 0.0, neginf = -1.0 / 0.0, NaN = -(0.0 / 0.0);
24
25 /*
26
27 Epsilon Comparisons
28
29 The range of values for which X compares EQ() to is [X - eps, X + eps].
30 For values to compare LT() and GT() x, they must fall outside of the range.
31
32 e.g. if eps = 1e-7, then EQ(1e-8, 2e-8) is true and LT(1e-8, 2e-8) is false.
33
34 */
35
36 const double eps = 1e-7;
37 #define EQ(a, b) (fabs((a) - (b)) <= eps) /* equal to */
```



```

38 #define NE(a, b) (fabs((a) - (b)) > eps) /* not equal to */
39 #define LT(a, b) ((a) < (b) - eps)      /* less than */
40 #define GT(a, b) ((a) > (b) + eps)      /* greater than */
41 #define LE(a, b) ((a) <= (b) + eps)     /* less than or equal to */
42 #define GE(a, b) ((a) >= (b) - eps)     /* greater than or equal to */
43
44 /*
45
46 Sign Function:
47
48 Returns: -1 (if x < 0), 0 (if x == 0), or 1 (if x > 0)
49 Doesn't handle the sign of NaN like signbit() or copysign()
50
51 */
52
53 template<class T> int sgn(const T & x) {
54     return (T(0) < x) - (x < T(0));
55 }
56
57 /*
58
59 signbit() and copysign() functions, only in C++11 and later.
60
61 signbit() returns whether the sign bit of the floating point
62 number is set to true. If signbit(x), then x is "negative."
63 Note that signbit(0.0) == 0 but signbit(-0.0) == 1. This
64 also works as expected on NaN, -NaN, posinf, and neginf.
65
66 We implement this by casting the floating point value to an
67 integer type with the same number of bits so we can perform
68 shift operations on it, then we extract the sign bit.
69 Another way is using unions, but this is non-portable
70 depending on endianness of the platform. Unfortunately, we
71 cannot find the signbit of long doubles using the method
72 below because there is no corresponding 96-bit integer type.
73 Note that this will cause complaints with the compiler.
74
75 copysign(x, y) returns a number with the magnitude of x but
76 the sign of y.
77
78 Assumptions: sizeof(float) == sizeof(int) and
79              sizeof(long long) == sizeof(double)
80              CHAR_BITS == 8 (8 bits to a byte)
81
82 */
83
84 inline bool signbit(float x) {
85     return (*(int*)&x) >> (sizeof(float) * 8 - 1);
86 }
87
88 inline bool signbit(double x) {
89     return (*(long long*)&x) >> (sizeof(double) * 8 - 1);
90 }
91
92 template<class Double>
93 inline Double copysign(Double x, Double y) {
94     return signbit(y) ? -fabs(x) : fabs(x);
95 }
96

```

```

97  /*
98
99  Floating Point Rounding Functions
100
101  floor() in <cmath> asymmetrically rounds down, towards -infinity,
102  while ceil() in <cmath> asymmetrically rounds up, towards +infinity.
103  The following are common alternative ways to round.
104
105  */
106
107  //symmetric round down, bias: towards zero (same as trunc() in C++11)
108  template<class Double> Double floor0(const Double & x) {
109      Double res = floor(fabs(x));
110      return (x < 0.0) ? -res : res;
111  }
112
113  //symmetric round up, bias: away from zero
114  template<class Double> Double ceil0(const Double & x) {
115      Double res = ceil(fabs(x));
116      return (x < 0.0) ? -res : res;
117  }
118
119  //round half up, bias: towards +infinity
120  template<class Double> Double roundhalfup(const Double & x) {
121      return floor(x + 0.5);
122  }
123
124  //round half up, bias: towards -infinity
125  template<class Double> Double roundhalfdown(const Double & x) {
126      return ceil(x - 0.5);
127  }
128
129  //symmetric round half down, bias: towards zero
130  template<class Double> Double roundhalfdown0(const Double & x) {
131      Double res = roundhalfdown(fabs(x));
132      return (x < 0.0) ? -res : res;
133  }
134
135  //symmetric round half up, bias: away from zero
136  template<class Double> Double roundhalfup0(const Double & x) {
137      Double res = roundhalfup(fabs(x));
138      return (x < 0.0) ? -res : res;
139  }
140
141  //round half to even (banker's rounding), bias: none
142  template<class Double>
143  Double roundhalfeven(const Double & x, const Double & eps = 1e-7) {
144      if (x < 0.0) return -roundhalfeven(-x, eps);
145      Double ipart;
146      modf(x, &ipart);
147      if (x - (ipart + 0.5) < eps)
148          return (fmod(ipart, 2.0) < eps) ? ipart : ceil0(ipart + 0.5);
149      return roundhalfup0(x);
150  }
151
152  //round alternating up/down for ties, bias: none for sequential calls
153  template<class Double> Double roundalternate(const Double & x) {
154      static bool up = true;
155      return (up = !up) ? roundhalfup(x) : roundhalfdown(x);

```

```

156 }
157
158 //symmetric round alternate, bias: none for sequential calls
159 template<class Double> Double roundalternate0(const Double & x) {
160     static bool up = true;
161     return (up = !up) ? roundhalfup0(x) : roundhalfdown0(x);
162 }
163
164 //round randomly for tie-breaking, bias: generator's bias
165 template<class Double> Double roundrandom(const Double & x) {
166     return (rand() % 2 == 0) ? roundhalfup0(x) : roundhalfdown0(x);
167 }
168
169 //round x to N digits after the decimal using the specified round function
170 //e.g. roundplaces(-1.23456, 3, roundhalfdown0<double>) returns -1.235
171 template<class Double, class RoundFunction>
172 double roundplaces(const Double & x, unsigned int N, RoundFunction f) {
173     return f(x * pow(10, N)) / pow(10, N);
174 }
175
176 /*
177
178 Error Function (erf() and erfc() in C++11)
179
180 erf(x) = 2/sqrt(pi) * integral of exp(-t^2) dt from 0 to x
181 erfc(x) = 1 - erf(x)
182 Note that the functions are co-dependent.
183
184 Adapted from: http://www.digitalmars.com/archives/cplusplus/3634.html#N3655
185
186 */
187
188 //calculate 12 significant figs (don't ask for more than 1e-15)
189 static const double rel_error = 1e-12;
190
191 double erf(double x) {
192     if (signbit(x)) return -erf(-x);
193     if (fabs(x) > 2.2) return 1.0 - erfc(x);
194     double sum = x, term = x, xsqr = x * x;
195     int j = 1;
196     do {
197         term *= xsqr / j;
198         sum -= term / (2 * (j++) + 1);
199         term *= xsqr / j;
200         sum += term / (2 * (j++) + 1);
201     } while (fabs(term) / sum > rel_error);
202     return 1.128379167095512574 * sum; //1.128 ~ 2/sqrt(pi)
203 }
204
205 double erfc(double x) {
206     if (fabs(x) < 2.2) return 1.0 - erf(x);
207     if (signbit(x)) return 2.0 - erfc(-x);
208     double a = 1, b = x, c = x, d = x * x + 0.5, q1, q2 = 0, n = 1.0, t;
209     do {
210         t = a * n + b * x; a = b; b = t;
211         t = c * n + d * x; c = d; d = t;
212         n += 0.5;
213         q1 = q2;
214         q2 = b / d;

```

```

215     } while (fabs(q1 - q2) / q2 > rel_error);
216     return 0.564189583547756287 * exp(-x * x) * q2; //0.564 ~ 1/sqrt(pi)
217 }
218
219 /*
220
221 Gamma and Log-Gamma Functions (tgamma() and lgamma() in C++11)
222 Warning: unlike the actual standard C++ versions, the following
223 function only works on positive numbers (returns NaN if x <= 0).
224 Adapted from: http://www.johndcook.com/blog/cpp\_gamma/
225
226 */
227
228 double lgamma(double x);
229
230 double tgamma(double x) {
231     if (x <= 0.0) return NaN;
232     static const double gamma = 0.577215664901532860606512090;
233     if (x < 1e-3) return 1.0 / (x * (1.0 + gamma * x));
234     if (x < 12.0) {
235         double y = x;
236         int n = 0;
237         bool arg_was_less_than_one = (y < 1.0);
238         if (arg_was_less_than_one) y += 1.0;
239         else y -= (n = static_cast<int>(floor(y)) - 1);
240         static const double p[] = {
241             -1.71618513886549492533811E+0, 2.47656508055759199108314E+1,
242             -3.79804256470945635097577E+2, 6.29331155312818442661052E+2,
243             8.66966202790413211295064E+2, -3.14512729688483675254357E+4,
244             -3.61444134186911729807069E+4, 6.64561438202405440627855E+4
245         };
246         static const double q[] = {
247             -3.08402300119738975254353E+1, 3.15350626979604161529144E+2,
248             -1.01515636749021914166146E+3, -3.10777167157231109440444E+3,
249             2.25381184209801510330112E+4, 4.75584627752788110767815E+3,
250             -1.34659959864969306392456E+5, -1.15132259675553483497211E+5
251         };
252         double num = 0.0, den = 1.0, z = y - 1;
253         for (int i = 0; i < 8; i++) {
254             num = (num + p[i]) * z;
255             den = den * z + q[i];
256         }
257         double result = num / den + 1.0;
258         if (arg_was_less_than_one) result /= (y - 1.0);
259         else for (int i = 0; i < n; i++) result *= y++;
260         return result;
261     }
262     return (x > 171.624) ? DBL_MAX * 2.0 : exp(lgamma(x));
263 }
264
265 double lgamma(double x) {
266     if (x <= 0.0) return NaN;
267     if (x < 12.0) return log(fabs(tgamma(x)));
268     static const double c[8] = {
269         1.0/12.0, -1.0/360.0, 1.0/1260.0, -1.0/1680.0, 1.0/1188.0,
270         -691.0/360360.0, 1.0/156.0, -3617.0/122400.0
271     };
272     double z = 1.0 / (x * x), sum = c[7];
273     for (int i = 6; i >= 0; i--) sum = sum * z + c[i];

```

```

274     static const double halflog2pi = 0.91893853320467274178032973640562;
275     return (x - 0.5) * log(x) - x + halflog2pi + sum / x;
276 }
277
278 /*
279
280 Base Conversion - O(N) on the number of digits
281
282 Given the digits of an integer x in base a, returns x's digits in base b.
283 Precondition: the base-10 value of x must be able to fit within an unsigned
284 long long. In other words, the value of x must be between 0 and 2^64 - 1.
285
286 Note: vector[0] stores the most significant digit in all usages below.
287
288 e.g. if x = {1, 2, 3} and a = 5 (i.e. x = 123 in base 5 = 38 in base 10),
289 then convert_base(x, 5, 3) returns {1, 1, 0, 2} (1102 in base 2).
290
291 */
292
293 std::vector<int> convert_base(const std::vector<int> & x, int a, int b) {
294     unsigned long long base10 = 0;
295     for (int i = 0; i < (int)x.size(); i++)
296         base10 += x[i] * pow(a, x.size() - i - 1);
297     int N = ceil(log(base10 + 1) / log(b));
298     std::vector<int> baseb;
299     for (int i = 1; i <= N; i++)
300         baseb.push_back(int(base10 / pow(b, N - i)) % b);
301     return baseb;
302 }
303
304 //returns digits of a number in base b
305 std::vector<int> base_digits(int x, int b = 10) {
306     std::vector<int> baseb;
307     while (x != 0) {
308         baseb.push_back(x % b);
309         x /= b;
310     }
311     std::reverse(baseb.begin(), baseb.end());
312     return baseb;
313 }
314
315 /*
316
317 Integer to Roman Numerals Conversion
318
319 Given an integer x, this function returns the Roman numeral representation
320 of x as a C++ string. More 'M's are appended to the front of the resulting
321 string if x is greater than 1000. e.g. to_roman(1234) returns "MCCXXXIV"
322 and to_roman(5678) returns "MMMMDCLXXVIII".
323
324 */
325
326 std::string to_roman(unsigned int x) {
327     static std::string h[] = {"", "C", "CC", "CCC", "CD", "D", "DC", "DCC", "DCCC", "CM"};
328     static std::string t[] = {"", "X", "XX", "XXX", "XL", "L", "LX", "LXX", "LXXX", "XC"};
329     static std::string o[] = {"", "I", "II", "III", "IV", "V", "VI", "VII", "VIII", "IX"};
330     std::string res(x / 1000, 'M');
331     x %= 1000;
332     return res + h[x / 100] + t[x / 10 % 10] + o[x % 10];

```

```

333 }
334
335 /** Example Usage */
336
337 #include <algorithm>
338 #include <cassert>
339 #include <iostream>
340 using namespace std;
341
342 int main() {
343     cout << "PI:␣" << PI << "\n";
344     cout << "E:␣" << E << "\n";
345     cout << "sqrt(2):␣" << root2 << "\n";
346     cout << "Golden_ratio:␣" << phi << "\n";
347
348     //some properties of posinf, neginf, and NaN:
349     double x = -1234.567890; //any normal value of x will work
350     assert((posinf > x) && (neginf < x) && (posinf == -neginf));
351     assert((posinf + x == posinf) && (posinf - x == posinf));
352     assert((neginf + x == neginf) && (neginf - x == neginf));
353     assert((posinf + posinf == posinf) && (neginf - posinf == neginf));
354     assert((NaN != x) && (NaN != NaN) && (NaN != posinf) && (NaN != neginf));
355     assert(!(NaN < x) && !(NaN > x) && !(NaN <= x) && !(NaN >= x));
356     assert(isnan(0.0*posinf) && isnan(0.0*neginf) && isnan(posinf/neginf));
357     assert(isnan(NaN) && isnan(-NaN) && isnan(NaN*x + x - x/-NaN));
358     assert(isnan(neginf-neginf) && isnan(posinf-posinf) && isnan(posinf+neginf));
359     assert(!signbit(NaN) && signbit(-NaN) && !signbit(posinf) && signbit(neginf));
360
361     assert(copysign(1.0, +2.0) == +1.0 && copysign(posinf, -2.0) == neginf);
362     assert(copysign(1.0, -2.0) == -1.0 && signbit(copysign(NaN, -2.0)));
363     assert(sgn(-1.234) == -1 && sgn(0.0) == 0 && sgn(5678) == 1);
364
365     assert(EQ(floor0(1.5), 1.0) && EQ(floor0(-1.5), -1.0));
366     assert(EQ(ceil0(1.5), 2.0) && EQ(ceil0(-1.5), -2.0));
367     assert(EQ(roundhalfup(1.5), 2.0) && EQ(roundhalfup(-1.5), -1.0));
368     assert(EQ(roundhalfdown(1.5), 1.0) && EQ(roundhalfdown(-1.5), -2.0));
369     assert(EQ(roundhalfup0(1.5), 2.0) && EQ(roundhalfup0(-1.5), -2.0));
370     assert(EQ(roundhalfdown0(1.5), 1.0) && EQ(roundhalfdown0(-1.5), -1.0));
371     assert(EQ(roundhalfeven(1.5), 2.0) && EQ(roundhalfeven(-1.5), -2.0));
372     assert(NE(roundalternate(1.5), roundalternate(1.5)));
373     assert(EQ(roundplaces(-1.23456, 3, roundhalfdown0<double>), -1.235));
374
375     assert(EQ(erf(1.0), 0.8427007929) && EQ(erf(-1.0), -0.8427007929));
376     assert(EQ(tgamma(0.5), 1.7724538509) && EQ(tgamma(1.0), 1.0));
377     assert(EQ(lgamma(0.5), 0.5723649429) && EQ(lgamma(1.0), 0.0));
378
379     int base10digs[] = {1, 2, 3, 4, 5, 6}, a = 20, b = 10;
380     vector<int> basea = base_digits(123456, a);
381     vector<int> baseb = convert_base(basea, a, b);
382     assert(equal(baseb.begin(), baseb.end(), base10digs));
383
384     assert(to_roman(1234) == "MCCXXXIV");
385     assert(to_roman(5678) == "MMMMDCLXXVIII");
386     return 0;
387 }

```

4.2 Combinatorics

4.2.1 Combinatorial Calculations

```

1  /*
2
3  4.2.1 - Combinatorial Calculations
4
5  The meanings of the following functions can respectively be
6  found with quick searches online. All of them computes the
7  answer modulo m, since contest problems typically ask us for
8  this due to the actual answer being potentially very large.
9  All functions using tables to generate every answer below
10 n and k can be optimized using recursion and memoization.
11
12 Note: The following are only defined for nonnegative inputs.
13
14 */
15
16 #include <vector>
17
18 typedef std::vector<std::vector<long long> > table;
19
20 //n! mod m in O(n)
21 long long factorial(int n, int m = 1000000007) {
22     long long res = 1;
23     for (int i = 2; i <= n; i++) res = (res * i) % m;
24     return res % m;
25 }
26
27 //n! mod p, where p is a prime number, in O(p log n)
28 long long factorialp(long long n, long long p = 1000000007) {
29     long long res = 1, h;
30     while (n > 1) {
31         res = (res * ((n / p) % 2 == 1 ? p - 1 : 1)) % p;
32         h = n % p;
33         for (int i = 2; i <= h; i++) res = (res * i) % p;
34         n /= p;
35     }
36     return res % p;
37 }
38
39 //first n rows of pascal's triangle (mod m) in O(n^2)
40 table binomial_table(int n, long long m = 1000000007) {
41     table t(n + 1);
42     for (int i = 0; i <= n; i++)
43         for (int j = 0; j <= i; j++)
44             if (i < 2 || j == 0 || i == j)
45                 t[i].push_back(1);
46             else
47                 t[i].push_back((t[i - 1][j - 1] + t[i - 1][j]) % m);
48     return t;
49 }
50
51 //if the product of two 64-bit ints (a*a, a*b, or b*b) can
52 //overflow, you must use mulmod (multiplication by adding)
53 long long powmod(long long a, long long b, long long m) {

```

```

54     long long x = 1, y = a;
55     for (; b > 0; b >>= 1) {
56         if (b & 1) x = (x * y) % m;
57         y = (y * y) % m;
58     }
59     return x % m;
60 }
61
62 //n choose k (mod a prime number p) in O(min(k, n - k))
63 //powmod is used to find the mod inverse to get num / den % m
64 long long choose(int n, int k, long long p = 1000000007) {
65     if (n < k) return 0;
66     if (k > n - k) k = n - k;
67     long long num = 1, den = 1;
68     for (int i = 0; i < k; i++)
69         num = (num * (n - i)) % p;
70     for (int i = 1; i <= k; i++)
71         den = (den * i) % p;
72     return num * powmod(den, p - 2, p) % p;
73 }
74
75 //n multichoose k (mod a prime number p) in O(k)
76 long long multichoose(int n, int k, long long p = 1000000007) {
77     return choose(n + k - 1, k, p);
78 }
79
80 //n permute k (mod m) on O(k)
81 long long permute(int n, int k, long long m = 1000000007) {
82     if (n < k) return 0;
83     long long res = 1;
84     for (int i = 0; i < k; i++)
85         res = (res * (n - i)) % m;
86     return res % m;
87 }
88
89 //number of partitions of n (mod m) in O(n^2)
90 long long partitions(int n, long long m = 1000000007) {
91     std::vector<long long> p(n + 1, 0);
92     p[0] = 1;
93     for (int i = 1; i <= n; i++)
94         for (int j = i; j <= n; j++)
95             p[j] = (p[j] + p[j - i]) % m;
96     return p[n] % m;
97 }
98
99 //partitions of n into exactly k parts (mod m) in O(n * k)
100 long long partitions(int n, int k, long long m = 1000000007) {
101     table t(n + 1, std::vector<long long>(k + 1, 0));
102     t[0][1] = 1;
103     for (int i = 1; i <= n; i++)
104         for (int j = 1, h = k < i ? k : i; j <= h; j++)
105             t[i][j] = (t[i - 1][j - 1] + t[i - j][j]) % m;
106     return t[n][k] % m;
107 }
108
109 //unsigned Stirling numbers of the 1st kind (mod m) in O(n * k)
110 long long stirling1(int n, int k, long long m = 1000000007) {
111     table t(n + 1, std::vector<long long>(k + 1, 0));
112     t[0][0] = 1;

```



```

113     for (int i = 1; i <= n; i++)
114         for (int j = 1; j <= k; j++) {
115             t[i][j] = ((i - 1) * t[i - 1][j]) % m;
116             t[i][j] = (t[i][j] + t[i - 1][j - 1]) % m;
117         }
118     return t[n][k] % m;
119 }
120
121 //Stirling numbers of the 2nd kind (mod m) in O(n * k)
122 long long stirling2(int n, int k, long long m = 1000000007) {
123     table t(n + 1, std::vector<long long>(k + 1, 0));
124     t[0][0] = 1;
125     for (int i = 1; i <= n; i++)
126         for (int j = 1; j <= k; j++) {
127             t[i][j] = (j * t[i - 1][j]) % m;
128             t[i][j] = (t[i][j] + t[i - 1][j - 1]) % m;
129         }
130     return t[n][k] % m;
131 }
132
133 //Eulerian numbers of the 1st kind (mod m) in O(n * k)
134 //precondition: n > k
135 long long eulerian1(int n, int k, long long m = 1000000007) {
136     if (k > n - 1 - k) k = n - 1 - k;
137     table t(n + 1, std::vector<long long>(k + 1, 1));
138     for (int j = 1; j <= k; j++) t[0][j] = 0;
139     for (int i = 1; i <= n; i++)
140         for (int j = 1; j <= k; j++) {
141             t[i][j] = ((i - j) * t[i - 1][j - 1]) % m;
142             t[i][j] = (t[i][j] + ((j + 1) * t[i - 1][j]) % m) % m;
143         }
144     return t[n][k] % m;
145 }
146
147 //Eulerian numbers of the 2nd kind (mod m) in O(n * k)
148 //precondition: n > k
149 long long eulerian2(int n, int k, long long m = 1000000007) {
150     table t(n + 1, std::vector<long long>(k + 1, 1));
151     for (int i = 1; i <= n; i++)
152         for (int j = 1; j <= k; j++) {
153             if (i == j) {
154                 t[i][j] = 0;
155             } else {
156                 t[i][j] = ((j + 1) * t[i - 1][j]) % m;
157                 t[i][j] = (((2 * i - 1 - j) * t[i - 1][j - 1]) % m
158                     + t[i][j]) % m;
159             }
160         }
161     return t[n][k] % m;
162 }
163
164 //nth Catalan number (mod a prime number p) in O(n)
165 long long catalan(int n, long long p = 1000000007) {
166     return choose(2 * n, n, p) * powmod(n + 1, p - 2, p) % p;
167 }
168
169 /** Example Usage */
170
171 #include <cassert>

```

```

172 #include <iostream>
173 using namespace std;
174
175 int main() {
176     table t = binomial_table(10);
177     for (int i = 0; i < (int)t.size(); i++) {
178         for (int j = 0; j < (int)t[i].size(); j++)
179             cout << t[i][j] << " ";
180         cout << "\n";
181     }
182     assert(factorial(10) == 3628800);
183     assert(factorialp(123456) == 639390503);
184     assert(choose(20, 7) == 77520);
185     assert(multichoose(20, 7) == 657800);
186     assert(permute(10, 4) == 5040);
187     assert(partitions(4) == 5);
188     assert(partitions(100, 5) == 38225);
189     assert(stirling1(4, 2) == 11);
190     assert(stirling2(4, 3) == 6);
191     assert(eulerian1(9, 5) == 88234);
192     assert(eulerian2(8, 3) == 195800);
193     assert(catalan(10) == 16796);
194     return 0;
195 }

```

4.2.2 Enumerating Arrangements

```

1  /*
2
3  4.2.2 - Enumerating Arrangements
4
5  We shall consider an arrangement to be a permutation of
6  all the integers from 0 to n - 1. For our purposes, the
7  difference between an arrangement and a permutation is
8  simply that a permutation can pertain to a set of any
9  given values, not just distinct integers from 0 to n-1.
10
11 */
12
13 #include <algorithm> /* std::copy(), std::fill() */
14 #include <vector>
15
16 /*
17
18 Changes a[] to the next lexicographically greater
19 permutation of any k distinct integers in range [0, n).
20 The values of a[] that's passed should be k distinct
21 integers, each in range [0, n).
22
23 returns: whether the function could rearrange a[] to
24 a lexicographically greater arrangement.
25
26 examples:
27 next_arrangement(4, 3, {0, 1, 2}) => 1,  a[] = {0, 1, 3}
28 next_arrangement(4, 3, {0, 1, 3}) => 1,  a[] = {0, 2, 1}
29 next_arrangement(4, 3, {3, 2, 1}) => 0,  a[] unchanged
30

```

```

31  */
32
33  bool next_arrangement(int n, int k, int a[]) {
34      std::vector<bool> used(n);
35      for (int i = 0; i < k; i++) used[a[i]] = true;
36      for (int i = k - 1; i >= 0; i--) {
37          used[a[i]] = false;
38          for (int j = a[i] + 1; j < n; j++) {
39              if (!used[j]) {
40                  a[i++] = j;
41                  used[j] = true;
42                  for (int x = 0; x < k; x++)
43                      if (!used[x]) a[i++] = x;
44                  return true;
45              }
46          }
47      }
48      return false;
49  }
50
51  /*
52
53  Computes n permute k using formula:  $nPk = n!/(n - k)!$ 
54  Complexity:  $O(k)$ . E.g. n_permute_k(10, 7) = 604800
55
56  */
57
58  long long n_permute_k(int n, int k) {
59      long long res = 1;
60      for (int i = 0; i < k; i++) res *= n - i;
61      return res;
62  }
63
64  /*
65
66  Given an integer rank x in range [0, n permute k), returns
67  a vector of integers representing the x-th lexicographically
68  smallest permutation of any k distinct integers in [0, n).
69
70  examples: arrangement_by_rank(4, 3, 0) => {0, 1, 2}
71            arrangement_by_rank(4, 3, 5) => {0, 3, 2}
72
73  */
74
75  std::vector<int> arrangement_by_rank(int n, int k, long long x) {
76      std::vector<int> free(n), res(k);
77      for (int i = 0; i < n; i++) free[i] = i;
78      for (int i = 0; i < k; i++) {
79          long long cnt = n_permute_k(n - 1 - i, k - 1 - i);
80          int pos = (int)(x / cnt);
81          res[i] = free[pos];
82          std::copy(free.begin() + pos + 1, free.end(),
83                  free.begin() + pos);
84          x %= cnt;
85      }
86      return res;
87  }
88
89  /*

```

```

90
91 Given an array a[] of k integers each in range [0, n), returns
92 the (0-based) lexicographical rank (counting from least to
93 greatest) of the arrangement specified by a[] in all possible
94 permutations of k distinct integers in range [0, n).
95
96 examples: rank_by_arrangement(4, 3, {0, 1, 2}) => 0
97            rank_by_arrangement(4, 3, {0, 3, 2}) => 5
98
99 */
100
101 long long rank_by_arrangement(int n, int k, int a[]) {
102     long long res = 0;
103     std::vector<bool> used(n);
104     for (int i = 0; i < k; i++) {
105         int cnt = 0;
106         for (int j = 0; j < a[i]; j++)
107             if (!used[j]) cnt++;
108         res += n_permute_k(n - i - 1, k - i - 1) * cnt;
109         used[a[i]] = true;
110     }
111     return res;
112 }
113
114 /*
115
116 Changes a[] to the next lexicographically greater
117 permutation of k (not-necessarily distinct) integers in
118 range [0, n). The values of a[] should be in range [0, n).
119 If a[] was interpreted as a base-n integer that is k digits
120 long, this function would be equivalent to incrementing a.
121 Ergo, there are n^k arrangements if repeats are allowed.
122
123 returns: whether the function could rearrange a[] to a
124 lexicographically greater arrangement with repeats.
125
126 examples:
127 n_a_w_r(4, 3, {0, 0, 0}) => 1,  a[] = {0, 0, 1}
128 n_a_w_r(4, 3, {0, 1, 3}) => 1,  a[] = {0, 2, 0}
129 n_a_w_r(4, 3, {3, 3, 3}) => 0,  a[] unchanged
130
131 */
132
133 bool next_arrangement_with_repeats(int n, int k, int a[]) {
134     for (int i = k - 1; i >= 0; i--) {
135         if (a[i] < n - 1) {
136             a[i]++;
137             std::fill(a + i + 1, a + k, 0);
138             return true;
139         }
140     }
141     return false;
142 }
143
144 /** Example Usage */
145
146 #include <cassert>
147 #include <iostream>
148 using namespace std;

```

```

149
150 template<class it> void print(it lo, it hi) {
151     for (; lo != hi; ++lo) cout << *lo << " ";
152     cout << "\n";
153 }
154
155 int main() {
156     {
157         int n = 4, k = 3, a[] = {0, 1, 2};
158         cout << n << "permute_" << k << "arrangements:\n";
159         int cnt = 0;
160         do {
161             print(a, a + k);
162             vector<int> b = arrangement_by_rank(n, k, cnt);
163             assert(equal(a, a + k, b.begin()));
164             assert(rank_by_arrangement(n, k, a) == cnt);
165             cnt++;
166         } while (next_arrangement(n, k, a));
167         cout << "\n";
168     }
169
170     {
171         int n = 4, k = 2, a[] = {0, 0};
172         cout << n << "^" << k << "arrangements_with_repeats:\n";
173         do {
174             print(a, a + k);
175         } while (next_arrangement_with_repeats(n, k, a));
176     }
177     return 0;
178 }

```

4.2.3 Enumerating Permutations

```

1  /*
2
3  4.2.3 - Enumerating Permutations
4
5  We shall consider a permutation of n objects to be an
6  ordered list of size n that contains all n elements,
7  where order is important. E.g. 1 1 2 0 and 0 1 2 1
8  are considered two different permutations of 0 1 1 2.
9  Compared to our prior definition of an arrangement, a
10 permutable range of size n may contain repeated values
11 of any type, not just the integers from 0 to n - 1.
12
13 */
14
15 #include <algorithm> /* copy, iter_swap, reverse, swap */
16 #include <vector>
17
18 //identical to std::next_permutation()
19 template<class It> bool _next_permutation(It lo, It hi) {
20     if (lo == hi) return false;
21     It i = lo;
22     if (++i == hi) return false;
23     i = hi; --i;
24     for (;;) {

```

```

25     It j = i; --i;
26     if (*i < *j) {
27         It k = hi;
28         while (!(*i < *--k)) /* pass */;
29         std::iter_swap(i, k);
30         std::reverse(j, hi);
31         return true;
32     }
33     if (i == lo) {
34         std::reverse(lo, hi);
35         return false;
36     }
37 }
38 }
39
40 //array version
41 template<class T> bool next_permutation(int n, T a[]) {
42     for (int i = n - 2; i >= 0; i--)
43         if (a[i] < a[i + 1])
44             for (int j = n - 1; ; j--)
45                 if (a[i] < a[j]) {
46                     std::swap(a[i++], a[j]);
47                     for (j = n - 1; i < j; i++, j--)
48                         std::swap(a[i], a[j]);
49                     return true;
50                 }
51     return false;
52 }
53
54 /*
55
56 Calls the custom function f(vector) on all permutations
57 of the integers from 0 to n - 1. This is more efficient
58 than making many consecutive calls to next_permutation(),
59 however, here, the permutations will not be printed in
60 lexicographically increasing order.
61
62 */
63
64 template<class ReportFunction>
65 void gen_permutations(int n, ReportFunction report,
66                     std::vector<int> & p, int d) {
67     if (d == n) {
68         report(p);
69         return;
70     }
71     for (int i = 0; i < n; i++) {
72         if (p[i] == 0) {
73             p[i] = d;
74             gen_permutations(n, report, p, d + 1);
75             p[i] = 0;
76         }
77     }
78 }
79
80 template<class ReportFunction>
81 void gen_permutations(int n, ReportFunction report) {
82     std::vector<int> perms(n, 0);
83     gen_permutations(n, report, perms, 0);

```

```

84 }
85
86 /*
87
88 Finds the next lexicographically greater permutation of
89 the binary digits of x. In other words, next_permutation()
90 simply returns the smallest integer greater than x which
91 has the same number of 1 bits (i.e. same popcount) as x.
92
93 examples: next_permutation(10101 base 2) = 10110
94           next_permutation(11100 base 2) = 100011
95
96 This can also be used to generate combinations as follows:
97 If we let k = popcount(x), then we can use this to generate
98 all possible masks to tell us which k items to take out of
99 n total items (represented by the first n bits of x).
100
101 */
102
103 long long next_permutation(long long x) {
104     long long s = x & -x, r = x + s;
105     return r | (((x ^ r) >> 2) / s);
106 }
107
108 /*
109
110 Given an integer rank x in range [0, n!), returns a vector
111 of integers representing the x-th lexicographically smallest
112 permutation of the integers in [0, n).
113
114 examples: permutation_by_rank(4, 0) => {0, 1, 2, 3}
115           permutation_by_rank(4, 5) => {0, 3, 2, 1}
116
117 */
118
119 std::vector<int> permutation_by_rank(int n, long long x) {
120     long long fact[n];
121     fact[0] = 1;
122     for (int i = 1; i < n; i++)
123         fact[i] = i * fact[i - 1];
124     std::vector<int> free(n), res(n);
125     for (int i = 0; i < n; i++) free[i] = i;
126     for (int i = 0; i < n; i++) {
127         int pos = x / fact[n - 1 - i];
128         res[i] = free[pos];
129         std::copy(free.begin() + pos + 1, free.end(),
130                 free.begin() + pos);
131         x %= fact[n - 1 - i];
132     }
133     return res;
134 }
135
136 /*
137
138 Given an array a[] of n integers each in range [0, n), returns
139 the (0-based) lexicographical rank (counting from least to
140 greatest) of the arrangement specified by a[] in all possible
141 permutations of the integers from 0 to n - 1.
142

```

```

143 examples: rank_by_permutation(3, {0, 1, 2}) => 0
144             rank_by_permutation(3, {2, 1, 0}) => 5
145
146 */
147
148 template<class T> long long rank_by_permutation(int n, T a[]) {
149     long long fact[n];
150     fact[0] = 1;
151     for (int i = 1; i < n; i++)
152         fact[i] = i * fact[i - 1];
153     long long res = 0;
154     for (int i = 0; i < n; i++) {
155         int v = a[i];
156         for (int j = 0; j < i; j++)
157             if (a[j] < a[i]) v--;
158         res += v * fact[n - 1 - i];
159     }
160     return res;
161 }
162
163 /*
164
165 Given a permutation a[] of the integers from 0 to n - 1,
166 returns a decomposition of the permutation into cycles.
167 A permutation cycle is a subset of a permutation whose
168 elements trade places with one another. For example, the
169 permutation {0, 2, 1, 3} decomposes to {0, 3, 2} and {1}.
170 Here, the notation {0, 3, 2} means that starting from the
171 original ordering {0, 1, 2, 3}, the 0th value is replaced
172 by the 3rd, the 3rd by the 2nd, and the 2nd by the first,
173 See: http://mathworld.wolfram.com/PermutationCycle.html
174
175 */
176
177 typedef std::vector<std::vector<int>> cycles;
178
179 cycles decompose_into_cycles(int n, int a[]) {
180     std::vector<bool> vis(n);
181     cycles res;
182     for (int i = 0; i < n; i++) {
183         if (vis[i]) continue;
184         int j = i;
185         std::vector<int> cur;
186         do {
187             cur.push_back(j);
188             vis[j] = true;
189             j = a[j];
190         } while (j != i);
191         res.push_back(cur);
192     }
193     return res;
194 }
195
196 /** Example Usage */
197
198 #include <bitset>
199 #include <cassert>
200 #include <iostream>
201 using namespace std;

```



```

202
203 void printperm(const vector<int> & perm) {
204     for (int i = 0; i < (int)perm.size(); i++)
205         cout << perm[i] << " ";
206     cout << "\n";
207 }
208
209 template<class it> void print(it lo, it hi) {
210     for (; lo != hi; ++lo) cout << *lo << " ";
211     cout << "\n";
212 }
213
214 int main() {
215     { //method 1: ordered
216         int n = 4, a[] = {0, 1, 2, 3};
217         int b[n], c[n];
218         for (int i = 0; i < n; i++) b[i] = c[i] = a[i];
219         cout << "Ordered permutations of 0 to " << n-1 << ":\n";
220         int cnt = 0;
221         do {
222             print(a, a + n);
223             assert(equal(b, b + n, a));
224             assert(equal(c, c + n, a));
225             vector<int> d = permutation_by_rank(n, cnt);
226             assert(equal(d.begin(), d.end(), a));
227             assert(rank_by_permutation(n, a) == cnt);
228             cnt++;
229             std::next_permutation(b, b + n);
230             _next_permutation(c, c + n);
231         } while (next_permutation(n, a));
232         cout << "\n";
233     }
234
235     { //method 2: unordered
236         int n = 3;
237         cout << "Unordered permutations of 0 to " << n-1 << ":\n";
238         gen_permutations(n, printperm);
239         cout << "\n";
240     }
241
242     { //permuting binary digits
243         const int n = 5;
244         cout << "Permutations of 2 zeros and 3 ones:\n";
245         long long lo = 7; // 00111 in base 2
246         long long hi = 35; // 100011 in base 2
247         do {
248             cout << bitset<n>(lo).to_string() << "\n";
249         } while ((lo = next_permutation(lo)) != hi);
250         cout << "\n";
251     }
252
253     { //permutation cycles
254         int n = 4, a[] = {3, 1, 0, 2};
255         cout << "Decompose 0 2 1 3 into cycles:\n";
256         cycles c = decompose_into_cycles(n, a);
257         for (int i = 0; i < (int)c.size(); i++) {
258             cout << "Cycle " << i + 1 << ":\n";
259             for (int j = 0; j < (int)c[i].size(); j++)
260                 cout << " " << c[i][j];

```

```

261     cout << "\n";
262 }
263 }
264 return 0;
265 }

```

4.2.4 Enumerating Combinations

```

1  /*
2
3  4.2.4 - Enumerating Combinations
4
5  We shall consider a combination n choose k to be an
6  set of k elements chosen from a total of n elements.
7  Unlike n permute k, the order here doesn't matter.
8  That is, 0 1 2 is considered the same as 0 2 1, so
9  we will consider the sorted representation of each
10 combination for purposes of the functions below.
11
12 */
13
14 #include <algorithm> /* iter_swap, rotate, swap, swap_ranges */
15 #include <iterator> /* std::iterator_traits */
16 #include <vector>
17
18 /*
19
20 Rearranges the values in the range [lo, hi) such that
21 elements in the range [lo, mid) becomes the next
22 lexicographically greater combination of the values from
23 [lo, hi) than it currently is, and returns whether the
24 function could rearrange [lo, hi) to a lexicographically
25 greater combination. If the range [lo, hi) contains n
26 elements and the range [lo, mid) contains k elements,
27 then starting off with a sorted range [lo, hi) and
28 calling next_combination() repeatedly will return true
29 for n choose k iterations before returning false.
30
31 */
32
33 template<class It>
34 bool next_combination(It lo, It mid, It hi) {
35     if (lo == mid || mid == hi) return false;
36     It l(mid - 1), h(hi - 1);
37     int sz1 = 1, sz2 = 1;
38     while (l != lo && !(*l < *h)) --l, ++sz1;
39     if (l == lo && !(*l < *h)) {
40         std::rotate(lo, mid, hi);
41         return false;
42     }
43     for (; mid < h; ++sz2) if (!(*l < *--h)) { ++h; break; }
44     if (sz1 == 1 || sz2 == 1) {
45         std::iter_swap(l, h);
46     } else if (sz1 == sz2) {
47         std::swap_ranges(l, mid, h);
48     } else {
49         std::iter_swap(l, h);

```

```

50     ++l; ++h; --sz1; --sz2;
51     int total = sz1 + sz2, gcd = total;
52     for (int i = sz1; i != 0; ) std::swap(gcd %= i, i);
53     int skip = total / gcd - 1;
54     for (int i = 0; i < gcd; i++) {
55         It curr(i < sz1 ? l + i : h + (i - sz1));
56         int k = i;
57         typename std::iterator_traits<It>::value_type v(*curr);
58         for (int j = 0; j < skip; j++) {
59             k = (k + sz1) % total;
60             It next(k < sz1 ? l + k : h + (k - sz1));
61             *curr = *next;
62             curr = next;
63         }
64         *curr = v;
65     }
66 }
67 return true;
68 }
69
70 /*
71
72 Changes a[] to the next lexicographically greater
73 combination of any k distinct integers in range [0, n).
74 The values of a[] that's passed should be k distinct
75 integers, each in range [0, n).
76
77 */
78
79 bool next_combination(int n, int k, int a[]) {
80     for (int i = k - 1; i >= 0; i--) {
81         if (a[i] < n - k + i) {
82             for (++a[i]; ++i < k; ) a[i] = a[i - 1] + 1;
83             return true;
84         }
85     }
86     return false;
87 }
88
89 /*
90
91 Finds the "mask" of the next combination of x. This is
92 equivalent to the next lexicographically greater permutation
93 of the binary digits of x. In other words, the function
94 simply returns the smallest integer greater than x which
95 has the same number of 1 bits (i.e. same popcount) as x.
96
97 examples: next_combination_mask(10101 base 2) = 10110
98           next_combination_mask(11100 base 2) = 100011
99
100 If we arbitrarily number the n items of our collection from
101 0 to n-1, then generating all combinations n choose k can
102 be done as follows: initialize x such that popcount(x) = k
103 and the first (least-significant) k bits are all set to 1
104 (e.g. to do 5 choose 3, start at x = 00111 (base 2) = 7).
105 Then, we repeatedly call x = next_combination_mask(x) until
106 we reach 11100 (the lexicographically greatest mask for 5
107 choose 3), after which we stop. At any point in the process,
108 we can say that the i-th item is being "taken" (0 <= i < n)

```

```

109  iff the i-th bit of x is set.
110
111  Note: this does not produce combinations in the same order
112  as next_combination, nor does it work if your n items have
113  repeated values (in that case, repeated combos will be
114  generated).
115
116  */
117
118  long long next_combination_mask(long long x) {
119      long long s = x & -x, r = x + s;
120      return r | (((x ^ r) >> 2) / s);
121  }
122
123  //n choose k in O(min(k, n - k))
124  long long n_choose_k(long long n, long long k) {
125      if (k > n - k) k = n - k;
126      long long res = 1;
127      for (int i = 0; i < k; i++)
128          res = res * (n - i) / (i + 1);
129      return res;
130  }
131
132  /*
133
134  Given an integer rank x in range [0, n choose k), returns
135  a vector of integers representing the x-th lexicographically
136  smallest combination k distinct integers in [0, n).
137
138  examples: combination_by_rank(4, 3, 0) => {0, 1, 2}
139            combination_by_rank(4, 3, 2) => {0, 2, 3}
140
141  */
142
143  std::vector<int> combination_by_rank(int n, int k, long long x) {
144      std::vector<int> res(k);
145      int cnt = n;
146      for (int i = 0; i < k; i++) {
147          int j = 1;
148          for (;;) {
149              long long am = n_choose_k(cnt - j, k - 1 - i);
150              if (x < am) break;
151              x -= am;
152          }
153          res[i] = i > 0 ? (res[i - 1] + j) : (j - 1);
154          cnt -= j;
155      }
156      return res;
157  }
158
159  /*
160
161  Given an array a[] of k integers each in range [0, n), returns
162  the (0-based) lexicographical rank (counting from least to
163  greatest) of the combination specified by a[] in all possible
164  combination of k distinct integers in range [0, n).
165
166  examples: rank_by_combination(4, 3, {0, 1, 2}) => 0
167            rank_by_combination(4, 3, {0, 2, 3}) => 2

```

```

168
169 */
170
171 long long rank_by_combination(int n, int k, int a[]) {
172     long long res = 0;
173     int prev = -1;
174     for (int i = 0; i < k; i++) {
175         for (int j = prev + 1; j < a[i]; j++)
176             res += n_choose_k(n - 1 - j, k - 1 - i);
177         prev = a[i];
178     }
179     return res;
180 }
181
182 /*
183
184 Changes a[] to the next lexicographically greater
185 combination of any k (not necessarily distinct) integers
186 in range [0, n). The values of a[] that's passed should
187 be k integers, each in range [0, n). Note that there are
188 a total of n multichoose k combinations with repetition,
189 where n multichoose k = (n + k - 1) choose k
190
191 */
192
193 bool next_combination_with_repeats(int n, int k, int a[]) {
194     for (int i = k - 1; i >= 0; i--) {
195         if (a[i] < n - 1) {
196             for (++a[i]; ++i < k; ) a[i] = a[i - 1];
197             return true;
198         }
199     }
200     return false;
201 }
202
203 /** Example Usage */
204
205 #include <cassert>
206 #include <iostream>
207 using namespace std;
208
209 template<class it> void print(it lo, it hi) {
210     for (; lo != hi; ++lo) cout << *lo << " ";
211     cout << "\n";
212 }
213
214 int main() {
215     { //like std::next_permutation(), repeats in the range allowed
216         int k = 3;
217         string s = "11234";
218         cout << s << " choose " << k << ":\n";
219         do {
220             cout << s.substr(0, k) << "\n";
221         } while (next_combination(s.begin(), s.begin() + k, s.end()));
222         cout << "\n";
223     }
224
225     { //unordered combinations with masks
226         int n = 5, k = 3;

```

```

227     string s = "abcde"; //must be distinct values
228     cout << s << "choose" << k << "with masks:\n";
229     long long mask = 0, dest = 0;
230     for (int i = 0; i < k; i++) mask |= 1 << i;
231     for (int i = k - 1; i < n; i++) dest |= 1 << i;
232     do {
233         for (int i = 0; i < n; i++)
234             if ((mask >> i) & 1) cout << s[i];
235         cout << "\n";
236         mask = next_combination_mask(mask);
237     } while (mask != dest);
238     cout << "\n";
239 }
240
241 { //only combinations of distinct integers from 0 to n - 1
242     int n = 5, k = 3, a[] = {0, 1, 2};
243     cout << n << "choose" << k << ":\n";
244     int cnt = 0;
245     do {
246         print(a, a + k);
247         vector<int> b = combination_by_rank(n, k, cnt);
248         assert(equal(a, a + k, b.begin()));
249         assert(rank_by_combination(n, k, a) == cnt);
250         cnt++;
251     } while (next_combination(n, k, a));
252     cout << "\n";
253 }
254
255 { //combinations with repetition
256     int n = 3, k = 2, a[] = {0, 0};
257     cout << n << "multichoose" << k << ":\n";
258     do {
259         print(a, a + k);
260     } while (next_combination_with_repeats(n, k, a));
261 }
262 return 0;
263 }

```

4.2.5 Enumerating Partitions

```

1  /*
2
3  4.2.5 - Enumerating Partitions
4
5  We shall consider a partition of an integer n to be an
6  unordered multiset of positive integers that has a total
7  sum equal to n. Since both 2 1 1 and 1 2 1 represent the
8  same partition of 4, we shall consider only descending
9  sorted lists as "valid" partitions for functions below.
10
11  */
12
13  #include <vector>
14
15  /*
16
17  Given a vector representing a partition of some

```

```

18 integer n (the sum of all values in the vector),
19 changes p to the next lexicographically greater
20 partition of n and returns whether the change was
21 successful (whether a lexicographically greater
22 partition existed). Note that the "initial" value
23 of p must be a vector of size n, all initialized 1.
24
25 e.g. next_partition({2, 1, 1}) => 1, p becomes {2, 2}
26     next_partition({2, 2})    => 1, p becomes {3, 1}
27     next_partition({4})      => 0, p is unchanged
28
29 */
30
31 bool next_partition(std::vector<int> & p) {
32     int n = p.size();
33     if (n <= 1) return false;
34     int s = p[n - 1] - 1, i = n - 2;
35     p.pop_back();
36     for (; i > 0 && p[i] == p[i - 1]; i--) {
37         s += p[i];
38         p.pop_back();
39     }
40     for (p[i]++; s-- > 0; ) p.push_back(1);
41     return true;
42 }
43
44 /* Returns the number of partitions of n. */
45
46 long long count_partitions(int n) {
47     std::vector<long long> p(n + 1, 0);
48     p[0] = 1;
49     for (int i = 1; i <= n; i++)
50         for (int j = i; j <= n; j++)
51             p[j] += p[j - i];
52     return p[n];
53 }
54
55 /* Helper function for partitioning by rank */
56
57 std::vector< std::vector<long long> >
58 p(1, std::vector<long long>(1, 1)); //memoization
59
60 long long partition_function(int a, int b) {
61     if (a >= (int)p.size()) {
62         int old = p.size();
63         p.resize(a + 1);
64         p[0].resize(a + 1);
65         for (int i = 1; i <= a; i++) {
66             p[i].resize(a + 1);
67             for (int j = old; j <= i; j++)
68                 p[i][j] = p[i - 1][j - 1] + p[i - j][j];
69         }
70     }
71     return p[a][b];
72 }
73
74 /*
75
76 Given an integer n to partition and a 0-based rank x,

```

```

77  returns a vector of integers representing the x-th
78  lexicographically smallest partition of n (if values
79  in each partition were sorted in decreasing order).
80
81  examples: partition_by_rank(4, 0) => {1, 1, 1, 1}
82             partition_by_rank(4, 3) => {3, 1}
83
84  */
85
86  std::vector<int> partition_by_rank(int n, long long x) {
87      std::vector<int> res;
88      for (int i = n; i > 0; ) {
89          int j = 1;
90          for (;;) j++; {
91              long long cnt = partition_function(i, j);
92              if (x < cnt) break;
93              x -= cnt;
94          }
95          res.push_back(j);
96          i -= j;
97      }
98      return res;
99  }
100
101  /*
102
103  Given a partition of an integer n (sum of all values
104  in vector p), returns a 0-based rank x of the partition
105  represented by p, considering partitions from least to
106  greatest in lexicographical order (if each partition
107  had values sorted in descending order).
108
109  examples: rank_by_partition({1, 1, 1, 1}) => 0
110             rank_by_partition({3, 1})      => 3
111
112  */
113
114  long long rank_by_partition(const std::vector<int> & p) {
115      long long res = 0;
116      int sum = 0;
117      for (int i = 0; i < (int)p.size(); i++) sum += p[i];
118      for (int i = 0; i < (int)p.size(); i++) {
119          for (int j = 0; j < p[i]; j++)
120              res += partition_function(sum, j);
121          sum -= p[i];
122      }
123      return res;
124  }
125
126  /*
127
128  Calls the custom function f(vector) on all partitions
129  which consist of strictly *increasing* integers.
130  This will exclude partitions such as {1, 1, 1, 1}.
131
132  */
133
134  template<class ReportFunction>
135  void gen_increasing_partitons(int left, int prev, int i,

```



```

136         ReportFunction f, std::vector<int> & p) {
137     if (left == 0) {
138         //warning: slow constructor - modify accordingly
139         f(std::vector<int>(p.begin(), p.begin() + i));
140         return;
141     }
142     for (p[i] = prev + 1; p[i] <= left; p[i]++)
143         gen_increasing_partitons(left - p[i], p[i], i + 1, f, p);
144 }
145
146 template<class ReportFunction>
147 void gen_increasing_partitons(int n, ReportFunction f) {
148     std::vector<int> partitions(n, 0);
149     gen_increasing_partitons(n, 0, 0, f, partitions);
150 }
151
152 /** Example Usage */
153
154 #include <cassert>
155 #include <iostream>
156 using namespace std;
157
158 void print(const vector<int> & v) {
159     for (int i = 0; i < (int)v.size(); i++)
160         cout << v[i] << " ";
161     cout << "\n";
162 }
163
164 int main() {
165     assert(count_partitions(5) == 7);
166     assert(count_partitions(20) == 627);
167     assert(count_partitions(30) == 5604);
168     assert(count_partitions(50) == 204226);
169     assert(count_partitions(100) == 190569292);
170
171     {
172         int n = 4;
173         vector<int> a(n, 1);
174         cout << "Partitions of " << n << ":\n";
175         int cnt = 0;
176         do {
177             print(a);
178             vector<int> b = partition_by_rank(n, cnt);
179             assert(equal(a.begin(), a.end(), b.begin()));
180             assert(rank_by_partition(a) == cnt);
181             cnt++;
182         } while (next_partition(a));
183         cout << "\n";
184     }
185
186     {
187         int n = 8;
188         cout << "Increasing partitions of " << n << ":\n";
189         gen_increasing_partitons(n, print);
190     }
191     return 0;
192 }

```

4.2.6 Enumerating Generic Combinatorial Sequences

```

1  /*
2
3  4.2.6 - Enumerating Generic Combinatorial Sequences
4
5  The follow provides a universal method for enumerating
6  abstract combinatorial sequences in  $O(n^2)$  time.
7
8  */
9
10 #include <vector>
11
12 class abstract_enumeration {
13 protected:
14     int range, length;
15
16     abstract_enumeration(int r, int l): range(r), length(l) {}
17
18     virtual long long count(const std::vector<int> & pre) {
19         return 0;
20     }
21
22     std::vector<int> next(std::vector<int> & seq) {
23         return from_number(to_number(seq) + 1);
24     }
25
26     long long total_count() {
27         return count(std::vector<int>(0));
28     }
29
30 public:
31     long long to_number(const std::vector<int> & seq) {
32         long long res = 0;
33         for (int i = 0; i < (int)seq.size(); i++) {
34             std::vector<int> pre(seq.begin(), seq.end());
35             pre.resize(i + 1);
36             for (pre[i] = 0; pre[i] < seq[i]; ++pre[i])
37                 res += count(pre);
38         }
39         return res;
40     }
41
42     std::vector<int> from_number(long long x) {
43         std::vector<int> seq(length);
44         for (int i = 0; i < (int)seq.size(); i++) {
45             std::vector<int> pre(seq.begin(), seq.end());
46             pre.resize(i + 1);
47             for (pre[i] = 0; pre[i] < range; ++pre[i]) {
48                 long long cur = count(pre);
49                 if (x < cur) break;
50                 x -= cur;
51             }
52             seq[i] = pre[i];
53         }
54         return seq;
55     }
56

```

```

57  template<class ReportFunction>
58  void enumerate(ReportFunction report) {
59      long long total = total_count();
60      for (long long i = 0; i < total; i++) {
61          //assert(i == to_number(from_number(i)));
62          report(from_number(i));
63      }
64  }
65  };
66
67  class arrangements: public abstract_enumeration {
68  public:
69      arrangements(int n, int k) : abstract_enumeration(n, k) {}
70
71      long long count(const std::vector<int> & pre) {
72          int sz = pre.size();
73          for (int i = 0; i < sz - 1; i++)
74              if (pre[i] == pre[sz - 1]) return 0;
75          long long res = 1;
76          for (int i = 0; i < length - sz; i++)
77              res *= range - sz - i;
78          return res;
79      }
80  };
81
82  class permutations: public arrangements {
83  public:
84      permutations(int n) : arrangements(n, n) {}
85  };
86
87  class combinations: public abstract_enumeration {
88      std::vector<std::vector<long long> > binomial;
89
90  public:
91      combinations(int n, int k) : abstract_enumeration(n, k),
92          binomial(n + 1, std::vector<long long>(n + 1, 0)) {
93          for (int i = 0; i <= n; i++)
94              for (int j = 0; j <= i; j++)
95                  binomial[i][j] = (j == 0) ? 1 :
96                      binomial[i - 1][j - 1] + binomial[i - 1][j];
97      }
98
99      long long count(const std::vector<int> & pre) {
100          int sz = pre.size();
101          if (sz >= 2 && pre[sz - 1] <= pre[sz - 2]) return 0;
102          int last = sz > 0 ? pre[sz - 1] : -1;
103          return binomial[range - 1 - last][length - sz];
104      }
105  };
106
107  class partitions: public abstract_enumeration {
108      std::vector<std::vector<long long> > p;
109
110  public:
111      partitions(int n) : abstract_enumeration(n + 1, n),
112          p(n + 1, std::vector<long long>(n + 1, 0)) {
113          std::vector<std::vector<long long> > pp(p);
114          pp[0][0] = 1;
115          for (int i = 1; i <= n; i++)

```

```

116     for (int j = 1; j <= i; j++)
117         pp[i][j] = pp[i - 1][j - 1] + pp[i - j][j];
118     for (int i = 1; i <= n; i++)
119         for (int j = 1; j <= n; j++)
120             p[i][j] = pp[i][j] + p[i][j - 1];
121 }
122
123 long long count(const std::vector<int> & pre) {
124     int size = pre.size(), sum = 0;
125     for (int i = 0; i < (int)pre.size(); i++) sum += pre[i];
126     if (sum == range - 1) return 1;
127     if (sum > range - 1 || (size > 0 && pre[size - 1] == 0) ||
128         (size >= 2 && pre[size - 1] > pre[size - 2])) return 0;
129     int last = size > 0 ? pre[size - 1] : range - 1;
130     return p[range - 1 - sum][last];
131 }
132 };
133
134 /** Example Usage */
135
136 #include <iostream>
137 using namespace std;
138
139 void print(const std::vector<int> & v) {
140     for (int i = 0; i < (int)v.size(); i++)
141         cout << v[i] << " ";
142     cout << "\n";
143 }
144
145 int main() {
146     cout << "Arrangement(3,2):\n";
147     arrangements arrg(3, 2);
148     arrg.enumerate(print);
149
150     cout << "Permutation(3):\n";
151     permutations perm(3);
152     perm.enumerate(print);
153
154     cout << "Combination(4,3):\n";
155     combinations comb(4, 3);
156     comb.enumerate(print);
157
158     cout << "Partition(4):\n";
159     partitions part(4);
160     part.enumerate(print);
161     return 0;
162 }

```

4.3 Number Theory

4.3.1 GCD, LCM, Mod Inverse, Chinese Remainder

```

1  /*
2
3  4.3.1 - GCD, LCM, Modular Inverse, Chinese Remainder Theorem
4

```

```

5  */
6
7  #include <utility> /* std::pair */
8  #include <vector>
9
10 //C++98 does not have abs() declared for long long
11 template<class T> inline T _abs(const T & x) {
12     return x < 0 ? -x : x;
13 }
14
15 //GCD using Euclid's algorithm - O(log(a + b))
16 template<class Int> Int gcd(Int a, Int b) {
17     return b == 0 ? _abs(a) : gcd(b, a % b);
18 }
19
20 //non-recursive version
21 template<class Int> Int gcd2(Int a, Int b) {
22     while (b != 0) {
23         Int t = b;
24         b = a % b;
25         a = t;
26     }
27     return _abs(a);
28 }
29
30 template<class Int> Int lcm(Int a, Int b) {
31     return _abs(a / gcd(a, b) * b);
32 }
33
34 //returns <gcd(a, b), <x, y>> such that gcd(a, b) = ax + by
35 template<class Int>
36 std::pair<Int, std::pair<Int, Int> > euclid(Int a, Int b) {
37     Int x = 1, y = 0, x1 = 0, y1 = 1;
38     //invariant: a = a * x + b * y, b = a * x1 + b * y1
39     while (b != 0) {
40         Int q = a / b, _x1 = x1, _y1 = y1, _b = b;
41         x1 = x - q * x1;
42         y1 = y - q * y1;
43         b = a - q * b;
44         x = _x1;
45         y = _y1;
46         a = _b;
47     }
48     return a > 0 ? std::make_pair(a, std::make_pair(x, y)) :
49         std::make_pair(-a, std::make_pair(-x, -y));
50 }
51
52 //recursive version
53 template<class Int>
54 std::pair<Int, std::pair<Int, Int> > euclid2(Int a, Int b) {
55     if (b == 0) {
56         return a > 0 ? std::make_pair(a, std::make_pair(1, 0)) :
57             std::make_pair(-a, std::make_pair(-1, 0));
58     }
59     std::pair<Int, std::pair<Int, Int> > r = euclid2(b, a % b);
60     return std::make_pair(r.first, std::make_pair(r.second.second,
61         r.second.first - a / b * r.second.second));
62 }
63

```

```

64  /*
65
66  Modulo Operation - Euclidean Definition
67
68  The % operator in C/C++ returns the remainder of division (which
69  may be positive or negative) The true Euclidean definition of
70  modulo, however, defines the remainder to be always nonnegative.
71  For positive operators, % and mod are the same. But for negative
72  operands, they differ. The result here is consistent with the
73  Euclidean division algorithm.
74
75  e.g. -21 % 4 == -1 since -21 / 4 == -5 and 4 * -5 + (-1) == -21
76       however, -21 mod 4 is equal to 3 because -21 + 4 * 6 is 3.
77
78  */
79
80  template<class Int> Int mod(Int a, Int m) {
81      Int r = (Int)(a % m);
82      return r >= 0 ? r : r + m;
83  }
84
85  //returns x such that a * x = 1 (mod m)
86  //precondition: m > 0 && gcd(a, m) = 1
87  template<class Int> Int mod_inverse(Int a, Int m) {
88      a = mod(a, m);
89      return a == 0 ? 0 : mod((1 - m * mod_inverse(m % a, a)) / a, m);
90  }
91
92  //precondition: m > 0 && gcd(a, m) = 1
93  template<class Int> Int mod_inverse2(Int a, Int m) {
94      return mod(euclid(a, m).second.first, m);
95  }
96
97  //returns a vector where i*v[i] = 1 (mod p) in O(p) time
98  //precondition: p is prime
99  std::vector<int> generate_inverses(int p) {
100      std::vector<int> res(p);
101      res[1] = 1;
102      for (int i = 2; i < p; i++)
103          res[i] = (p - (p / i) * res[p % i] % p) % p;
104      return res;
105  }
106
107  /*
108
109  Chinese Remainder Theorem
110
111  Let r and s be positive integers which are relatively prime and
112  let a and b be any two integers. Then there exists an integer N
113  such that N = a (mod r) and N = b (mod s). Moreover, N is
114  uniquely determined modulo rs.
115
116  More generally, given a set of simultaneous congruences for
117  which all values in p[] are pairwise relative prime:
118
119      x = a[i] (mod p[i]), for i = 1..n
120
121  the solution of the set of congruences is:
122

```

```

123  x = a[1] * b[1] * (M/p[1]) + ... + a[n] * b[n] * (M/p[n]) (mod M)
124
125  where M = p[1] * p[2] ... * p[n] and the b[i] are determined for
126
127  b[i] * (M/p[i]) = 1 (mod p[i]).
128
129  The following functions solves for this value of x, with the
130  first function computed using the method above while the
131  second function using a special case of Garner's algorithm.
132
133  http://e-maxx-eng.github.io/algebra/chinese-remainder-theorem.html
134
135  */
136
137  long long simple_restore(int n, int a[], int p[]) {
138      long long res = 0, m = 1;
139      for (int i = 0; i < n; i++) {
140          while (res % p[i] != a[i]) res += m;
141          m *= p[i];
142      }
143      return res;
144  }
145
146  long long garner_restore(int n, int a[], int p[]) {
147      int x[n];
148      for (int i = 0; i < n; i++) x[i] = a[i];
149      for (int i = 0; i < n; i++) {
150          for (int j = 0; j < i; j++)
151              x[i] = mod_inverse((long long)p[j], (long long)p[i]) *
152                  (long long)(x[i] - x[j]);
153          x[i] = (x[i] % p[i] + p[i]) % p[i];
154      }
155      long long res = x[0], m = 1;
156      for (int i = 1; i < n; i++) {
157          m *= p[i - 1];
158          res += x[i] * m;
159      }
160      return res;
161  }
162
163  /** Example Usage */
164
165  #include <cassert>
166  #include <cstdlib>
167  #include <ctime>
168  #include <iostream>
169  using namespace std;
170
171  int main() {
172      {
173          srand(time(0));
174          for (int steps = 0; steps < 10000; steps++) {
175              int a = rand() % 200 - 10;
176              int b = rand() % 200 - 10;
177              int g1 = gcd(a, b), g2 = gcd2(a, b);
178              assert(g1 == g2);
179              if (g1 == 1 && b > 1) {
180                  int inv1 = mod_inverse(a, b);
181                  int inv2 = mod_inverse2(a, b);

```

```

182     assert(inv1 == inv2 && mod(a * inv1, b) == 1);
183 }
184 pair<int, pair<int, int> > euc1 = euclid(a, b);
185 pair<int, pair<int, int> > euc2 = euclid2(a, b);
186 assert(euc1.first == g1 && euc1 == euc2);
187 int x = euc1.second.first;
188 int y = euc1.second.second;
189 assert(g1 == a * x + b * y);
190 }
191 }
192
193 {
194     long long a = 6, b = 9;
195     pair<int, pair<int, int> > r = euclid(6, 9);
196     cout << r.second.first << " * " << a << " " << " + ";
197     cout << r.second.second << " * " << b << " " << "= gcd ";
198     cout << a << " , " << b << " ) = " << r.first << "\n";
199 }
200
201 {
202     int prime = 17;
203     std::vector<int> res = generate_inverses(prime);
204     for (int i = 0; i < prime; i++) {
205         if (i > 0) assert(mod(i * res[i], prime) == 1);
206         cout << res[i] << " ";
207     }
208     cout << "\n";
209 }
210
211 {
212     int n = 3, a[] = {2, 3, 1}, m[] = {3, 4, 5};
213     //solves for x in the simultaneous congruences:
214     //x = 2 (mod 3)
215     //x = 3 (mod 4)
216     //x = 1 (mod 5)
217     int x1 = simple_restore(n, a, m);
218     int x2 = Garner_restore(n, a, m);
219     assert(x1 == x2);
220     for (int i = 0; i < n; i++)
221         assert(mod(x1, m[i]) == a[i]);
222     cout << "Solution: " << x1 << "\n"; //11
223 }
224
225 return 0;
226 }

```

4.3.2 Generating Primes

```

1  /*
2
3  4.3.2 - Generating Primes
4
5  The following are three methods to generate primes.
6  Although the latter two functions are theoretically
7  linear, the former function with the sieve of
8  Eratosthenes is still significantly the fastest even
9  for n under 1 billion, since its constant factor is

```



```

10 so much better because of its minimal arithmetic
11 operations. For this reason, it should be favored
12 over the other two algorithms in most contest
13 applications. For the computation of larger primes,
14 you should replace int with long long or an arbitrary
15 precision class.
16
17 */
18
19 #include <cmath> /* ceil(), sqrt() */
20 #include <vector>
21
22 //Sieve of Eratosthenes in  $\sim O(n \log \log n)$ 
23 //returns: a vector of all primes under n
24 std::vector<int> gen_primes(int n) {
25     std::vector<bool> prime(n + 1, true);
26     int sqrtn = (int)ceil(sqrt(n));
27     for (int i = 2; i <= sqrtn; i++) {
28         if (prime[i])
29             for (int j = i * i; j <= n; j += i)
30                 prime[j] = false;
31     }
32     std::vector<int> res;
33     for (int i = 2; i <= n; i++)
34         if (prime[i]) res.push_back(i);
35     return res;
36 }
37
38 //Technically  $O(n)$ , but on -O2, this is about
39 //as fast as the above sieve for n = 100 million
40 std::vector<int> gen_primes_linear(int n) {
41     std::vector<int> lp(n + 1), res;
42     for (int i = 2; i <= n; i++) {
43         if (lp[i] == 0) {
44             lp[i] = i;
45             res.push_back(i);
46         }
47         for (int j = 0; j < (int)res.size(); j++) {
48             if (res[j] > lp[i] || i * res[j] > n)
49                 break;
50             lp[i * res[j]] = res[j];
51         }
52     }
53     return res;
54 }
55
56 //Sieve of Atkins in  $O(n)$ , somewhat slow due to
57 //its heavier arithmetic compared to the above
58 std::vector<int> gen_primes_atkins(int n) {
59     std::vector<bool> prime(n + 1, false);
60     std::vector<int> res;
61     prime[2] = true;
62     prime[3] = true;
63     int num, lim = ceil(sqrt(n));
64     for (int x = 1; x <= lim; x++) {
65         for (int y = 1; y <= lim; y++) {
66             num = 4 * x * x + y * y;
67             if (num <= n && (num % 12 == 1 || num % 12 == 5))
68                 prime[num] = true;

```

```

69     num = 3 * x * x + y * y;
70     if (num <= n && (num % 12 == 7))
71         prime[num] = true;
72     if (x > y) {
73         num = (3 * x * x - y * y);
74         if (num <= n && num % 12 == 11)
75             prime[num] = true;
76     }
77 }
78 }
79 for (int i = 5; i <= lim; i++) {
80     if (prime[i])
81         for (int j = i * i; j <= n; j += i)
82             prime[j] = false;
83 }
84 for (int i = 2; i <= n; i++)
85     if (prime[i]) res.push_back(i);
86 return res;
87 }
88
89 //Double sieve to find primes in [1, h]
90 //Approximately O(sqrt(h) * log log(h - 1))
91 std::vector<int> gen_primes(int l, int h) {
92     int sqrth = (int)ceil(sqrt(h));
93     int sqrtsqrth = (int)ceil(sqrt(sqrth));
94     std::vector<bool> prime1(sqrth + 1, true);
95     std::vector<bool> prime2(h - l + 1, true);
96     for (int i = 2; i <= sqrtsqrth; i++) {
97         if (prime1[i])
98             for (int j = i * i; j <= sqrth; j += i)
99                 prime1[j] = false;
100     }
101     for (int i = 2, n = h - l; i <= sqrth; i++) {
102         if (prime1[i])
103             for (int j = l / i * i - l; j <= n; j += i)
104                 if (j >= 0 && j + l != i)
105                     prime2[j] = false;
106     }
107     std::vector<int> res;
108     for (int i = l > 1 ? l : 2; i <= h; i++)
109         if (prime2[i - l]) res.push_back(i);
110     return res;
111 }
112
113 /** Example Usage */
114
115 #include <cassert>
116 #include <ctime>
117 #include <iostream>
118 using namespace std;
119
120 template<class It> void print(It lo, It hi) {
121     while (lo != hi) cout << *(lo++) << " ";
122     cout << "\n";
123 }
124
125 int main() {
126     int pmax = 10000000;
127     vector<int> p;

```

```

128     time_t start;
129     double delta;
130
131     cout << "Generating primes up to " << pmax << "... \n";
132     start = clock();
133     p = gen_primes(pmax);
134     delta = (double)(clock() - start)/CLOCKS_PER_SEC;
135     cout << "gen_primes() took " << delta << "s. \n";
136
137     start = clock();
138     p = gen_primes_linear(pmax);
139     delta = (double)(clock() - start)/CLOCKS_PER_SEC;
140     cout << "gen_primes_linear() took " << delta << "s. \n";
141
142     start = clock();
143     p = gen_primes_atkins(pmax);
144     delta = (double)(clock() - start)/CLOCKS_PER_SEC;
145     cout << "gen_primes_atkins() took " << delta << "s. \n";
146
147     cout << "Generated " << p.size() << " primes. \n";
148     //print(p.begin(), p.end());
149
150     for (int i = 0; i <= 1000; i++) {
151         assert(gen_primes(i) == gen_primes_linear(i));
152         assert(gen_primes(i) == gen_primes_atkins(i));
153     }
154
155     int l = 1000000000, h = 1000000500;
156     cout << "Generating primes in " << l << ", " << h << " ... \n";
157     start = clock();
158     p = gen_primes(l, h);
159     delta = (double)(clock() - start)/CLOCKS_PER_SEC;
160     cout << "Generated " << p.size() << " primes in " << delta << "s. \n";
161     print(p.begin(), p.end());
162     return 0;
163 }

```

4.3.3 Primality Testing

```

1  /* 4.3.3 - Primality Testing */
2
3  #include <cstdlib> /* rand(), srand() */
4  #include <ctime>   /* time() */
5  #include <stdint.h> /* uint64_t */
6
7  /*
8
9  Trial division in O(sqrt(n)) to return whether n is prime
10 Applies an optimization based on the fact that all
11 primes greater than 3 take the form 6n + 1 or 6n - 1.
12
13 */
14
15 template<class Int> bool is_prime(Int n) {
16     if (n == 2 || n == 3) return true;
17     if (n < 2 || !(n % 2) || !(n % 3)) return false;
18     for (Int i = 5, w = 4; i * i <= n; i += (w = 6 - w))

```

```

19     if (n % i == 0) return false;
20     return true;
21 }
22
23 /*
24
25 Miller-Rabin Primality Test (Probabilistic)
26
27 Checks whether a number n is probably prime. If n is prime,
28 the function is guaranteed to return 1. If n is composite,
29 the function returns 1 with a probability of  $(1/4)^k$ ,
30 where k is the number of iterations. With k = 1, the
31 probability of a composite being falsely predicted to be a
32 prime is 25%. If k = 5, the probability for this error is
33 just less than 0.1%. Thus, k = 18 to 20 is accurate enough
34 for most applications. All values of  $n < 2^{63}$  is supported.
35
36 Complexity:  $O(k \log^3(n))$ . In comparison to trial division,
37 the Miller-Rabin algorithm on 32-bit ints take ~45
38 operations for k = 10 iterations (~0.0001% error), while the
39 former takes ~10,000.
40
41 Warning: Due to the overflow of modular exponentiation,
42         this will only work on inputs less than  $2^{63}$ .
43
44 */
45
46 uint64_t mulmod(uint64_t a, uint64_t b, uint64_t m) {
47     uint64_t x = 0, y = a % m;
48     for (; b > 0; b >>= 1) {
49         if (b & 1) x = (x + y) % m;
50         y = (y << 1) % m;
51     }
52     return x % m;
53 }
54
55 uint64_t powmod(uint64_t a, uint64_t b, uint64_t m) {
56     uint64_t x = 1, y = a;
57     for (; b > 0; b >>= 1) {
58         if (b & 1) x = mulmod(x, y, m);
59         y = mulmod(y, y, m);
60     }
61     return x % m;
62 }
63
64 //5 calls to rand() is unnecessary if RAND_MAX is  $2^{31}-1$ 
65 uint64_t rand64u() {
66     return ((uint64_t)(rand() & 0xf) << 60) |
67         ((uint64_t)(rand() & 0x7fff) << 45) |
68         ((uint64_t)(rand() & 0x7fff) << 30) |
69         ((uint64_t)(rand() & 0x7fff) << 15) |
70         ((uint64_t)(rand() & 0x7fff));
71 }
72
73 bool is_probable_prime(long long n, int k = 20) {
74     if (n < 2 || (n != 2 && !(n & 1))) return false;
75     uint64_t s = n - 1, p = n - 1, x, r;
76     while (!(s & 1)) s >>= 1;
77     for (int i = 0; i < k; i++) {

```

```

78     r = powmod(rand64u() % p + 1, s, n);
79     for (x = s; x != p && r != 1 && r != p; x <= 1)
80         r = mulmod(r, r, n);
81     if (r != p && !(x & 1)) return false;
82 }
83 return true;
84 }
85
86 /*
87
88 Miller-Rabin - Deterministic for all unsigned long long
89
90 Although Miller-Rabin is generally probabilistic, the seven
91 bases 2, 325, 9375, 28178, 450775, 9780504, 1795265022 have
92 been proven to deterministically test the primality of all
93 numbers under 2^64. See: http://miller-rabin.appspot.com/
94
95 Complexity:  $O(\log^3(n))$ .
96 Warning: Due to the overflow of modular exponentiation,
97         this will only work on inputs less than 2^63.
98
99 */
100
101 bool is_prime_fast(long long n) {
102     static const uint64_t witnesses[] =
103         {2, 325, 9375, 28178, 450775, 9780504, 1795265022};
104     if (n <= 1) return false;
105     if (n <= 3) return true;
106     if ((n & 1) == 0) return false;
107     uint64_t d = n - 1;
108     int s = 0;
109     for (; ~d & 1; s++) d >>= 1;
110     for (int i = 0; i < 7; i++) {
111         if (witnesses[i] > (uint64_t)n - 2) break;
112         uint64_t x = powmod(witnesses[i], d, n);
113         if (x == 1 || x == (uint64_t)n - 1) continue;
114         bool flag = false;
115         for (int j = 0; j < s; j++) {
116             x = powmod(x, 2, n);
117             if (x == 1) return false;
118             if (x == (uint64_t)n - 1) {
119                 flag = true;
120                 break;
121             }
122         }
123         if (!flag) return false;
124     }
125     return true;
126 }
127
128 /** Example Usage */
129
130 #include <cassert>
131
132 int main() {
133     int len = 20;
134     unsigned long long v[] = {
135         0, 1, 2, 3, 4, 5, 11,
136         1000000ull,

```

```

137     772023803ull,
138     792904103ull,
139     813815117ull,
140     834753187ull,
141     855718739ull,
142     876717799ull,
143     897746119ull,
144     2147483647ull,
145     5705234089ull,
146     5914686649ull,
147     6114145249ull,
148     6339503641ull,
149     6548531929ull
150 };
151 for (int i = 0; i < len; i++) {
152     bool p = is_prime(v[i]);
153     assert(p == is_prime_fast(v[i]));
154     assert(p == is_probable_prime(v[i]));
155 }
156 return 0;
157 }

```

4.3.4 Integer Factorization

```

1  /* 4.3.4 - Integer Factorization */
2
3  #include <algorithm> /* std::sort() */
4  #include <cmath>     /* sqrt() */
5  #include <cstdlib>    /* rand(), srand() */
6  #include <stdint.h>  /* uint64_t */
7  #include <vector>
8
9  /*
10
11  Trial division in O(sqrt(n))
12
13  Returns a vector of pair<prime divisor, exponent>
14  e.g. prime_factorize(15435) => {(3,2),(5,1),(7,3)}
15  because 3^2 * 5^1 * 7^3 = 15435
16
17  */
18
19  template<class Int>
20  std::vector<std::pair<Int, int> > prime_factorize(Int n) {
21      std::vector<std::pair<Int, int> > res;
22      for (Int d = 2; ; d++) {
23          int power = 0, quot = n / d, rem = n - quot * d;
24          if (d > quot || (d == quot && rem > 0)) break;
25          for (; rem == 0; rem = n - quot * d) {
26              power++;
27              n = quot;
28              quot = n / d;
29          }
30          if (power > 0) res.push_back(std::make_pair(d, power));
31      }
32      if (n > 1) res.push_back(std::make_pair(n, 1));
33      return res;

```

```

34 }
35
36 /*
37
38 Trial division in  $O(\sqrt{n})$ 
39
40 Returns a sorted vector of all divisors of n.
41 e.g. get_all_divisors(28) => {1, 2, 4, 7, 14, 28}
42
43 */
44
45 template<class Int>
46 std::vector<Int> get_all_divisors(Int n) {
47     std::vector<Int> res;
48     for (int d = 1; d * d <= n; d++) {
49         if (n % d == 0) {
50             res.push_back(d);
51             if (d * d != n)
52                 res.push_back(n / d);
53         }
54     }
55     std::sort(res.begin(), res.end());
56     return res;
57 }
58
59 /*
60
61 Fermat's Method  $\sim O(\sqrt{N})$ 
62
63 Given a number n, returns one factor of n that is
64 not necessary prime. Fermat's algorithm is pretty
65 good when the number you wish to factor has two
66 factors very near to  $\sqrt{n}$ . Otherwise, it is just
67 as slow as the basic trial division algorithm.
68
69 e.g. 14917627 => 1 (it's a prime), or
70     1234567 => 127 (because 127*9721 = 1234567)
71
72 */
73
74 long long fermat(long long n) {
75     if (n % 2 == 0) return 2;
76     long long x = sqrt(n), y = 0;
77     long long r = x * x - y * y - n;
78     while (r != 0) {
79         if (r < 0) {
80             r += x + x + 1;
81             x++;
82         } else {
83             r -= y + y + 1;
84             y++;
85         }
86     }
87     return x != y ? x - y : x + y;
88 }
89
90 /*
91
92 Pollard's rho Algorithm with Brent's Optimization

```

```

93
94 Brent's algorithm is a much faster variant of Pollard's
95 rho algorithm using Brent's cycle-finding method. The
96 following function returns a (not necessarily prime) factor
97 of n, or n if n is prime. Note that this is not necessarily
98 guaranteed to always work perfectly. brent(9) may return 9
99 instead of 3. However, it works well when coupled with trial
100 division in the function prime_factorize_big() below.
101
102 */
103
104 uint64_t mulmod(uint64_t a, uint64_t b, uint64_t m) {
105     uint64_t x = 0, y = a % m;
106     for (; b > 0; b >>= 1) {
107         if (b & 1) x = (x + y) % m;
108         y = (y << 1) % m;
109     }
110     return x % m;
111 }
112
113 //5 calls to rand() is unnecessary if RAND_MAX is 2^31-1
114 uint64_t rand64u() {
115     return ((uint64_t)(rand() & 0xf) << 60) |
116         ((uint64_t)(rand() & 0x7fff) << 45) |
117         ((uint64_t)(rand() & 0x7fff) << 30) |
118         ((uint64_t)(rand() & 0x7fff) << 15) |
119         ((uint64_t)(rand() & 0x7fff));
120 }
121
122 uint64_t gcd(uint64_t a, uint64_t b) {
123     return b == 0 ? a : gcd(b, a % b);
124 }
125
126 long long brent(long long n) {
127     if (n % 2 == 0) return 2;
128     long long y = rand64u() % (n - 1) + 1;
129     long long c = rand64u() % (n - 1) + 1;
130     long long m = rand64u() % (n - 1) + 1;
131     long long g = 1, r = 1, q = 1, ys = 0, hi = 0, x = 0;
132     while (g == 1) {
133         x = y;
134         for (int i = 0; i < r; i++)
135             y = (mulmod(y, y, n) + c) % n;
136         for (long long k = 0; k < r && g == 1; k += m) {
137             ys = y;
138             hi = std::min(m, r - k);
139             for (int j = 0; j < hi; j++) {
140                 y = (mulmod(y, y, n) + c) % n;
141                 q = mulmod(q, x > y ? x - y : y - x, n);
142             }
143             g = gcd(q, n);
144         }
145         r *= 2;
146     }
147     if (g == n) do {
148         ys = (mulmod(ys, ys, n) + c) % n;
149         g = gcd(x > ys ? x - ys : ys - x, n);
150     } while (g <= 1);
151     return g;

```



```

152 }
153
154 /*
155
156 Combines Brent's method with trial division to efficiently
157 generate the prime factorization of large integers.
158
159 Returns a vector of prime divisors that multiply to n.
160 e.g. prime_factorize(15435) => {3, 3, 5, 7, 7, 7}
161     because 3^2 * 5^1 * 7^3 = 15435
162
163 */
164
165 std::vector<long long> prime_factorize_big(long long n) {
166     if (n <= 0) return std::vector<long long>(0);
167     if (n == 1) return std::vector<long long>(1, 1);
168     std::vector<long long> res;
169     for (; n % 2 == 0; n /= 2) res.push_back(2);
170     for (; n % 3 == 0; n /= 3) res.push_back(3);
171     int mx = 1000000; //trial division for factors <= 1M
172     for (int i = 5, w = 2; i <= mx; i += w, w = 6 - w) {
173         for (; n % i == 0; n /= i) res.push_back(i);
174     }
175     for (long long p = 0, p1; n > mx; n /= p1) { //brent
176         for (p1 = n; p1 != p; p1 = brent(p)) p = p1;
177         res.push_back(p1);
178     }
179     if (n != 1) res.push_back(n);
180     sort(res.begin(), res.end());
181     return res;
182 }
183
184 /** Example Usage **/
185
186 #include <cassert>
187 #include <iostream>
188 #include <ctime>
189 using namespace std;
190
191 template<class It> void print(It lo, It hi) {
192     while (lo != hi) cout << *(lo++) << "□";
193     cout << "\n";
194 }
195
196 template<class It> void printp(It lo, It hi) {
197     for (; lo != hi; ++lo)
198         cout << "(" << lo->first << ", " << lo->second << ")□";
199     cout << "\n";
200 }
201
202 int main() {
203     srand(time(0));
204
205     vector< pair<int, int> > v1 = prime_factorize(15435);
206     printp(v1.begin(), v1.end());
207
208     vector<int> v2 = get_all_divisors(28);
209     print(v2.begin(), v2.end());
210

```

```

211     long long n = 100000311*10000003711;
212     assert(fermat(n) == 100000311);
213
214     vector<long long> v3 = prime_factorize_big(n);
215     print(v3.begin(), v3.end());
216
217     return 0;
218 }

```

4.3.5 Euler's Totient Function

```

1  /*
2
3  4.3.5 - Euler's Totient Function
4
5  Euler's totient function (or Euler's phi function) counts
6  the positive integers less than or equal to n that are
7  relatively prime to n. (These integers are sometimes
8  referred to as totatives of n.) Thus, phi(n) is the number
9  of integers k in the range [1, n] for which gcd(n, k) = 1.
10
11  E.g. if n = 9. Then gcd(9, 3) = gcd(9, 6) = 3 and gcd(9, 9)
12  = 9. The other six numbers in the range [1, 9], i.e. 1, 2,
13  4, 5, 7 and 8 are relatively prime to 9. Thus, phi(9) = 6.
14
15  */
16
17  #include <vector>
18
19  int phi(int n) {
20      int res = n;
21      for (int i = 2; i * i <= n; i++)
22          if (n % i == 0) {
23              while (n % i == 0) n /= i;
24              res -= res / i;
25          }
26      if (n > 1) res -= res / n;
27      return res;
28  }
29
30  std::vector<int> phi_table(int n) {
31      std::vector<int> res(n + 1);
32      for (int i = 1; i <= n; i++)
33          res[i] = i;
34      for (int i = 1; i <= n; i++)
35          for (int j = i + i; j <= n; j += i)
36              res[j] -= res[i];
37      return res;
38  }
39
40  /** Example Usage */
41
42  #include <cassert>
43  #include <iostream>
44  using namespace std;
45
46  int main() {

```

```

47  cout << phi(1) << "\n";          //1
48  cout << phi(9) << "\n";          //6
49  cout << phi(1234567) << "\n";    //1224720
50
51  int n = 1000;
52  vector<int> v = phi_table(n);
53  for (int i = 0; i <= n; i++)
54      assert(v[i] == phi(i));
55  return 0;
56 }

```

4.4 Arbitrary Precision Arithmetic

4.4.1 Big Integers (Simple)

```

1  /*
2
3  4.4.1 - Big Integers (Simple)
4
5  Description: Integer arbitrary precision functions.
6  To use, pass bigints to the functions by addresses.
7  e.g. add(&a, &b, &c) stores the sum of a and b into c.
8
9  Complexity: comp(), to_string(), digit_shift(), add(),
10 and sub() are O(N) on the number of digits. mul() and
11 div() are O(N^2). zero_justify() is amortized constant.
12
13 */
14
15 #include <string>
16
17 struct bigint {
18     static const int maxdigits = 1000;
19
20     char dig[maxdigits], sign;
21     int last;
22
23     bigint(long long x = 0): sign(x < 0 ? -1 : 1) {
24         for (int i = 0; i < maxdigits; i++) dig[i] = 0;
25         if (x == 0) { last = 0; return; }
26         if (x < 0) x = -x;
27         for (last = -1; x > 0; x /= 10) dig[++last] = x % 10;
28     }
29
30     bigint(const std::string & s): sign(s[0] == '-' ? -1 : 1) {
31         for (int i = 0; i < maxdigits; i++) dig[i] = 0;
32         last = -1;
33         for (int i = s.size() - 1; i >= 0; i--)
34             dig[++last] = (s[i] - '0');
35         if (dig[last] + '0' == '-') dig[last--] = 0;
36     }
37 };
38
39 void zero_justify(bigint * x) {
40     while (x->last > 0 && !x->dig[x->last]) x->last--;
41     if (x->last == 0 && x->dig[0] == 0) x->sign = 1;

```

```

42 }
43
44 void add(bigint * a, bigint * b, bigint * c);
45 void sub(bigint * a, bigint * b, bigint * c);
46
47 //returns: -1 if a < b, 0 if a == b, or 1 if a > b
48 int comp(bigint * a, bigint * b) {
49     if (a->sign != b->sign) return b->sign;
50     if (b->last > a->last) return a->sign;
51     if (a->last > b->last) return -a->sign;
52     for (int i = a->last; i >= 0; i--) {
53         if (a->dig[i] > b->dig[i]) return -a->sign;
54         if (b->dig[i] > a->dig[i]) return a->sign;
55     }
56     return 0;
57 }
58
59 void add(bigint * a, bigint * b, bigint * c) {
60     if (a->sign != b->sign) {
61         if (a->sign == -1)
62             a->sign = 1, sub(b, a, c), a->sign = -1;
63         else
64             b->sign = 1, sub(a, b, c), b->sign = -1;
65         return;
66     }
67     c->sign = a->sign;
68     c->last = (a->last > b->last ? a->last : b->last) + 1;
69     for (int i = 0, carry = 0; i <= c->last; i++) {
70         c->dig[i] = (carry + a->dig[i] + b->dig[i]) % 10;
71         carry = (carry + a->dig[i] + b->dig[i]) / 10;
72     }
73     zero_justify(c);
74 }
75
76 void sub(bigint * a, bigint * b, bigint * c) {
77     if (a->sign == -1 || b->sign == -1) {
78         b->sign *= -1, add(a, b, c), b->sign *= -1;
79         return;
80     }
81     if (comp(a, b) == 1) {
82         sub(b, a, c), c->sign = -1;
83         return;
84     }
85     c->last = (a->last > b->last) ? a->last : b->last;
86     for (int i = 0, borrow = 0, v; i <= c->last; i++) {
87         v = a->dig[i] - borrow;
88         if (i <= b->last) v -= b->dig[i];
89         if (a->dig[i] > 0) borrow = 0;
90         if (v < 0) v += 10, borrow = 1;
91         c->dig[i] = v % 10;
92     }
93     zero_justify(c);
94 }
95
96 void digit_shift(bigint * x, int n) {
97     if (!x->last && !x->dig[0]) return;
98     for (int i = x->last; i >= 0; i--)
99         x->dig[i + n] = x->dig[i];
100    for (int i = 0; i < n; i++) x->dig[i] = 0;

```

```

101     x->last += n;
102 }
103
104 void mul(bigint * a, bigint * b, bigint * c) {
105     bigint row = *a, tmp;
106     for (int i = 0; i <= b->last; i++) {
107         for (int j = 1; j <= b->dig[i]; j++) {
108             add(c, &row, &tmp);
109             *c = tmp;
110         }
111         digit_shift(&row, 1);
112     }
113     c->sign = a->sign * b->sign;
114     zero_justify(c);
115 }
116
117 void div(bigint * a, bigint * b, bigint * c) {
118     bigint row, tmp;
119     int asign = a->sign, bsign = b->sign;
120     a->sign = b->sign = 1;
121     c->last = a->last;
122     for (int i = a->last; i >= 0; i--) {
123         digit_shift(&row, 1);
124         row.dig[0] = a->dig[i];
125         c->dig[i] = 0;
126         for (; comp(&row, b) != 1; row = tmp) {
127             c->dig[i]++;
128             sub(&row, b, &tmp);
129         }
130     }
131     c->sign = (a->sign = asign) * (b->sign = bsign);
132     zero_justify(c);
133 }
134
135 std::string to_string(bigint * x) {
136     std::string s(x->sign == -1 ? "-" : "");
137     for (int i = x->last; i >= 0; i--)
138         s += (char)('0' + x->dig[i]);
139     return s;
140 }
141
142 /** Example Usage */
143
144 #include <cassert>
145
146 int main() {
147     bigint a("-9899819294989142124"), b("12398124981294214");
148     bigint sum; add(&a, &b, &sum);
149     bigint dif; sub(&a, &b, &dif);
150     bigint prd; mul(&a, &b, &prd);
151     bigint quo; div(&a, &b, &quo);
152     assert(to_string(&sum) == "-9887421170007847910");
153     assert(to_string(&dif) == "-9912217419970436338");
154     assert(to_string(&prd) == "-122739196911503356525379735104870536");
155     assert(to_string(&quo) == "-798");
156     return 0;
157 }

```

4.4.2 Big Integer and Rational Class

```

1  /*
2
3  4.4.2 - Big Integer and Rational Class
4
5  The following bigint class is implemented by storing "chunks"
6  of the big integer in a large base that is a power of 10 so
7  it can be efficiently stored, operated on, and printed.
8
9  It has extensive features including karatsuba multiplication,
10 exponentiation by squaring, and n-th root using binary search.
11 The class is thoroughly templated, so you can use it as
12 easily as you do for normal ints. For example, you may use
13 operators with a bigint and a string (e.g. bigint(1234)+"-567"
14 and the result will be correctly promoted to a bigint that has
15 a value of 667). I/O is done using <iostream>. For example:
16     bigint a, b; cin >> a >> b; cout << a + b << "\n";
17 adds two integers together and prints the result, just as you
18 would expect for a normal int, except with arbitrary precision.
19 The class also supports other streams such as fstream.
20
21 After the bigint class, a class for rational numbers is
22 implemented, using two bigints to store its numerators and
23 denominators. It is useful for when exact results of division
24 operations are needed.
25
26 */
27
28 #include <algorithm> /* std::max(), std::swap() */
29 #include <cmath>     /* sqrt() */
30 #include <cstdlib>    /* rand() */
31 #include <iomanip>    /* std::setw(), std::setfill() */
32 #include <istream>
33 #include <ostream>
34 #include <sstream>
35 #include <stdexcept> /* std::runtime_error() */
36 #include <string>
37 #include <utility>   /* std::pair */
38 #include <vector>
39
40 struct bigint {
41     //base should be a power of 10 for I/O to work
42     //base and base_digits should be consistent
43     static const int base = 1000000000, base_digits = 9;
44
45     typedef std::vector<int> vint;
46     typedef std::vector<long long> vll;
47
48     vint a; //a[0] stores right-most (least significant) base-digit
49     int sign;
50
51     bigint() : sign(1) {}
52     bigint(int v) { *this = (long long)v; }
53     bigint(long long v) { *this = v; }
54     bigint(const std::string & s) { read(s); }
55     bigint(const char * s) { read(std::string(s)); }
56

```

```

57 void trim() {
58     while (!a.empty() && a.back() == 0) a.pop_back();
59     if (a.empty()) sign = 1;
60 }
61
62 void read(const std::string & s) {
63     sign = 1;
64     a.clear();
65     int pos = 0;
66     while (pos < (int)s.size() && (s[pos] == '-' || s[pos] == '+')) {
67         if (s[pos] == '-') sign = -sign;
68         pos++;
69     }
70     for (int i = s.size() - 1; i >= pos; i -= base_digits) {
71         int x = 0;
72         for (int j = std::max(pos, i - base_digits + 1); j <= i; j++)
73             x = x * 10 + s[j] - '0';
74         a.push_back(x);
75     }
76     trim();
77 }
78
79 void operator = (const bigint & v) {
80     sign = v.sign;
81     a = v.a;
82 }
83
84 void operator = (long long v) {
85     sign = 1;
86     if (v < 0) sign = -1, v = -v;
87     a.clear();
88     for (; v > 0; v /= base) a.push_back(v % base);
89 }
90
91 bigint operator + (const bigint & v) const {
92     if (sign == v.sign) {
93         bigint res = v;
94         int carry = 0;
95         for (int i = 0; i < (int)std::max(a.size(), v.a.size()) || carry; i++) {
96             if (i == (int)res.a.size()) res.a.push_back(0);
97             res.a[i] += carry + (i < (int)a.size() ? a[i] : 0);
98             carry = res.a[i] >= base;
99             if (carry) res.a[i] -= base;
100         }
101         return res;
102     }
103     return *this - (-v);
104 }
105
106 bigint operator - (const bigint & v) const {
107     if (sign == v.sign) {
108         if (abs() >= v.abs()) {
109             bigint res(*this);
110             for (int i = 0, carry = 0; i < (int)v.a.size() || carry; i++) {
111                 res.a[i] -= carry + (i < (int)v.a.size() ? v.a[i] : 0);
112                 carry = res.a[i] < 0;
113                 if (carry) res.a[i] += base;
114             }
115             res.trim();

```

```

116         return res;
117     }
118     return -(v - *this);
119 }
120 return *this + (-v);
121 }
122
123 void operator *= (int v) {
124     if (v < 0) sign = -sign, v = -v;
125     for (int i = 0, carry = 0; i < (int)a.size() || carry; i++) {
126         if (i == (int)a.size()) a.push_back(0);
127         long long cur = a[i] * (long long)v + carry;
128         carry = (int)(cur / base);
129         a[i] = (int)(cur % base);
130         //asm("divl %%ecx" : "=a"(carry), "=d"(a[i]) : "A"(cur), "c"(base));
131     }
132     trim();
133 }
134
135 bigint operator * (int v) const {
136     bigint res(*this);
137     res *= v;
138     return res;
139 }
140
141 static vint convert_base(const vint & a, int l1, int l2) {
142     vll p(std::max(l1, l2) + 1);
143     p[0] = 1;
144     for (int i = 1; i < (int)p.size(); i++) p[i] = p[i - 1] * 10;
145     vint res;
146     long long cur = 0;
147     for (int i = 0, cur_digits = 0; i < (int)a.size(); i++) {
148         cur += a[i] * p[cur_digits];
149         cur_digits += l1;
150         while (cur_digits >= l2) {
151             res.push_back((int)(cur % p[l2]));
152             cur /= p[l2];
153             cur_digits -= l2;
154         }
155     }
156     res.push_back((int)cur);
157     while (!res.empty() && res.back() == 0) res.pop_back();
158     return res;
159 }
160
161 //complexity:  $O(3N^{\log_2(3)}) \sim O(3N^{1.585})$ 
162 static vll karatsuba_multiply(const vll & a, const vll & b) {
163     int n = a.size();
164     vll res(n + n);
165     if (n <= 32) {
166         for (int i = 0; i < n; i++)
167             for (int j = 0; j < n; j++)
168                 res[i + j] += a[i] * b[j];
169         return res;
170     }
171     int k = n >> 1;
172     vll a1(a.begin(), a.begin() + k), a2(a.begin() + k, a.end());
173     vll b1(b.begin(), b.begin() + k), b2(b.begin() + k, b.end());
174     vll a1b1 = karatsuba_multiply(a1, b1);

```



```

175     vll a2b2 = karatsuba_multiply(a2, b2);
176     for (int i = 0; i < k; i++) a2[i] += a1[i];
177     for (int i = 0; i < k; i++) b2[i] += b1[i];
178     vll r = karatsuba_multiply(a2, b2);
179     for (int i = 0; i < (int)a1b1.size(); i++) r[i] -= a1b1[i];
180     for (int i = 0; i < (int)a2b2.size(); i++) r[i] -= a2b2[i];
181     for (int i = 0; i < (int)r.size(); i++) res[i + k] += r[i];
182     for (int i = 0; i < (int)a1b1.size(); i++) res[i] += a1b1[i];
183     for (int i = 0; i < (int)a2b2.size(); i++) res[i + n] += a2b2[i];
184     return res;
185 }
186
187 bigint operator * (const bigint & v) const {
188     //if really big values cause overflow, use smaller _base
189     static const int _base = 10000, _base_digits = 4;
190     vint _a = convert_base(this->a, base_digits, _base_digits);
191     vint _b = convert_base(v.a, base_digits, _base_digits);
192     vll a(_a.begin(), _a.end());
193     vll b(_b.begin(), _b.end());
194     while (a.size() < b.size()) a.push_back(0);
195     while (b.size() < a.size()) b.push_back(0);
196     while (a.size() & (a.size() - 1)) {
197         a.push_back(0);
198         b.push_back(0);
199     }
200     vll c = karatsuba_multiply(a, b);
201     bigint res;
202     res.sign = sign * v.sign;
203     for (int i = 0, carry = 0; i < (int)c.size(); i++) {
204         long long cur = c[i] + carry;
205         res.a.push_back((int)(cur % _base));
206         carry = (int)(cur / _base);
207     }
208     res.a = convert_base(res.a, _base_digits, base_digits);
209     res.trim();
210     return res;
211 }
212
213 bigint operator ^ (const bigint & v) const {
214     if (v.sign == -1) return bigint(0);
215     bigint x(*this), n(v), res(1);
216     while (!n.is_zero()) {
217         if (n.a[0] % 2 == 1) res *= x;
218         x *= x;
219         n /= 2;
220     }
221     return res;
222 }
223
224 friend std::pair<bigint, bigint> divmod(const bigint & a1, const bigint & b1) {
225     int norm = base / (b1.a.back() + 1);
226     bigint a = a1.abs() * norm;
227     bigint b = b1.abs() * norm;
228     bigint q, r;
229     q.a.resize(a.a.size());
230     for (int i = a.a.size() - 1; i >= 0; i--) {
231         r *= base;
232         r += a.a[i];
233         int s1 = r.a.size() <= b.a.size() ? 0 : r.a[b.a.size()];

```

```

234     int s2 = r.a.size() <= b.a.size() - 1 ? 0 : r.a[b.a.size() - 1];
235     int d = ((long long)base * s1 + s2) / b.a.back();
236     for (r -= b * d; r < 0; r += b) d--;
237     q.a[i] = d;
238 }
239 q.sign = a1.sign * b1.sign;
240 r.sign = a1.sign;
241 q.trim();
242 r.trim();
243 return std::make_pair(q, r / norm);
244 }
245
246 bigint operator / (const bigint & v) const { return divmod(*this, v).first; }
247 bigint operator % (const bigint & v) const { return divmod(*this, v).second; }
248
249 bigint & operator /= (int v) {
250     if (v < 0) sign = -sign, v = -v;
251     for (int i = a.size() - 1, rem = 0; i >= 0; i--) {
252         long long cur = a[i] + rem * (long long)base;
253         a[i] = (int)(cur / v);
254         rem = (int)(cur % v);
255     }
256     trim();
257     return *this;
258 }
259
260 bigint operator / (int v) const {
261     bigint res(*this);
262     res /= v;
263     return res;
264 }
265
266 int operator % (int v) const {
267     if (v < 0) v = -v;
268     int m = 0;
269     for (int i = a.size() - 1; i >= 0; i--)
270         m = (a[i] + m * (long long)base) % v;
271     return m * sign;
272 }
273
274 bigint operator ++(int) { bigint t(*this); operator++(); return t; }
275 bigint operator --(int) { bigint t(*this); operator--(); return t; }
276 bigint & operator ++() { *this = *this + bigint(1); return *this; }
277 bigint & operator --() { *this = *this - bigint(1); return *this; }
278 bigint & operator += (const bigint & v) { *this = *this + v; return *this; }
279 bigint & operator -= (const bigint & v) { *this = *this - v; return *this; }
280 bigint & operator *= (const bigint & v) { *this = *this * v; return *this; }
281 bigint & operator /= (const bigint & v) { *this = *this / v; return *this; }
282 bigint & operator %= (const bigint & v) { *this = *this % v; return *this; }
283 bigint & operator ^= (const bigint & v) { *this = *this ^ v; return *this; }
284
285 bool operator < (const bigint & v) const {
286     if (sign != v.sign) return sign < v.sign;
287     if (a.size() != v.a.size())
288         return a.size() * sign < v.a.size() * v.sign;
289     for (int i = a.size() - 1; i >= 0; i--)
290         if (a[i] != v.a[i])
291             return a[i] * sign < v.a[i] * v.sign;
292     return false;

```

```

293 }
294
295 bool operator > (const bigint & v) const { return v < *this; }
296 bool operator <= (const bigint & v) const { return !(v < *this); }
297 bool operator >= (const bigint & v) const { return !(*this < v); }
298 bool operator == (const bigint & v) const { return !(*this < v) && !(v < *this); }
299 bool operator != (const bigint & v) const { return *this < v || v < *this; }
300
301 int size() const {
302     if (a.empty()) return 1;
303     std::ostringstream oss;
304     oss << a.back();
305     return oss.str().length() + base_digits*(a.size() - 1);
306 }
307
308 bool is_zero() const {
309     return a.empty() || (a.size() == 1 && !a[0]);
310 }
311
312 bigint operator - () const {
313     bigint res(*this);
314     res.sign = -sign;
315     return res;
316 }
317
318 bigint abs() const {
319     bigint res(*this);
320     res.sign *= res.sign;
321     return res;
322 }
323
324 friend bigint abs(const bigint & a) {
325     return a.abs();
326 }
327
328 friend bigint gcd(const bigint & a, const bigint & b) {
329     return b.is_zero() ? a : gcd(b, a % b);
330 }
331
332 friend bigint lcm(const bigint & a, const bigint & b) {
333     return a / gcd(a, b) * b;
334 }
335
336 friend bigint sqrt(const bigint & x) {
337     bigint a = x;
338     while (a.a.empty() || a.a.size() % 2 == 1) a.a.push_back(0);
339     int n = a.a.size();
340     int firstdig = sqrt((double)a.a[n - 1] * base + a.a[n - 2]);
341     int norm = base / (firstdig + 1);
342     a *= norm;
343     a *= norm;
344     while (a.a.empty() || a.a.size() % 2 == 1) a.a.push_back(0);
345     bigint r = (long long)a.a[n - 1] * base + a.a[n - 2];
346     firstdig = sqrt((double)a.a[n - 1] * base + a.a[n - 2]);
347     int q = firstdig;
348     bigint res;
349     for (int j = n / 2 - 1; j >= 0; j--) {
350         for (; q--;) {
351             bigint r1 = (r - (res * 2 * base + q) * q) * base * base + (j > 0 ?

```

```

352         (long long)a.a[2 * j - 1] * base + a.a[2 * j - 2] : 0);
353     if (r1 >= 0) {
354         r = r1;
355         break;
356     }
357 }
358 res = (res * base) + q;
359 if (j > 0) {
360     int d1 = res.a.size() + 2 < r.a.size() ? r.a[res.a.size() + 2] : 0;
361     int d2 = res.a.size() + 1 < r.a.size() ? r.a[res.a.size() + 1] : 0;
362     int d3 = res.a.size() < r.a.size() ? r.a[res.a.size()] : 0;
363     q = ((long long)d1*base*base + (long long)d2*base + d3)/(firstdig * 2);
364 }
365 }
366 res.trim();
367 return res / norm;
368 }
369
370 friend bigint nthroot(const bigint & x, const bigint & n) {
371     bigint hi = 1;
372     while ((hi ^ n) <= x) hi *= 2;
373     bigint lo = hi / 2, mid, midn;
374     while (lo < hi) {
375         mid = (lo + hi) / 2;
376         midn = mid ^ n;
377         if (lo < mid && midn < x) {
378             lo = mid;
379         } else if (mid < hi && x < midn) {
380             hi = mid;
381         } else {
382             return mid;
383         }
384     }
385     return mid + 1;
386 }
387
388 friend std::istream & operator >> (std::istream & in, bigint & v) {
389     std::string s;
390     in >> s;
391     v.read(s);
392     return in;
393 }
394
395 friend std::ostream & operator << (std::ostream & out, const bigint & v) {
396     if (v.sign == -1) out << '-';
397     out << (v.a.empty() ? 0 : v.a.back());
398     for (int i = v.a.size() - 2; i >= 0; i--)
399         out << std::setw(base_digits) << std::setfill('0') << v.a[i];
400     return out;
401 }
402
403 std::string to_string() const {
404     std::ostringstream oss;
405     if (sign == -1) oss << '-';
406     oss << (a.empty() ? 0 : a.back());
407     for (int i = a.size() - 2; i >= 0; i--)
408         oss << std::setw(base_digits) << std::setfill('0') << a[i];
409     return oss.str();
410 }

```

```

411
412     long long to_llong() const {
413         long long res = 0;
414         for (int i = a.size() - 1; i >= 0; i--)
415             res = res * base + a[i];
416         return res * sign;
417     }
418
419     double to_double() const {
420         std::stringstream ss(to_string());
421         double res;
422         ss >> res;
423         return res;
424     }
425
426     long double to_ldouble() const {
427         std::stringstream ss(to_string());
428         long double res;
429         ss >> res;
430         return res;
431     }
432
433     static bigint rand(int len) {
434         if (len == 0) return bigint(0);
435         std::string s(1, '1' + (::rand() % 9));
436         for (int i = 1; i < len; i++) s += '0' + (::rand() % 10);
437         return bigint(s);
438     }
439 };
440
441 template<class T> bool operator > (const T & a, const bigint & b) { return bigint(a) > b; }
442 template<class T> bool operator < (const T & a, const bigint & b) { return bigint(a) < b; }
443 template<class T> bool operator >= (const T & a, const bigint & b) { return bigint(a) >= b; }
444 template<class T> bool operator <= (const T & a, const bigint & b) { return bigint(a) <= b; }
445 template<class T> bool operator == (const T & a, const bigint & b) { return bigint(a) == b; }
446 template<class T> bool operator != (const T & a, const bigint & b) { return bigint(a) != b; }
447 template<class T> bigint operator + (const T & a, const bigint & b) { return bigint(a) + b; }
448 template<class T> bigint operator - (const T & a, const bigint & b) { return bigint(a) - b; }
449 template<class T> bigint operator ^ (const T & a, const bigint & b) { return bigint(a) ^ b; }
450
451 /*
452
453 Exclude *, /, and % to force a user decision between int and bigint algorithms
454
455 bigint operator * (bigint a, bigint b) vs. bigint operator * (bigint a, int b)
456 bigint operator / (bigint a, bigint b) vs. bigint operator / (bigint a, int b)
457 bigint operator % (bigint a, bigint b) vs. int operator % (bigint a, int b)
458
459 */
460
461 struct rational {
462     bigint num, den;
463
464     rational(): num(0), den(1) {}
465     rational(long long n): num(n), den(1) {}
466     rational(const bigint & n) : num(n), den(1) {}
467
468     template<class T1, class T2>
469     rational(const T1 & n, const T2 & d): num(n), den(d) {

```

```

470     if (den == 0)
471         throw std::runtime_error("Rational_division_by_zero.");
472     if (den < 0) {
473         num = -num;
474         den = -den;
475     }
476     bigint a(num < 0 ? -num : num), b(den), tmp;
477     while (a != 0 && b != 0) {
478         tmp = a % b;
479         a = b;
480         b = tmp;
481     }
482     bigint gcd = (b == 0) ? a : b;
483     num /= gcd;
484     den /= gcd;
485 }
486
487 bool operator < (const rational & r) const {
488     return num * r.den < r.num * den;
489 }
490
491 bool operator > (const rational & r) const {
492     return r.num * den < num * r.den;
493 }
494
495 bool operator <= (const rational & r) const {
496     return !(r < *this);
497 }
498
499 bool operator >= (const rational & r) const {
500     return !(*this < r);
501 }
502
503 bool operator == (const rational & r) const {
504     return num == r.num && den == r.den;
505 }
506
507 bool operator != (const rational & r) const {
508     return num != r.num || den != r.den;
509 }
510
511 rational operator + (const rational & r) const {
512     return rational(num * r.den + r.num * den, den * r.den);
513 }
514
515 rational operator - (const rational & r) const {
516     return rational(num * r.den - r.num * den, r.den * den);
517 }
518
519 rational operator * (const rational & r) const {
520     return rational(num * r.num, r.den * den);
521 }
522
523 rational operator / (const rational & r) const {
524     return rational(num * r.den, den * r.num);
525 }
526
527 rational operator % (const rational & r) const {
528     return *this - r * rational(num * r.den / (r.num * den), 1);

```

```

529 }
530
531 rational operator ^ (const bigint & p) const {
532     return rational(num ^ p, den ^ p);
533 }
534
535 rational operator ++(int) { rational t(*this); operator++(); return t; }
536 rational operator --(int) { rational t(*this); operator--(); return t; }
537 rational & operator ++() { *this = *this + 1; return *this; }
538 rational & operator --() { *this = *this - 1; return *this; }
539 rational & operator += (const rational & r) { *this = *this + r; return *this; }
540 rational & operator -= (const rational & r) { *this = *this - r; return *this; }
541 rational & operator *= (const rational & r) { *this = *this * r; return *this; }
542 rational & operator /= (const rational & r) { *this = *this / r; return *this; }
543 rational & operator %= (const rational & r) { *this = *this % r; return *this; }
544 rational & operator ^= (const bigint & r) { *this = *this ^ r; return *this; }
545
546 rational operator - () const {
547     return rational(-num, den);
548 }
549
550 rational abs() const {
551     return rational(num.abs(), den);
552 }
553
554 long long to_llong() const {
555     return num.to_llong() / den.to_llong();
556 }
557
558 double to_double() const {
559     return num.to_double() / den.to_double();
560 }
561
562 friend rational abs(const rational & r) {
563     return rational(r.num.abs(), r.den);
564 }
565
566 friend std::istream & operator >> (std::istream & in, rational & r) {
567     std::string s;
568     in >> r.num;
569     r.den = 1;
570     return in;
571 }
572
573 friend std::ostream & operator << (std::ostream & out, const rational & r) {
574     out << r.num << "/" << r.den;
575     return out;
576 }
577
578 //rational in range [0, 1] with precision no greater than prec
579 static rational rand(int prec) {
580     rational r(bigint::rand(prec), bigint::rand(prec));
581     if (r.num > r.den) std::swap(r.num, r.den);
582     return r;
583 }
584 };
585
586 template<class T> bool operator > (const T & a, const rational & b) { return rational(a) > b; }
587 template<class T> bool operator < (const T & a, const rational & b) { return rational(a) < b; }

```

```

588 template<class T> bool operator >= (const T & a, const rational & b) { return rational(a) >= b; }
589 template<class T> bool operator <= (const T & a, const rational & b) { return rational(a) <= b; }
590 template<class T> bool operator == (const T & a, const rational & b) { return rational(a) == b; }
591 template<class T> bool operator != (const T & a, const rational & b) { return rational(a) != b; }
592 template<class T> rational operator + (const T & a, const rational & b) { return rational(a) + b; }
593 template<class T> rational operator - (const T & a, const rational & b) { return rational(a) - b; }
594 template<class T> rational operator * (const T & a, const rational & b) { return rational(a) * b; }
595 template<class T> rational operator / (const T & a, const rational & b) { return rational(a) / b; }
596 template<class T> rational operator % (const T & a, const rational & b) { return rational(a) % b; }
597 template<class T> rational operator ^ (const T & a, const rational & b) { return rational(a) ^ b; }
598
599 /** Example Usage */
600
601 #include <cassert>
602 #include <cstdio>
603 #include <ctime>
604 #include <iostream>
605 using namespace std;
606
607 int main() {
608     for (int i = 0; i < 20; i++) {
609         int n = rand() % 100 + 1;
610         bigint a = bigint::rand(n);
611         bigint res = sqrt(a);
612         bigint xx(res * res);
613         bigint yy(res + 1);
614         yy *= yy;
615         assert(xx <= a && yy > a);
616         int m = rand() % n + 1;
617         bigint b = bigint::rand(m) + 1;
618         res = a / b;
619         xx = res * b;
620         yy = b * (res + 1);
621         assert(a >= xx && a < yy);
622     }
623
624     assert("995291497" ==
625         nthroot(bigint("981298591892498189249182998429898124"), 4));
626
627     bigint x(5);
628     x = -6;
629     assert(x.to_llong() == -6ll);
630     assert(x.to_string() == "-6");
631
632     clock_t start;
633
634     start = clock();
635     bigint c = bigint::rand(10000) / bigint::rand(2000);
636     cout << "Div took " << (float)(clock() - start)/CLOCKS_PER_SEC << "s\n";
637
638     start = clock();
639     assert((20^bigint(12345)).size() == 16062);
640     cout << "Pow took " << (float)(clock() - start)/CLOCKS_PER_SEC << "s\n";
641
642     int nn = -21, dd = 2;
643     rational n(nn, 1), d(dd);
644     cout << (nn % dd) << "\n";
645     cout << (n % d) << "\n";
646     cout << fmod(-5.3, -1.7) << "\n";

```



```

647 cout << rational(-53, 10) % rational(-17, 10) << "\n";
648 cout << rational(-53, 10).abs() << "\n";
649 cout << (rational(-53, 10) ^ 20) << "\n";
650 cout << rational::rand(20) << "\n";
651 return 0;
652 }

```

4.4.3 FFT and Multiplication

```

1  /*
2
3  4.4.3 - Fast Fourier Transform and Multiplication
4
5  A discrete Fourier transform (DFT) converts a list of equally
6  spaced samples of a function into the list of coefficients of
7  a finite combination of complex sinusoids, ordered by their
8  frequencies, that has those same sample values. A Fast Fourier
9  Transform (FFT) rapidly computes the DFT by factorizing the
10 DFT matrix into a product of sparse (mostly zero) factors.
11 The FFT can be used to solve problems such as efficiently
12 multiplying big integers or polynomials
13
14 The fft() function below is a generic function that will
15 work well in many applications beyond just multiplying
16 big integers. While Karatsuba multiplication is  $\sim O(n^{1.58})$ ,
17 the complexity of the fft multiplication is only  $O(n \log n)$ .
18
19 Note that mul(string, string) in the following implementation
20 only works for strings of strictly digits from '0' to '9'.
21 It is also easy to adapt this for the bigint class in the
22 previous section. Simply replace the old bigint operator *
23 definition with the following modified version of mul():
24
25 bigint operator * (const bigint & v) const {
26     static const int _base = 10000, _base_digits = 4;
27     vint _a = convert_base(this->a, base_digits, _base_digits);
28     vint _b = convert_base(v.a, base_digits, _base_digits);
29     int len = 32 - __builtin_clz(std::max(_a.size(), _b.size()) - 1);
30     len = 1 << (len + 1);
31     vcd a(len), b(len);
32     for (int i = 0; i < _a.size(); i++) a[i] = cd(_a[i], 0);
33     for (int i = 0; i < _b.size(); i++) b[i] = cd(_b[i], 0);
34     a = fft(a);
35     b = fft(b);
36     for (int i = 0; i < len; i++) {
37         double real = a[i].real() * b[i].real() - a[i].imag() * b[i].imag();
38         a[i].imag() = a[i].imag() * b[i].real() + b[i].imag() * a[i].real();
39         a[i].real() = real;
40     }
41     a = fft(a, true);
42     vll c(len);
43     for (int i = 0; i < len; i++) c[i] = (long long)(a[i].real() + 0.5);
44     bigint res;
45     res.sign = sign * v.sign;
46     for (int i = 0, carry = 0; i < c.size(); i++) {
47         long long cur = c[i] + carry;
48         res.a.push_back((int)(cur % _base));

```

```

49     carry = (int)(cur / _base);
50 }
51 res.a = convert_base(res.a, _base_digits, base_digits);
52 res.trim();
53 return res;
54 }
55
56 */
57
58 #include <algorithm> /* std::max(), std::reverse() */
59 #include <cmath>     /* M_PI, cos(), sin() */
60 #include <complex>
61 #include <iomanip>    /* std::setw(), std::setfill() */
62 #include <sstream>
63 #include <string>
64 #include <vector>
65
66 typedef std::complex<double> cd;
67 typedef std::vector<cd> vcd;
68
69 vcd fft(const vcd & v, bool inverse = false) {
70     static const double PI = acos(-1.0);
71     int n = v.size(), k = 0, high1 = -1;
72     while ((1 << k) < n) k++;
73     std::vector<int> rev(n);
74     rev[0] = 0;
75     for (int i = 1; i < n; i++) {
76         if ((i & (i - 1)) == 0) high1++;
77         rev[i] = rev[i ^ (1 << high1)];
78         rev[i] |= (1 << (k - high1 - 1));
79     }
80     vcd roots(n), res(n);
81     for (int i = 0; i < n; i++) {
82         double alpha = 2 * PI * i / n;
83         roots[i] = cd(cos(alpha), sin(alpha));
84     }
85     for (int i = 0; i < n; i++) res[i] = v[rev[i]];
86     for (int len = 1; len < n; len <= 1) {
87         vcd tmp(n);
88         int rstep = roots.size() / (len * 2);
89         for (int pdest = 0; pdest < n; pdest++) {
90             int p1 = pdest;
91             for (int i = 0; i < len; i++) {
92                 cd val = roots[i * rstep] * res[p1 + len];
93                 tmp[pdest] = res[p1] + val;
94                 tmp[pdest + len] = res[p1] - val;
95                 pdest++, p1++;
96             }
97             pdest += len;
98         }
99         res.swap(tmp);
100     }
101     if (inverse) {
102         for (int i = 0; i < (int)res.size(); i++) res[i] /= v.size();
103         std::reverse(res.begin() + 1, res.end());
104     }
105     return res;
106 }
107

```

```

108 typedef std::vector<long long> vll;
109
110 vll mul(const vll & va, const vll & vb) {
111     int len = 32 - __builtin_clz(std::max(va.size(), vb.size()) - 1);
112     len = 1 << (len + 1);
113     vcd a(len), b(len);
114     for (int i = 0; i < (int)va.size(); i++) a[i] = cd(va[i], 0);
115     for (int i = 0; i < (int)vb.size(); i++) b[i] = cd(vb[i], 0);
116     a = fft(a);
117     b = fft(b);
118     for (int i = 0; i < len; i++) {
119         double real = a[i].real() * b[i].real() - a[i].imag() * b[i].imag();
120         a[i].imag() = a[i].imag() * b[i].real() + b[i].imag() * a[i].real();
121         a[i].real() = real;
122     }
123     a = fft(a, true);
124     vll res(len);
125     for (int i = 0; i < len; i++) res[i] = (long long)(a[i].real() + 0.5);
126     return res;
127 }
128
129 const int base = 10000, base_digits = 4;
130
131 std::string mul(const std::string & as, const std::string & bs) {
132     vll a, b;
133     for (int i = as.size() - 1; i >= 0; i -= base_digits) {
134         int x = 0;
135         for (int j = std::max(0, i - base_digits + 1); j <= i; j++)
136             x = x * 10 + as[j] - '0';
137         a.push_back(x);
138     }
139     for (int i = bs.size() - 1; i >= 0; i -= base_digits) {
140         int x = 0;
141         for (int j = std::max(0, i - base_digits + 1); j <= i; j++)
142             x = x * 10 + bs[j] - '0';
143         b.push_back(x);
144     }
145     vll c = mul(a, b);
146     long long carry = 0;
147     for (int i = 0; i < (int)c.size(); i++) {
148         c[i] += carry;
149         carry = c[i] / base;
150         c[i] %= base;
151     }
152     while (c.back() == 0) c.pop_back();
153     if (c.empty()) c.push_back(0);
154     std::ostringstream oss;
155     oss << (c.empty() ? 0 : c.back());
156     for (int i = c.size() - 2; i >= 0; i--)
157         oss << std::setw(base_digits) << std::setfill('0') << c[i];
158     return oss.str();
159 }
160
161 /** Example Usage */
162
163 #include <cassert>
164
165 int main() {
166     assert(mul("98904189", "244212") == "24153589804068");

```

```

167     return 0;
168 }

```

4.5 Linear Algebra

4.5.1 Matrix Class

```

1  /*
2
3  4.5.1 - Matrix Class
4
5  Basic matrix class with support for arithmetic operations
6  as well as matrix multiplication and exponentiation. You
7  can access/modify indices using m(r, c) or m[r][c]. You
8  can also treat it as a 2d vector, since the cast operator
9  to a reference to its internal 2d vector is defined. This
10 makes it compatible with the 2d vector functions such as
11 det() and lu_decompose() in later sections.
12
13 */
14
15 #include <ostream>
16 #include <stdexcept> /* std::runtime_error() */
17 #include <vector>
18
19 template<class val_t> class matrix {
20     int r, c;
21     std::vector<std::vector<val_t> > mat;
22
23 public:
24     matrix(int rows, int cols, val_t init = val_t()) {
25         r = rows;
26         c = cols;
27         mat.resize(r, std::vector<val_t>(c, init));
28     }
29
30     matrix(const std::vector<std::vector<val_t> > & m) {
31         r = m.size();
32         c = m[0].size();
33         mat = m;
34         mat.resize(r, std::vector<val_t>(c));
35     }
36
37     template<size_t rows, size_t cols>
38     matrix(val_t (&init)[rows][cols]) {
39         r = rows;
40         c = cols;
41         mat.resize(r, std::vector<val_t>(c));
42         for (int i = 0; i < r; i++)
43             for (int j = 0; j < c; j++)
44                 mat[i][j] = init[i][j];
45     }
46
47     operator std::vector<std::vector<val_t> > &() { return mat; }
48     val_t & operator() (int r, int c) { return mat[r][c]; }
49     std::vector<val_t> & operator[] (int r) { return mat[r]; }

```

```

50  val_t at(int r, int c) const { return mat[r][c]; }
51  int rows() const { return r; }
52  int cols() const { return c; }
53
54  friend bool operator < (const matrix & a, const matrix & b) { return a.mat < b.mat; }
55  friend bool operator > (const matrix & a, const matrix & b) { return a.mat > b.mat; }
56  friend bool operator <= (const matrix & a, const matrix & b) { return a.mat <= b.mat; }
57  friend bool operator >= (const matrix & a, const matrix & b) { return a.mat >= b.mat; }
58  friend bool operator == (const matrix & a, const matrix & b) { return a.mat == b.mat; }
59  friend bool operator != (const matrix & a, const matrix & b) { return a.mat != b.mat; }
60
61  friend matrix operator + (const matrix & a, const matrix & b) {
62      if (a.r != b.r || a.c != b.c)
63          throw std::runtime_error("Matrix_dimensions_don't_match.");
64      matrix res(a);
65      for (int i = 0; i < res.r; i++)
66          for (int j = 0; j < res.c; j++)
67              res.mat[i][j] += b.mat[i][j];
68      return res;
69  }
70
71  friend matrix operator - (const matrix & a, const matrix & b) {
72      if (a.r != b.r || a.c != b.c)
73          throw std::runtime_error("Matrix_dimensions_don't_match.");
74      matrix res(a);
75      for (int i = 0; i < a.r; i++)
76          for (int j = 0; j < a.c; j++)
77              res.mat[i][j] -= b.mat[i][j];
78      return res;
79  }
80
81  friend matrix operator * (const matrix & a, const matrix & b) {
82      if (a.c != b.r)
83          throw std::runtime_error("#_of_a_cols_must_equal_#_of_b_rows.");
84      matrix res(a.r, b.c, 0);
85      for (int i = 0; i < a.r; i++)
86          for (int j = 0; j < b.c; j++)
87              for (int k = 0; k < a.c; k++)
88                  res.mat[i][j] += a.mat[i][k] * b.mat[k][j];
89      return res;
90  }
91
92  friend matrix operator + (const matrix & a, const val_t & v) {
93      matrix res(a);
94      for (int i = 0; i < a.r; i++)
95          for (int j = 0; j < a.c; j++) res.mat[i][j] += v;
96      return res;
97  }
98
99  friend matrix operator - (const matrix & a, const val_t & v) {
100      matrix res(a);
101      for (int i = 0; i < a.r; i++)
102          for (int j = 0; j < a.c; j++) res.mat[i][j] -= v;
103      return res;
104  }
105
106  friend matrix operator * (const matrix & a, const val_t & v) {
107      matrix res(a);
108      for (int i = 0; i < a.r; i++)

```

```

109     for (int j = 0; j < a.c; j++) res.mat[i][j] *= v;
110     return res;
111 }
112
113 friend matrix operator / (const matrix & a, const val_t & v) {
114     matrix res(a);
115     for (int i = 0; i < a.r; i++)
116         for (int j = 0; j < a.c; j++)
117             res.mat[i][j] /= v;
118     return res;
119 }
120
121 //raise matrix to the n-th power. precondition: a must be a square matrix
122 friend matrix operator ^ (const matrix & a, unsigned int n) {
123     if (a.r != a.c)
124         throw std::runtime_error("Matrix must be square for exponentiation.");
125     if (n == 0) return identity_matrix(a.r);
126     if (n % 2 == 0) return (a * a) ^ (n / 2);
127     return a * (a ^ (n - 1));
128 }
129
130 //returns a^1 + a^2 + ... + a^n
131 friend matrix powsum(const matrix & a, unsigned int n) {
132     if (n == 0) return matrix(a.r, a.r);
133     if (n % 2 == 0)
134         return powsum(a, n / 2) * (identity_matrix(a.r) + (a ^ (n / 2)));
135     return a + a * powsum(a, n - 1);
136 }
137
138 matrix & operator += (const matrix & m) { *this = *this + m; return *this; }
139 matrix & operator -= (const matrix & m) { *this = *this - m; return *this; }
140 matrix & operator *= (const matrix & m) { *this = *this * m; return *this; }
141 matrix & operator += (const val_t & v) { *this = *this + v; return *this; }
142 matrix & operator -= (const val_t & v) { *this = *this - v; return *this; }
143 matrix & operator *= (const val_t & v) { *this = *this * v; return *this; }
144 matrix & operator /= (const val_t & v) { *this = *this / v; return *this; }
145 matrix & operator ^= (unsigned int n) { *this = *this ^ n; return *this; }
146
147 static matrix identity_matrix(int n) {
148     matrix res(n, n);
149     for (int i = 0; i < n; i++) res[i][i] = 1;
150     return res;
151 }
152
153 friend std::ostream & operator << (std::ostream & out, const matrix & m) {
154     out << "[";
155     for (int i = 0; i < m.r; i++) {
156         out << (i > 0 ? ", [" : "[";
157         for (int j = 0; j < m.c; j++)
158             out << (j > 0 ? ", " : "") << m.mat[i][j];
159         out << "]";
160     }
161     out << "]";
162     return out;
163 }
164 };
165
166 /** Example Usage */
167

```

```

168 #include <cassert>
169 #include <iostream>
170 using namespace std;
171
172 int main() {
173     int a[2][2] = {{1,8}, {5,9}};
174     matrix<int> m(5, 5, 10), m2(a);
175     m += 10;
176     m[0][0] += 10;
177     assert(m[0][0] == 30 && m[1][1] == 20);
178     assert(powsum(m2, 3) == m2 + m2*m2 + (m2^3));
179     return 0;
180 }

```

4.5.2 Determinant (Gauss)

```

1  /*
2
3  4.5.2 - Determinant (Gauss's Method)
4
5  The following are ways to compute the determinant of a
6  matrix directly using Gaussian elimination. See the
7  following section for a generalized solution using LU
8  decompositions. Since the determinant can get very large,
9  look out for overflows and floating-point inaccuracies.
10 Bignums are recommended for maximal correctness.
11
12 Complexity:  $O(N^3)$ , except for the adjustment for
13 overflow in the integer det() function.
14
15 Precondition: All input matrices must be square.
16
17 */
18
19 #include <algorithm> /* std::swap() */
20 #include <cassert>
21 #include <cmath>     /* fabs() */
22 #include <map>
23 #include <vector>
24
25 static const double eps = 1e-10;
26 typedef std::vector<std::vector<int> > vvi;
27 typedef std::vector<std::vector<double> > vvd;
28
29 double det(vvd a) {
30     int n = a.size();
31     assert(!a.empty() && n == (int)a[0].size());
32     double res = 1;
33     std::vector<bool> used(n, false);
34     for (int i = 0; i < n; i++) {
35         int p;
36         for (p = 0; p < n; p++)
37             if (!used[p] && fabs(a[p][i]) > eps)
38                 break;
39         if (p >= n) return 0;
40         res *= a[p][i];
41         used[p] = true;

```

```

42     double z = 1 / a[p][i];
43     for (int j = 0; j < n; j++) a[p][j] *= z;
44     for (int j = 0; j < n; j++) {
45         if (j == p) continue;
46         z = a[j][i];
47         for (int k = 0; k < n; k++)
48             a[j][k] -= z * a[p][k];
49     }
50 }
51 return res;
52 }
53
54 /*
55
56 Determinant of Integer Matrix
57
58 This is prone to overflow, so it is recommended you use your
59 own bigint class instead of long long. At the end of this
60 function, the final answer is found as a product of powers.
61 You have two choices: change the "#if 0" to "#if 1" and use
62 the naive method to compute this product and risk overflow,
63 or keep it as "#if 0" and try to make the situation better
64 through prime factorization (less efficient). Note that
65 even in the prime factorization method, overflow may happen
66 if the final answer is too big for a long long.
67
68 */
69
70 //C++98 doesn't have an abs() for long long
71 template<class T> inline T _abs(const T & x) {
72     return x < 0 ? -x : x;
73 }
74
75 long long det(const vvi & a) {
76     int n = a.size();
77     assert(!a.empty() && n == (int)a[0].size());
78     long long b[n][n], det = 1;
79     for (int i = 0; i < n; i++)
80         for (int j = 0; j < n; j++) b[i][j] = a[i][j];
81     int sign = 1, exponent[n];
82     for (int i = 0; i < n; i++) {
83         exponent[i] = 0;
84         int k = i;
85         for (int j = i + 1; j < n; j++) {
86             if (b[k][i] == 0 || (b[j][i] != 0 && _abs(b[k][i]) > _abs(b[j][i])))
87                 k = j;
88         }
89         if (b[k][i] == 0) return 0;
90         if (i != k) {
91             sign = -sign;
92             for (int j = 0; j < n; j++)
93                 std::swap(b[i][j], b[k][j]);
94         }
95         exponent[i]++;
96         for (int j = i + 1; j < n; j++)
97             if (b[j][i] != 0) {
98                 for (int p = i + 1; p < n; ++p)
99                     b[j][p] = b[j][p] * b[i][i] - b[i][p] * b[j][i];
100                 exponent[i]--;

```



```

101     }
102 }
103
104 #if 0
105     for (int i = 0; i < n; i++)
106         for (; exponent[i] > 0; exponent[i]--)
107             det *= b[i][i];
108     for (int i = 0; i < n; i++)
109         for (; exponent[i] < 0; exponent[i]++)
110             det /= b[i][i];
111 #else
112     std::map<long long, int> m;
113     for (int i = 0; i < n; i++) {
114         long long x = b[i][i];
115         for (long long d = 2; ; d++) {
116             long long power = 0, quo = x / d, rem = x - quo * d;
117             if (d > quo || (d == quo && rem > 0)) break;
118             for (; rem == 0; rem = x - quo * d) {
119                 power++;
120                 x = quo;
121                 quo = x / d;
122             }
123             if (power > 0) m[d] += power * exponent[i];
124         }
125         if (x > 1) m[x] += exponent[i];
126     }
127     std::map<long long, int>::iterator it;
128     for (it = m.begin(); it != m.end(); ++it)
129         for (int i = 0; i < it->second; i++)
130             det *= it->first;
131 #endif
132
133     return sign < 0 ? -det : det;
134 }
135
136 /** Example Usage */
137
138 #include <iostream>
139 using namespace std;
140
141 int main() {
142     const int n = 3;
143     int a[n][n] = {{6,1,1},{4,-2,5},{2,8,7}};
144     vvi v1(n);
145     vvd v2(n);
146     for (int i = 0; i < n; i++) {
147         v1[i] = vector<int>(a[i], a[i] + n);
148         v2[i] = vector<double>(a[i], a[i] + n);
149     }
150     int d1 = det(v1);
151     int d2 = (int)det(v2);
152     assert(d1 == d2 && d2 == -306);
153     return 0;
154 }

```

4.5.3 Gaussian Elimination

```

1  /*
2
3  4.5.3 - System Solver (Gaussian Elimination)
4
5  Given a system of m linear equations with n unknowns:
6
7  A(1,1)*x(1) + A(1,2)*x(2) + ... + A(1,n)*x(n) = B(1)
8  A(2,1)*x(1) + A(2,2)*x(2) + ... + A(2,n)*x(n) = B(2)
9      ...
10 A(m,1)*x(1) + A(m,2)*x(2) + ... + A(m,n)*x(n) = B(m)
11
12 For any system of linear equations, there will either
13 be no solution (in 2d, lines are parallel), a single
14 solution (in 2d, the lines intersect at a point), or
15 or infinite solutions (in 2d, lines are the same).
16
17 Using Gaussian elimination in O(n^3), this program
18 solves for the values of x(1) ... x(n) or determines
19 that no unique solution of x() exists. Note that
20 the implementation below uses 0-based indices.
21
22 */
23
24 #include <algorithm> /* std::swap() */
25 #include <cmath>     /* fabs() */
26 #include <vector>
27
28 const double eps = 1e-9;
29 typedef std::vector<double> vd;
30 typedef std::vector<vd> vvd;
31
32 //note: A[i][n] stores B[i]
33 //if no unique solution found, returns empty vector
34 vd solve_system(vvd A) {
35     int m = A.size(), n = A[0].size() - 1;
36     vd x(n);
37     if (n > m) goto fail;
38     for (int k = 0; k < n; k++) {
39         double mv = 0;
40         int mi = -1;
41         for (int i = k; i < m; i++)
42             if (mv < fabs(A[i][k])) {
43                 mv = fabs(A[i][k]);
44                 mi = i;
45             }
46         if (mv < eps) goto fail;
47         for (int i = 0; i <= n; i++)
48             std::swap(A[mi][i], A[k][i]);
49         for (int i = k + 1; i < m; i++) {
50             double v = A[i][k] / A[k][k];
51             for (int j = k; j <= n; j++)
52                 A[i][j] -= v * A[k][j];
53             A[i][k] = 0;
54         }
55     }
56     for (int i = n; i < m; i++)
57         if (fabs(A[i][n]) > eps) goto fail;
58     for (int i = n - 1; i >= 0; i--) {
59         if (fabs(A[i][i]) < eps) goto fail;

```

```

60     double v = 0;
61     for (int j = i + 1; j < n; j++)
62         v += A[i][j] * x[j];
63     v = A[i][n] - v;
64     x[i] = v / A[i][i];
65 }
66 return x;
67 fail:
68     return vd();
69 }
70
71 /** Example Usage (wcipeg.com/problem/syssolve) */
72
73 #include <iostream>
74 using namespace std;
75
76 int main() {
77     int n, m;
78     cin >> n >> m;
79     vvd a(m, vd(n + 1));
80     for (int i = 0; i < m; i++)
81         for (int j = 0; j <= n; j++)
82             cin >> a[i][j];
83     vd x = solve_system(a);
84     if (x.empty()) {
85         cout << "NO_UNIQUE_SOLUTION\n";
86     } else {
87         cout.precision(6);
88         for (int i = 0; i < n; i++)
89             cout << fixed << x[i] << "\n";
90     }
91     return 0;
92 }

```

4.5.4 LU Decomposition

```

1  /*
2
3  4.5.4 - LU Decomposition
4
5  The LU (lower upper) decomposition of a matrix is a factorization
6  of a matrix as the product of a lower triangular matrix and an
7  upper triangular matrix. With the LU decomposition, we can solve
8  many problems, including the determinant of the matrix, a systems
9  of linear equations, and the inverse of a matrix.
10
11 Note: in the following implementation, each call to det(),
12 solve_system(), and inverse() recomputes the lu decomposition.
13 For the same matrix, you should precompute the lu decomposition
14 and reuse it for several of these operations afterwards.
15
16 Complexity:  $O(n^3)$  for lu_decompose(). det() uses the running time
17 of lu_decompose(), plus an addition  $O(n)$  term. solve_system() and
18 inverse() both have the running time of lu_decompose(), plus an
19 additional  $O(n^3)$  term.
20
21 */

```

```

22
23 #include <algorithm> /* std::swap() */
24 #include <cassert>
25 #include <cmath> /* fabs() */
26 #include <vector>
27
28 static const double eps = 1e-10;
29 typedef std::vector<double> vd;
30 typedef std::vector<vd> vvd;
31
32 /*
33
34 LU decomposition with Gauss-Jordan elimination. This is generalized
35 for rectangular matrices. Since the resulting L and U matrices have
36 all mutually exclusive 0's (except when i == j), we can merge them
37 into a single LU matrix to save memory. Note: l[i][i] = 1 for all i.
38
39 Optionally determine the permutation vector p. If an array p is
40 passed, p[i] will be populated such that p[i] is the only column of
41 the i-th row of the permutation matrix that is equal to 1.
42
43 Returns: a matrix m, the merged lower/upper triangular matrix:
44         m[i][j] = l[i][j] (for i > j) or u[i][j] (for i <= j)
45
46 */
47
48 vvd lu_decompose(vvd a, int * detsign = 0, int * p = 0) {
49     int n = a.size(), m = a[0].size();
50     int sign = 1;
51     if (p != 0)
52         for (int i = 0; i < n; i++) p[i] = i;
53     for (int r = 0, c = 0; r < n && c < m; r++, c++) {
54         int pr = r;
55         for (int i = r + 1; i < n; i++)
56             if (fabs(a[i][c]) > fabs(a[pr][c]))
57                 pr = i;
58         if (fabs(a[pr][c]) <= eps) {
59             r--;
60             continue;
61         }
62         if (pr != r) {
63             if (p != 0) std::swap(p[r], p[pr]);
64             sign = -sign;
65             for (int i = 0; i < m; i++)
66                 std::swap(a[r][i], a[pr][i]);
67         }
68         for (int s = r + 1; s < n; s++) {
69             a[s][c] /= a[r][c];
70             for (int d = c + 1; d < m; d++)
71                 a[s][d] -= a[s][c] * a[r][d];
72         }
73     }
74     if (detsign != 0) *detsign = sign;
75     return a;
76 }
77
78 double getl(const vvd & lu, int i, int j) {
79     if (i > j) return lu[i][j];
80     return i < j ? 0.0 : 1.0;

```

```

81 }
82
83 double getu(const vvd & lu, int i, int j) {
84     return i <= j ? lu[i][j] : 0.0;
85 }
86
87 //Precondition: A is square matrix.
88 double det(const vvd & a) {
89     int n = a.size(), detsign;
90     assert(!a.empty() && n == (int)a[0].size());
91     vvd lu = lu_decompose(a, &detsign);
92     double det = 1;
93     for (int i = 0; i < n; i++)
94         det *= lu[i][i];
95     return detsign < 0 ? -det : det;
96 }
97
98 /*
99
100 Solves system of linear equations with forward/backwards
101 substitution. Precondition: A must be n*n and B must be n*m.
102 Returns: an n by m matrix X such that A*X = B.
103
104 */
105
106 vvd solve_system(const vvd & a, const vvd & b) {
107     int n = b.size(), m = b[0].size();
108     assert(!a.empty() && n == (int)a.size() && n == (int)a[0].size());
109     int detsign, p[a.size()];
110     vvd lu = lu_decompose(a, &detsign, p);
111     //forward substitute for Y in L*Y = B
112     vvd y(n, vd(m));
113     for (int j = 0; j < m; j++) {
114         y[0][j] = b[p[0]][j] / getl(lu, 0, 0);
115         for (int i = 1; i < n; i++) {
116             double s = 0;
117             for (int k = 0; k < i; k++)
118                 s += getl(lu, i, k) * y[k][j];
119             y[i][j] = (b[p[i]][j] - s) / getl(lu, i, i);
120         }
121     }
122     //backward substitute for X in U*X = Y
123     vvd x(n, vd(m));
124     for (int j = 0; j < m; j++) {
125         x[n - 1][j] = y[n - 1][j] / getu(lu, n - 1, n - 1);
126         for (int i = n - 2; i >= 0; i--) {
127             double s = 0;
128             for (int k = i + 1; k < n; k++)
129                 s += getu(lu, i, k) * x[k][j];
130             x[i][j] = (y[i][j] - s) / getu(lu, i, i);
131         }
132     }
133     return x;
134 }
135
136 /*
137
138 Find the inverse A^-1 of a matrix A. The inverse of a matrix
139 satisfies A * A^-1 = I, where I is the identity matrix (for

```

```

140 all pairs (i, j), I[i][j] = 1 iff i = j, else I[i][j] = 0).
141 The inverse of a matrix exists if and only if det(a) is not 0.
142 We're lazy, so we just generate I and call solve_system().
143
144 Precondition: A is a square and det(A) != 0.
145
146 */
147
148 vvd inverse(const vvd & a) {
149     int n = a.size();
150     assert(!a.empty() && n == (int)a[0].size());
151     vvd I(n, vd(n));
152     for (int i = 0; i < n; i++) I[i][i] = 1;
153     return solve_system(a, I);
154 }
155
156 /** Example Usage */
157
158 #include <cstdio>
159 #include <iostream>
160 using namespace std;
161
162 void print(const vvd & m) {
163     cout << "[";
164     for (int i = 0; i < (int)m.size(); i++) {
165         cout << (i > 0 ? ",[" : "[";
166         for (int j = 0; j < (int)m[0].size(); j++)
167             cout << (j > 0 ? ", " : "") << m[i][j];
168         cout << "]";
169     }
170     cout << "]\n";
171 }
172
173 void printlu(const vvd & lu) {
174     printf("L:\n");
175     for (int i = 0; i < (int)lu.size(); i++) {
176         for (int j = 0; j < (int)lu[0].size(); j++)
177             printf("%10.5f", getl(lu, i, j));
178         printf("\n");
179     }
180     printf("U:\n");
181     for (int i = 0; i < (int)lu.size(); i++) {
182         for (int j = 0; j < (int)lu[0].size(); j++)
183             printf("%10.5f", getu(lu, i, j));
184         printf("\n");
185     }
186 }
187
188 int main() {
189     { //determinant of 3x3
190         const int n = 3;
191         double a[n][n] = {{1,3,5},{2,4,7},{1,1,0}};
192         vvd v(n);
193         for (int i = 0; i < n; i++)
194             v[i] = vector<double>(a[i], a[i] + n);
195         printlu(lu_decompose(v));
196         cout << "determinant:" << det(v) << "\n"; //4
197     }
198 }

```

```

199 { //determinant of 4x4
200     const int n = 4;
201     double a[n][n] = {{11,9,24,2},{1,5,2,6},{3,17,18,1},{2,5,7,1}};
202     vvd v(n);
203     for (int i = 0; i < n; i++)
204         v[i] = vector<double>(a[i], a[i] + n);
205     printlu(lu_decompose(v));
206     cout << "determinant:_" << det(v) << "\n"; //284
207 }
208
209 { //solve for [x, y] in x + 3y = 4 && 2x + 3y = 6
210     const int n = 2;
211     double a[n][n] = {{1,3},{2,3}};
212     double b[n] = {4, 6};
213     vvd va(n), vb(n);
214     for (int i = 0; i < n; i++) {
215         va[i] = vector<double>(a[i], a[i] + n);
216         vb[i] = vector<double>(1, b[i]);
217     }
218     vvd x = solve_system(va, vb);
219     for (int i = 0; i < n; i++) {
220         assert(fabs(a[i][0]*x[0][0] + a[i][1]*x[1][0] - b[i]) < eps);
221     }
222 }
223
224 { //find inverse by solving a system
225     const int n = 2;
226     double a[n][n] = {{2,3},{1,2}};
227     vvd v(n);
228     for (int i = 0; i < n; i++)
229         v[i] = vector<double>(a[i], a[i] + n);
230     print(inverse(v)); //[[2,-3],[-1,2]]
231 }
232 return 0;
233 }

```

4.5.5 Simplex Algorithm

```

1  /*
2
3  4.5.5 - Linear Programming using Simplex Algorithm
4
5  Description: The canonical form of a linear programming
6  problem is to maximize  $c^T x$ , subject to  $Ax \leq b$ , and  $x \geq 0$ .
7  where  $x$  is the vector of variables (to be solved),  $c$  and  $b$ 
8  are vectors of (known) coefficients,  $A$  is a (known) matrix of
9  coefficients, and  $(.)^T$  is the matrix transpose. The following
10 implementation solves  $n$  variables in a system of  $m$  constraints.
11
12 Precondition:  $ab$  has dimensions  $m$  by  $n+1$  and  $c$  has length  $n+1$ .
13
14 Complexity: The simplex method is remarkably efficient in
15 practice, usually taking  $2m$  or  $3m$  iterations, converging in
16 expected polynomial time for certain distributions of random
17 inputs. However, its worst-case complexity is exponential,
18 and can be demonstrated with carefully constructed examples.
19

```

```

20 */
21
22 #include <algorithm> /* std::swap() */
23 #include <cfloat> /* DBL_MAX */
24 #include <cmath> /* fabs() */
25 #include <vector>
26
27 typedef std::vector<double> vd;
28 typedef std::vector<vd> vvd;
29
30 //ab[i][0..n-1] stores A and ab[i][n] stores B
31 vd simplex(const vvd & ab, const vd & c, bool max = true) {
32     const double eps = 1e-10;
33     int n = c.size() - 1, m = ab.size();
34     vvd ts(m + 2, vd(n + 2));
35     ts[1][1] = max ? c[n] : -c[n];
36     for (int j = 1; j <= n; j++)
37         ts[1][j + 1] = max ? c[j - 1] : -c[j - 1];
38     for (int i = 1; i <= m; i++) {
39         for (int j = 1; j <= n; j++)
40             ts[i + 1][j + 1] = -ab[i - 1][j - 1];
41         ts[i + 1][1] = ab[i - 1][n];
42     }
43     for (int j = 1; j <= n; j++)
44         ts[0][j + 1] = j;
45     for (int i = n + 1; i <= n + m; i++)
46         ts[i - n + 1][0] = i;
47     double p1 = 0.0, p2 = 0.0;
48     bool done = true;
49     do {
50         double mn = DBL_MAX, xmax = 0.0, v;
51         for (int j = 2; j <= n + 1; j++)
52             if (ts[1][j] > 0.0 && ts[1][j] > xmax) {
53                 p2 = j;
54                 xmax = ts[1][j];
55             }
56         for (int i = 2; i <= m + 1; i++) {
57             v = fabs(ts[i][1] / ts[i][p2]);
58             if (ts[i][p2] < 0.0 && mn > v) {
59                 mn = v;
60                 p1 = i;
61             }
62         }
63         std::swap(ts[p1][0], ts[0][p2]);
64         for (int i = 1; i <= m + 1; i++) {
65             if (i == p1) continue;
66             for (int j = 1; j <= n + 1; j++)
67                 if (j != p2)
68                     ts[i][j] -= ts[p1][j] * ts[i][p2] / ts[p1][p2];
69         }
70         ts[p1][p2] = 1.0 / ts[p1][p2];
71         for (int j = 1; j <= n + 1; j++) {
72             if (j != p2)
73                 ts[p1][j] *= fabs(ts[p1][p2]);
74         }
75         for (int i = 1; i <= m + 1; i++) {
76             if (i != p1)
77                 ts[i][p2] *= ts[p1][p2];
78         }
79     }

```



```

79     for (int i = 2; i <= m + 1; i++)
80         if (ts[i][1] < 0.0) return vd(); //no solution
81     done = true;
82     for (int j = 2; j <= n + 1; j++)
83         if (ts[i][j] > 0) done = false;
84 } while (!done);
85 vd res;
86 for (int i = 1; i <= n; i++)
87     for (int j = 2; j <= m + 1; j++)
88         if (fabs(ts[j][0] - i) <= eps)
89             res.push_back(ts[j][1]);
90 //the solution is stored in ts[1][1]
91 return res;
92 }
93
94 /** Example Usage */
95
96 #include <iostream>
97 using namespace std;
98
99 /*
100  Maximize 3x + 4y + 5, subject to x, y >= 0 and:
101      -2x +    1y <=  0
102       1x + 0.85y <=  9
103       1x +    2y <= 14
104
105  Note: The solution is 38.3043 at (5.30435, 4.34783).
106  */
107
108 int main() {
109     const int n = 2, m = 3;
110     double ab[m][n + 1] = {{-2, 1, 0}, {1, 0.85, 9}, {1, 2, 14}};
111     double c[n + 1] = {3, 4, 5};
112     vvd vab(m, vd(n + 1));
113     vd vc(c, c + n + 1);
114     for (int i = 0; i < m; i++) {
115         for (int j = 0; j <= n; j++)
116             vab[i][j] = ab[i][j];
117     }
118     vd x = simplex(vab, vc);
119     if (x.empty()) {
120         cout << "No solution.\n";
121     } else {
122         double solval = c[n];
123         for (int i = 0; i < (int)x.size(); i++)
124             solval += c[i] * x[i];
125         cout << "Solution = " << solval;
126         cout << " at (" << x[0];
127         for (int i = 1; i < (int)x.size(); i++)
128             cout << ", " << x[i];
129         cout << ").\n";
130     }
131     return 0;
132 }

```

4.6 Root-Finding

4.6.1 Real Root Finding (Differentiation)

```

1  /*
2
3  4.6.1 - Real Root Finding (Differentiation)
4
5  Real roots can be found via binary searching, a.k.a the bisection
6  method. If two x-coordinates evaluate to y-coordinates that have
7  opposite signs, a root must exist between them. For a polynomial
8  function, at most 1 root lies between adjacent local extrema.
9  Since local extrema exist where the derivative equals 0, we can
10 break root-finding into the subproblem of finding the roots of
11 the derivative. Recursively solve for local extrema until we get
12 to a base case of degree 0. For each set of local extrema found,
13 binary search between pairs of extrema for a root. This method is
14 easy, robust, and allows us to find the root to an arbitrary level
15 of accuracy. We're limited only by the precision of the arithmetic.
16
17 Complexity: For a degree N polynomial, repeatedly differentiating
18 it will take  $N + (N-1) + \dots + 1 = O(N^2)$  operations. At each step
19 we binary search the number of times equal to the current degree.
20 If we want to make roots precise to  $\text{eps}=10^{-P}$ , each binary search
21 will take  $O(\log P)$ . Thus the overall complexity is  $O(N^2 \log P)$ .
22
23 */
24
25 #include <cmath>    /* fabs(), powl() */
26 #include <limits>   /* std::numeric_limits<>::quiet_NaN() */
27 #include <utility>  /* std::pair<> */
28 #include <vector>
29
30 typedef long double Double;
31 typedef std::vector<std::pair<Double, int> > poly;
32
33 const Double epsa = 1e-11; //required precision of roots in absolute error
34 const Double epsr = 1e-15; //required precision of roots in relative error
35 const Double eps0 = 1e-17; //x is considered a root if fabs(eval(x))<=eps0
36 const Double inf = 1e20;   //[-inf, inf] is the range of roots to consider
37 const Double NaN = std::numeric_limits<Double>::quiet_NaN();
38
39 Double eval(const poly & p, Double x) {
40     Double res = 0;
41     for (int i = 0; i < (int)p.size(); i++)
42         res += p[i].first * powl(x, p[i].second);
43     return res;
44 }
45
46 Double find_root(const poly & p, Double x1, Double x2) {
47     Double y1 = eval(p, x1), y2 = eval(p, x2);
48     if (fabs(y1) <= eps0) return x1;
49     bool neg1 = (y1 < 0), neg2 = (y2 < 0);
50     if (fabs(y2) <= eps0 || neg1 == neg2) return NaN;
51     while (x2 - x1 > epsa && x1 * (1 + epsr) < x2 && x2 * (1 + epsr) > x1) {
52         Double x = (x1 + x2) / 2;
53         ((eval(p, x) < 0) == neg1 ? x1 : x2) = x;

```

```

54     }
55     return x1;
56 }
57
58 std::vector<Double> find_all_roots(const poly & p) {
59     poly dif;
60     for (int i = 0; i < (int)p.size(); i++)
61         if (p[i].second > 0)
62             dif.push_back(std::make_pair(p[i].first * p[i].second, p[i].second - 1));
63     if (dif.empty()) return std::vector<Double>();
64     std::vector<Double> res, r = find_all_roots(dif);
65     r.insert(r.begin(), -inf);
66     r.push_back(inf);
67     for (int i = 0; i < (int)r.size() - 1; i++) {
68         Double root = find_root(p, r[i], r[i + 1]);
69         if (root != root) continue; //NaN, not found
70         if (res.empty() || root != res.back())
71             res.push_back(root);
72     }
73     return res;
74 }
75
76 /** Example Usage (http://wcipeg.com/problem/rootsolve) */
77
78 #include <iostream>
79 using namespace std;
80
81 int main() {
82     int n, d;
83     Double c;
84     poly p;
85     cin >> n;
86     for (int i = 0; i < n; i++) {
87         cin >> c >> d;
88         p.push_back(make_pair(c, d));
89     }
90     vector<Double> sol = find_all_roots(p);
91     if (sol.empty()) {
92         cout << "NO_REAL_ROOTS\n";
93     } else {
94         cout.precision(9);
95         for (int i = 0; i < (int)sol.size(); i++)
96             cout << fixed << sol[i] << "\n";
97     }
98     return 0;
99 }

```

4.6.2 Complex Root Finding (Laguerre's)

```

1  /*
2
3  4.6.2 - Complex Root Finding (Laguerre's Method)
4
5  Laguerre's method can be used to not only find complex roots of
6  a polynomial, the polynomial may also have complex coefficients.
7  From extensive empirical study, Laguerre's method is observed to
8  be very close to being a "sure-fire" method, as it is almost

```

```

9  guaranteed to always converge to some root of the polynomial
10 regardless of what initial guess is chosen.
11
12 */
13
14 #include <complex>
15 #include <cstdlib> /* rand(), RAND_MAX */
16 #include <vector>
17
18 typedef long double Double;
19 typedef std::complex<Double> cdouble;
20 typedef std::vector<cdouble> poly;
21
22 const Double eps = 1e-12;
23
24 std::pair<poly, cdouble> horner(const poly & a, const cdouble & x) {
25     int n = a.size();
26     poly b = poly(std::max(1, n - 1));
27     for (int i = n - 1; i > 0; i--)
28         b[i - 1] = a[i] + (i < n - 1 ? b[i] * x : 0);
29     return std::make_pair(b, a[0] + b[0] * x);
30 }
31
32 cdouble eval(const poly & p, const cdouble & x) {
33     return horner(p, x).second;
34 }
35
36 poly derivative(const poly & p) {
37     int n = p.size();
38     poly r(std::max(1, n - 1));
39     for(int i = 1; i < n; i++)
40         r[i - 1] = p[i] * cdouble(i);
41     return r;
42 }
43
44 int comp(const cdouble & x, const cdouble & y) {
45     Double diff = std::abs(x) - std::abs(y);
46     return diff < -eps ? -1 : (diff > eps ? 1 : 0);
47 }
48
49 cdouble find_one_root(const poly & p, cdouble x) {
50     int n = p.size() - 1;
51     poly p1 = derivative(p), p2 = derivative(p1);
52     for (int step = 0; step < 10000; step++) {
53         cdouble y0 = eval(p, x);
54         if (comp(y0, 0) == 0) break;
55         cdouble G = eval(p1, x) / y0;
56         cdouble H = G * G - eval(p2, x) / y0;
57         cdouble R = std::sqrt(cdouble(n - 1) * (H * cdouble(n) - G * G));
58         cdouble D1 = G + R, D2 = G - R;
59         cdouble a = cdouble(n) / (comp(D1, D2) > 0 ? D1 : D2);
60         x -= a;
61         if (comp(a, 0) == 0) break;
62     }
63     return x;
64 }
65
66 std::vector<cdouble> find_all_roots(const poly & p) {
67     std::vector<cdouble> res;

```

```

68  poly q = p;
69  while (q.size() > 2) {
70      cdouble z(rand()/Double(RAND_MAX), rand()/Double(RAND_MAX));
71      z = find_one_root(q, z);
72      z = find_one_root(p, z);
73      q = horner(q, z).first;
74      res.push_back(z);
75  }
76  res.push_back(-q[0] / q[1]);
77  return res;
78 }
79
80 /** Example Usage **/
81
82 #include <cstdio>
83 #include <iostream>
84 using namespace std;
85
86 void print_roots(vector<cdouble> roots) {
87     for (int i = 0; i < (int)roots.size(); i++) {
88         printf("(%9.5f, ", (double)roots[i].real());
89         printf("%9.5f)\n", (double)roots[i].imag());
90     }
91 }
92
93 int main() {
94     { // x^3 - 8x^2 - 13x + 140 = (x + 4)(x - 5)(x - 7)
95         printf("Roots of x^3 - 8x^2 - 13x + 140:\n");
96         poly p;
97         p.push_back(140);
98         p.push_back(-13);
99         p.push_back(-8);
100        p.push_back(1);
101        vector<cdouble> roots = find_all_roots(p);
102        print_roots(roots);
103    }
104
105    { // (-6+4i)x^4 + (-26+12i)x^3 + (-30+40i)x^2 + (-26+12i)x + (-24+36i)
106        // = ((2+3i)x + 6)*(x + i)*(2x + (6+4i))*(x*i + 1)
107        printf("Roots of ((2+3i)x + 6)(x + i)(2x + (6+4i))(x*i + 1):\n");
108        poly p;
109        p.push_back(cdouble(-24, 36));
110        p.push_back(cdouble(-26, 12));
111        p.push_back(cdouble(-30, 40));
112        p.push_back(cdouble(-26, 12));
113        p.push_back(cdouble(-6, 4));
114        vector<cdouble> roots = find_all_roots(p);
115        print_roots(roots);
116    }
117    return 0;
118 }

```

4.6.3 Complex Root Finding (RPOLY)

```

1  /*
2
3  4.6.3 - Complex Root Finding (Jenkins-Traub Algorithm)

```

```

4
5 Determine the complex roots of a polynomial with real coefficients.
6 This is the variant of the Jenkins-Traub algorithm for polynomials
7 with real coefficient, known as RPOLY. RPOLY follows follows the
8 same pattern as the CPOLY algorithm, but computes two roots at a
9 time, either two real roots or a pair of conjugate complex roots.
10 See: https://en.wikipedia.org/wiki/Jenkins%E2%80%93Traub\_algorithm
11
12 The following is a translation of TOMS493 (www.netlib.org/toms/)
13 from FORTRAN to C++, with a simple wrapper at the end for the C++
14 <complex> class. Although the code is not meant to be read, it is
15 extremely efficient and robust, capable of achieving an accuracy
16 of at least 5 decimal places for even the most strenuous inputs.
17
18 */
19
20 #include <cfloat> /* LDBL_EPSILON, LDBL_MAX, LDBL_MIN */
21 #include <cmath> /* cosl, expl, fabs1, logl, powl, sinl, sqrtl */
22
23 typedef long double LD;
24
25 void divide_quadratic(int n, LD u, LD v, LD p[], LD q[], LD * a, LD * b) {
26     q[0] = *b = p[0];
27     q[1] = *a = -((*b) * u) + p[1];
28     for (int i = 2; i < n; i++) {
29         q[i] = -((*a) * u + (*b) * v) + p[i];
30         *b = *a;
31         *a = q[i];
32     }
33 }
34
35 int get_flag(int n, LD a, LD b, LD * a1, LD * a3, LD * a7,
36             LD * c, LD * d, LD * e, LD * f, LD * g, LD * h,
37             LD k[], LD u, LD v, LD qk[]) {
38     divide_quadratic(n, u, v, k, qk, c, d);
39     if (fabs1(*c) <= 100.0 * LDBL_EPSILON * fabs1(k[n - 1]) &&
40         fabs1(*d) <= 100.0 * LDBL_EPSILON * fabs1(k[n - 2])) return 3;
41     *h = v * b;
42     if (fabs1(*d) >= fabs1(*c)) {
43         *e = a / (*d);
44         *f = (*c) / (*d);
45         *g = u * b;
46         *a1 = (*f) * b - a;
47         *a3 = (*e) * ((*g) + a) + (*h) * (b / (*d));
48         *a7 = (*h) + ((*f) + u) * a;
49         return 2;
50     }
51     *e = a / (*c);
52     *f = (*d) / (*c);
53     *g = (*e) * u;
54     *a1 = -(a * ((*d) / (*c))) + b;
55     *a3 = (*e) * a + ((*g) + (*h) / (*c)) * b;
56     *a7 = (*g) * (*d) + (*h) * (*f) + a;
57     return 1;
58 }
59
60 void find_polynomials(int n, int flag, LD a, LD b, LD a1, LD * a3,
61                     LD * a7, LD k[], LD qk[], LD qp[]) {
62     if (flag == 3) {

```

```

63     k[1] = k[0] = 0.0;
64     for (int i = 2; i < n; i++) k[i] = qk[i - 2];
65     return;
66 }
67 if (fabs1(a1) > 10.0 * LDL_EPSILON * fabs1(flag == 1 ? b : a)) {
68     *a7 /= a1;
69     *a3 /= a1;
70     k[0] = qp[0];
71     k[1] = qp[1] - (*a7) * qp[0];
72     for (int i = 2; i < n; i++)
73         k[i] = qp[i] - ((*a7) * qp[i - 1]) + (*a3) * qk[i - 2];
74 } else {
75     k[0] = 0.0;
76     k[1] = -(*a7) * qp[0];
77     for (int i = 2; i < n; i++)
78         k[i] = (*a3) * qk[i - 2] - (*a7) * qp[i - 1];
79 }
80 }
81
82 void estimate_coeff(int flag, LD * uu, LD * vv, LD a, LD a1, LD a3, LD a7,
83                   LD b, LD c, LD d, LD f, LD g, LD h, LD u, LD v, LD k[],
84                   int n, LD p[]) {
85     LD a4, a5, b1, b2, c1, c2, c3, c4, temp;
86     *vv = *uu = 0.0;
87     if (flag == 3) return;
88     if (flag != 2) {
89         a4 = a + u * b + h * f;
90         a5 = c + (u + v * f) * d;
91     } else {
92         a4 = (a + g) * f + h;
93         a5 = (f + u) * c + v * d;
94     }
95     b1 = -k[n - 1] / p[n];
96     b2 = -(k[n - 2] + b1 * p[n - 1]) / p[n];
97     c1 = v * b2 * a1;
98     c2 = b1 * a7;
99     c3 = b1 * b1 * a3;
100    c4 = c1 - c2 - c3;
101    temp = b1 * a4 - c4 + a5;
102    if (temp != 0.0) {
103        *uu = u - (u * (c3 + c2) + v * (b1 * a1 + b2 * a7)) / temp;
104        *vv = v * (1.0 + c4 / temp);
105    }
106 }
107
108 void solve_quadratic(LD a, LD b1, LD c, LD * sr, LD * si, LD * lr, LD * li) {
109     LD b, d, e;
110     *sr = *si = *lr = *li = 0.0;
111     if (a == 0) {
112         *sr = (b1 != 0) ? -c / b1 : *sr;
113         return;
114     }
115     if (c == 0) {
116         *lr = -b1 / a;
117         return;
118     }
119     b = b1 / 2.0;
120     if (fabs1(b) < fabs1(c)) {
121         e = (c >= 0) ? a : -a;

```

```

122     e = b * (b / fabs1(c)) - e;
123     d = sqrt1(fabs1(e)) * sqrt1(fabs1(c));
124 } else {
125     e = 1.0 - (a / b) * (c / b);
126     d = sqrt1(fabs1(e)) * fabs1(b);
127 }
128 if (e >= 0) {
129     d = (b >= 0) ? -d : d;
130     *lr = (d - b) / a;
131     *sr = (*lr != 0) ? (c / *lr / a) : *sr;
132 } else {
133     *lr = *sr = -b / a;
134     *si = fabs1(d / a);
135     *li = -(*si);
136 }
137 }
138
139 void quadratic_iterate(int N, int * NZ, LD uu, LD vv,
140                      LD * szr, LD * szi, LD * lzt, LD * lzi, LD qp[],
141                      int n, LD * a, LD * b, LD p[], LD qk[],
142                      LD * a1, LD * a3, LD * a7, LD * c, LD * d, LD * e,
143                      LD * f, LD * g, LD * h, LD k[]) {
144     int steps = 0, flag, tried_flag = 0;
145     LD ee, mp, omp = 0.0, relstp = 0.0, t, u, ui, v, vi, zm;
146     *NZ = 0;
147     u = uu;
148     v = vv;
149     do {
150         solve_quadratic(1.0, u, v, szr, szi, lzt, lzi);
151         if (fabs1(fabs1(*szr) - fabs1(*lzt)) > 0.01 * fabs1(*lzt)) break;
152         divide_quadratic(n, u, v, p, qp, a, b);
153         mp = fabs1(-(*szr) * (*b)) + *a + fabs1((*szi) * (*b));
154         zm = sqrt1(fabs1(v));
155         ee = 2.0 * fabs1(qp[0]);
156         t = -(*szr) * (*b);
157         for (int i = 1; i < N; i++) ee = ee * zm + fabs1(qp[i]);
158         ee = ee * zm + fabs1(*a + t);
159         ee = ee * 9.0 + 2.0 * fabs1(t) - 7.0 * (fabs1(*a + t) + zm * fabs1(*b));
160         ee *= LDBL_EPSILON;
161         if (mp <= 20.0 * ee) {
162             *NZ = 2;
163             break;
164         }
165         if (++steps > 20) break;
166         if (steps >= 2 && relstp <= 0.01 && mp >= omp && !tried_flag) {
167             relstp = (relstp < LDBL_EPSILON) ? sqrt1(LDBL_EPSILON) : sqrt1(relstp);
168             u -= u * relstp;
169             v += v * relstp;
170             divide_quadratic(n, u, v, p, qp, a, b);
171             for (int i = 0; i < 5; i++) {
172                 flag = get_flag(N, *a, *b, a1, a3, a7, c, d, e, f, g, h, k, u, v, qk);
173                 find_polynomials(N, flag, *a, *b, *a1, a3, a7, k, qk, qp);
174             }
175             tried_flag = 1;
176             steps = 0;
177         }
178         omp = mp;
179         flag = get_flag(N, *a, *b, a1, a3, a7, c, d, e, f, g, h, k, u, v, qk);
180         find_polynomials(N, flag, *a, *b, *a1, a3, a7, k, qk, qp);

```



```

181     flag = get_flag(N, *a, *b, a1, a3, a7, c, d, e, f, g, h, k, u, v, qk);
182     estimate_coef(flag, &ui, &vi, *a, *a1, *a3, *a7, *b, *c, *d, *f, *g, *h,
183                   u, v, k, N, p);
184     if (vi != 0) {
185         relstp = fabsl((-v + vi) / vi);
186         u = ui;
187         v = vi;
188     }
189 } while (vi != 0);
190 }
191
192 void real_iterate(int * flag, int * nz, LD * sss, int n, LD p[],
193                 int nn, LD qp[], LD * szr, LD * szl, LD k[], LD qk[]) {
194     int steps = 0;
195     LD ee, kv, mp, ms, omp = 0.0, pv, s, t = 0.0;
196     *flag = *nz = 0;
197     for (s = *sss; ; s += t) {
198         pv = p[0];
199         qp[0] = pv;
200         for (int i = 1; i < nn; i++) qp[i] = pv = pv * s + p[i];
201         mp = fabsl(pv);
202         ms = fabsl(s);
203         ee = 0.5 * fabsl(qp[0]);
204         for (int i = 1; i < nn; i++) ee = ee * ms + fabsl(qp[i]);
205         if (mp <= 20.0 * LDBL_EPSILON * (2.0 * ee - mp)) {
206             *nz = 1;
207             *szr = s;
208             *szl = 0.0;
209             break;
210         }
211         if (++steps > 10) break;
212         if (steps >= 2 && fabsl(t) <= 0.001 * fabsl(s - t) && mp > omp) {
213             *flag = 1;
214             *sss = s;
215             break;
216         }
217         omp = mp;
218         qk[0] = kv = k[0];
219         for (int i = 1; i < n; i++) qk[i] = kv = kv * s + k[i];
220         if (fabsl(kv) > fabsl(k[n - 1]) * 10.0 * LDBL_EPSILON) {
221             t = -pv / kv;
222             k[0] = qp[0];
223             for (int i = 1; i < n; i++)
224                 k[i] = t * qk[i - 1] + qp[i];
225         } else {
226             k[0] = 0.0;
227             for (int i = 1; i < n; i++)
228                 k[i] = qk[i - 1];
229         }
230         kv = k[0];
231         for (int i = 1; i < n; i++) kv = kv * s + k[i];
232         t = fabsl(kv) > (fabsl(k[n - 1]) * 10.0 * LDBL_EPSILON) ? -pv / kv : 0.0;
233     }
234 }
235
236 void solve_fixedshift(int l2, int * nz, LD sr, LD v, LD k[], int n,
237                     LD p[], int nn, LD qp[], LD u, LD qk[], LD svk[],
238                     LD * lzi, LD * lzt, LD * szl, LD * szr) {
239     int flag, _flag, __flag = 1, spass, stry, vpass, vtry;

```

```

240 LD a, a1, a3, a7, b, betas, betav, c, d, e, f, g, h;
241 LD oss, ots = 0.0, otv = 0.0, ovv, s, ss, ts, tss, tv, tvv, ui, vi, vv;
242 *nz = 0;
243 betav = betas = 0.25;
244 oss = sr;
245 ovv = v;
246 divide_quadratic(nn, u, v, p, qp, &a, &b);
247 flag = get_flag(n, a, b, &a1, &a3, &a7, &c, &d, &e, &f, &g, &h,
248               k, u, v, qk);
249 for (int j = 0; j < 12; j++) {
250     _flag = 1;
251     find_polynomials(n, flag, a, b, a1, &a3, &a7, k, qk, qp);
252     flag = get_flag(n, a, b, &a1, &a3, &a7, &c, &d, &e, &f, &g, &h,
253                   k, u, v, qk);
254     estimate_coeff(flag, &ui, &vi, a, a1, a3, a7, b, c, d, f, g, h,
255                  u, v, k, n, p);
256     vv = vi;
257     ss = k[n - 1] != 0.0 ? -p[n] / k[n - 1] : 0.0;
258     ts = tv = 1.0;
259     if (j != 0 && flag != 3) {
260         tv = (vv != 0.0) ? fabs1((vv - ovv) / vv) : tv;
261         ts = (ss != 0.0) ? fabs1((ss - oss) / ss) : ts;
262         tvv = (tv < otv) ? tv * otv : 1.0;
263         tss = (ts < ots) ? ts * ots : 1.0;
264         vpass = (tvv < betav) ? 1 : 0;
265         spass = (tss < betas) ? 1 : 0;
266         if (spass || vpass) {
267             for (int i = 0; i < n; i++) svk[i] = k[i];
268             s = ss; stry = vtry = 0;
269             for (;;) {
270                 if (!(_flag && spass && (!vpass || tss < tvv))) {
271                     quadratic_iterate(n, nz, ui, vi, szr, szl, lzi, qp, nn,
272                                     &a, &b, p, qk, &a1, &a3, &a7, &c, &d, &e, &f, &g, &h, k);
273                     if (*nz > 0) return;
274                     __flag = vtry = 1;
275                     betav *= 0.25;
276                     if (stry || !spass) {
277                         __flag = 0;
278                     } else {
279                         for (int i = 0; i < n; i++) k[i] = svk[i];
280                     }
281                 }
282                 _flag = 0;
283                 if (__flag != 0) {
284                     real_iterate(&__flag, nz, &s, n, p, nn, qp, szr, szl, k, qk);
285                     if (*nz > 0) return;
286                     stry = 1;
287                     betas *= 0.25;
288                     if (__flag != 0) {
289                         ui = -(s + s);
290                         vi = s * s;
291                         continue;
292                     }
293                 }
294                 for (int i = 0; i < n; i++) k[i] = svk[i];
295                 if (!vpass || vtry) break;
296             }
297             divide_quadratic(nn, u, v, p, qp, &a, &b);
298             flag = get_flag(n, a, b, &a1, &a3, &a7, &c, &d, &e, &f, &g, &h,

```

```

299         k, u, v, qk);
300     }
301 }
302 ovv = vv;
303 oss = ss;
304 otv = tv;
305 ots = ts;
306 }
307 }
308
309 void find_roots(int degree, LD co[], LD re[], LD im[]) {
310     int j, jj, n, nm1, nn, nz, zero, SZ = degree + 1;
311     LD k[SZ], p[SZ], pt[SZ], qp[SZ], temp[SZ], qk[SZ], svk[SZ];
312     LD bnd, df, dx, factor, ff, moduli_max, moduli_min, sc, x, xm;
313     LD aa, bb, cc, lzi, lzt, sr, szi, szr, t, u, xx, xxx, yy;
314     n = degree;
315     xx = sqrtl(0.5);
316     yy = -xx;
317     for (j = 0; co[n] == 0; n--, j++) re[j] = im[j] = 0.0;
318     nn = n + 1;
319     for (int i = 0; i < nn; i++) p[i] = co[i];
320     while (n >= 1) {
321         if (n <= 2) {
322             if (n < 2) {
323                 re[degree - 1] = -p[1] / p[0];
324                 im[degree - 1] = 0.0;
325             } else {
326                 solve_quadratic(p[0], p[1], p[2], &re[degree - 2], &im[degree - 2],
327                                 &re[degree - 1], &im[degree - 1]);
328             }
329             break;
330         }
331         moduli_max = 0.0;
332         moduli_min = LDBL_MAX;
333         for (int i = 0; i < nn; i++) {
334             x = fabsl(p[i]);
335             if (x > moduli_max) moduli_max = x;
336             if (x != 0 && x < moduli_min) moduli_min = x;
337         }
338         sc = LDBL_MIN / LDBL_EPSILON / moduli_min;
339         if ((sc <= 1.0 && moduli_max >= 10) ||
340             (sc > 1.0 && LDBL_MAX / sc >= moduli_max)) {
341             sc = (sc == 0) ? LDBL_MIN : sc;
342             factor = powl(2.0, logl(sc) / logl(2.0));
343             if (factor != 1.0)
344                 for (int i = 0; i < nn; i++) p[i] *= factor;
345         }
346         for (int i = 0; i < nn; i++) pt[i] = fabsl(p[i]);
347         pt[n] = -pt[n];
348         nm1 = n - 1;
349         x = expl((logl(-pt[n]) - logl(pt[0])) / (LD)n);
350         if (pt[nm1] != 0) {
351             xm = -pt[n] / pt[nm1];
352             if (xm < x) x = xm;
353         }
354         xm = x;
355         do {
356             x = xm;
357             xm = 0.1 * x;

```

```

358     ff = pt[0];
359     for (int i = 1; i < nn; i++) ff = ff * xm + pt[i];
360 } while (ff > 0);
361 dx = x;
362 do {
363     df = ff = pt[0];
364     for (int i = 1; i < n; i++) {
365         ff = x * ff + pt[i];
366         df = x * df + ff;
367     }
368     ff = x * ff + pt[n];
369     dx = ff / df;
370     x -= dx;
371 } while (fabsl(dx / x) > 0.005);
372 bnd = x;
373 for (int i = 1; i < n; i++)
374     k[i] = (LD)(n - i) * p[i] / (LD)n;
375 k[0] = p[0];
376 aa = p[n];
377 bb = p[nm1];
378 zero = (k[nm1] == 0) ? 1 : 0;
379 for (jj = 0; jj < 5; jj++) {
380     cc = k[nm1];
381     if (zero) {
382         for (int i = 0; i < nm1; i++) {
383             j = nm1 - i;
384             k[j] = k[j - 1];
385         }
386         k[0] = 0;
387         zero = (k[nm1] == 0) ? 1 : 0;
388     } else {
389         t = -aa / cc;
390         for (int i = 0; i < nm1; i++) {
391             j = nm1 - i;
392             k[j] = t * k[j - 1] + p[j];
393         }
394         k[0] = p[0];
395         zero = (fabsl(k[nm1]) <= fabsl(bb) * LDBL_EPSILON * 10.0) ? 1 : 0;
396     }
397 }
398 for (int i = 0; i < n; i++) temp[i] = k[i];
399 static const LD DEG = 0.01745329251994329576923690768489L;
400 for (jj = 1; jj <= 20; jj++) {
401     xxx = -sinl(94.0 * DEG) * yy + cosl(94.0 * DEG) * xx;
402     yy = sinl(94.0 * DEG) * xx + cosl(94.0 * DEG) * yy;
403     xx = xxx;
404     sr = bnd * xx;
405     u = -2.0 * sr;
406     for (int i = 0; i < nn; i++) qk[i] = svk[i] = 0.0;
407     solve_fixedshift(20 * jj, &nz, sr, bnd, k, n, p, nn, qp, u,
408                     qk, svk, &lzi, &lzr, &szi, &szr);
409     if (nz != 0) {
410         j = degree - n;
411         re[j] = szr;
412         im[j] = szi;
413         nn = nn - nz;
414         n = nn - 1;
415         for (int i = 0; i < nn; i++) p[i] = qp[i];
416         if (nz != 1) {

```

```

417         re[j + 1] = lzt;
418         im[j + 1] = lzi;
419     }
420     break;
421 } else {
422     for (int i = 0; i < n; i++) k[i] = temp[i];
423 }
424 }
425 if (jj > 20) break;
426 }
427 }
428
429 /** Wrapper */
430
431 #include <algorithm> /* std::reverse(), std::sort() */
432 #include <complex>
433 #include <vector>
434
435 typedef std::complex<LD> root;
436
437 bool comp(const root & a, const root & b) {
438     if (real(a) != real(b)) return real(a) < real(b);
439     return imag(a) < imag(b);
440 }
441
442 std::vector<root> find_roots(int degree, LD coefficients[]) {
443     std::reverse(coefficients, coefficients + degree + 1);
444     LD re[degree], im[degree];
445     find_roots(degree, coefficients, re, im);
446     std::vector<root> res;
447     for (int i = 0; i < degree; i++)
448         res.push_back(root(re[i], im[i]));
449     std::sort(res.begin(), res.end(), comp);
450     return res;
451 }
452
453 /** Example Usage (http://wcipeg.com/problem/rootsolve) */
454
455 #include <iostream>
456 using namespace std;
457
458 int T, degree, p;
459 LD c, coeff[101];
460
461 int main() {
462     degree = 0;
463     cin >> T;
464     for (int i = 0; i < T; i++) {
465         cin >> c >> p;
466         if (p > degree) degree = p;
467         coeff[p] = c;
468     }
469     std::vector<root> roots = find_roots(degree, coeff);
470     bool printed = false;
471     cout.precision(6);
472     for (int i = 0; i < (int)roots.size(); i++) {
473         if (fabsl(roots[i].imag()) < LDBL_EPSILON) {
474             cout << fixed << roots[i].real() << "\n";
475             printed = true;

```

```

476     }
477 }
478 if (!printed) cout << "NO_REAL_ROOTS\n";
479 return 0;
480 }

```

4.7 Integration

4.7.1 Simpson's Rule

```

1  /*
2
3  4.7.1 - Integration (Simpson's Rule)
4
5  Simpson's rule is a method for numerical integration, the
6  numerical approximation of definite integrals. The rule is:
7
8  Integral of f(x) dx from a to b ~=
9  [f(a) + 4*f((a + b)/2) + f(b)] * (b - a)/6
10
11 */
12
13 #include <cmath> /* fabs() */
14
15 template<class DoubleFunction>
16 double simpsons(DoubleFunction f, double a, double b) {
17     return (f(a) + 4 * f((a + b)/2) + f(b)) * (b - a)/6;
18 }
19
20 template<class DoubleFunction>
21 double integrate(DoubleFunction f, double a, double b) {
22     static const double eps = 1e-10;
23     double m = (a + b) / 2;
24     double am = simpsons(f, a, m);
25     double mb = simpsons(f, m, b);
26     double ab = simpsons(f, a, b);
27     if (fabs(am + mb - ab) < eps) return ab;
28     return integrate(f, a, m) + integrate(f, m, b);
29 }
30
31 /** Example Usage */
32
33 #include <iostream>
34 using namespace std;
35
36 double f(double x) { return sin(x); }
37
38 int main () {
39     double PI = acos(-1.0);
40     cout << integrate(f, 0.0, PI/2) << "\n"; //1
41     return 0;
42 }

```

Chapter 5

Geometry

5.1 Geometric Classes

5.1.1 Point

```
1  /*
2
3  5.1.1 - 2D Point Class
4
5  This class is very similar to std::complex, except it uses epsilon
6  comparisons and also supports other operations such as reflection
7  and rotation. In addition, this class supports many arithmetic
8  operations (e.g. overloaded operators for vector addition, subtraction,
9  multiplication, and division; dot/cross products, etc.) pertaining to
10 2D cartesian vectors.
11
12 All operations are O(1) in time and space.
13
14 */
15
16 #include <cmath>    /* atan(), fabs(), sqrt() */
17 #include <ostream>
18 #include <utility> /* std::pair */
19
20 const double eps = 1e-9;
21
22 #define EQ(a, b) (fabs((a) - (b)) <= eps) /* equal to */
23 #define LT(a, b) ((a) < (b) - eps)       /* less than */
24
25 struct point {
26
27     double x, y;
28
29     point() : x(0), y(0) {}
30     point(const point & p) : x(p.x), y(p.y) {}
31     point(const std::pair<double, double> & p) : x(p.first), y(p.second) {}
32     point(const double & a, const double & b) : x(a), y(b) {}
33
34     bool operator < (const point & p) const {
35         return EQ(x, p.x) ? LT(y, p.y) : LT(x, p.x);
36     }
37 }
```

```

36 }
37
38 bool operator > (const point & p) const {
39     return EQ(x, p.x) ? LT(p.y, y) : LT(p.x, x);
40 }
41
42 bool operator == (const point & p) const { return EQ(x, p.x) && EQ(y, p.y); }
43 bool operator != (const point & p) const { return !(*this == p); }
44 bool operator <= (const point & p) const { return !(*this > p); }
45 bool operator >= (const point & p) const { return !(*this < p); }
46 point operator + (const point & p) const { return point(x + p.x, y + p.y); }
47 point operator - (const point & p) const { return point(x - p.x, y - p.y); }
48 point operator + (const double & v) const { return point(x + v, y + v); }
49 point operator - (const double & v) const { return point(x - v, y - v); }
50 point operator * (const double & v) const { return point(x * v, y * v); }
51 point operator / (const double & v) const { return point(x / v, y / v); }
52 point & operator += (const point & p) { x += p.x; y += p.y; return *this; }
53 point & operator -= (const point & p) { x -= p.x; y -= p.y; return *this; }
54 point & operator += (const double & v) { x += v; y += v; return *this; }
55 point & operator -= (const double & v) { x -= v; y -= v; return *this; }
56 point & operator *= (const double & v) { x *= v; y *= v; return *this; }
57 point & operator /= (const double & v) { x /= v; y /= v; return *this; }
58 friend point operator + (const double & v, const point & p) { return p + v; }
59 friend point operator * (const double & v, const point & p) { return p * v; }
60
61 double norm() const { return x * x + y * y; }
62 double abs() const { return sqrt(x * x + y * y); }
63 double arg() const { return atan2(y, x); }
64 double dot(const point & p) const { return x * p.x + y * p.y; }
65 double cross(const point & p) const { return x * p.y - y * p.x; }
66 double proj(const point & p) const { return dot(p) / p.abs(); } //onto p
67 point rot90() const { return point(-y, x); }
68
69 //proportional unit vector of (x, y) such that x^2 + y^2 = 1
70 point normalize() const {
71     return (EQ(x, 0) && EQ(y, 0)) ? point(0, 0) : (point(x, y) / abs());
72 }
73
74 //rotate t radians CW about origin
75 point rotateCW(const double & t) const {
76     return point(x * cos(t) + y * sin(t), y * cos(t) - x * sin(t));
77 }
78
79 //rotate t radians CCW about origin
80 point rotateCCW(const double & t) const {
81     return point(x * cos(t) - y * sin(t), x * sin(t) + y * cos(t));
82 }
83
84 //rotate t radians CW about point p
85 point rotateCW(const point & p, const double & t) const {
86     return (*this - p).rotateCW(t) + p;
87 }
88
89 //rotate t radians CCW about point p
90 point rotateCCW(const point & p, const double & t) const {
91     return (*this - p).rotateCCW(t) + p;
92 }
93
94 //reflect across point p

```



```

95     point reflect(const point & p) const {
96         return point(2 * p.x - x, 2 * p.y - y);
97     }
98
99     //reflect across the line containing points p and q
100    point reflect(const point & p, const point & q) const {
101        if (p == q) return reflect(p);
102        point r(*this - p), s = q - p;
103        r = point(r.x * s.x + r.y * s.y, r.x * s.y - r.y * s.x) / s.norm();
104        r = point(r.x * s.x - r.y * s.y, r.x * s.y + r.y * s.x) + p;
105        return r;
106    }
107
108    friend double norm(const point & p) { return p.norm(); }
109    friend double abs(const point & p) { return p.abs(); }
110    friend double arg(const point & p) { return p.arg(); }
111    friend double dot(const point & p, const point & q) { return p.dot(q); }
112    friend double cross(const point & p, const point & q) { return p.cross(q); }
113    friend double proj(const point & p, const point & q) { return p.proj(q); }
114    friend point rot90(const point & p) { return p.rot90(); }
115    friend point normalize(const point & p) { return p.normalize(); }
116    friend point rotateCW(const point & p, const double & t) { return p.rotateCW(t); }
117    friend point rotateCCW(const point & p, const double & t) { return p.rotateCCW(t); }
118    friend point rotateCW(const point & p, const point & q, const double & t) { return p.rotateCW(q, t); }
119    friend point rotateCCW(const point & p, const point & q, const double & t) { return p.rotateCCW(q, t); }
120
121    friend point reflect(const point & p, const point & q) { return p.reflect(q); }
122    friend point reflect(const point & p, const point & a, const point & b) { return p.reflect(a, b); }
123
124    friend std::ostream & operator << (std::ostream & out, const point & p) {
125        out << "(";
126        out << (fabs(p.x) < eps ? 0 : p.x) << ",";
127        out << (fabs(p.y) < eps ? 0 : p.y) << ")";
128        return out;
129    }
130
131    /** Example Usage */
132
133    #include <cassert>
134    #define pt point
135
136    const double PI = acos(-1.0);
137
138    int main() {
139        pt p(-10, 3);
140        assert(pt(-18, 29) == p + pt(-3, 9) * 6 / 2 - pt(-1, 1));
141        assert(EQ(109, p.norm()));
142        assert(EQ(10.44030650891, p.abs()));
143        assert(EQ(2.850135859112, p.arg()));
144        assert(EQ(0, p.dot(pt(3, 10))));
145        assert(EQ(0, p.cross(pt(10, -3))));
146        assert(EQ(10, p.proj(pt(-10, 0))));
147        assert(EQ(1, p.normalize().abs()));
148        assert(pt(-3, -10) == p.rot90());
149        assert(pt(3, 12) == p.rotateCW(pt(1, 1), PI / 2));
150        assert(pt(1, -10) == p.rotateCCW(pt(2, 2), PI / 2));
151        assert(pt(10, -3) == p.reflect(pt(0, 0)));
152        assert(pt(-10, -3) == p.reflect(pt(-2, 0), pt(5, 0)));

```

```

153     return 0;
154 }

```

5.1.2 Line

```

1  /*
2
3  5.1.2 - 2D Line Class
4
5  A 2D line is expressed in the form  $Ax + By + C = 0$ . All lines can be
6  "normalized" to a canonical form by insisting that the y-coefficient
7  equal 1 if it is non-zero. Otherwise, we set the x-coefficient to 1.
8  If B is non-zero, then we have the common case where the slope = -A
9  after normalization.
10
11 All operations are  $O(1)$  in time and space.
12
13 */
14
15 #include <cmath>    /* fabs() */
16 #include <limits>   /* std::numeric_limits */
17 #include <ostream>
18 #include <utility>  /* std::pair */
19
20 const double eps = 1e-9, NaN = std::numeric_limits<double>::quiet_NaN();
21
22 #define EQ(a, b) (fabs((a) - (b)) <= eps) /* equal to */
23 #define LT(a, b) ((a) < (b) - eps)        /* less than */
24
25 typedef std::pair<double, double> point;
26 #define x first
27 #define y second
28
29 struct line {
30
31     double a, b, c;
32
33     line(): a(0), b(0), c(0) {} //invalid or uninitialized line
34
35     line(const double & A, const double & B, const double & C) {
36         a = A;
37         b = B;
38         c = C;
39         if (!EQ(b, 0)) {
40             a /= b; c /= b; b = 1;
41         } else {
42             c /= a; a = 1; b = 0;
43         }
44     }
45
46     line(const double & slope, const point & p) {
47         a = -slope;
48         b = 1;
49         c = slope * p.x - p.y;
50     }
51
52     line(const point & p, const point & q): a(0), b(0), c(0) {

```

```

53     if (EQ(p.x, q.x)) {
54         if (EQ(p.y, q.y)) return; //invalid line
55         //vertical line
56         a = 1;
57         b = 0;
58         c = -p.x;
59         return;
60     }
61     a = -(p.y - q.y) / (p.x - q.x);
62     b = 1;
63     c = -(a * p.x) - (b * p.y);
64 }
65
66 bool operator == (const line & l) const {
67     return EQ(a, l.a) && EQ(b, l.b) && EQ(c, l.c);
68 }
69
70 bool operator != (const line & l) const {
71     return !(*this == l);
72 }
73
74 //whether the line is initialized and normalized
75 bool valid() const {
76     if (EQ(a, 0)) return !EQ(b, 0);
77     return EQ(b, 1) || (EQ(b, 0) && EQ(a, 1));
78 }
79
80 bool horizontal() const { return valid() && EQ(a, 0); }
81 bool vertical() const { return valid() && EQ(b, 0); }
82
83 double slope() const {
84     if (!valid() || EQ(b, 0)) return NaN; //vertical
85     return -a;
86 }
87
88 //solve for x, given y
89 //for horizontal lines, either +inf, -inf, or nan is returned
90 double x(const double & y) const {
91     if (!valid() || EQ(a, 0)) return NaN; //invalid or horizontal
92     return (-c - b * y) / a;
93 }
94
95 //solve for y, given x
96 //for vertical lines, either +inf, -inf, or nan is returned
97 double y(const double & x) const {
98     if (!valid() || EQ(b, 0)) return NaN; //invalid or vertical
99     return (-c - a * x) / b;
100 }
101
102 //returns whether p exists on the line
103 bool contains(const point & p) const {
104     return EQ(a * p.x + b * p.y + c, 0);
105 }
106
107 //returns whether the line is parallel to l
108 bool parallel(const line & l) const {
109     return EQ(a, l.a) && EQ(b, l.b);
110 }
111

```

```

112 //returns whether the line is perpendicular to l
113 bool perpendicular(const line & l) const {
114     return EQ(-a * l.a, b * l.b);
115 }
116
117 //return the parallel line passing through point p
118 line parallel(const point & p) const {
119     return line(a, b, -a * p.x - b * p.y);
120 }
121
122 //return the perpendicular line passing through point p
123 line perpendicular(const point & p) const {
124     return line(-b, a, b * p.x - a * p.y);
125 }
126
127 friend std::ostream & operator << (std::ostream & out, const line & l) {
128     out << (fabs(l.a) < eps ? 0 : l.a) << "x" << std::showpos;
129     out << (fabs(l.b) < eps ? 0 : l.b) << "y";
130     out << (fabs(l.c) < eps ? 0 : l.c) << "=0" << std::noshowpos;
131     return out;
132 }
133 };
134
135 /** Example Usage */
136
137 #include <cassert>
138
139 int main() {
140     line l(2, -5, -8);
141     line para = line(2, -5, -8).parallel(point(-6, -2));
142     line perp = line(2, -5, -8).perpendicular(point(-6, -2));
143     assert(l.parallel(para) && l.perpendicular(perp));
144     assert(l.slope() == 0.4);
145     assert(para == line(-0.4, 1, -0.4)); // -0.4x+1y-0.4=0
146     assert(perp == line(2.5, 1, 17));    // 2.5x+1y+17=0
147     return 0;
148 }

```

5.1.3 Circle

```

1  /*
2
3  5.1.3 - 2D Circle Class
4
5  A 2D circle with center at (h, k) and a radius of r can be expressed by
6  the relation (x - h)^2 + (y - k)^2 = r^2. In the following definition,
7  the radius used to construct it is forced to be a positive number.
8
9  All operations are O(1) in time and space.
10
11 */
12
13 #include <cmath>      /* fabs(), sqrt() */
14 #include <ostream>
15 #include <stdexcept> /* std::runtime_error() */
16 #include <utility>    /* std::pair */
17

```

```

18  const double eps = 1e-9;
19
20  #define EQ(a, b) (fabs((a) - (b)) <= eps) /* equal to */
21  #define GT(a, b) ((a) > (b) + eps)      /* greater than */
22  #define LE(a, b) ((a) <= (b) + eps)     /* less than or equal to */
23
24  typedef std::pair<double, double> point;
25  #define x first
26  #define y second
27
28  double norm(const point & a) { return a.x * a.x + a.y * a.y; }
29  double abs(const point & a) { return sqrt(norm(a)); }
30
31  struct circle {
32
33      double h, k, r;
34
35      circle(): h(0), k(0), r(0) {}
36      circle(const double & R): h(0), k(0), r(fabs(R)) {}
37      circle(const point & o, const double & R): h(o.x), k(o.y), r(fabs(R)) {}
38      circle(const double & H, const double & K, const double & R):
39          h(H), k(K), r(fabs(R)) {}
40
41      //circumcircle with the diameter equal to the distance from a to b
42      circle(const point & a, const point & b) {
43          h = (a.x + b.x) / 2.0;
44          k = (a.y + b.y) / 2.0;
45          r = abs(point(a.x - h, a.y - k));
46      }
47
48      //circumcircle of 3 points - throws exception if abc are collinear/equal
49      circle(const point & a, const point & b, const point & c) {
50          double an = norm(point(b.x - c.x, b.y - c.y));
51          double bn = norm(point(a.x - c.x, a.y - c.y));
52          double cn = norm(point(a.x - b.x, a.y - b.y));
53          double wa = an * (bn + cn - an);
54          double wb = bn * (an + cn - bn);
55          double wc = cn * (an + bn - cn);
56          double w = wa + wb + wc;
57          if (fabs(w) < eps)
58              throw std::runtime_error("No circle from collinear points.");
59          h = (wa * a.x + wb * b.x + wc * c.x) / w;
60          k = (wa * a.y + wb * b.y + wc * c.y) / w;
61          r = abs(point(a.x - h, a.y - k));
62      }
63
64      //circle from 2 points and a radius - many possible edge cases!
65      //in the "normal" case, there will be 2 possible circles, one
66      //centered at (h1, k1) and the other (h2, k2). Only one is used.
67      //note that (h1, k1) equals (h2, k2) if dist(a, b) = 2 * r = d
68      circle(const point & a, const point & b, const double & R) {
69          r = fabs(R);
70          if (LE(r, 0) && a == b) { //circle is a point
71              h = a.x;
72              k = a.y;
73              return;
74          }
75          double d = abs(point(b.x - a.x, b.y - a.y));
76          if (EQ(d, 0))

```

```

77     throw std::runtime_error("Identical_points,_infinite_circles.");
78     if (GT(d, r * 2.0))
79         throw std::runtime_error("Points_too_far_away_to_make_circle.");
80     double v = sqrt(r * r - d * d / 4.0) / d;
81     point m((a.x + b.x) / 2.0, (a.y + b.y) / 2.0);
82     h = m.x + (a.y - b.y) * v;
83     k = m.y + (b.x - a.x) * v;
84     //other answer is (h, k) = (m.x-(a.y-b.y)*v, m.y-(b.x-a.x)*v)
85 }
86
87 bool operator == (const circle & c) const {
88     return EQ(h, c.h) && EQ(k, c.k) && EQ(r, c.r);
89 }
90
91 bool operator != (const circle & c) const {
92     return !(*this == c);
93 }
94
95 bool contains(const point & p) const {
96     return LE(norm(point(p.x - h, p.y - k)), r * r);
97 }
98
99 bool on_edge(const point & p) const {
100     return EQ(norm(point(p.x - h, p.y - k)), r * r);
101 }
102
103 point center() const {
104     return point(h, k);
105 }
106
107 friend std::ostream & operator << (std::ostream & out, const circle & c) {
108     out << std::showpos;
109     out << "(x" << -(fabs(c.h) < eps ? 0 : c.h) << ")^2+";
110     out << "(y" << -(fabs(c.k) < eps ? 0 : c.k) << ")^2";
111     out << std::noshowpos;
112     out << "=" << (fabs(c.r) < eps ? 0 : c.r * c.r);
113     return out;
114 }
115 };
116
117 //circle inscribed within points a, b, and c
118 circle incircle(const point & a, const point & b, const point & c) {
119     double al = abs(point(b.x - c.x, b.y - c.y));
120     double bl = abs(point(a.x - c.x, a.y - c.y));
121     double cl = abs(point(a.x - b.x, a.y - b.y));
122     double p = al + bl + cl;
123     if (EQ(p, 0)) return circle(a.x, a.y, 0);
124     circle res;
125     res.h = (al * a.x + bl * b.x + cl * c.x) / p;
126     res.k = (al * a.y + bl * b.y + cl * c.y) / p;
127     res.r = fabs((a.x - c.x) * (b.y - c.y) - (a.y - c.y) * (b.x - c.x)) / p;
128     return res;
129 }
130
131 /** Example Usage */
132
133 #include <cassert>
134
135 int main() {

```

```

136   circle c(-2, 5, sqrt(10)); //(x+2)^2+(y-5)^2=10
137   assert(c == circle(point(-2, 5), sqrt(10)));
138   assert(c == circle(point(1, 6), point(-5, 4)));
139   assert(c == circle(point(-3, 2), point(-3, 8), point(-1, 8)));
140   assert(c == incircle(point(-12, 5), point(3, 0), point(0, 9)));
141   assert(c.contains(point(-2, 8)) && !c.contains(point(-2, 9)));
142   assert(c.on_edge(point(-1, 2)) && !c.on_edge(point(-1.01, 2)));
143   return 0;
144 }

```

5.2 Geometric Calculations

5.2.1 Angles

```

1  /*
2
3  5.2.1 - Angles (2D)
4
5  Angle calculations in 2 dimensions. All returned angles are in radians,
6  except for reduce_deg(). If x is an angle in radians, then you may use
7  x * DEG to convert x to degrees, and vice versa to radians with x * RAD.
8
9  All operations are O(1) in time and space.
10
11 */
12
13 #include <cmath>      /* acos(), fabs(), sqrt(), atan2() */
14 #include <utility>    /* std::pair */
15
16 typedef std::pair<double, double> point;
17 #define x first
18 #define y second
19
20 const double PI = acos(-1.0), RAD = 180 / PI, DEG = PI / 180;
21
22 double abs(const point & a) { return sqrt(a.x * a.x + a.y * a.y); }
23
24 //reduce angles to the range [0, 360) degrees. e.g. reduce_deg(-630) = 90
25 double reduce_deg(const double & t) {
26     if (t < -360) return reduce_deg(fmod(t, 360));
27     if (t < 0) return t + 360;
28     return t >= 360 ? fmod(t, 360) : t;
29 }
30
31 //reduce angles to the range [0, 2*pi) radians. e.g. reduce_rad(720.5) = 0.5
32 double reduce_rad(const double & t) {
33     if (t < -2 * PI) return reduce_rad(fmod(t, 2 * PI));
34     if (t < 0) return t + 2 * PI;
35     return t >= 2 * PI ? fmod(t, 2 * PI) : t;
36 }
37
38 //like std::polar(), but returns a point instead of an std::complex
39 point polar_point(const double & r, const double & theta) {
40     return point(r * cos(theta), r * sin(theta));
41 }
42

```

```

43 //angle of segment (0, 0) to p, relative (CCW) to the +ve x-axis in radians
44 double polar_angle(const point & p) {
45     double t = atan2(p.y, p.x);
46     return t < 0 ? t + 2 * PI : t;
47 }
48
49 //smallest angle formed by points aob (angle is at point o) in radians
50 double angle(const point & a, const point & o, const point & b) {
51     point u(o.x - a.x, o.y - a.y), v(o.x - b.x, o.y - b.y);
52     return acos((u.x * v.x + u.y * v.y) / (abs(u) * abs(v)));
53 }
54
55 //angle of line segment ab relative (CCW) to the +ve x-axis in radians
56 double angle_between(const point & a, const point & b) {
57     double t = atan2(a.x * b.y - a.y * b.x, a.x * b.x + a.y * b.y);
58     return t < 0 ? t + 2 * PI : t;
59 }
60
61 //Given the A, B values of two lines in Ax + By + C = 0 form, finds the
62 //minimum angle in radians between the two lines in the range [0, PI/2]
63 double angle_between(const double & a1, const double & b1,
64                     const double & a2, const double & b2) {
65     double t = atan2(a1 * b2 - a2 * b1, a1 * a2 + b1 * b2);
66     if (t < 0) t += PI; //force angle to be positive
67     if (t > PI / 2) t = PI - t; //force angle to be <= 90 degrees
68     return t;
69 }
70
71 //magnitude of the 3D cross product with Z component implicitly equal to 0
72 //the answer assumes the origin (0, 0) is instead shifted to point o.
73 //this is equal to 2x the signed area of the triangle from these 3 points.
74 double cross(const point & o, const point & a, const point & b) {
75     return (a.x - o.x) * (b.y - o.y) - (a.y - o.y) * (b.x - o.x);
76 }
77
78 //does the path a->o->b form:
79 // -1 ==> a left turn on the plane?
80 // 0 ==> a single straight line segment? (i.e. are a,o,b collinear?) or
81 // +1 ==> a right turn on the plane?
82 //warning: the order of parameters is a,o,b, and NOT o,a,b as in cross()
83 int turn(const point & a, const point & o, const point & b) {
84     double c = cross(o, a, b);
85     return c < 0 ? -1 : (c > 0 ? 1 : 0);
86 }
87
88 /** Example Usage */
89
90 #include <cassert>
91 #define pt point
92 #define EQ(a, b) (fabs((a) - (b)) <= 1e-9)
93
94 int main() {
95     assert(EQ(123, reduce_deg(-(8 * 360) + 123)));
96     assert(EQ(1.2345, reduce_rad(2 * PI * 8 + 1.2345)));
97     point p = polar_point(4, PI), q = polar_point(4, -PI / 2);
98     assert(EQ(p.x, -4) && EQ(p.y, 0));
99     assert(EQ(q.x, 0) && EQ(q.y, -4));
100     assert(EQ(45, polar_angle(pt(5, 5)) * RAD));
101     assert(EQ(135, polar_angle(pt(-4, 4)) * RAD));

```



```

102  assert(EQ(90,  angle(pt(5, 0), pt(0, 5), pt(-5, 0)) * RAD));
103  assert(EQ(225, angle_between(pt(0, 5), pt(5, -5)) * RAD));
104  assert(EQ(90,  angle_between(-1, 1, -1, -1) * RAD)); //y=x and y=-x
105  assert(-1 == cross(pt(0, 0), pt(0, 1), pt(1, 0)));
106  assert(+1 == turn(pt(0, 1), pt(0, 0), pt(-5, -5)));
107  return 0;
108  }

```

5.2.2 Distances

```

1  /*
2
3  5.2.2 - Distances (2D)
4
5  Distance calculations in 2 dimensions between points, lines, and segments.
6  All operations are O(1) in time and space.
7
8  */
9
10 #include <algorithm> /* std::max(), std::min() */
11 #include <cmath>     /* fabs(), sqrt() */
12 #include <utility>   /* std::pair */
13
14 typedef std::pair<double, double> point;
15 #define x first
16 #define y second
17
18 const double eps = 1e-9;
19
20 #define EQ(a, b) (fabs((a) - (b)) <= eps) /* equal to */
21 #define LE(a, b) ((a) <= (b) + eps)      /* less than or equal to */
22 #define GE(a, b) ((a) >= (b) - eps)      /* greater than or equal to */
23
24 double norm(const point & a) { return a.x * a.x + a.y * a.y; }
25 double abs(const point & a) { return sqrt(norm(a)); }
26
27 //distance from point a to point b
28 double dist(const point & a, const point & b) {
29     return abs(point(b.x - a.x, b.y - a.y));
30 }
31
32 //squared distance from point a to point b
33 double dist2(const point & a, const point & b) {
34     return norm(point(b.x - a.x, b.y - a.y));
35 }
36
37 //minimum distance from point p to line l denoted by ax + by + c = 0
38 //if a = b = 0, then -inf, nan, or +inf is returned depending on sgn(c)
39 double dist_line(const point & p,
40                 const double & a, const double & b, const double & c) {
41     return fabs(a * p.x + b * p.y + c) / sqrt(a * a + b * b);
42 }
43
44 //minimum distance from point p to the infinite line containing a and b
45 //if a = b, then the point distance from p to the single point is returned
46 double dist_line(const point & p, const point & a, const point & b) {
47     double ab2 = dist2(a, b);

```

```

48     if (EQ(ab2, 0)) return dist(p, a);
49     double u = ((p.x - a.x) * (b.x - a.x) + (p.y - a.y) * (b.y - a.y)) / ab2;
50     return abs(point(a.x + u * (b.x - a.x) - p.x, a.y + u * (b.y - a.y) - p.y));
51 }
52
53 //distance between two lines each denoted by the form ax + by + c = 0
54 //if the lines are nonparallel, then the distance is 0, otherwise
55 //it is the perpendicular distance from a point on one line to the other
56 double dist_lines(const double & a1, const double & b1, const double & c1,
57                  const double & a2, const double & b2, const double & c2) {
58     if (EQ(a1 * b2, a2 * b1)) {
59         double factor = EQ(b1, 0) ? (a1 / a2) : (b1 / b2);
60         if (EQ(c1, c2 * factor)) return 0;
61         return fabs(c2 * factor - c1) / sqrt(a1 * a1 + b1 * b1);
62     }
63     return 0;
64 }
65
66 //distance between two infinite lines respectively containing ab and cd
67 //same results as above, except we solve for the lines here first.
68 double dist_lines(const point & a, const point & b,
69                  const point & c, const point & d) {
70     double A1 = a.y - b.y, B1 = b.x - a.x;
71     double A2 = c.y - d.y, B2 = d.x - c.x;
72     double C1 = -A1 * a.x - B1 * a.y, C2 = -A2 * c.x - B2 * c.y;
73     return dist_lines(A1, B1, C1, A2, B2, C2);
74 }
75
76 //minimum distance from point p to any point on segment ab
77 double dist_seg(const point & p, const point & a, const point & b) {
78     if (a == b) return dist(p, a);
79     point ab(b.x - a.x, b.y - a.y), ap(p.x - a.x, p.y - a.y);
80     double n = norm(ab), d = ab.x * ap.x + ab.y * ap.y;
81     if (LE(d, 0) || EQ(n, 0)) return abs(ap);
82     if (GE(d, n)) return abs(point(ap.x - ab.x, ap.y - ab.y));
83     return abs(point(ap.x - ab.x * (d / n), ap.y - ab.y * (d / n)));
84 }
85
86 double dot(const point & a, const point & b) { return a.x * b.x + a.y * b.y; }
87 double cross(const point & a, const point & b) { return a.x * b.y - a.y * b.x; }
88
89 //minimum distance from any point on segment ab to any point on segment cd
90 double dist_segs(const point & a, const point & b,
91                 const point & c, const point & d) {
92     //check if segments are touching or intersecting - if so, distance is 0
93     point ab(b.x - a.x, b.y - a.y);
94     point ac(c.x - a.x, c.y - a.y);
95     point cd(d.x - c.x, d.y - c.y);
96     double c1 = cross(ab, cd), c2 = cross(ac, ab);
97     if (EQ(c1, 0) && EQ(c2, 0)) {
98         double t0 = dot(ac, ab) / norm(ab);
99         double t1 = t0 + dot(cd, ab) / norm(ab);
100         if (LE(std::min(t0, t1), 1) && LE(0, std::max(t0, t1)))
101             return 0;
102     } else {
103         double t = cross(ac, cd) / c1, u = c2 / c1;
104         if (!EQ(c1, 0) && LE(0, t) && LE(t, 1) && LE(0, u) && LE(u, 1))
105             return 0;
106     }

```

```

107 //find min distances across each endpoint to opposing segment
108 return std::min(std::min(dist_seg(a, c, d), dist_seg(b, c, d)),
109                std::min(dist_seg(c, a, b), dist_seg(d, a, b)));
110 }
111
112 /** Example Usage */
113
114 #include <cassert>
115 #define pt point
116
117 int main() {
118     assert(EQ(5, dist(pt(-1, -1), pt(2, 3))));
119     assert(EQ(25, dist2(pt(-1, -1), pt(2, 3))));
120     assert(EQ(1.2, dist_line(pt(2, 1), -4, 3, -1)));
121     assert(EQ(0.8, dist_line(pt(3, 3), pt(-1, -1), pt(2, 3))));
122     assert(EQ(1.2, dist_line(pt(2, 1), pt(-1, -1), pt(2, 3))));
123     assert(EQ(0.0, dist_lines(-4, 3, -1, 8, 6, 2)));
124     assert(EQ(0.8, dist_lines(-4, 3, -1, -8, 6, -10)));
125     assert(EQ(1.0, dist_seg(pt(3, 3), pt(-1, -1), pt(2, 3))));
126     assert(EQ(1.2, dist_seg(pt(2, 1), pt(-1, -1), pt(2, 3))));
127     assert(EQ(0.0, dist_segs(pt(0, 2), pt(3, 3), pt(-1, -1), pt(2, 3))));
128     assert(EQ(0.6, dist_segs(pt(-1, 0), pt(-2, 2), pt(-1, -1), pt(2, 3))));
129     return 0;
130 }

```

5.2.3 Line Intersections

```

1  /*
2
3  5.2.3 - Line Intersections (2D)
4
5  Intersections between straight lines, as well as between line segments
6  in 2 dimensions. Also included are functions to determine the closest
7  point to a line, which is done by finding the intersection through the
8  perpendicular. Note that you should modify the TOUCH_IS_INTERSECT flag
9  used for line segment intersection, depending on whether you wish for
10 the algorithm to consider barely touching segments to intersect.
11
12 All operations are O(1) in time and space.
13
14 */
15
16 #include <algorithm> /* std::min(), std::max() */
17 #include <cmath>     /* fabs(), sqrt() */
18 #include <utility>   /* std::pair */
19
20 typedef std::pair<double, double> point;
21 #define x first
22 #define y second
23
24 const double eps = 1e-9;
25
26 #define EQ(a, b) (fabs((a) - (b)) <= eps) /* equal to */
27 #define LT(a, b) ((a) < (b) - eps)       /* less than */
28 #define LE(a, b) ((a) <= (b) + eps)      /* less than or equal to */
29
30 //intersection of line l1 and line l2, each in ax + by + c = 0 form

```

```

31 //returns: -1, if lines do not intersect,
32 //          0, if there is exactly one intersection point, or
33 //          +1, if there are infinite intersection
34 //in the 2nd case, the intersection point is optionally stored into p
35 int line_intersection(const double & a1, const double & b1, const double & c1,
36                      const double & a2, const double & b2, const double & c2,
37                      point * p = 0) {
38     if (EQ(a1 * b2, a2 * b1))
39         return (EQ(a1 * c2, a2 * c1) || EQ(b1 * c2, b2 * c1)) ? 1 : -1;
40     if (p != 0) {
41         p->x = (b1 * c1 - b1 * c2) / (a2 * b1 - a1 * b2);
42         if (!EQ(b1, 0)) p->y = -(a1 * p->x + c1) / b1;
43         else p->y = -(a2 * p->x + c2) / b2;
44     }
45     return 0;
46 }
47
48 //intersection of line through p1, p2, and line through p2, p3
49 //returns: -1, if lines do not intersect,
50 //          0, if there is exactly one intersection point, or
51 //          +1, if there are infinite intersections
52 //in the 2nd case, the intersection point is optionally stored into p
53 int line_intersection(const point & p1, const point & p2,
54                      const point & p3, const point & p4, point * p = 0) {
55     double a1 = p2.y - p1.y, b1 = p1.x - p2.x;
56     double c1 = -(p1.x * p2.y - p2.x * p1.y);
57     double a2 = p4.y - p3.y, b2 = p3.x - p4.x;
58     double c2 = -(p3.x * p4.y - p4.x * p3.y);
59     double x = -(c1 * b2 - c2 * b1), y = -(a1 * c2 - a2 * c1);
60     double det = a1 * b2 - a2 * b1;
61     if (EQ(det, 0))
62         return (EQ(x, 0) && EQ(y, 0)) ? 1 : -1;
63     if (p != 0) *p = point(x / det, y / det);
64     return 0;
65 }
66
67 //Line Segment Intersection (http://stackoverflow.com/a/565282)
68
69 double norm(const point & a) { return a.x * a.x + a.y * a.y; }
70 double abs(const point & a) { return sqrt(norm(a)); }
71 double dot(const point & a, const point & b) { return a.x * b.x + a.y * b.y; }
72 double cross(const point & a, const point & b) { return a.x * b.y - a.y * b.x; }
73
74 //should we consider barely touching segments an intersection?
75 const bool TOUCH_IS_INTERSECT = true;
76
77 //does [l, h] contain m?
78 //precondition: l <= h
79 bool contain(const double & l, const double & m, const double & h) {
80     if (TOUCH_IS_INTERSECT) return LE(l, m) && LE(m, h);
81     return LT(l, m) && LT(m, h);
82 }
83
84 //does [l1, h1] overlap with [l2, h2]?
85 //precondition: l1 <= h1 and l2 <= h2
86 bool overlap(const double & l1, const double & h1,
87              const double & l2, const double & h2) {
88     if (TOUCH_IS_INTERSECT) return LE(l1, h2) && LE(l2, h1);
89     return LT(l1, h2) && LT(l2, h1);

```

```

90 }
91
92 //intersection of line segment ab with line segment cd
93 //returns: -1, if segments do not intersect,
94 //          0, if there is exactly one intersection point
95 //          +1, if the intersection is another line segment
96 //In case 2, the intersection point is stored into p
97 //In case 3, the intersection segment is stored into p and q
98 int seg_intersection(const point & a, const point & b,
99                    const point & c, const point & d,
100                    point * p = 0, point * q = 0) {
101     point ab(b.x - a.x, b.y - a.y);
102     point ac(c.x - a.x, c.y - a.y);
103     point cd(d.x - c.x, d.y - c.y);
104     double c1 = cross(ab, cd), c2 = cross(ac, ab);
105     if (EQ(c1, 0) && EQ(c2, 0)) { //collinear
106         double t0 = dot(ac, ab) / norm(ab);
107         double t1 = t0 + dot(cd, ab) / norm(ab);
108         if (overlap(std::min(t0, t1), std::max(t0, t1), 0, 1)) {
109             point res1 = std::max(std::min(a, b), std::min(c, d));
110             point res2 = std::min(std::max(a, b), std::max(c, d));
111             if (res1 == res2) {
112                 if (p != 0) *p = res1;
113                 return 0; //collinear, meeting at an endpoint
114             }
115             if (p != 0 && q != 0) *p = res1, *q = res2;
116             return 1; //collinear and overlapping
117         } else {
118             return -1; //collinear and disjoint
119         }
120     }
121     if (EQ(c1, 0)) return -1; //parallel and disjoint
122     double t = cross(ac, cd) / c1, u = c2 / c1;
123     if (contain(0, t, 1) && contain(0, u, 1)) {
124         if (p != 0) *p = point(a.x + t * ab.x, a.y + t * ab.y);
125         return 0; //non-parallel with one intersection
126     }
127     return -1; //non-parallel with no intersections
128 }
129
130 //determines the point on line ax + by + c = 0 that is closest to point p
131 //this always lies on the line through p perpendicular to l.
132 point closest_point(const double & a, const double & b, const double & c,
133                   const point & p) {
134     if (EQ(a, 0)) return point(p.x, -c); //horizontal line
135     if (EQ(b, 0)) return point(-c, p.y); //vertical line
136     point res;
137     line_intersection(a, b, c, -b, a, b * p.x - a * p.y, &res);
138     return res;
139 }
140
141 //determines the point on segment ab closest to point p
142 point closest_point(const point & a, const point & b, const point & p) {
143     if (a == b) return a;
144     point ap(p.x - a.x, p.y - a.y), ab(b.x - a.x, b.y - a.y);
145     double t = dot(ap, ab) / norm(ab);
146     if (t <= 0) return a;
147     if (t >= 1) return b;
148     return point(a.x + t * ab.x, a.y + t * ab.y);

```

```

149 }
150
151 /** Example Usage **/
152
153 #include <cassert>
154 #define pt point
155
156 int main() {
157     point p;
158     assert(line_intersection(-1, 1, 0, 1, 1, -3, &p) == 0);
159     assert(p == pt(1.5, 1.5));
160     assert(line_intersection(pt(0, 0), pt(1, 1), pt(0, 4), pt(4, 0), &p) == 0);
161     assert(p == pt(2, 2));
162
163     //tests for segment intersection (examples in order from link below)
164     //http://martin-thoma.com/how-to-check-if-two-line-segments-intersect/
165     {
166 #define test(a,b,c,d,e,f,g,h) seg_intersection(pt(a,b),pt(c,d),pt(e,f),pt(g,h),&p,&q)
167         pt p, q;
168         //intersection is a point
169         assert(0 == test(-4, 0, 4, 0, 0, -4, 0, 4));    assert(p == pt(0, 0));
170         assert(0 == test(0, 0, 10, 10, 2, 2, 16, 4));  assert(p == pt(2, 2));
171         assert(0 == test(-2, 2, -2, -2, -2, 0, 0, 0)); assert(p == pt(-2, 0));
172         assert(0 == test(0, 4, 4, 4, 4, 0, 4, 8));     assert(p == pt(4, 4));
173
174         //intersection is a segment
175         assert(1 == test(10, 10, 0, 0, 2, 2, 6, 6));
176         assert(p == pt(2, 2) && q == pt(6, 6));
177         assert(1 == test(6, 8, 14, -2, 14, -2, 6, 8));
178         assert(p == pt(6, 8) && q == pt(14, -2));
179
180         //no intersection
181         assert(-1 == test(6, 8, 8, 10, 12, 12, 4, 4));
182         assert(-1 == test(-4, 2, -8, 8, 0, 0, -4, 6));
183         assert(-1 == test(4, 4, 4, 6, 0, 2, 0, 0));
184         assert(-1 == test(4, 4, 6, 4, 0, 2, 0, 0));
185         assert(-1 == test(-2, -2, 4, 4, 10, 10, 6, 6));
186         assert(-1 == test(0, 0, 2, 2, 4, 0, 1, 4));
187         assert(-1 == test(2, 2, 2, 8, 4, 4, 6, 4));
188         assert(-1 == test(4, 2, 4, 4, 0, 8, 10, 0));
189     }
190     assert(pt(2.5, 2.5) == closest_point(-1, -1, 5, pt(0, 0)));
191     assert(pt(3, 0) == closest_point(1, 0, -3, pt(0, 0)));
192     assert(pt(0, 3) == closest_point(0, 1, -3, pt(0, 0)));
193
194     assert(pt(3, 0) == closest_point(pt(3, 0), pt(3, 3), pt(0, 0)));
195     assert(pt(2, -1) == closest_point(pt(2, -1), pt(4, -1), pt(0, 0)));
196     assert(pt(4, -1) == closest_point(pt(2, -1), pt(4, -1), pt(5, 0)));
197     return 0;
198 }

```

5.2.4 Circle Intersections

```

1  /*
2
3  5.2.4 - Circle Intersection (2D)
4

```

```

5  Tangent lines to circles, circle-line intersections, and circle-circle
6  intersections (intersection point(s) as well as area) in 2 dimensions.
7
8  All operations are O(1) in time and space.
9
10 */
11
12 #include <algorithm> /* std::min(), std::max() */
13 #include <cmath>     /* acos(), fabs(), sqrt() */
14 #include <utility>   /* std::pair */
15
16 typedef std::pair<double, double> point;
17 #define x first
18 #define y second
19
20 const double eps = 1e-9;
21
22 #define EQ(a, b) (fabs((a) - (b)) <= eps) /* equal to */
23 #define NE(a, b) (fabs((a) - (b)) > eps) /* not equal to */
24 #define LT(a, b) ((a) < (b) - eps)      /* less than */
25 #define GT(a, b) ((a) > (b) + eps)      /* greater than */
26 #define LE(a, b) ((a) <= (b) + eps)     /* less than or equal to */
27 #define GE(a, b) ((a) >= (b) - eps)     /* greater than or equal to */
28
29 struct circle {
30     double h, k, r;
31
32     circle(const double & h, const double & k, const double & r) {
33         this->h = h;
34         this->k = k;
35         this->r = r;
36     }
37 };
38
39 //note: this is a simplified version of line that is not canonicalized.
40 // e.g. comparing lines with == signs will not work as intended. For a
41 // fully featured line class, see the whole geometry library.
42 struct line {
43     double a, b, c;
44
45     line() { a = b = c = 0; }
46
47     line(const double & a, const double & b, const double & c) {
48         this->a = a;
49         this->b = b;
50         this->c = c;
51     }
52
53     line(const point & p, const point & q) {
54         a = p.y - q.y,
55         b = q.x - p.x;
56         c = -a * p.x - b * p.y;
57     }
58 };
59
60 double norm(const point & a) { return a.x * a.x + a.y * a.y; }
61 double abs(const point & a) { return sqrt(norm(a)); }
62 double dot(const point & a, const point & b) { return a.x * b.x + a.y * b.y; }
63

```

```

64 //tangent line(s) to circle c passing through p. there are 3 cases:
65 //returns: 0, if there are no lines (p is strictly inside c)
66 //          1, if there is 1 tangent line (p is on the edge)
67 //          2, if there are 2 tangent lines (p is strictly outside)
68 //If there is only 1 tangent, then the line will be stored in l1.
69 //If there are 2, then they will be stored in l1 and l2 respectively.
70 int tangents(const circle & c, const point & p, line * l1 = 0, line * l2 = 0) {
71     point vop(p.x - c.h, p.y - c.k);
72     if (EQ(norm(vop), c.r * c.r)) { //on an edge, get perpendicular through p
73         if (l1 != 0) {
74             *l1 = line(point(c.h, c.k), p);
75             *l1 = line(-l1->b, l1->a, l1->b * p.x - l1->a * p.y);
76         }
77         return 1;
78     }
79     if (LE(norm(vop), c.r * c.r)) return 0; //inside circle
80     point q(vop.x / c.r, vop.y / c.r);
81     double n = norm(q), d = q.y * sqrt(norm(q) - 1.0);
82     point t1((q.x - d) / n, c.k), t2((q.x + d) / n, c.k);
83     if (NE(q.y, 0)) { //common case
84         t1.y += c.r * (1.0 - t1.x * q.x) / q.y;
85         t2.y += c.r * (1.0 - t2.x * q.x) / q.y;
86     } else { //point at center horizontal, y = 0
87         d = c.r * sqrt(1.0 - t1.x * t1.x);
88         t1.y += d;
89         t2.y -= d;
90     }
91     t1.x = t1.x * c.r + c.h;
92     t2.x = t2.x * c.r + c.h;
93     //note: here, t1 and t2 are the two points of tangencies
94     if (l1 != 0) *l1 = line(p, t1);
95     if (l2 != 0) *l2 = line(p, t2);
96     return 2;
97 }
98
99 //determines the intersection(s) between a circle c and line l
100 //returns: 0, if the line does not intersect with the circle
101 //          1, if the line is tangent (one intersection)
102 //          2, if the line crosses through the circle
103 //If there is 1 intersection point, it will be stored in p
104 //If there are 2, they will be stored in p and q respectively
105 int intersection(const circle & c, const line & l,
106                 point * p = 0, point * q = 0) {
107     double v = c.h * l.a + c.k * l.b + l.c;
108     double aabb = l.a * l.a + l.b * l.b;
109     double disc = v * v / aabb - c.r * c.r;
110     if (disc > eps) return 0;
111     double x0 = -l.a * l.c / aabb, y0 = -l.b * v / aabb;
112     if (disc > -eps) {
113         if (p != 0) *p = point(x0 + c.h, y0 + c.k);
114         return 1;
115     }
116     double k = sqrt((disc /= -aabb) < 0 ? 0 : disc);
117     if (p != 0) *p = point(x0 + k * l.b + c.h, y0 - k * l.a + c.k);
118     if (q != 0) *q = point(x0 - k * l.b + c.h, y0 + k * l.a + c.k);
119     return 2;
120 }
121
122 //determines the intersection points between two circles c1 and c2

```



```

123 //returns: -2, if circle c2 completely encloses circle c1
124 //          -1, if circle c1 completely encloses circle c2
125 //          0, if the circles are completely disjoint
126 //          1, if the circles are tangent (one intersection point)
127 //          2, if the circles intersect at two points
128 //          3, if the circles intersect at infinite points (c1 = c2)
129 //If one intersection, the intersection point is stored in p
130 //If two, the intersection points are stored in p and q respectively
131 int intersection(const circle & c1, const circle & c2,
132                 point * p = 0, point * q = 0) {
133     if (EQ(c1.h, c2.h) && EQ(c1.k, c2.k))
134         return EQ(c1.r, c2.r) ? 3 : (c1.r > c2.r ? -1 : -2);
135     point d12(point(c2.h - c1.h, c2.k - c1.k));
136     double d = abs(d12);
137     if (GT(d, c1.r + c2.r)) return 0;
138     if (LT(d, fabs(c1.r - c2.r))) return c1.r > c2.r ? -1 : -2;
139     double a = (c1.r * c1.r - c2.r * c2.r + d * d) / (2 * d);
140     double x0 = c1.h + (d12.x * a / d);
141     double y0 = c1.k + (d12.y * a / d);
142     double s = sqrt(c1.r * c1.r - a * a);
143     double rx = -d12.y * s / d, ry = d12.x * s / d;
144     if (EQ(rx, 0) && EQ(ry, 0)) {
145         if (p != 0) *p = point(x0, y0);
146         return 1;
147     }
148     if (p != 0) *p = point(x0 - rx, y0 - ry);
149     if (q != 0) *q = point(x0 + rx, y0 + ry);
150     return 2;
151 }
152
153 const double PI = acos(-1.0);
154
155 //intersection area of circles c1 and c2
156 double intersection_area(const circle & c1, const circle & c2) {
157     double r = std::min(c1.r, c2.r), R = std::max(c1.r, c2.r);
158     double d = abs(point(c2.h - c1.h, c2.k - c1.k));
159     if (LE(d, R - r)) return PI * r * r;
160     if (GE(d, R + r)) return 0;
161     return r * r * acos((d * d + r * r - R * R) / 2 / d / r) +
162         R * R * acos((d * d + R * R - r * r) / 2 / d / R) -
163         0.5 * sqrt((-d + r + R) * (d + r - R) * (d - r + R) * (d + r + R));
164 }
165
166 /** Example Usage */
167
168 #include <cassert>
169 #include <iostream>
170 using namespace std;
171 #define pt point
172
173 int main() {
174     line l1, l2;
175     assert(0 == tangents(circle(0, 0, 4), pt(1, 1), &l1, &l2));
176     assert(1 == tangents(circle(0, 0, sqrt(2)), pt(1, 1), &l1, &l2));
177     cout << l1.a << " " << l1.b << " " << l1.c << "\n"; // -x - y + 2 = 0
178     assert(2 == tangents(circle(0, 0, 2), pt(2, 2), &l1, &l2));
179     cout << l1.a << " " << l1.b << " " << l1.c << "\n"; // -2y + 4 = 0
180     cout << l2.a << " " << l2.b << " " << l2.c << "\n"; // 2x - 4 = 0
181

```

```

182 pt p, q;
183 assert(0 == intersection(circle(1, 1, 3), line(5, 3, -30), &p, &q));
184 assert(1 == intersection(circle(1, 1, 3), line(0, 1, -4), &p, &q));
185 assert(p == pt(1, 4));
186 assert(2 == intersection(circle(1, 1, 3), line(0, 1, -1), &p, &q));
187 assert(p == pt(4, 1));
188 assert(q == pt(-2, 1));
189
190 assert(-2 == intersection(circle(1, 1, 1), circle(0, 0, 3), &p, &q));
191 assert(-1 == intersection(circle(0, 0, 3), circle(1, 1, 1), &p, &q));
192 assert(0 == intersection(circle(5, 0, 4), circle(-5, 0, 4), &p, &q));
193 assert(1 == intersection(circle(-5, 0, 5), circle(5, 0, 5), &p, &q));
194 assert(p == pt(0, 0));
195 assert(2 == intersection(circle(-0.5, 0, 1), circle(0.5, 0, 1), &p, &q));
196 assert(p == pt(0, -sqrt(3) / 2));
197 assert(q == pt(0, sqrt(3) / 2));
198
199 //example where each circle passes through the other circle's center
200 //http://math.stackexchange.com/a/402891
201 double r = 3;
202 double a = intersection_area(circle(-r / 2, 0, r), circle(r / 2, 0, r));
203 assert(EQ(a, r * r * (2 * PI / 3 - sqrt(3) / 2)));
204 return 0;
205 }

```

5.3 Common Geometric Computations

5.3.1 Polygon Sorting and Area

```

1  /*
2
3  5.3.1 - Polygon Sorting and Area
4
5  centroid() - Simply returns the geometric average point of all the
6  points given. This could be used to find the reference center point
7  for the following function. An empty range will result in (0, 0).
8  Complexity: O(n) on the number of points in the given range.
9
10 cw_comp() - Given a set of points, these points could possibly form
11 many different polygons. The following sorting comparators, when
12 used in conjunction with std::sort, will produce one such ordering
13 of points which is sorted in clockwise order relative to a custom-
14 defined center point that must be set beforehand. This could very
15 well be the result of mean_point(). ccw_comp() is the opposite
16 function, which produces the points in counterclockwise order.
17 Complexity: O(1) per call.
18
19 polygon_area() - A given range of points is interpreted as a polygon
20 based on the ordering they're given in. The shoelace formula is used
21 to determine its area. The polygon does not necessarily have to be
22 sorted using one of the functions above, but may be any ordering that
23 produces a valid polygon. You may optionally pass the last point in
24 the range equal to the first point and still expect the correct result.
25 Complexity: O(n) on the number of points in the range, assuming that
26 the points are already sorted in the order that specifies the polygon.
27

```

```

28 */
29
30 #include <algorithm> /* std::sort() */
31 #include <cmath>     /* fabs() */
32 #include <utility>   /* std::pair */
33
34 typedef std::pair<double, double> point;
35 #define x first
36 #define y second
37
38 const double eps = 1e-9;
39
40 #define EQ(a, b) (fabs((a) - (b)) <= eps) /* equal to */
41 #define LT(a, b) ((a) < (b) - eps)       /* less than */
42 #define GE(a, b) ((a) >= (b) - eps)      /* greater than or equal to */
43
44 //magnitude of the 3D cross product with Z component implicitly equal to 0
45 //the answer assumes the origin (0, 0) is instead shifted to point o.
46 //this is equal to 2x the signed area of the triangle from these 3 points.
47 double cross(const point & o, const point & a, const point & b) {
48     return (a.x - o.x) * (b.y - o.y) - (a.y - o.y) * (b.x - o.x);
49 }
50
51 point ctr;
52
53 template<class It> point centroid(It lo, It hi) {
54     if (lo == hi) return point(0, 0);
55     double xtot = 0, ytot = 0, points = hi - lo;
56     for (; lo != hi; ++lo) {
57         xtot += lo->x;
58         ytot += lo->y;
59     }
60     return point(xtot / points, ytot / points);
61 }
62
63 //ctr must be defined beforehand
64 bool cw_comp(const point & a, const point & b) {
65     if (GE(a.x - ctr.x, 0) && LT(b.x - ctr.x, 0)) return true;
66     if (LT(a.x - ctr.x, 0) && GE(b.x - ctr.x, 0)) return false;
67     if (EQ(a.x - ctr.x, 0) && EQ(b.x - ctr.x, 0)) {
68         if (GE(a.y - ctr.y, 0) || GE(b.y - ctr.y, 0))
69             return a.y > b.y;
70         return b.y > a.y;
71     }
72     double det = cross(ctr, a, b);
73     if (EQ(det, 0))
74         return (a.x - ctr.x) * (a.x - ctr.x) + (a.y - ctr.y) * (a.y - ctr.y) >
75             (b.x - ctr.x) * (b.x - ctr.x) + (b.y - ctr.y) * (b.y - ctr.y);
76     return det < 0;
77 }
78
79 bool ccw_comp(const point & a, const point & b) {
80     return cw_comp(b, a);
81 }
82
83 //area of a polygon specified by range [lo, hi) - shoelace formula in O(n)
84 //[lo, hi) must point to the polygon vertices, sorted in CW or CCW order
85 template<class It> double polygon_area(It lo, It hi) {
86     if (lo == hi) return 0;

```

```

87     double area = 0;
88     if (*lo != *--hi)
89         area += (lo->x - hi->x) * (lo->y + hi->y);
90     for (It i = hi, j = hi - 1; i != lo; --i, --j)
91         area += (i->x - j->x) * (i->y + j->y);
92     return fabs(area / 2.0);
93 }
94
95 /** Example Usage **/
96
97 #include <cassert>
98 #include <vector>
99 using namespace std;
100 #define pt point
101
102 int main() {
103     //irregular pentagon with only (1, 2) not on the convex hull
104     //the ordering here is already sorted in ccw order around their centroid
105     //we will scramble them and see if our comparator works
106     pt pts[] = {pt(1, 3), pt(1, 2), pt(2, 1), pt(0, 0), pt(-1, 3)};
107     vector<pt> v(pts, pts + 5);
108     std::random_shuffle(v.begin(), v.end());
109     ctr = centroid(v.begin(), v.end()); //note: ctr is a global variable
110     assert(EQ(ctr.x, 0.6) && EQ(ctr.y, 1.8));
111     sort(v.begin(), v.end(), cw_comp);
112     for (int i = 0; i < (int)v.size(); i++) assert(v[i] == pts[i]);
113     assert(EQ(polygon_area(v.begin(), v.end()), 5));
114     return 0;
115 }

```

5.3.2 Point in Polygon Query

```

1  /*
2
3  5.3.2 - Point in Polygon Query
4
5  Given a single point p and another range of points specifying a
6  polygon, determine whether p lies within the polygon. Note that
7  you should modify the EDGE_IS_INSIDE flag, depending on whether
8  you wish for the algorithm to consider points lying on an edge of
9  the polygon to be inside it.
10
11 Complexity: O(n) on the number of vertices in the polygon.
12
13 */
14
15 #include <algorithm> /* std::sort() */
16 #include <cmath>     /* fabs() */
17 #include <utility>   /* std::pair */
18
19 typedef std::pair<double, double> point;
20 #define x first
21 #define y second
22
23 const double eps = 1e-9;
24
25 #define EQ(a, b) (fabs((a) - (b)) <= eps) /* equal to */

```

```

26 #define GT(a, b) ((a) > (b) + eps)          /* greater than */
27 #define LE(a, b) ((a) <= (b) + eps)         /* less than or equal to */
28
29 //should we consider points lying on an edge to be inside the polygon?
30 const bool EDGE_IS_INSIDE = true;
31
32 //magnitude of the 3D cross product with Z component implicitly equal to 0
33 //the answer assumes the origin (0, 0) is instead shifted to point o.
34 //this is equal to 2x the signed area of the triangle from these 3 points.
35 double cross(const point & o, const point & a, const point & b) {
36     return (a.x - o.x) * (b.y - o.y) - (a.y - o.y) * (b.x - o.x);
37 }
38
39 //return whether point p is in polygon specified by range [lo, hi) in O(n)
40 //[lo, hi) must point to the polygon vertices, sorted in CW or CCW order
41 template<class It> bool point_in_polygon(const point & p, It lo, It hi) {
42     int cnt = 0;
43     for (It i = lo, j = hi - 1; i != hi; j = i++) {
44         if (EQ(i->y, p.y) && (EQ(i->x, p.x) ||
45             (EQ(j->y, p.y) && (LE(i->x, p.x) || LE(j->x, p.x)))))
46             return EDGE_IS_INSIDE; //on an edge
47         if (GT(i->y, p.y) != GT(j->y, p.y)) {
48             double det = cross(p, *i, *j);
49             if (EQ(det, 0)) return EDGE_IS_INSIDE; //on an edge
50             if (GT(det, 0) != GT(j->y, i->y)) cnt++;
51         }
52     }
53     return cnt % 2 == 1;
54 }
55
56 /** Example Usage */
57
58 #include <cassert>
59 using namespace std;
60 #define pt point
61
62 int main() {
63     //irregular trapezoid
64     pt p[] = {pt(-1, 3), pt(1, 3), pt(2, 1), pt(0, 0)};
65     assert(point_in_polygon(pt(1, 2), p, p + 4));
66     assert(point_in_polygon(pt(0, 3), p, p + 4));
67     assert(!point_in_polygon(pt(0, 3.01), p, p + 4));
68     assert(!point_in_polygon(pt(2, 2), p, p + 4));
69     return 0;
70 }

```

5.3.3 Convex Hull

```

1  /*
2
3  5.3.3 - 2D Convex Hull
4
5  Determines the convex hull from a range of points, that is, the
6  smallest convex polygon (a polygon such that every line which
7  crosses through it will only cross through it once) that contains
8  all of the points. This function uses the monotone chain algorithm
9  to compute the upper and lower hulls separately.

```

```

10
11 Returns: a vector of the convex hull points in clockwise order.
12 Complexity:  $O(n \log n)$  on the number of points given
13
14 Notes: To yield the hull points in counterclockwise order,
15         replace every usage of GE() in the function with LE().
16         To have the first point on the hull repeated as the last,
17         replace the last line of the function to res.resize(k);
18
19 */
20
21 #include <algorithm> /* std::sort() */
22 #include <cmath>     /* fabs() */
23 #include <utility>   /* std::pair */
24 #include <vector>
25
26 typedef std::pair<double, double> point;
27 #define x first
28 #define y second
29
30 //change < 0 comparisons to > 0 to produce hull points in CCW order
31 double cw(const point & o, const point & a, const point & b) {
32     return (a.x - o.x) * (b.y - o.y) - (a.y - o.y) * (b.x - o.x) < 0;
33 }
34
35 //convex hull from a range [lo, hi) of points
36 //monotone chain in  $O(n \log n)$  to find hull points in CW order
37 //notes: the range of input points will be sorted lexicographically
38 template<class It> std::vector<point> convex_hull(It lo, It hi) {
39     int k = 0;
40     if (hi - lo <= 1) return std::vector<point>(lo, hi);
41     std::vector<point> res(2 * (int)(hi - lo));
42     std::sort(lo, hi); //compare by x, then by y if x-values are equal
43     for (It it = lo; it != hi; ++it) {
44         while (k >= 2 && !cw(res[k - 2], res[k - 1], *it)) k--;
45         res[k++] = *it;
46     }
47     int t = k + 1;
48     for (It it = hi - 2; it != lo - 1; --it) {
49         while (k >= t && !cw(res[k - 2], res[k - 1], *it)) k--;
50         res[k++] = *it;
51     }
52     res.resize(k - 1);
53     return res;
54 }
55
56 /** Example Usage */
57
58 #include <iostream>
59 using namespace std;
60
61 int main() {
62     //irregular pentagon with only (1, 2) not on the convex hull
63     vector<point> v;
64     v.push_back(point(1, 3));
65     v.push_back(point(1, 2));
66     v.push_back(point(2, 1));
67     v.push_back(point(0, 0));
68     v.push_back(point(-1, 3));

```

```

69  std::random_shuffle(v.begin(), v.end());
70  vector<point> h = convex_hull(v.begin(), v.end());
71  cout << "hull_points:";
72  for (int i = 0; i < (int)h.size(); i++)
73      cout << " (" << h[i].x << ", " << h[i].y << ")";
74  cout << "\n";
75  return 0;
76 }

```

5.3.4 Minimum Enclosing Circle

```

1  /*
2
3  5.3.4 - Minimum Enclosing Circle (2D)
4
5  Given a range of points on the 2D cartesian plane, determine
6  the equation of the circle with smallest possible area which
7  encloses all of the points. Note: in an attempt to avoid the
8  worst case, the circles are randomly shuffled before the
9  algorithm is performed. This is not necessary to obtain the
10 correct answer, and may be removed if the input order must
11 be preserved.
12
13 Time Complexity: O(n) average on the number of points given.
14
15 */
16
17 #include <algorithm>
18 #include <cmath>
19 #include <stdexcept>
20 #include <utility>
21
22 const double eps = 1e-9;
23
24 #define LE(a, b) ((a) <= (b) + eps)      /* less than or equal to */
25
26 typedef std::pair<double, double> point;
27 #define x first
28 #define y second
29
30 double norm(const point & a) { return a.x * a.x + a.y * a.y; }
31 double abs(const point & a) { return sqrt(norm(a)); }
32
33 struct circle {
34
35     double h, k, r;
36
37     circle(): h(0), k(0), r(0) {}
38     circle(const double & H, const double & K, const double & R):
39         h(H), k(K), r(fabs(R)) {}
40
41     //circumcircle with the diameter equal to the distance from a to b
42     circle(const point & a, const point & b) {
43         h = (a.x + b.x) / 2.0;
44         k = (a.y + b.y) / 2.0;
45         r = abs(point(a.x - h, a.y - k));
46     }

```

```

47
48 //circumcircle of 3 points - throws exception if abc are collinear/equal
49 circle(const point & a, const point & b, const point & c) {
50     double an = norm(point(b.x - c.x, b.y - c.y));
51     double bn = norm(point(a.x - c.x, a.y - c.y));
52     double cn = norm(point(a.x - b.x, a.y - b.y));
53     double wa = an * (bn + cn - an);
54     double wb = bn * (an + cn - bn);
55     double wc = cn * (an + bn - cn);
56     double w = wa + wb + wc;
57     if (fabs(w) < eps)
58         throw std::runtime_error("No circle from collinear points.");
59     h = (wa * a.x + wb * b.x + wc * c.x) / w;
60     k = (wa * a.y + wb * b.y + wc * c.y) / w;
61     r = abs(point(a.x - h, a.y - k));
62 }
63
64 bool contains(const point & p) const {
65     return LE(norm(point(p.x - h, p.y - k)), r * r);
66 }
67
68 };
69
70 template<class It> circle smallest_circle(It lo, It hi) {
71     if (lo == hi) return circle(0, 0, 0);
72     if (lo + 1 == hi) return circle(lo->x, lo->y, 0);
73     std::random_shuffle(lo, hi);
74     circle res(*lo, *(lo + 1));
75     for (It i = lo + 2; i != hi; ++i) {
76         if (res.contains(*i)) continue;
77         res = circle(*lo, *i);
78         for (It j = lo + 1; j != i; ++j) {
79             if (res.contains(*j)) continue;
80             res = circle(*i, *j);
81             for (It k = lo; k != j; ++k)
82                 if (!res.contains(*k)) res = circle(*i, *j, *k);
83         }
84     }
85     return res;
86 }
87
88 /** Example Usage */
89
90 #include <iostream>
91 #include <vector>
92 using namespace std;
93
94 int main() {
95     vector<point> v;
96     v.push_back(point(0, 0));
97     v.push_back(point(0, 1));
98     v.push_back(point(1, 0));
99     v.push_back(point(1, 1));
100     circle res = smallest_circle(v.begin(), v.end());
101     cout << "center: " << res.h << ", " << res.k << ")\n";
102     cout << "radius: " << res.r << "\n";
103     return 0;
104 }

```


5.3.5 Diameter of Point Set

```

1  /*
2
3  5.3.5 - Diameter of Point Set (2D)
4
5  Determines the diametral pair of a range of points. The diameter
6  of a set of points is the largest distance between any two
7  points in the set. A diametral pair is a pair of points in the
8  set whose distance is equal to the set's diameter. The following
9  program uses rotating calipers method to find a solution.
10
11  Time Complexity:  $O(n \log n)$  on the number of points in the set.
12
13  */
14
15  #include <algorithm> /* std::sort() */
16  #include <cmath>     /* fabs(), sqrt() */
17  #include <utility>   /* std::pair */
18  #include <vector>
19
20  typedef std::pair<double, double> point;
21  #define x first
22  #define y second
23
24  double sqdist(const point & a, const point & b) {
25      double dx = a.x - b.x, dy = a.y - b.y;
26      return sqrt(dx * dx + dy * dy);
27  }
28
29  double cross(const point & o, const point & a, const point & b) {
30      return (a.x - o.x) * (b.y - o.y) - (a.y - o.y) * (b.x - o.x);
31  }
32
33  bool cw(const point & o, const point & a, const point & b) {
34      return cross(o, a, b) < 0;
35  }
36
37  double area(const point & o, const point & a, const point & b) {
38      return fabs(cross(o, a, b));
39  }
40
41  template<class It> std::vector<point> convex_hull(It lo, It hi) {
42      int k = 0;
43      if (hi - lo <= 1) return std::vector<point>(lo, hi);
44      std::vector<point> res(2 * (int)(hi - lo));
45      std::sort(lo, hi); //compare by x, then by y if x-values are equal
46      for (It it = lo; it != hi; ++it) {
47          while (k >= 2 && !cw(res[k - 2], res[k - 1], *it)) k--;
48          res[k++] = *it;
49      }
50      int t = k + 1;
51      for (It it = hi - 2; it != lo - 1; --it) {
52          while (k >= t && !cw(res[k - 2], res[k - 1], *it)) k--;
53          res[k++] = *it;
54      }
55      res.resize(k - 1);
56      return res;

```

```

57 }
58
59 template<class It> std::pair<point, point> diametral_pair(It lo, It hi) {
60     std::vector<point> h = convex_hull(lo, hi);
61     int m = h.size();
62     if (m == 1) return std::make_pair(h[0], h[0]);
63     if (m == 2) return std::make_pair(h[0], h[1]);
64     int k = 1;
65     while (area(h[m - 1], h[0], h[(k + 1) % m]) > area(h[m - 1], h[0], h[k]))
66         k++;
67     double maxdist = 0, d;
68     std::pair<point, point> res;
69     for (int i = 0, j = k; i <= k && j < m; i++) {
70         d = sqdist(h[i], h[j]);
71         if (d > maxdist) {
72             maxdist = d;
73             res = std::make_pair(h[i], h[j]);
74         }
75         while (j < m && area(h[i], h[(i + 1) % m], h[(j + 1) % m]) >
76             area(h[i], h[(i + 1) % m], h[j])) {
77             d = sqdist(h[i], h[(j + 1) % m]);
78             if (d > maxdist) {
79                 maxdist = d;
80                 res = std::make_pair(h[i], h[(j + 1) % m]);
81             }
82             j++;
83         }
84     }
85     return res;
86 }
87
88 /** Example Usage */
89
90 #include <iostream>
91 using namespace std;
92
93 int main() {
94     vector<point> v;
95     v.push_back(point(0, 0));
96     v.push_back(point(3, 0));
97     v.push_back(point(0, 3));
98     v.push_back(point(1, 1));
99     v.push_back(point(4, 4));
100     pair<point, point> res = diametral_pair(v.begin(), v.end());
101     cout << "diametral_pair:␣" << res.first.x << "," << res.first.y << "␣";
102     cout << "(" << res.second.x << "," << res.second.y << "␣\n";
103     cout << "diameter:␣" << sqrt(sqdist(res.first, res.second)) << "\n";
104     return 0;
105 }

```

5.3.6 Closest Point Pair

```

1  /*
2
3  5.3.6 - Closest Point Pair (2D)
4
5  Given a range containing distinct points on the Cartesian plane,

```

```

6  determine two points which have the closest possible distance.
7  A divide and conquer algorithm is used. Note that the ordering
8  of points in the input range may be changed by the function.
9
10 Time Complexity:  $O(n \log^2 n)$  where  $n$  is the number of points.
11
12 */
13
14 #include <algorithm> /* std::min, std::sort */
15 #include <cfloat>     /* DBL_MAX */
16 #include <cmath>      /* fabs */
17 #include <utility>    /* std::pair */
18
19 typedef std::pair<double, double> point;
20 #define x first
21 #define y second
22
23 double sqdist(const point & a, const point & b) {
24     double dx = a.x - b.x, dy = a.y - b.y;
25     return dx * dx + dy * dy;
26 }
27
28 bool cmp_x(const point & a, const point & b) { return a.x < b.x; }
29 bool cmp_y(const point & a, const point & b) { return a.y < b.y; }
30
31 template<class It>
32 double rec(It lo, It hi, std::pair<point, point> & res, double mindist) {
33     if (lo == hi) return DBL_MAX;
34     It mid = lo + (hi - lo) / 2;
35     double midx = mid->x;
36     double d1 = rec(lo, mid, res, mindist);
37     mindist = std::min(mindist, d1);
38     double d2 = rec(mid + 1, hi, res, mindist);
39     mindist = std::min(mindist, d2);
40     std::sort(lo, hi, cmp_y);
41     int size = 0;
42     It t[hi - lo];
43     for (It it = lo; it != hi; ++it)
44         if (fabs(it->x - midx) < mindist)
45             t[size++] = it;
46     for (int i = 0; i < size; i++) {
47         for (int j = i + 1; j < size; j++) {
48             point a = *t[i], b = *t[j];
49             if (b.y - a.y >= mindist) break;
50             double dist = sqdist(a, b);
51             if (mindist > dist) {
52                 mindist = dist;
53                 res = std::make_pair(a, b);
54             }
55         }
56     }
57     return mindist;
58 }
59
60 template<class It> std::pair<point, point> closest_pair(It lo, It hi) {
61     std::pair<point, point> res;
62     std::sort(lo, hi, cmp_x);
63     rec(lo, hi, res, DBL_MAX);
64     return res;

```

```

65 }
66
67 /** Example Usage **/
68
69 #include <iostream>
70 #include <vector>
71 using namespace std;
72
73 int main() {
74     vector<point> v;
75     v.push_back(point(2, 3));
76     v.push_back(point(12, 30));
77     v.push_back(point(40, 50));
78     v.push_back(point(5, 1));
79     v.push_back(point(12, 10));
80     v.push_back(point(3, 4));
81     pair<point, point> res = closest_pair(v.begin(), v.end());
82     cout << "closest_pair: (" << res.first.x << ", " << res.first.y << ") ";
83     cout << "(" << res.second.x << ", " << res.second.y << ") \n";
84     cout << "dist: " << sqrt(sqdist(res.first, res.second)) << " \n"; //1.41421
85     return 0;
86 }

```

5.3.7 Segment Intersection Finding

```

1  /*
2
3  5.3.7 - Segment Intersection Finding
4
5  Given a range of segments on the Cartesian plane, identify one
6  pair of segments which intersect each other. This is done using
7  a sweep line algorithm.
8
9  Time Complexity: O(n log n) where n is the number of segments.
10
11 */
12
13 #include <algorithm> /* std::min(), std::max(), std::sort() */
14 #include <cmath>     /* fabs() */
15 #include <set>
16 #include <utility>   /* std::pair */
17
18 typedef std::pair<double, double> point;
19 #define x first
20 #define y second
21
22 const double eps = 1e-9;
23
24 #define EQ(a, b) (fabs((a) - (b)) <= eps) /* equal to */
25 #define LT(a, b) ((a) < (b) - eps)       /* less than */
26 #define LE(a, b) ((a) <= (b) + eps)      /* less than or equal to */
27
28 double norm(const point & a) { return a.x * a.x + a.y * a.y; }
29 double dot(const point & a, const point & b) { return a.x * b.x + a.y * b.y; }
30 double cross(const point & a, const point & b) { return a.x * b.y - a.y * b.x; }
31 double cross(const point & o, const point & a, const point & b) {
32     return (a.x - o.x) * (b.y - o.y) - (a.y - o.y) * (b.x - o.x);

```

```

33 }
34
35 const bool TOUCH_IS_INTERSECT = true;
36
37 bool contain(const double & l, const double & m, const double & h) {
38     if (TOUCH_IS_INTERSECT) return LE(l, m) && LE(m, h);
39     return LT(l, m) && LT(m, h);
40 }
41
42 bool overlap(const double & l1, const double & h1,
43             const double & l2, const double & h2) {
44     if (TOUCH_IS_INTERSECT) return LE(l1, h2) && LE(l2, h1);
45     return LT(l1, h2) && LT(l2, h1);
46 }
47
48 int seg_intersection(const point & a, const point & b,
49                    const point & c, const point & d) {
50     point ab(b.x - a.x, b.y - a.y);
51     point ac(c.x - a.x, c.y - a.y);
52     point cd(d.x - c.x, d.y - c.y);
53     double c1 = cross(ab, cd), c2 = cross(ac, ab);
54     if (EQ(c1, 0) && EQ(c2, 0)) {
55         double t0 = dot(ac, ab) / norm(ab);
56         double t1 = t0 + dot(cd, ab) / norm(ab);
57         if (overlap(std::min(t0, t1), std::max(t0, t1), 0, 1)) {
58             point res1 = std::max(std::min(a, b), std::min(c, d));
59             point res2 = std::min(std::max(a, b), std::max(c, d));
60             return (res1 == res2) ? 0 : 1;
61         }
62         return -1;
63     }
64     if (EQ(c1, 0)) return -1;
65     double t = cross(ac, cd) / c1, u = c2 / c1;
66     if (contain(0, t, 1) && contain(0, u, 1)) return 0;
67     return -1;
68 }
69
70 struct segment {
71     point p, q;
72
73     segment() {}
74     segment(const point & p, const point & q) {
75         if (p < q) {
76             this->p = p;
77             this->q = q;
78         } else {
79             this->p = q;
80             this->q = p;
81         }
82     }
83
84     bool operator < (const segment & rhs) const {
85         if (p.x < rhs.p.x) {
86             double c = cross(p, q, rhs.p);
87             if (c != 0) return c > 0;
88         } else if (p.x > rhs.p.x) {
89             double c = cross(rhs.p, rhs.q, q);
90             if (c != 0) return c < 0;
91         }

```

```

92     return p.y < rhs.p.y;
93 }
94 };
95
96 template<class SegIt> struct event {
97     point p;
98     int type;
99     SegIt seg;
100
101     event() {}
102     event(const point & p, const int type, SegIt seg) {
103         this->p = p;
104         this->type = type;
105         this->seg = seg;
106     }
107
108     bool operator < (const event & rhs) const {
109         if (p.x != rhs.p.x) return p.x < rhs.p.x;
110         if (type != rhs.type) return type > rhs.type;
111         return p.y < rhs.p.y;
112     }
113 };
114
115 bool intersect(const segment & s1, const segment & s2) {
116     return seg_intersection(s1.p, s1.q, s2.p, s2.q) >= 0;
117 }
118
119 //returns whether any pair of segments in the range [lo, hi) intersect
120 //if the result is true, one such intersection pair will be stored
121 //into values pointed to by res1 and res2.
122 template<class It>
123 bool find_intersection(It lo, It hi, segment * res1, segment * res2) {
124     int cnt = 0;
125     event<It> e[2 * (hi - lo)];
126     for (It it = lo; it != hi; ++it) {
127         if (it->p > it->q) std::swap(it->p, it->q);
128         e[cnt++] = event<It>(it->p, 1, it);
129         e[cnt++] = event<It>(it->q, -1, it);
130     }
131     std::sort(e, e + cnt);
132     std::set<segment> s;
133     std::set<segment>::iterator it, next, prev;
134     for (int i = 0; i < cnt; i++) {
135         It seg = e[i].seg;
136         if (e[i].type == 1) {
137             it = s.lower_bound(*seg);
138             if (it != s.end() && intersect(*it, *seg)) {
139                 *res1 = *it; *res2 = *seg;
140                 return true;
141             }
142             if (it != s.begin() && intersect(*--it, *seg)) {
143                 *res1 = *it; *res2 = *seg;
144                 return true;
145             }
146             s.insert(*seg);
147         } else {
148             it = s.lower_bound(*seg);
149             next = prev = it;
150             prev = it;

```

```

151     if (it != s.begin() && it != --s.end()) {
152         ++next;
153         --prev;
154         if (intersect(*next, *prev)) {
155             *res1 = *next; *res2 = *prev;
156             return true;
157         }
158     }
159     s.erase(it);
160 }
161 }
162 return false;
163 }
164
165 /** Example Usage */
166
167 #include <iostream>
168 #include <vector>
169 using namespace std;
170
171 void print(const segment & s) {
172     cout << "(" << s.p.x << ", " << s.p.y << ")<->";
173     cout << "(" << s.q.x << ", " << s.q.y << ")\\n";
174 }
175
176 int main() {
177     vector<segment> v;
178     v.push_back(segment(point(0, 0), point(2, 2)));
179     v.push_back(segment(point(3, 0), point(0, -1)));
180     v.push_back(segment(point(0, 2), point(2, -2)));
181     v.push_back(segment(point(0, 3), point(9, 0)));
182     segment res1, res2;
183     bool res = find_intersection(v.begin(), v.end(), &res1, &res2);
184     if (res) {
185         print(res1);
186         print(res2);
187     } else {
188         cout << "No\\intersections.\\n";
189     }
190     return 0;
191 }

```

5.4 Advanced Geometric Computations

5.4.1 Convex Polygon Cut

```

1  /*
2
3  5.4.1 - Convex Polygon Cut
4
5  Given a range of points specifying a polygon on the Cartesian
6  plane, as well as two points specifying an infinite line, "cut"
7  off the right part of the polygon with the line and return the
8  resulting polygon that is the left part.
9
10 Time Complexity: O(n) on the number of points in the poylgon.

```

```

11
12 */
13
14 #include <cmath>    /* fabs() */
15 #include <utility> /* std::pair */
16 #include <vector>
17
18 typedef std::pair<double, double> point;
19 #define x first
20 #define y second
21
22 const double eps = 1e-9;
23
24 #define EQ(a, b) (fabs((a) - (b)) <= eps) /* equal to */
25 #define LT(a, b) ((a) < (b) - eps)       /* less than */
26 #define GT(a, b) ((a) > (b) + eps)       /* greater than */
27
28 double cross(const point & o, const point & a, const point & b) {
29     return (a.x - o.x) * (b.y - o.y) - (a.y - o.y) * (b.x - o.x);
30 }
31
32 int orientation(const point & o, const point & a, const point & b) {
33     double c = cross(o, a, b);
34     return LT(c, 0) ? -1 : (GT(c, 0) ? 1 : 0);
35 }
36
37 int line_intersection(const point & p1, const point & p2,
38                      const point & p3, const point & p4, point * p = 0) {
39     double a1 = p2.y - p1.y, b1 = p1.x - p2.x;
40     double c1 = -(p1.x * p2.y - p2.x * p1.y);
41     double a2 = p4.y - p3.y, b2 = p3.x - p4.x;
42     double c2 = -(p3.x * p4.y - p4.x * p3.y);
43     double x = -(c1 * b2 - c2 * b1), y = -(a1 * c2 - a2 * c1);
44     double det = a1 * b2 - a2 * b1;
45     if (EQ(det, 0))
46         return (EQ(x, 0) && EQ(y, 0)) ? 1 : -1;
47     if (p != 0) *p = point(x / det, y / det);
48     return 0;
49 }
50
51 template<class It>
52 std::vector<point> convex_cut(It lo, It hi, const point & p, const point & q) {
53     std::vector<point> res;
54     for (It i = lo, j = hi - 1; i != hi; j = i++) {
55         int d1 = orientation(p, q, *j), d2 = orientation(p, q, *i);
56         if (d1 >= 0) res.push_back(*j);
57         if (d1 * d2 < 0) {
58             point r;
59             line_intersection(p, q, *j, *i, &r);
60             res.push_back(r);
61         }
62     }
63     return res;
64 }
65
66 /** Example Usage */
67
68 #include <iostream>
69 using namespace std;

```



```

70
71 int main() {
72     //irregular pentagon with only (1, 2) not on the convex hull
73     vector<point> v;
74     v.push_back(point(1, 3));
75     v.push_back(point(1, 2));
76     v.push_back(point(2, 1));
77     v.push_back(point(0, 0));
78     v.push_back(point(-1, 3));
79     //cut using the vertical line through (0, 0)
80     vector<point> res = convex_cut(v.begin(), v.end(), point(0, 0), point(0, 1));
81     cout << "left_cut:\n";
82     for (int i = 0; i < (int)res.size(); i++)
83         cout << "(" << res[i].x << ", " << res[i].y << ")\n";
84     return 0;
85 }

```

5.4.2 Polygon Union and Intersection

```

1  /*
2
3  5.4.2 - Polygon Union and Intersection Area
4
5  Given two ranges of points respectively denoting the vertices of
6  two polygons, determine the intersection area of those polygons.
7  Using this, we can easily calculate their union with the formula:
8      union_area(A, B) = area(A) + area(B) - intersection_area(A, B)
9
10 Time Complexity:  $O(n^2 \log n)$ , where n is the total number of vertices.
11
12 */
13
14 #include <algorithm> /* std::sort() */
15 #include <cmath> /* fabs(), sqrt() */
16 #include <set>
17 #include <utility> /* std::pair */
18 #include <vector>
19
20 const double eps = 1e-9;
21
22 #define EQ(a, b) (fabs((a) - (b)) <= eps) /* equal to */
23 #define LT(a, b) ((a) < (b) - eps) /* less than */
24 #define LE(a, b) ((a) <= (b) + eps) /* less than or equal to */
25
26 typedef std::pair<double, double> point;
27 #define x first
28 #define y second
29
30 inline int sgn(const double & x) {
31     return (0.0 < x) - (x < 0.0);
32 }
33
34 //Line and line segment intersection (see their own sections)
35
36 int line_intersection(const point & p1, const point & p2,
37                     const point & p3, const point & p4, point * p = 0) {
38     double a1 = p2.y - p1.y, b1 = p1.x - p2.x;

```

```

39  double c1 = -(p1.x * p2.y - p2.x * p1.y);
40  double a2 = p4.y - p3.y, b2 = p3.x - p4.x;
41  double c2 = -(p3.x * p4.y - p4.x * p3.y);
42  double x = -(c1 * b2 - c2 * b1), y = -(a1 * c2 - a2 * c1);
43  double det = a1 * b2 - a2 * b1;
44  if (EQ(det, 0))
45      return (EQ(x, 0) && EQ(y, 0)) ? 1 : -1;
46  if (p != 0) *p = point(x / det, y / det);
47  return 0;
48 }
49
50 double norm(const point & a) { return a.x * a.x + a.y * a.y; }
51 double dot(const point & a, const point & b) { return a.x * b.x + a.y * b.y; }
52 double cross(const point & a, const point & b) { return a.x * b.y - a.y * b.x; }
53
54 const bool TOUCH_IS_INTERSECT = true;
55
56 bool contain(const double & l, const double & m, const double & h) {
57     if (TOUCH_IS_INTERSECT) return LE(l, m) && LE(m, h);
58     return LT(l, m) && LT(m, h);
59 }
60
61 bool overlap(const double & l1, const double & h1,
62             const double & l2, const double & h2) {
63     if (TOUCH_IS_INTERSECT) return LE(l1, h2) && LE(l2, h1);
64     return LT(l1, h2) && LT(l2, h1);
65 }
66
67 int seg_intersection(const point & a, const point & b,
68                    const point & c, const point & d,
69                    point * p = 0, point * q = 0) {
70     point ab(b.x - a.x, b.y - a.y);
71     point ac(c.x - a.x, c.y - a.y);
72     point cd(d.x - c.x, d.y - c.y);
73     double c1 = cross(ab, cd), c2 = cross(ac, ab);
74     if (EQ(c1, 0) && EQ(c2, 0)) { //collinear
75         double t0 = dot(ac, ab) / norm(ab);
76         double t1 = t0 + dot(cd, ab) / norm(ab);
77         if (overlap(std::min(t0, t1), std::max(t0, t1), 0, 1)) {
78             point res1 = std::max(std::min(a, b), std::min(c, d));
79             point res2 = std::min(std::max(a, b), std::max(c, d));
80             if (res1 == res2) {
81                 if (p != 0) *p = res1;
82                 return 0; //collinear, meeting at an endpoint
83             }
84             if (p != 0 && q != 0) *p = res1, *q = res2;
85             return 1; //collinear and overlapping
86         } else {
87             return -1; //collinear and disjoint
88         }
89     }
90     if (EQ(c1, 0)) return -1; //parallel and disjoint
91     double t = cross(ac, cd) / c1, u = c2 / c1;
92     if (contain(0, t, 1) && contain(0, u, 1)) {
93         if (p != 0) *p = point(a.x + t * ab.x, a.y + t * ab.y);
94         return 0; //non-parallel with one intersection
95     }
96     return -1; //non-parallel with no intersections
97 }

```

```

98
99 struct event {
100     double y;
101     int mask_delta;
102
103     event(double y = 0, int mask_delta = 0) {
104         this->y = y;
105         this->mask_delta = mask_delta;
106     }
107
108     bool operator < (const event & e) const {
109         if (y != e.y) return y < e.y;
110         return mask_delta < e.mask_delta;
111     }
112 };
113
114 template<class It>
115 double intersection_area(It lo1, It hi1, It lo2, It hi2) {
116     It plo[2] = {lo1, lo2}, phi[] = {hi1, hi2};
117     std::set<double> xs;
118     for (It i1 = lo1; i1 != hi1; ++i1) xs.insert(i1->x);
119     for (It i2 = lo2; i2 != hi2; ++i2) xs.insert(i2->x);
120     for (It i1 = lo1, j1 = hi1 - 1; i1 != hi1; j1 = i1++) {
121         for (It i2 = lo2, j2 = hi2 - 1; i2 != hi2; j2 = i2++) {
122             point p;
123             if (seg_intersection(*i1, *j1, *i2, *j2, &p) == 0)
124                 xs.insert(p.x);
125         }
126     }
127     std::vector<double> xsa(xs.begin(), xs.end());
128     double res = 0;
129     for (int k = 0; k < (int)xsa.size() - 1; k++) {
130         double x = (xsa[k] + xsa[k + 1]) / 2;
131         point sweep0(x, 0), sweep1(x, 1);
132         std::vector<event> events;
133         for (int poly = 0; poly < 2; poly++) {
134             It lo = plo[poly], hi = phi[poly];
135             double area = 0;
136             for (It i = lo, j = hi - 1; i != hi; j = i++)
137                 area += (j->x - i->x) * (j->y + i->y);
138             for (It j = lo, i = hi - 1; j != hi; i = j++) {
139                 point p;
140                 if (line_intersection(*j, *i, sweep0, sweep1, &p) == 0) {
141                     double y = p.y, x0 = i->x, x1 = j->x;
142                     if (x0 < x && x1 > x) {
143                         events.push_back(event(y, sgn(area) * (1 << poly)));
144                     } else if (x0 > x && x1 < x) {
145                         events.push_back(event(y, -sgn(area) * (1 << poly)));
146                     }
147                 }
148             }
149         }
150         std::sort(events.begin(), events.end());
151         double a = 0.0;
152         int mask = 0;
153         for (int j = 0; j < (int)events.size(); j++) {
154             if (mask == 3)
155                 a += events[j].y - events[j - 1].y;
156             mask += events[j].mask_delta;

```

```

157     }
158     res += a * (xsa[k + 1] - xsa[k]);
159 }
160 return res;
161 }
162
163 template<class It> double polygon_area(It lo, It hi) {
164     if (lo == hi) return 0;
165     double area = 0;
166     if (*lo != *--hi)
167         area += (lo->x - hi->x) * (lo->y + hi->y);
168     for (It i = hi, j = hi - 1; i != lo; --i, --j)
169         area += (i->x - j->x) * (i->y + j->y);
170     return fabs(area / 2.0);
171 }
172
173 template<class It>
174 double union_area(It lo1, It hi1, It lo2, It hi2) {
175     return polygon_area(lo1, hi1) + polygon_area(lo2, hi2) -
176         intersection_area(lo1, hi1, lo2, hi2);
177 }
178
179 /** Example Usage */
180
181 #include <cassert>
182 using namespace std;
183
184 int main() {
185     vector<point> p1, p2;
186
187     //irregular pentagon with area 1.5 triangle in quadrant 2
188     p1.push_back(point(1, 3));
189     p1.push_back(point(1, 2));
190     p1.push_back(point(2, 1));
191     p1.push_back(point(0, 0));
192     p1.push_back(point(-1, 3));
193     //a big square in quadrant 2
194     p2.push_back(point(0, 0));
195     p2.push_back(point(0, 3));
196     p2.push_back(point(-3, 3));
197     p2.push_back(point(-3, 0));
198
199     assert(EQ(1.5, intersection_area(p1.begin(), p1.end(),
200                                     p2.begin(), p2.end())));
201     assert(EQ(12.5, union_area(p1.begin(), p1.end(),
202                                p2.begin(), p2.end())));
203     return 0;
204 }

```

5.4.3 Delaunay Triangulation (Simple)

```

1  /*
2
3  5.4.3 - Delaunay Triangulation (Simple)
4
5  Given a range of points P on the Cartesian plane, the Delaunay
6  Triangulation of said points is a set of non-overlapping triangles

```

```

7  covering the entire convex hull of P, such that no point in P lies
8  within the circumcircle of any of the resulting triangles. The
9  triangulation maximizes the minimum angle of all the angles of the
10 triangles in the triangulation. In addition, for any point p in the
11 convex hull (not necessarily in P), the nearest point is guaranteed
12 to be a vertex of the enclosing triangle from the triangulation.
13 See: https://en.wikipedia.org/wiki/Delaunay\_triangulation
14
15 The triangulation may not exist (e.g. for a set of collinear points)
16 or it may not be unique (multiple possible triangulations may exist).
17 The triangulation may not exist (e.g. for a set of collinear points)
18 or it may not be unique (multiple possible triangulations may exist).
19 The following program assumes that a triangulation exists, and
20 produces one such valid result using one of the simplest algorithms
21 to solve this problem. It involves encasing the simplex in a circle
22 and rejecting the simplex if another point in the tessellation is
23 within the generalized circle.
24
25 Time Complexity:  $O(n^4)$  on the number of input points.
26
27 */
28
29 #include <algorithm> /* std::sort() */
30 #include <cmath>     /* fabs(), sqrt() */
31 #include <utility>   /* std::pair */
32 #include <vector>
33
34 const double eps = 1e-9;
35
36 #define EQ(a, b) (fabs((a) - (b)) <= eps) /* equal to */
37 #define LT(a, b) ((a) < (b) - eps)        /* less than */
38 #define GT(a, b) ((a) > (b) + eps)        /* greater than */
39 #define LE(a, b) ((a) <= (b) + eps)       /* less than or equal to */
40 #define GE(a, b) ((a) >= (b) - eps)       /* greater than or equal to */
41
42 typedef std::pair<double, double> point;
43 #define x first
44 #define y second
45
46 double norm(const point & a) { return a.x * a.x + a.y * a.y; }
47 double dot(const point & a, const point & b) { return a.x * b.x + a.y * b.y; }
48 double cross(const point & a, const point & b) { return a.x * b.y - a.y * b.x; }
49
50 const bool TOUCH_IS_INTERSECT = false;
51
52 bool contain(const double & l, const double & m, const double & h) {
53     if (TOUCH_IS_INTERSECT) return LE(l, m) && LE(m, h);
54     return LT(l, m) && LT(m, h);
55 }
56
57 bool overlap(const double & l1, const double & h1,
58             const double & l2, const double & h2) {
59     if (TOUCH_IS_INTERSECT) return LE(l1, h2) && LE(l2, h1);
60     return LT(l1, h2) && LT(l2, h1);
61 }
62
63 int seg_intersection(const point & a, const point & b,
64                    const point & c, const point & d) {
65     point ab(b.x - a.x, b.y - a.y);

```

```

66 point ac(c.x - a.x, c.y - a.y);
67 point cd(d.x - c.x, d.y - c.y);
68 double c1 = cross(ab, cd), c2 = cross(ac, ab);
69 if (EQ(c1, 0) && EQ(c2, 0)) {
70     double t0 = dot(ac, ab) / norm(ab);
71     double t1 = t0 + dot(cd, ab) / norm(ab);
72     if (overlap(std::min(t0, t1), std::max(t0, t1), 0, 1)) {
73         point res1 = std::max(std::min(a, b), std::min(c, d));
74         point res2 = std::min(std::max(a, b), std::max(c, d));
75         return (res1 == res2) ? 0 : 1;
76     }
77     return -1;
78 }
79 if (EQ(c1, 0)) return -1;
80 double t = cross(ac, cd) / c1, u = c2 / c1;
81 if (contain(0, t, 1) && contain(0, u, 1)) return 0;
82 return -1;
83 }
84
85 struct triangle { point a, b, c; };
86
87 template<class It>
88 std::vector<triangle> delaunay_triangulation(It lo, It hi) {
89     int n = hi - lo;
90     std::vector<double> x, y, z;
91     for (It it = lo; it != hi; ++it) {
92         x.push_back(it->x);
93         y.push_back(it->y);
94         z.push_back((it->x) * (it->x) + (it->y) * (it->y));
95     }
96     std::vector<triangle> res;
97     for (int i = 0; i < n - 2; i++) {
98         for (int j = i + 1; j < n; j++) {
99             for (int k = i + 1; k < n; k++) {
100                 if (j == k) continue;
101                 double nx = (y[j] - y[i]) * (z[k] - z[i]) - (y[k] - y[i]) * (z[j] - z[i]);
102                 double ny = (x[k] - x[i]) * (z[j] - z[i]) - (x[j] - x[i]) * (z[k] - z[i]);
103                 double nz = (x[j] - x[i]) * (y[k] - y[i]) - (x[k] - x[i]) * (y[j] - y[i]);
104                 if (GE(nz, 0)) continue;
105                 bool done = false;
106                 for (int m = 0; m < n; m++)
107                     if (x[m] - x[i] * nx + (y[m] - y[i]) * ny + (z[m] - z[i]) * nz > 0) {
108                         done = true;
109                         break;
110                     }
111                 if (!done) { //handle 4 points on a circle
112                     point s1[] = { *(lo + i), *(lo + j), *(lo + k), *(lo + i) };
113                     for (int t = 0; t < (int)res.size(); t++) {
114                         point s2[] = { res[t].a, res[t].b, res[t].c, res[t].a };
115                         for (int u = 0; u < 3; u++)
116                             for (int v = 0; v < 3; v++)
117                                 if (seg_intersection(s1[u], s1[u + 1], s2[v], s2[v + 1]) == 0)
118                                     goto skip;
119                     }
120                     res.push_back(triangle){*(lo + i), *(lo + j), *(lo + k)};
121                 }
122             }
123         }
124     }

```

```

125     }
126     return res;
127 }
128
129 /** Example Usage */
130
131 #include <iostream>
132 using namespace std;
133
134 int main() {
135     vector<point> v;
136     v.push_back(point(1, 3));
137     v.push_back(point(1, 2));
138     v.push_back(point(2, 1));
139     v.push_back(point(0, 0));
140     v.push_back(point(-1, 3));
141     vector<triangle> dt = delaunay_triangulation(v.begin(), v.end());
142     for (int i = 0; i < (int)dt.size(); i++) {
143         cout << "Triangle: ";
144         cout << "(" << dt[i].a.x << "," << dt[i].a.y << ") ";
145         cout << "(" << dt[i].b.x << "," << dt[i].b.y << ") ";
146         cout << "(" << dt[i].c.x << "," << dt[i].c.y << ") \n";
147     }
148     return 0;
149 }

```

5.4.4 Delaunay Triangulation (Fast)

```

1  /*
2
3  5.4.3 - Delaunay Triangulation (Fast)
4
5  Given a range of points P on the Cartesian plane, the Delaunay
6  Triangulation of said points is a set of non-overlapping triangles
7  covering the entire convex hull of P, such that no point in P lies
8  within the circumcircle of any of the resulting triangles. The
9  triangulation maximizes the minimum angle of all the angles of the
10 triangles in the triangulation. In addition, for any point p in the
11 convex hull (not necessarily in P), the nearest point is guaranteed
12 to be a vertex of the enclosing triangle from the triangulation.
13 See: https://en.wikipedia.org/wiki/Delaunay\_triangulation
14
15 The triangulation may not exist (e.g. for a set of collinear points)
16 or it may not be unique (multiple possible triangulations may exist).
17 The following program assumes that a triangulation exists, and
18 produces one such valid result. The following is a C++ adaptation of
19 a FORTRAN90 program, which applies a divide and conquer algorithm
20 with complex linear-time merging. The original program can be found
21 via the following link. It contains more thorough documentation,
22 comments, and debugging messages associated with the current asserts().
23 http://people.sc.fsu.edu/~burkardt/f\_src/table\_delaunay/table\_delaunay.html
24
25 Time Complexity:  $O(n \log n)$  on the number of input points.
26
27 */
28
29 #include <algorithm> /* std::min(), std::max() */

```

```

30 #include <cassert>
31 #include <cmath>      /* fabs(), sqrt() */
32 #include <utility>    /* std::pair */
33 #include <vector>
34
35 int wrap(int ival, int ilo, int ihi) {
36     int jlo = std::min(ilo, ihi), jhi = std::max(ilo, ihi);
37     int wide = jhi + 1 - jlo, res = jlo;
38     if (wide != 1) {
39         assert(wide != 0);
40         int tmp = (ival - jlo) % wide;
41         if (tmp < 0) res += abs(wide);
42         res += tmp;
43     }
44     return res;
45 }
46
47 double epsilon() {
48     double r = 1;
49     while (1 < (double)(r + 1)) r /= 2;
50     return 2 * r;
51 }
52
53 void permute(int n, double a[][2], int p[]) {
54     for (int istart = 1; istart <= n; istart++) {
55         if (p[istart - 1] < 0) continue;
56         if (p[istart - 1] == istart) {
57             p[istart - 1] = -p[istart - 1];
58             continue;
59         }
60         double tmp0 = a[istart - 1][0];
61         double tmp1 = a[istart - 1][1];
62         int iget = istart;
63         for (;;) {
64             int input = iget;
65             iget = p[iget - 1];
66             p[input - 1] = -p[input - 1];
67             assert(!(iget < 1 || n < iget));
68             if (iget == istart) {
69                 a[input - 1][0] = tmp0;
70                 a[input - 1][1] = tmp1;
71                 break;
72             }
73             a[input - 1][0] = a[iget - 1][0];
74             a[input - 1][1] = a[iget - 1][1];
75         }
76     }
77     for (int i = 0; i < n; i++) p[i] = -p[i];
78     return;
79 }
80
81 int * sort_heap(int n, double a[][2]) {
82     double aval[2];
83     int i, ir, j, l, idx;
84     int *idx;
85     if (n < 1) return NULL;
86     if (n == 1) {
87         idx = new int[1];
88         idx[0] = 1;

```



```

89     return idx;
90 }
91 idx = new int[n];
92 for (int i = 0; i < n; i++) idx[i] = i + 1;
93 l = n / 2 + 1;
94 ir = n;
95 for (;;) {
96     if (l < 1) {
97         l--;
98         idxt = idx[l - 1];
99         aval[0] = a[idxt - 1][0];
100        aval[1] = a[idxt - 1][1];
101    } else {
102        idxt = idx[ir - 1];
103        aval[0] = a[idxt - 1][0];
104        aval[1] = a[idxt - 1][1];
105        idx[ir - 1] = idx[0];
106        if (--ir == 1) {
107            idx[0] = idxt;
108            break;
109        }
110    }
111    i = 1;
112    j = 2 * l;
113    while (j <= ir) {
114        if (j < ir && (a[idx[j - 1] - 1][0] < a[idx[j] - 1][0] ||
115                    (a[idx[j - 1] - 1][0] == a[idx[j] - 1][0] &&
116                     a[idx[j - 1] - 1][1] < a[idx[j] - 1][1]))) {
117            j++;
118        }
119        if (aval[0] < a[idx[j - 1] - 1][0] ||
120            (aval[0] == a[idx[j - 1] - 1][0] &&
121             aval[1] < a[idx[j - 1] - 1][1])) {
122            idx[i - 1] = idx[j - 1];
123            i = j;
124            j *= 2;
125        } else {
126            j = ir + 1;
127        }
128    }
129    idx[i - 1] = idxt;
130 }
131 return idx;
132 }
133
134 int lrline(double xu, double yu, double xv1, double yv1,
135           double xv2, double yv2, double dv) {
136     double tol = 1e-7;
137     double dx = xv2 - xv1, dy = yv2 - yv1;
138     double dxu = xu - xv1, dyu = yu - yv1;
139     double t = dy * dxu - dx * dyu + dv * sqrt(dx * dx + dy * dy);
140     double tolabs = tol * std::max(std::max(fabs(dx), fabs(dy)),
141                                     std::max(fabs(dxu), std::max(fabs(dyu), fabs(dv))));
142     if (tolabs < t) return 1;
143     if (-tolabs <= t) return 0;
144     return -1;
145 }
146
147 void vbedg(double x, double y, int point_num, double point_xy[][2],

```

```

148         int tri_num, int tri_nodes[][3], int tri_neigh[][3],
149         int *ltri, int *ledg, int *rtri, int *redg) {
150     int a, b;
151     double ax, ay, bx, by;
152     bool done;
153     int e, l, t;
154     if (*ltri == 0) {
155         done = false;
156         *ltri = *rtri;
157         *ledg = *redg;
158     } else {
159         done = true;
160     }
161     for (;;) {
162         l = -tri_neigh[(*rtri) - 1][(*redg) - 1];
163         t = l / 3;
164         e = l % 3 + 1;
165         a = tri_nodes[t - 1][e - 1];
166         if (e <= 2) {
167             b = tri_nodes[t - 1][e];
168         } else {
169             b = tri_nodes[t - 1][0];
170         }
171         ax = point_xy[a - 1][0];
172         ay = point_xy[a - 1][1];
173         bx = point_xy[b - 1][0];
174         by = point_xy[b - 1][1];
175         if (lrline(x, y, ax, ay, bx, by, 0.0) <= 0) break;
176         *rtri = t;
177         *redg = e;
178     }
179     if (done) return;
180     t = *ltri;
181     e = *ledg;
182     for (;;) {
183         b = tri_nodes[t - 1][e - 1];
184         e = wrap(e - 1, 1, 3);
185         while (0 < tri_neigh[t - 1][e - 1]) {
186             t = tri_neigh[t - 1][e - 1];
187             if (tri_nodes[t - 1][0] == b) {
188                 e = 3;
189             } else if (tri_nodes[t - 1][1] == b) {
190                 e = 1;
191             } else {
192                 e = 2;
193             }
194         }
195         a = tri_nodes[t - 1][e - 1];
196         ax = point_xy[a - 1][0];
197         ay = point_xy[a - 1][1];
198         bx = point_xy[b - 1][0];
199         by = point_xy[b - 1][1];
200         if (lrline(x, y, ax, ay, bx, by, 0.0) <= 0) break;
201     }
202     *ltri = t;
203     *ledg = e;
204     return;
205 }
206

```

```

207 int diaedg(double x0, double y0, double x1, double y1,
208           double x2, double y2, double x3, double y3) {
209     double ca, cb, s, tol, tola, tolb;
210     int value;
211     tol = 100.0 * epsilon();
212     double dx10 = x1 - x0, dy10 = y1 - y0;
213     double dx12 = x1 - x2, dy12 = y1 - y2;
214     double dx30 = x3 - x0, dy30 = y3 - y0;
215     double dx32 = x3 - x2, dy32 = y3 - y2;
216     tola = tol * std::max(std::max(fabs(dx10), fabs(dy10)),
217                          std::max(fabs(dx30), fabs(dy30)));
218     tolb = tol * std::max(std::max(fabs(dx12), fabs(dy12)),
219                          std::max(fabs(dx32), fabs(dy32)));
220     ca = dx10 * dx30 + dy10 * dy30;
221     cb = dx12 * dx32 + dy12 * dy32;
222     if (tola < ca && tolb < cb) {
223         value = -1;
224     } else if (ca < -tola && cb < -tolb) {
225         value = 1;
226     } else {
227         tola = std::max(tola, tolb);
228         s = (dx10 * dy30 - dx30 * dy10) * cb + (dx32 * dy12 - dx12 * dy32) * ca;
229         if (tola < s) {
230             value = -1;
231         } else if (s < -tola) {
232             value = 1;
233         } else {
234             value = 0;
235         }
236     }
237     return value;
238 }
239
240 int swapec(int i, int *top, int *btri, int *bedg,
241           int point_num, double point_xy[][2],
242           int tri_num, int tri_nodes[][3], int tri_neigh[][3], int stack[]) {
243     int a, b, c, e, ee, em1, ep1, f, fm1, fp1, l, r, s, swap, t, tt, u;
244     double x = point_xy[i - 1][0];
245     double y = point_xy[i - 1][1];
246     for (;;) {
247         if (*top <= 0) break;
248         t = stack[*top - 1];
249         *top = *top - 1;
250         if (tri_nodes[t - 1][0] == i) {
251             e = 2;
252             b = tri_nodes[t - 1][2];
253         } else if (tri_nodes[t - 1][1] == i) {
254             e = 3;
255             b = tri_nodes[t - 1][0];
256         } else {
257             e = 1;
258             b = tri_nodes[t - 1][1];
259         }
260         a = tri_nodes[t - 1][e - 1];
261         u = tri_neigh[t - 1][e - 1];
262         if (tri_neigh[u - 1][0] == t) {
263             f = 1;
264             c = tri_nodes[u - 1][2];
265         } else if (tri_neigh[u - 1][1] == t) {

```

```

266     f = 2;
267     c = tri_nodes[u - 1][0];
268 } else {
269     f = 3;
270     c = tri_nodes[u - 1][1];
271 }
272 swap = diaedg(x, y, point_xy[a - 1][0], point_xy[a - 1][1],
273             point_xy[c - 1][0], point_xy[c - 1][1],
274             point_xy[b - 1][0], point_xy[b - 1][1]);
275 if (swap == 1) {
276     em1 = wrap(e - 1, 1, 3);
277     ep1 = wrap(e + 1, 1, 3);
278     fm1 = wrap(f - 1, 1, 3);
279     fp1 = wrap(f + 1, 1, 3);
280     tri_nodes[t - 1][ep1 - 1] = c;
281     tri_nodes[u - 1][fp1 - 1] = i;
282     r = tri_neigh[t - 1][ep1 - 1];
283     s = tri_neigh[u - 1][fp1 - 1];
284     tri_neigh[t - 1][ep1 - 1] = u;
285     tri_neigh[u - 1][fp1 - 1] = t;
286     tri_neigh[t - 1][e - 1] = s;
287     tri_neigh[u - 1][f - 1] = r;
288     if (0 < tri_neigh[u - 1][fm1 - 1]) {
289         *top = *top + 1;
290         stack[*top - 1] = u;
291     }
292     if (0 < s) {
293         if (tri_neigh[s - 1][0] == u) {
294             tri_neigh[s - 1][0] = t;
295         } else if (tri_neigh[s - 1][1] == u) {
296             tri_neigh[s - 1][1] = t;
297         } else {
298             tri_neigh[s - 1][2] = t;
299         }
300         *top = *top + 1;
301         if (point_num < *top) return 8;
302         stack[*top - 1] = t;
303     } else {
304         if (u == *btri && fp1 == *bedg) {
305             *btri = t;
306             *bedg = e;
307         }
308         l = - (3 * t + e - 1);
309         tt = t;
310         ee = em1;
311         while (0 < tri_neigh[tt - 1][ee - 1]) {
312             tt = tri_neigh[tt - 1][ee - 1];
313             if (tri_nodes[tt - 1][0] == a) {
314                 ee = 3;
315             } else if (tri_nodes[tt - 1][1] == a) {
316                 ee = 1;
317             } else {
318                 ee = 2;
319             }
320         }
321         tri_neigh[tt - 1][ee - 1] = l;
322     }
323     if (0 < r) {
324         if (tri_neigh[r - 1][0] == t) {

```

```

325     tri_neigh[r - 1][0] = u;
326   } else if (tri_neigh[r - 1][1] == t) {
327     tri_neigh[r - 1][1] = u;
328   } else {
329     tri_neigh[r - 1][2] = u;
330   }
331 } else {
332   if (t == *btri && ep1 == *bedg) {
333     *btri = u;
334     *bedg = f;
335   }
336   l = -(3 * u + f - 1);
337   tt = u;
338   ee = fm1;
339   while (0 < tri_neigh[tt - 1][ee - 1]) {
340     tt = tri_neigh[tt - 1][ee - 1];
341     if (tri_nodes[tt - 1][0] == b) {
342       ee = 3;
343     } else if (tri_nodes[tt - 1][1] == b) {
344       ee = 1;
345     } else {
346       ee = 2;
347     }
348   }
349   tri_neigh[tt - 1][ee - 1] = 1;
350 }
351 }
352 }
353 return 0;
354 }
355
356 void perm_inv(int n, int p[]) {
357   int i, i0, i1, i2;
358   assert(n > 0);
359   for (i = 1; i <= n; i++) {
360     i1 = p[i - 1];
361     while (i < i1) {
362       i2 = p[i1 - 1];
363       p[i1 - 1] = -i2;
364       i1 = i2;
365     }
366     p[i - 1] = -p[i - 1];
367   }
368   for (i = 1; i <= n; i++) {
369     i1 = -p[i - 1];
370     if (0 <= i1) {
371       i0 = i;
372       for (;;) {
373         i2 = p[i1 - 1];
374         p[i1 - 1] = i0;
375         if (i2 < 0) break;
376         i0 = i1;
377         i1 = i2;
378       }
379     }
380   }
381   return;
382 }
383

```

```

384 int dtris2(int point_num, double point_xy[][2],
385           int tri_nodes[][3], int tri_neigh[][3]) {
386     double cmax;
387     int e, error;
388     int i, j, k, l, m, m1, m2, n;
389     int ledg, lr, ltri, redg, rtri, t, top;
390     double tol;
391     int *stack = new int[point_num];
392     tol = 100.0 * epsilon();
393     int *idx = sort_heap(point_num, point_xy);
394     permute(point_num, point_xy, idx);
395     m1 = 0;
396     for (i = 1; i < point_num; i++) {
397         m = m1;
398         m1 = i;
399         k = -1;
400         for (j = 0; j <= 1; j++) {
401             cmax = std::max(fabs(point_xy[m][j]), fabs(point_xy[m1][j]));
402             if (tol * (cmax + 1.0) < fabs(point_xy[m][j] - point_xy[m1][j])) {
403                 k = j;
404                 break;
405             }
406         }
407         assert(k != -1);
408     }
409     m1 = 1;
410     m2 = 2;
411     j = 3;
412     for (;;) {
413         assert(point_num >= j);
414         m = j;
415         lr = lrline(point_xy[m - 1][0], point_xy[m - 1][1],
416                  point_xy[m1 - 1][0], point_xy[m1 - 1][1],
417                  point_xy[m2 - 1][0], point_xy[m2 - 1][1], 0.0);
418         if (lr != 0) break;
419         j++;
420     }
421     int tri_num = j - 2;
422     if (lr == -1) {
423         tri_nodes[0][0] = m1;
424         tri_nodes[0][1] = m2;
425         tri_nodes[0][2] = m;
426         tri_neigh[0][2] = -3;
427         for (i = 2; i <= tri_num; i++) {
428             m1 = m2;
429             m2 = i + 1;
430             tri_nodes[i - 1][0] = m1;
431             tri_nodes[i - 1][1] = m2;
432             tri_nodes[i - 1][2] = m;
433             tri_neigh[i - 1][0] = -3 * i;
434             tri_neigh[i - 1][1] = i;
435             tri_neigh[i - 1][2] = i - 1;
436         }
437         tri_neigh[tri_num - 1][0] = -3 * tri_num - 1;
438         tri_neigh[tri_num - 1][1] = -5;
439         ledg = 2;
440         ltri = tri_num;
441     } else {
442         tri_nodes[0][0] = m2;

```

```

443     tri_nodes[0][1] = m1;
444     tri_nodes[0][2] = m;
445     tri_neigh[0][0] = -4;
446     for (i = 2; i <= tri_num; i++) {
447         m1 = m2;
448         m2 = i+1;
449         tri_nodes[i - 1][0] = m2;
450         tri_nodes[i - 1][1] = m1;
451         tri_nodes[i - 1][2] = m;
452         tri_neigh[i - 2][2] = i;
453         tri_neigh[i - 1][0] = -3 * i - 3;
454         tri_neigh[i - 1][1] = i - 1;
455     }
456     tri_neigh[tri_num - 1][2] = -3 * (tri_num);
457     tri_neigh[0][1] = -3 * (tri_num) - 2;
458     ledg = 2;
459     ltri = 1;
460 }
461 top = 0;
462 for (i = j + 1; i <= point_num; i++) {
463     m = i;
464     m1 = tri_nodes[ltri - 1][ledg - 1];
465     if (ledg <= 2) {
466         m2 = tri_nodes[ltri - 1][ledg];
467     } else {
468         m2 = tri_nodes[ltri - 1][0];
469     }
470     lr = lrline(point_xy[m - 1][0], point_xy[m - 1][1],
471                point_xy[m1 - 1][0], point_xy[m1 - 1][1],
472                point_xy[m2 - 1][0], point_xy[m2 - 1][1], 0.0);
473     if (0 < lr) {
474         rtri = ltri;
475         redg = ledg;
476         ltri = 0;
477     } else {
478         l = -tri_neigh[ltri - 1][ledg - 1];
479         rtri = l / 3;
480         redg = (l % 3) + 1;
481     }
482     vbedg(point_xy[m - 1][0], point_xy[m - 1][1],
483           point_num, point_xy, tri_num, tri_nodes, tri_neigh,
484           &ltri, &ledg, &rtri, &redg);
485     n = tri_num + 1;
486     l = -tri_neigh[ltri - 1][ledg - 1];
487     for (;;) {
488         t = l / 3;
489         e = (l % 3) + 1;
490         l = -tri_neigh[t - 1][e - 1];
491         m2 = tri_nodes[t - 1][e - 1];
492         if (e <= 2) {
493             m1 = tri_nodes[t - 1][e];
494         } else {
495             m1 = tri_nodes[t - 1][0];
496         }
497         tri_num++;
498         tri_neigh[t - 1][e - 1] = tri_num;
499         tri_nodes[tri_num - 1][0] = m1;
500         tri_nodes[tri_num - 1][1] = m2;
501         tri_nodes[tri_num - 1][2] = m;

```

```

502     tri_neigh[tri_num - 1][0] = t;
503     tri_neigh[tri_num - 1][1] = tri_num - 1;
504     tri_neigh[tri_num - 1][2] = tri_num + 1;
505     top++;
506     assert(point_num >= top);
507     stack[top - 1] = tri_num;
508     if (t == rtri && e == redg) break;
509 }
510 tri_neigh[ltri - 1][ledg - 1] = -3 * n - 1;
511 tri_neigh[n - 1][1] = -3 * tri_num - 2;
512 tri_neigh[tri_num - 1][2] = -1;
513 ltri = n;
514 ledg = 2;
515 error = swapec(m, &top, &ltri, &ledg, point_num, point_xy,
516               tri_num, tri_nodes, tri_neigh, stack);
517 assert(error == 0);
518 }
519 for (i = 0; i < 3; i++)
520     for (j = 0; j < tri_num; j++)
521         tri_nodes[j][i] = idx[tri_nodes[j][i] - 1];
522 perm_inv(point_num, idx);
523 permute(point_num, point_xy, idx);
524 delete[] idx;
525 delete[] stack;
526 return tri_num;
527 }
528
529 /** C++ Wrapper */
530
531 typedef std::pair<double, double> point;
532 #define x first
533 #define y second
534
535 struct triangle { point a, b, c; };
536
537 template<class It>
538 std::vector<triangle> delaunay_triangulation(It lo, It hi) {
539     int n = hi - lo;
540     double points[n][2];
541     int tri_nodes[3 * n][3], tri_neigh[3 * n][3];
542     int curr = 0;
543     for (It it = lo; it != hi; ++curr, ++it) {
544         points[curr][0] = it->x;
545         points[curr][1] = it->y;
546     }
547     int m = dtris2(n, points, tri_nodes, tri_neigh);
548     std::vector<triangle> res;
549     for (int i = 0; i < m; i++)
550         res.push_back((triangle){*(lo + (tri_nodes[i][0] - 1)),
551                                   *(lo + (tri_nodes[i][1] - 1)),
552                                   *(lo + (tri_nodes[i][2] - 1))});
553     return res;
554 }
555
556 /** Example Usage */
557
558 #include <iostream>
559 using namespace std;
560

```



```
561 int main() {
562     vector<point> v;
563     v.push_back(point(1, 3));
564     v.push_back(point(1, 2));
565     v.push_back(point(2, 1));
566     v.push_back(point(0, 0));
567     v.push_back(point(-1, 3));
568     vector<triangle> dt = delaunay_triangulation(v.begin(), v.end());
569     for (int i = 0; i < (int)dt.size(); i++) {
570         cout << "Triangle:␣";
571         cout << "(" << dt[i].a.x << "," << dt[i].a.y << ")␣";
572         cout << "(" << dt[i].b.x << "," << dt[i].b.y << ")␣";
573         cout << "(" << dt[i].c.x << "," << dt[i].c.y << ")\\n";
574     }
575     return 0;
576 }
```

Chapter 6

Strings

6.1 Strings Toolbox

```
1  /*
2
3  6.1 - Strings Toolbox
4
5  Useful or trivial string operations. These functions are not particularly
6  algorithmic. They are typically naive implementations using C++ features.
7  They depend on many features of the C++ <string> library, which tend to
8  have an unspecified complexity. They may not be optimally efficient.
9
10 */
11
12 #include <cstdlib>
13 #include <sstream>
14 #include <string>
15 #include <vector>
16
17 //integer to string conversion and vice versa using C++ features
18
19 //note that a similar std::to_string is introduced in C++0x
20 template<class Int>
21 std::string to_string(const Int & i) {
22     std::ostringstream oss;
23     oss << i;
24     return oss.str();
25 }
26
27 //like atoi, except during special cases like overflows
28 int to_int(const std::string & s) {
29     std::istringstream iss(s);
30     int res;
31     if (!(iss >> res)) /* complain */;
32     return res;
33 }
34
35 /*
36
37 itoa implementation (fast)
```

```

38 documentation: http://www.cplusplus.com/reference/cstdlib/itoa/
39 taken from: http://www.jb.man.ac.uk/~slowe/cpp/itoa.html
40
41 */
42
43 char* itoa(int value, char * str, int base = 10) {
44     if (base < 2 || base > 36) {
45         *str = '\0';
46         return str;
47     }
48     char *ptr = str, *ptr1 = str, tmp_c;
49     int tmp_v;
50     do {
51         tmp_v = value;
52         value /= base;
53         *ptr++ = "zyxwvutsrqponmlkjihgfedcba9876543210123456789"
54             "abcdefghijklmnopqrstuvwxy"[35 + (tmp_v - value * base)];
55     } while (value);
56     if (tmp_v < 0) *ptr++ = '-';
57     for (*ptr-- = '\0'; ptr1 < ptr; *ptr1++ = tmp_c) {
58         tmp_c = *ptr;
59         *ptr-- = *ptr1;
60     }
61     return str;
62 }
63
64 /*
65
66 Trimming functions (in place). Given a string and optionally a series
67 of characters to be considered for trimming, trims the string's ends
68 (left, right, or both) and returns the string. Note that the ORIGINAL
69 string is trimmed as it's passed by reference, despite the original
70 reference being returned for convenience.
71
72 */
73
74 std::string& ltrim(std::string & s, const std::string & delim = "\n\t\v\f\r") {
75     unsigned int pos = s.find_first_not_of(delim);
76     if (pos != std::string::npos) s.erase(0, pos);
77     return s;
78 }
79
80 std::string& rtrim(std::string & s, const std::string & delim = "\n\t\v\f\r") {
81     unsigned int pos = s.find_last_not_of(delim);
82     if (pos != std::string::npos) s.erase(pos);
83     return s;
84 }
85
86 std::string& trim(std::string & s, const std::string & delim = "\n\t\v\f\r") {
87     return ltrim(rtrim(s));
88 }
89
90 /*
91
92 Returns a copy of the string s with all occurrences of the given
93 string search replaced with the given string replace.
94
95 Time Complexity: Unspecified, but proportional to the number of times
96 the search string occurs and the complexity of std::string::replace,

```

```

97  which is unspecified.
98
99  */
100
101  std::string replace(std::string s,
102                    const std::string & search,
103                    const std::string & replace) {
104      if (search.empty()) return s;
105      unsigned int pos = 0;
106      while ((pos = s.find(search, pos)) != std::string::npos) {
107          s.replace(pos, search.length(), replace);
108          pos += replace.length();
109      }
110      return s;
111  }
112
113  /*
114
115  Tokenizes the string s based on single character delimiters.
116
117  Version 1: Simpler. Only one delimiter character allowed, and this will
118  not skip empty tokens.
119      e.g. split("a:b", ":") yields {"a", "b"}, not {"a", "", "b"}.
120
121  Version 2: All of the characters in the delim parameter that also exists
122  in s will be removed from s, and the token(s) of s that are left over will
123  be added sequentially to a vector and returned. Empty tokens are skipped.
124      e.g. split("a:b", ":") yields {"a", "b"}, not {"a", "", "b"}.
125
126  Time Complexity: O(s.length() * delim.length())
127
128  */
129
130  std::vector<std::string> split(const std::string & s, char delim) {
131      std::vector<std::string> res;
132      std::stringstream ss(s);
133      std::string curr;
134      while (std::getline(ss, curr, delim))
135          res.push_back(curr);
136      return res;
137  }
138
139  std::vector<std::string> split(const std::string & s,
140                              const std::string & delim = "_\\n\\t\\v\\f\\r") {
141      std::vector<std::string> res;
142      std::string curr;
143      for (int i = 0; i < (int)s.size(); i++) {
144          if (delim.find(s[i]) == std::string::npos) {
145              curr += s[i];
146          } else if (!curr.empty()) {
147              res.push_back(curr);
148              curr = "";
149          }
150      }
151      if (!curr.empty()) res.push_back(curr);
152      return res;
153  }
154
155  /*

```

```

156
157 Like the explode() function in PHP, the string s is tokenized based
158 on delim, which is considered as a whole boundary string, not just a
159 sequence of possible boundary characters like the split() function above.
160 This will not skip empty tokens.
161 e.g. explode("a::b", ":") yields {"a", "", "b"}, not {"a", "b"}.
162
163 Time Complexity: O(s.length() * delim.length())
164
165 */
166
167 std::vector<std::string> explode(const std::string & s,
168                               const std::string & delim) {
169     std::vector<std::string> res;
170     unsigned int last = 0, next = 0;
171     while ((next = s.find(delim, last)) != std::string::npos) {
172         res.push_back(s.substr(last, next - last));
173         last = next + delim.size();
174     }
175     res.push_back(s.substr(last));
176     return res;
177 }
178
179 /** Example Usage */
180
181 #include <cassert>
182 #include <cstdio>
183 #include <iostream>
184 using namespace std;
185
186 void print(const vector<string> & v) {
187     cout << "[";
188     for (int i = 0; i < (int)v.size(); i++)
189         cout << (i ? "\",\n" : "\"") << v[i];
190     cout << "]\n";
191 }
192
193 int main() {
194     assert(to_string(123) + "4" == "1234");
195     assert(to_int("1234") == 1234);
196     char buffer[50];
197     assert(string(itoa(1750, buffer, 10)) == "1750");
198     assert(string(itoa(1750, buffer, 16)) == "6d6");
199     assert(string(itoa(1750, buffer, 2)) == "11011010110");
200
201     string s("   abc\n");
202     string t = s;
203     assert(ltrim(s) == "abc\n");
204     assert(rtrim(s) == trim(t));
205     assert(replace("abcdabba", "ab", "00") == "00cd00ba");
206
207     vector<string> tokens;
208
209     tokens = split("a\nb\ncde\nf", '\n');
210     cout << "split_v1:\n";
211     print(tokens); //["a", "b", "cde", "f"]
212
213     tokens = split("a::b,cde:,f", ":",");
214     cout << "split_v2:\n";

```

```

215     print(tokens); //[ "a", "b", "cde", "f" ]
216
217     tokens = explode("a..b.cde...f", "..");
218     cout << "explode:␣";
219     print(tokens); //[ "a", ".b.cde", "", ".f" ]
220     return 0;
221 }

```

6.2 Expression Parsing

6.2.1 Recursive Descent

```

1  /*
2
3  6.2.1 Recursive Descent Parser
4
5  Evaluate a mathematical expression in accordance to the order
6  of operations (parentheses, exponents, multiplication, division,
7  addition, subtraction). Does not handle unary operators like '-'.
8
9  */
10
11  /** Example Usage */
12
13  #include <cctype>
14  #include <cmath>
15  #include <sstream>
16  #include <stdexcept>
17  #include <string>
18
19  class parser {
20      int pos;
21      double tokval;
22      std::string s;
23
24      bool is_dig_or_dot(char c) {
25          return isdigit(c) || c == '.';
26      }
27
28      double to_double(const std::string & s) {
29          std::stringstream ss(s);
30          double res;
31          ss >> res;
32          return res;
33      }
34
35  public:
36      char token;
37
38      parser(const std::string & s) {
39          this->s = s;
40          pos = 0;
41      }
42
43      int next() {
44          for (;;) {

```

```

45     if (pos == (int)s.size())
46         return token = -1;
47     char c = s[pos++];
48     if (std::string("+-*/^()\n").find(c) != std::string::npos)
49         return token = c;
50     if (isspace(c)) continue;
51     if (isdigit(c) || c == '.') {
52         std::string operand(1, c);
53         while (pos < (int)s.size() && is_dig_or_dot(s[pos]))
54             operand += (c = s[pos++]);
55         tokval = to_double(operand);
56         return token = 'n';
57     }
58     throw std::runtime_error(std::string("Bad character: ") + c);
59 }
60 }
61
62 void skip(int ch) {
63     if (token != ch)
64         throw std::runtime_error(std::string("Bad character: ") + token + std::string(", expected: ") +
65             (char)ch);
66     next();
67 }
68
69 double number() {
70     if (token == 'n') {
71         double v = tokval;
72         skip('n');
73         return v;
74     }
75     skip('(');
76     double v = expression();
77     skip(')');
78     return v;
79 }
80
81 // factor ::= number | number '^' factor
82 double factor() {
83     double v = number();
84     if (token == '^') {
85         skip('^');
86         v = pow(v, factor());
87     }
88     return v;
89 }
90
91 // term ::= factor | term '*' factor | term '/' factor
92 double term() {
93     double v = factor();
94     for (;;) {
95         if (token == '*') {
96             skip('*');
97             v *= factor();
98         } else if (token == '/') {
99             skip('/');
100            v /= factor();
101        } else {
102            return v;
103        }
104    }

```

```

103     }
104 }
105
106 // expression ::= term | expression '+' term | expression '-' term
107 double expression() {
108     double v = term();
109     for (;;) {
110         if (token == '+') {
111             skip('+');
112             v += term();
113         } else if (token == '-') {
114             skip('-');
115             v -= term();
116         } else {
117             return v;
118         }
119     }
120 }
121 };
122
123 #include <iostream>
124 using namespace std;
125
126 int main() {
127     parser p("1+2*3*4+3*(2+2)-100\n");
128     p.next();
129     while (p.token != -1) {
130         if (p.token == '\n') {
131             p.skip('\n');
132             continue;
133         }
134         cout << p.expression() << "\n";
135     }
136     return 0;
137 }

```

6.2.2 Recursive Descent (Simple)

```

1  /*
2
3  6.2.2 Recursive Descent Parser (Simple)
4
5  Evaluate a mathematica expression in accordance to the order
6  of operations (parentheses, exponents, multiplication, division,
7  addition, subtraction). This handles unary operators like '-'.
8
9  */
10
11 #include <string>
12
13 template<class It> int eval(It & it, int prec) {
14     if (prec == 0) {
15         int sign = 1, ret = 0;
16         for (; *it == '+' || *it == '-'; it++) sign *= -1;
17         if (*it == '(') {
18             ret = eval(++it, 2);
19             it++;

```



```

20     } else while (*it >= '0' && *it <= '9') {
21         ret = 10 * ret + (*(it++) - '0');
22     }
23     return sign * ret;
24 }
25 int num = eval(it, prec - 1);
26 while (!((prec == 2 && *it != '+' && *it != '-') ||
27         (prec == 1 && *it != '*' && *it != '/'))) {
28     switch (*(it++)) {
29         case '+': num += eval(it, prec - 1); break;
30         case '-': num -= eval(it, prec - 1); break;
31         case '*': num *= eval(it, prec - 1); break;
32         case '/': num /= eval(it, prec - 1); break;
33     }
34 }
35 return num;
36 }
37
38 /** Wrapper Function */
39
40 int eval(const std::string & s) {
41     std::string::iterator it = std::string(s).begin();
42     return eval(it, 2);
43 }
44
45 /** Example Usage */
46
47 #include <iostream>
48 using namespace std;
49
50 int main() {
51     cout << eval("1+2*3*4+3*(2+2)-100") << "\n";
52     return 0;
53 }

```

6.2.3 Shunting Yard Algorithm

```

1  /*
2
3  6.2.3 - Shunting Yard Expression Parser
4
5  Evaluate a mathematica expression in accordance to the order
6  of operations (parentheses, exponents, multiplication, division,
7  addition, subtraction). This also handles unary operators like '-'.
8  We use strings for operators so we can even define things like "sqrt"
9  and "mod" as unary operators by changing prec() and split_expr()
10 accordingly.
11
12 Time Complexity: O(n) on the total number of operators and operands.
13
14 */
15
16 #include <cstdlib>    /* strtol() */
17 #include <stack>
18 #include <stdexcept> /* std::runtime_error */
19 #include <string>
20 #include <vector>

```

```

21
22 // Classify the precedences of operators here.
23 inline int prec(const std::string & op, bool unary) {
24     if (unary) {
25         if (op == "+" || op == "-") return 3;
26         return 0; // not a unary operator
27     }
28     if (op == "*" || op == "/") return 2;
29     if (op == "+" || op == "-") return 1;
30     return 0; // not a binary operator
31 }
32
33 inline int calc1(const std::string & op, int val) {
34     if (op == "+") return +val;
35     if (op == "-") return -val;
36     throw std::runtime_error("Invalid unary operator: " + op);
37 }
38
39 inline int calc2(const std::string & op, int L, int R) {
40     if (op == "+") return L + R;
41     if (op == "-") return L - R;
42     if (op == "*") return L * R;
43     if (op == "/") return L / R;
44     throw std::runtime_error("Invalid binary operator: " + op);
45 }
46
47 inline bool is_operand(const std::string & s) {
48     return s != "(" && s != ")" && !prec(s, 0) && !prec(s, 1);
49 }
50
51 int eval(std::vector<std::string> E) { // E stores the tokens
52     E.insert(E.begin(), "(");
53     E.push_back(")");
54     std::stack<std::pair<std::string, bool>> ops;
55     std::stack<int> vals;
56     for (int i = 0; i < (int)E.size(); i++) {
57         if (is_operand(E[i])) {
58             vals.push(strtol(E[i].c_str(), 0, 10)); // convert to int
59             continue;
60         }
61         if (E[i] == "(") {
62             ops.push(std::make_pair("(", 0));
63             continue;
64         }
65         if (prec(E[i], 1) && (i == 0 || E[i - 1] == "(" || prec(E[i - 1], 0))) {
66             ops.push(std::make_pair(E[i], 1));
67             continue;
68         }
69         while(prec(ops.top().first, ops.top().second) >= prec(E[i], 0)) {
70             std::string op = ops.top().first;
71             bool is_unary = ops.top().second;
72             ops.pop();
73             if (op == "(") break;
74             int y = vals.top(); vals.pop();
75             if (is_unary) {
76                 vals.push(calc1(op, y));
77             } else {
78                 int x = vals.top(); vals.pop();
79                 vals.push(calc2(op, x, y));

```

```

80     }
81 }
82 if (E[i] != ")") ops.push(std::make_pair(E[i], 0));
83 }
84 return vals.top();
85 }
86
87 /*
88
89 Split a string expression to tokens, ignoring whitespace delimiters.
90 A vector of tokens is a more flexible format since you can decide to
91 parse the expression however you wish just by modifying this function.
92 e.g. "1+(51 * -100)" converts to {"1","+","(", "51","*","-", "100",")"}
93
94 */
95
96 std::vector<std::string> split_expr(const std::string &s,
97     const std::string &delim = "\n\t\v\f\r") {
98     std::vector<std::string> ret;
99     std::string acc = "";
100    for (int i = 0; i < (int)s.size(); i++)
101        if (s[i] >= '0' && s[i] <= '9') {
102            acc += s[i];
103        } else {
104            if (i > 0 && s[i - 1] >= '0' && s[i - 1] <= '9')
105                ret.push_back(acc);
106            acc = "";
107            if (delim.find(s[i]) != std::string::npos) continue;
108            ret.push_back(std::string("") + s[i]);
109        }
110    if (s[s.size() - 1] >= '0' && s[s.size() - 1] <= '9')
111        ret.push_back(acc);
112    return ret;
113 }
114
115 int eval(const std::string & s) {
116     return eval(split_expr(s));
117 }
118
119 /** Example Usage */
120
121 #include <iostream>
122 using namespace std;
123
124 int main() {
125     cout << eval("1+2*3*4+3*(2+2)-100") << endl;
126     return 0;
127 }

```

6.3 String Searching

6.3.1 Longest Common Substring

```

1  /*
2
3  6.3.1 - String Searching (Knuth-Morris-Pratt)

```

```

4
5 Given an text and a pattern to be searched for within the text,
6 determine the first position in which the pattern occurs in
7 the text. The KMP algorithm is much faster than the naive,
8 quadratic time, string searching algorithm that is found in
9 string.find() in the C++ standard library.
10
11 KMP generates a table using a prefix function of the pattern.
12 Then, the precomputed table of the pattern can be used indefinitely
13 for any number of texts.
14
15 Time Complexity:  $O(n + m)$  where  $n$  is the length of the text
16 and  $m$  is the length of the pattern.
17
18 Space Complexity:  $O(m)$  auxiliary on the length of the pattern.
19
20 */
21
22 #include <string>
23 #include <vector>
24
25 int find(const std::string & text, const std::string & pattern) {
26     if (pattern.empty()) return 0;
27     //generate table using pattern
28     std::vector<int> p(pattern.size());
29     for (int i = 0, j = p[0] = -1; i < (int)pattern.size(); ) {
30         while (j >= 0 && pattern[i] != pattern[j])
31             j = p[j];
32         i++;
33         j++;
34         p[i] = (pattern[i] == pattern[j]) ? p[j] : j;
35     }
36     //use the precomputed table to search within text
37     //the following can be repeated on many different texts
38     for (int i = 0, j = 0; j < (int)text.size(); ) {
39         while (i >= 0 && pattern[i] != text[j])
40             i = p[i];
41         i++;
42         j++;
43         if (i >= (int)pattern.size())
44             return j - i;
45     }
46     return std::string::npos;
47 }
48
49 /** Example Usage */
50
51 #include <cassert>
52
53 int main() {
54     assert(15 == find("ABC_ABCDAB_ABCDABCDABDE", "ABCDABD"));
55     return 0;
56 }

```

6.3.2 Longest Common Subsequence

```

1 /*

```

6.3.2 - String Searching (Aho-Corasick)

Given a text and multiple patterns to be searched for within the text, simultaneously determine the position of all matches. All of the patterns will be first required for precomputing the automata, after which any input text may be given without having to recompute the automata for the pattern.

Time Complexity: $O(n)$ for `build_automata()`, where n is the sum of all pattern lengths, and $O(1)$ amortized for `next_state()`. However, since it must be called m times for an input text of length m , and if there are z matches throughout the entire text, then the entire algorithm will have a running time of $O(n + m + z)$.

Note that in this implementation, a bitset is used to speed up `build_automata()` at the cost of making the later text search cost $O(n * m)$. To truly make the algorithm $O(n + m + z)$, bitset must be substituted for an `unordered_set`, which will not encounter any blank spaces during iteration of the bitset. However, for simply counting the number of matches, bitsets are clearly advantages.

Space Complexity: $O(l * c)$, where l is the sum of all pattern lengths and c is the size of the alphabet.

```

*/
#include <bitset>
#include <cstring>
#include <queue>
#include <string>
#include <vector>

const int MAXP = 1000; //maximum number of patterns
const int MAXL = 10000; //max possible sum of all pattern lengths
const int MAXC = 26;    //size of the alphabet (e.g. 'a'..'z')

//This function should be customized to return a mapping from
//the input alphabet (e.g. 'a'..'z') to the integers 0..MAXC-1
inline int map_alphabet(char c) {
    return (int)(c - 'a');
}

std::bitset<MAXP> out[MAXL]; //std::unordered_set<int> out[MAXL]
int fail[MAXL], g[MAXL][MAXC + 1];

int build_automata(const std::vector<std::string> & patterns) {
    memset(fail, -1, sizeof fail);
    memset(g, -1, sizeof g);
    for (int i = 0; i < MAXL; i++)
        out[i].reset(); //out[i].clear();
    int states = 1;
    for (int i = 0; i < (int)patterns.size(); i++) {
        const std::string & pattern = patterns[i];
        int curr = 0;
        for (int j = 0; j < (int)pattern.size(); j++) {
            int c = map_alphabet(pattern[j]);
            if (g[curr][c] == -1)
                g[curr][c] = states++;
        }
    }
}

```

```

61     curr = g[curr][c];
62 }
63 out[curr][i] = out[curr][i] | 1; //out[curr].insert(i);
64 }
65 for (int c = 0; c < MAXC; c++)
66     if (g[0][c] == -1) g[0][c] = 0;
67 std::queue<int> q;
68 for (int c = 0; c <= MAXC; c++) {
69     if (g[0][c] != -1 && g[0][c] != 0) {
70         fail[g[0][c]] = 0;
71         q.push(g[0][c]);
72     }
73 }
74 while (!q.empty()) {
75     int s = q.front(), t;
76     q.pop();
77     for (int c = 0; c <= MAXC; c++) {
78         t = g[s][c];
79         if (t != -1) {
80             int f = fail[s];
81             while (g[f][c] == -1)
82                 f = fail[f];
83             f = g[f][c];
84             fail[t] = f;
85             out[t] |= out[f]; //out[t].insert(out[f].begin(), out[f].end());
86             q.push(t);
87         }
88     }
89 }
90 return states;
91 }
92
93 int next_state(int curr, char ch) {
94     int next = curr, c = map_alphabet(ch);
95     while (g[next][c] == -1)
96         next = fail[next];
97     return g[next][c];
98 }
99
100 /** Example Usage (en.wikipedia.org/wiki/AhoCorasick_algorithm) */
101
102 #include <iostream>
103 using namespace std;
104
105 int main() {
106     vector<string> patterns;
107     patterns.push_back("a");
108     patterns.push_back("ab");
109     patterns.push_back("bab");
110     patterns.push_back("bc");
111     patterns.push_back("bca");
112     patterns.push_back("c");
113     patterns.push_back("caa");
114     build_automata(patterns);
115
116     string text("abccab");
117     int state = 0;
118     for (int i = 0; i < (int)text.size(); i++) {
119         state = next_state(state, text[i]);

```

```

120     cout << "Matches ending at position_" << i << ":" << endl;
121     if (out[state].any())
122         for (int j = 0; j < (int)out[state].size(); j++)
123             if (out[state][j])
124                 cout << " " << patterns[j] << " " << endl;
125 }
126 return 0;
127 }

```

6.3.3 Edit Distance

```

1  /*
2
3  6.3.3 - String Searching (Z Algorithm)
4
5  Given an text and a pattern to be searched for within the text,
6  determine the positions of all patterns within the text. This
7  is as efficient as KMP, but does so through computing the
8  "Z function." For a string S, Z[i] stores the length of the longest
9  substring starting from S[i] which is also a prefix of S, i.e. the
10 maximum k such that S[j] = S [ i + j ] for all 0 <= j < k .
11
12 Time Complexity: O(n + m) where n is the length of the text
13 and m is the length of the pattern.
14
15 Space Complexity: O(m) auxiliary on the length of the pattern.
16
17 */
18
19 #include <algorithm>
20 #include <string>
21 #include <vector>
22
23 std::vector<int> z_function(const std::string & s) {
24     std::vector<int> z(s.size());
25     for (int i = 1, l = 0, r = 0; i < (int)z.size(); i++) {
26         if (i <= r)
27             z[i] = std::min(r - i + 1, z[i - l]);
28         while (i + z[i] < (int)z.size() && s[z[i]] == s[i + z[i]])
29             z[i]++;
30         if (r < i + z[i] - 1) {
31             l = i;
32             r = i + z[i] - 1;
33         }
34     }
35     return z;
36 }
37
38 /** Example Usage **/
39
40 #include <iostream>
41 using namespace std;
42
43 int main() {
44     string text = "abcabaaaababab";
45     string pattern = "aba";
46     vector<int> z = z_function(pattern + "$" + text);

```

```

47     for (int i = (int)pattern.size() + 1; i < (int)z.size(); i++) {
48         if (z[i] == (int)pattern.size())
49             cout << "Pattern found starting at index_"
50                 << (i - (int)pattern.size() - 1) << "." << endl;
51     }
52     return 0;
53 }

```

6.4 Dynamic Programming

6.4.1 Longest Common Substring

```

1  /*
2
3  6.4.1 - Longest Common Substring
4
5  A substring is a consecutive part of a longer string (e.g. "ABC" is
6  a substring of "ABCDE" but "ABD" is not). Using dynamic programming,
7  determine the longest string which is a substring common to any two
8  input strings.
9
10 Time Complexity:  $O(n * m)$  where  $n$  and  $m$  are the lengths of the two
11 input strings, respectively.
12
13 Space Complexity:  $O(\min(n, m))$  auxiliary.
14
15 */
16
17 #include <string>
18
19 std::string longest_common_substring
20 (const std::string & s1, const std::string & s2) {
21     if (s1.empty() || s2.empty()) return "";
22     if (s1.size() < s2.size())
23         return longest_common_substring(s2, s1);
24     int * A = new int[s2.size()];
25     int * B = new int[s2.size()];
26     int startpos = 0, maxlen = 0;
27     for (int i = 0; i < (int)s1.size(); i++) {
28         for (int j = 0; j < (int)s2.size(); j++) {
29             if (s1[i] == s2[j]) {
30                 A[j] = (i > 0 && j > 0) ? 1 + B[j - 1] : 1;
31                 if (maxlen < A[j]) {
32                     maxlen = A[j];
33                     startpos = i - A[j] + 1;
34                 }
35             } else {
36                 A[j] = 0;
37             }
38         }
39         int * temp = A;
40         A = B;
41         B = temp;
42     }
43     delete[] A;
44     delete[] B;

```



```

45     return s1.substr(startpos, maxlen);
46 }
47
48 /** Example Usage */
49
50 #include <cassert>
51
52 int main() {
53     assert(longest_common_substring("bbbabca", "aababcd") == "babc");
54     return 0;
55 }

```

6.4.2 Longest Common Subsequence

```

1  /*
2
3  6.4.2 - Longest Common Subsequence
4
5  A subsequence is a sequence that can be derived from another sequence
6  by deleting some elements without changing the order of the remaining
7  elements (e.g. "ACE" is a subsequence of "ABCDE", but "BAE" is not).
8  Using dynamic programming, determine the longest string which
9  is a subsequence common to any two input strings.
10
11 In addition, the shortest common supersequence between two strings is
12 a closely related problem, which involves finding the shortest string
13 which has both input strings as subsequences (e.g. "ABBC" and "BCB" has
14 the shortest common supersequence of "ABBCB"). The answer is simply:
15     (sum of lengths of s1 and s2) - (length of LCS of s1 and s2)
16
17 Time Complexity:  $O(n * m)$  where n and m are the lengths of the two
18 input strings, respectively.
19
20 Space Complexity:  $O(n * m)$  auxiliary.
21
22 */
23
24 #include <string>
25 #include <vector>
26
27 std::string longest_common_subsequence
28 (const std::string & s1, const std::string & s2) {
29     int n = s1.size(), m = s2.size();
30     std::vector< std::vector<int> > dp;
31     dp.resize(n + 1, std::vector<int>(m + 1, 0));
32     for (int i = 0; i < n; i++) {
33         for (int j = 0; j < m; j++) {
34             if (s1[i] == s2[j]) {
35                 dp[i + 1][j + 1] = dp[i][j] + 1;
36             } else if (dp[i + 1][j] > dp[i][j + 1]) {
37                 dp[i + 1][j + 1] = dp[i + 1][j];
38             } else {
39                 dp[i + 1][j + 1] = dp[i][j + 1];
40             }
41         }
42     }
43     std::string ret;

```

```

44     for (int i = n, j = m; i > 0 && j > 0; ) {
45         if (s1[i - 1] == s2[j - 1]) {
46             ret = s1[i - 1] + ret;
47             i--;
48             j--;
49         } else if (dp[i - 1][j] < dp[i][j - 1]) {
50             j--;
51         } else {
52             i--;
53         }
54     }
55     return ret;
56 }
57
58 /** Example Usage */
59
60 #include <cassert>
61
62 int main() {
63     assert(longest_common_subsequence("xmjyauz", "mzjawxu") == "mjau");
64     return 0;
65 }

```

6.4.3 Edit Distance

```

1  /*
2
3  6.4.3 - Edit Distance
4
5  Given two strings s1 and s2, the edit distance between them is the
6  minimum number of operations required to transform s1 into s2,
7  where each operation can be any one of the following:
8      - insert a letter anywhere into the current string
9      - delete any letter from the current string
10     - replace any letter of the current string with any other letter
11
12 Time Complexity:  $O(n * m)$  where n and m are the lengths of the two
13 input strings, respectively.
14
15 Space Complexity:  $O(n * m)$  auxiliary.
16
17 */
18
19 #include <algorithm>
20 #include <string>
21 #include <vector>
22
23 int edit_distance(const std::string & s1, const std::string & s2) {
24     int n = s1.size(), m = s2.size();
25     std::vector< std::vector<int> > dp;
26     dp.resize(n + 1, std::vector<int>(m + 1, 0));
27     for (int i = 0; i <= n; i++) dp[i][0] = i;
28     for (int j = 0; j <= m; j++) dp[0][j] = j;
29     for (int i = 0; i < n; i++) {
30         for (int j = 0; j < m; j++) {
31             if (s1[i] == s2[j]) {
32                 dp[i + 1][j + 1] = dp[i][j];

```

```

33     } else {
34         dp[i + 1][j + 1] = 1 + std::min(dp[i][j],          //replace
35                                         std::min(dp[i + 1][j], //insert
36                                                     dp[i][j + 1])); //delete
37     }
38 }
39 }
40 return dp[n][m];
41 }
42
43 /** Example Usage **/
44
45 #include <cassert>
46
47 int main() {
48     assert(edit_distance("abxdef", "abcdefg") == 2);
49     return 0;
50 }

```

6.5 Suffix Array and LCP

6.5.1 $\mathcal{O}(N \log^2 N)$ Construction

```

1  /*
2
3  6.5.1 - Suffix and LCP Array (N log N Construction)
4
5  A suffix array SA of a string S[1..n] is a sorted array of indices of
6  all the suffixes of S ("abc" has suffixes "abc", "bc", and "c").
7  SA[i] contains the starting position of the i-th smallest suffix in S,
8  ensuring that for all  $1 < i \leq n$ ,  $S[SA[i - 1], n] < S[A[i], n]$  holds.
9  It is a simple, space efficient alternative to suffix trees.
10 By binary searching on a suffix array, one can determine whether a
11 substring exists in a string in  $\mathcal{O}(\log n)$  time per query.
12
13 The longest common prefix array (LCP array) stores the lengths of the
14 longest common prefixes between all pairs of consecutive suffixes in
15 a sorted suffix array and can be found in  $\mathcal{O}(n)$  given the suffix array.
16
17 The following algorithm uses a "gap" partitioning algorithm
18 explained here: http://stackoverflow.com/a/17763563
19
20 Time Complexity:  $\mathcal{O}(n \log^2 n)$  for suffix_array() and  $\mathcal{O}(n)$  for
21 lcp_array(), where n is the length of the input string.
22
23 Space Complexity:  $\mathcal{O}(n)$  auxiliary.
24
25 */
26
27 #include <algorithm>
28 #include <string>
29 #include <vector>
30
31 std::vector<long long> rank2;
32
33 bool comp(const int & a, const int & b) {

```

```

34     return rank2[a] < rank2[b];
35 }
36
37 std::vector<int> suffix_array(const std::string & s) {
38     int n = s.size();
39     std::vector<int> sa(n), rank(n);
40     for (int i = 0; i < n; i++) {
41         sa[i] = i;
42         rank[i] = (int)s[i];
43     }
44     rank2.resize(n);
45     for (int len = 1; len < n; len *= 2) {
46         for (int i = 0; i < n; i++)
47             rank2[i] = ((long long)rank[i] << 32) +
48                 (i + len < n ? rank[i + len] + 1 : 0);
49         std::sort(sa.begin(), sa.end(), comp);
50         for (int i = 0; i < n; i++)
51             rank[sa[i]] = (i > 0 && rank2[sa[i - 1]] == rank2[sa[i]]) ?
52                 rank[sa[i - 1]] : i;
53     }
54     return sa;
55 }
56
57 std::vector<int> lcp_array(const std::string & s,
58                          const std::vector<int> & sa) {
59     int n = sa.size();
60     std::vector<int> rank(n), lcp(n - 1);
61     for (int i = 0; i < n; i++)
62         rank[sa[i]] = i;
63     for (int i = 0, h = 0; i < n; i++) {
64         if (rank[i] < n - 1) {
65             int j = sa[rank[i] + 1];
66             while (std::max(i, j) + h < n && s[i + h] == s[j + h])
67                 h++;
68             lcp[rank[i]] = h;
69             if (h > 0) h--;
70         }
71     }
72     return lcp;
73 }
74
75 /** Example Usage */
76
77 #include <cassert>
78 using namespace std;
79
80 int main() {
81     string s("banana");
82     vector<int> sa = suffix_array(s);
83     vector<int> lcp = lcp_array(s, sa);
84     int sa_ans[] = {5, 3, 1, 0, 4, 2};
85     int lcp_ans[] = {1, 3, 0, 0, 2};
86     assert(equal(sa.begin(), sa.end(), sa_ans));
87     assert(equal(lcp.begin(), lcp.end(), lcp_ans));
88     return 0;
89 }

```

6.5.2 $O(N \log N)$ Construction

```

1  /*
2
3  6.5.2 - Suffix and LCP Array (N log N Construction)
4
5  A suffix array SA of a string S[1..n] is a sorted array of indices of
6  all the suffixes of S ("abc" has suffixes "abc", "bc", and "c").
7  SA[i] contains the starting position of the i-th smallest suffix in S,
8  ensuring that for all  $1 < i \leq n$ ,  $S[SA[i - 1], n] < S[A[i], n]$  holds.
9  It is a simple, space efficient alternative to suffix trees.
10 By binary searching on a suffix array, one can determine whether a
11 substring exists in a string in  $O(\log n)$  time per query.
12
13 The longest common prefix array (LCP array) stores the lengths of the
14 longest common prefixes between all pairs of consecutive suffixes in
15 a sorted suffix array and can be found in  $O(n)$  given the suffix array.
16
17 The following algorithm uses a "gap" partitioning algorithm
18 explained here: http://stackoverflow.com/a/17763563, except that the
19  $O(n \log n)$  comparison-based sort is substituted for an  $O(n)$  counting
20 sort to reduce the running time by an order of  $\log n$ .
21
22 Time Complexity:  $O(n \log n)$  for suffix_array() and  $O(n)$  for
23 lcp_array(), where n is the length of the input string.
24
25 Space Complexity:  $O(n)$  auxiliary.
26
27 */
28
29 #include <algorithm>
30 #include <string>
31 #include <vector>
32
33 const std::string * str;
34
35 bool comp(const int & a, const int & b) {
36     return (*str)[a] < (*str)[b];
37 }
38
39 std::vector<int> suffix_array(const std::string & s) {
40     int n = s.size();
41     std::vector<int> sa(n), order(n), rank(n);
42     for (int i = 0; i < n; i++)
43         order[i] = n - 1 - i;
44     str = &s;
45     std::stable_sort(order.begin(), order.end(), comp);
46     for (int i = 0; i < n; i++) {
47         sa[i] = order[i];
48         rank[i] = (int)s[i];
49     }
50     std::vector<int> r(n), cnt(n), _sa(n);
51     for (int len = 1; len < n; len *= 2) {
52         r = rank;
53         _sa = sa;
54         for (int i = 0; i < n; i++)
55             cnt[i] = i;
56         for (int i = 0; i < n; i++) {

```

```

57     if (i > 0 && r[sa[i - 1]] == r[sa[i]] && sa[i - 1] + len < n &&
58         r[sa[i - 1] + len / 2] == r[sa[i] + len / 2]) {
59         rank[sa[i]] = rank[sa[i - 1]];
60     } else {
61         rank[sa[i]] = i;
62     }
63 }
64 for (int i = 0; i < n; i++) {
65     int s1 = _sa[i] - len;
66     if (s1 >= 0)
67         sa[cnt[rank[s1]]++] = s1;
68 }
69 }
70 return sa;
71 }
72
73 std::vector<int> lcp_array(const std::string & s,
74                          const std::vector<int> & sa) {
75     int n = sa.size();
76     std::vector<int> rank(n), lcp(n - 1);
77     for (int i = 0; i < n; i++)
78         rank[sa[i]] = i;
79     for (int i = 0, h = 0; i < n; i++) {
80         if (rank[i] < n - 1) {
81             int j = sa[rank[i] + 1];
82             while (std::max(i, j) + h < n && s[i + h] == s[j + h])
83                 h++;
84             lcp[rank[i]] = h;
85             if (h > 0) h--;
86         }
87     }
88     return lcp;
89 }
90
91 /** Example Usage **/
92
93 #include <cassert>
94 using namespace std;
95
96 int main() {
97     string s("banana");
98     vector<int> sa = suffix_array(s);
99     vector<int> lcp = lcp_array(s, sa);
100     int sa_ans[] = {5, 3, 1, 0, 4, 2};
101     int lcp_ans[] = {1, 3, 0, 0, 2};
102     assert(equal(sa.begin(), sa.end(), sa_ans));
103     assert(equal(lcp.begin(), lcp.end(), lcp_ans));
104     return 0;
105 }

```

6.5.3 $\mathcal{O}(N \log N)$ Construction (DC3/Skew)

```

1  /*
2
3  6.5.2 - Suffix and LCP Array (Linear Construction, DC3)
4
5  A suffix array SA of a string S[1, n] is a sorted array of indices of

```

```

6 all the suffixes of S ("abc" has suffixes "abc", "bc", and "c").
7 SA[i] contains the starting position of the i-th smallest suffix in S,
8 ensuring that for all  $1 < i \leq n$ ,  $S[SA[i - 1], n] < S[SA[i], n]$  holds.
9 It is a simple, space efficient alternative to suffix trees.
10 By binary searching on a suffix array, one can determine whether a
11 substring exists in a string in  $O(\log n)$  time per query.
12
13 The longest common prefix array (LCP array) stores the lengths of the
14 longest common prefixes between all pairs of consecutive suffixes in
15 a sorted suffix array and can be found in  $O(n)$  given the suffix array.
16
17 The following implementation uses the sophisticated DC3/skew algorithm
18 by Karkkainen & Sanders (2003), using radix sort on integer alphabets
19 for linear construction. The function suffix_array(s, SA, n, K) takes
20 in s, an array  $[0, n - 1]$  of ints with n values in the range  $[1, K]$ .
21 It stores the indices defining the suffix array into SA. The last value
22 of the input array  $s[n - 1]$  must be equal 0, the sentinel character. A
23 C++ wrapper function suffix_array(std::string) is implemented below it.
24
25 Time Complexity:  $O(n)$  for suffix_array() and lcp_array(), where n is
26 the length of the input string.
27
28 Space Complexity:  $O(n)$  auxiliary.
29
30 */
31
32 inline bool leq(int a1, int a2, int b1, int b2) {
33     return a1 < b1 || (a1 == b1 && a2 <= b2);
34 }
35
36 inline bool leq(int a1, int a2, int a3, int b1, int b2, int b3) {
37     return a1 < b1 || (a1 == b1 && leq(a2, a3, b2, b3));
38 }
39
40 static void radix_pass(int * a, int * b, int * r, int n, int K) {
41     int *c = new int[K + 1];
42     for (int i = 0; i <= K; i++)
43         c[i] = 0;
44     for (int i = 0; i < n; i++)
45         c[r[a[i]]]++;
46     for (int i = 0, sum = 0; i <= K; i++) {
47         int tmp = c[i];
48         c[i] = sum;
49         sum += tmp;
50     }
51     for (int i = 0; i < n; i++)
52         b[c[r[a[i]]]++] = a[i];
53     delete[] c;
54 }
55
56 void suffix_array(int * s, int * sa, int n, int K) {
57     int n0 = (n + 2) / 3, n1 = (n + 1) / 3, n2 = n / 3, n02 = n0 + n2;
58     int *s12 = new int[n02 + 3], *SA12 = new int[n02 + 3];
59     s12[n02] = s12[n02 + 1] = s12[n02 + 2] = 0;
60     SA12[n02] = SA12[n02 + 1] = SA12[n02 + 2] = 0;
61     int *s0 = new int[n0], *SA0 = new int[n0];
62     for (int i = 0, j = 0; i < n + n0 - n1; i++)
63         if (i % 3 != 0) s12[j++] = i;
64     radix_pass(s12, SA12, s + 2, n02, K);

```

```

65 radix_pass(SA12, s12, s + 1, n02, K);
66 radix_pass(s12, SA12, s, n02, K);
67 int name = 0, c0 = -1, c1 = -1, c2 = -1;
68 for (int i = 0; i < n02; i++) {
69     if (s[SA12[i]] != c0 || s[SA12[i] + 1] != c1 || s[SA12[i] + 2] != c2) {
70         name++;
71         c0 = s[SA12[i]];
72         c1 = s[SA12[i] + 1];
73         c2 = s[SA12[i] + 2];
74     }
75     if (SA12[i] % 3 == 1)
76         s12[SA12[i] / 3] = name;
77     else
78         s12[SA12[i] / 3 + n0] = name;
79 }
80 if (name < n02) {
81     suffix_array(s12, SA12, n02, name);
82     for (int i = 0; i < n02; i++)
83         s12[SA12[i]] = i + 1;
84 } else {
85     for (int i = 0; i < n02; i++)
86         SA12[s12[i] - 1] = i;
87 }
88 for (int i = 0, j = 0; i < n02; i++)
89     if (SA12[i] < n0)
90         s0[j++] = 3 * SA12[i];
91 radix_pass(s0, SA0, s, n0, K);
92 #define GetI() (SA12[t] < n0 ? SA12[t] * 3 + 1 : (SA12[t] - n0) * 3 + 2)
93 for (int p = 0, t = n0 - n1, k = 0; k < n; k++) {
94     int i = GetI(), j = SA0[p];
95     if (SA12[t] < n0 ? leq(s[i], s12[SA12[t] + n0], s[j], s12[j/3]) :
96         leq(s[i], s[i + 1], s12[SA12[t] - n0 + 1], s[j], s[j + 1], s12[j / 3 + n0])) {
97         sa[k] = i;
98         if (++t == n02)
99             for (k++; p < n0; p++, k++)
100                 sa[k] = SA0[p];
101     } else {
102         sa[k] = j;
103         if (++p == n0)
104             for (k++; t < n02; t++, k++)
105                 sa[k] = GetI();
106     }
107 }
108 #undef GetI
109 delete[] s12;
110 delete[] SA12;
111 delete[] SA0;
112 delete[] s0;
113 }
114
115 #include <string>
116 #include <vector>
117
118 // C++ wrapper function
119 std::vector<int> suffix_array(const std::string & s) {
120     int n = s.size();
121     int *str = new int[n + 5], *sa = new int[n + 1];
122     for (int i = 0; i < n + 5; i++) str[i] = 0;
123     for (int i = 0; i < n; i++) str[i] = (int)s[i];

```



```

124     suffix_array(str, sa, n + 1, 256);
125     return std::vector<int>(sa + 1, sa + n + 1);
126 }
127
128 std::vector<int> lcp_array(const std::string & s,
129                          const std::vector<int> & sa) {
130     int n = sa.size();
131     std::vector<int> rank(n), lcp(n - 1);
132     for (int i = 0; i < n; i++)
133         rank[sa[i]] = i;
134     for (int i = 0, h = 0; i < n; i++) {
135         if (rank[i] < n - 1) {
136             int j = sa[rank[i] + 1];
137             while (std::max(i, j) + h < n && s[i + h] == s[j + h])
138                 h++;
139             lcp[rank[i]] = h;
140             if (h > 0) h--;
141         }
142     }
143     return lcp;
144 }
145
146 /** Example Usage **/
147
148 #include <cassert>
149 using namespace std;
150
151 int main() {
152     string s("banana");
153     vector<int> sa = suffix_array(s);
154     vector<int> lcp = lcp_array(s, sa);
155     int sa_ans[] = {5, 3, 1, 0, 4, 2};
156     int lcp_ans[] = {1, 3, 0, 0, 2};
157     assert(equal(sa.begin(), sa.end(), sa_ans));
158     assert(equal(lcp.begin(), lcp.end(), lcp_ans));
159     return 0;
160 }

```

6.6 String Data Structures

6.5.1 Simple Trie

```

1  /*
2
3  6.6.1 - Trie (Simple)
4
5  A trie, digital tree, or prefix tree, is an ordered tree data
6  structure that is used to store a dynamic set or associative array
7  where the keys are strings. Each leaf node represents a string that
8  has been inserted into the trie. This makes tries easier to implement
9  than balanced binary search trees, and also potentially faster.
10
11 Time Complexity:  $O(n)$  for insert(), contains(), and erase(), where
12 n is the length of the string being inserted, searched, or erased.
13
14 Space Complexity: At worst  $O(l * \text{ALPHABET\_SIZE})$ , where l is the

```

```

15  sum of all lengths of strings that have been inserted so far.
16
17  */
18
19  #include <string>
20
21  class trie {
22      static const int ALPHABET_SIZE = 26;
23
24      static int map_alphabet(char c) {
25          return (int)(c - 'a');
26      }
27
28      struct node_t {
29          bool leaf;
30
31          node_t * children[ALPHABET_SIZE];
32
33          node_t(): leaf(false) {
34              for (int i = 0; i < ALPHABET_SIZE; i++)
35                  children[i] = 0;
36          }
37
38          bool is_free() {
39              for (int i = 0; i < ALPHABET_SIZE; i++)
40                  if (this->children[i] != 0) return true;
41              return false;
42          }
43      } *root;
44
45      bool erase(const std::string & s, node_t * n, int depth) {
46          if (n == 0) return false;
47          if (depth == (int)s.size()) {
48              if (n->leaf) {
49                  n->leaf = false;
50                  return n->is_free();
51              }
52          } else {
53              int idx = map_alphabet(s[depth]);
54              if (erase(s, n->children[idx], depth + 1)) {
55                  delete n->children[idx];
56                  return !n->leaf && n->is_free();
57              }
58          }
59          return false;
60      }
61
62      static void clean_up(node_t * n) {
63          if (n == 0 || n->leaf) return;
64          for (int i = 0; i < ALPHABET_SIZE; i++)
65              clean_up(n->children[i]);
66          delete n;
67      }
68
69  public:
70      trie() { root = new node_t(); }
71      ~trie() { clean_up(root); }
72
73      void insert(const std::string & s) {

```

```

74     node_t * n = root;
75     for (int i = 0; i < (int)s.size(); i++) {
76         int c = map_alphabet(s[i]);
77         if (n->children[c] == 0)
78             n->children[c] = new node_t();
79         n = n->children[c];
80     }
81     n->leaf = true;
82 }
83
84 bool contains(const std::string & s) {
85     node_t *n = root;
86     for (int i = 0; i < (int)s.size(); i++) {
87         int c = map_alphabet(s[i]);
88         if (n->children[c] == 0)
89             return false;
90         n = n->children[c];
91     }
92     return n != 0 && n->leaf;
93 }
94
95 bool erase(const std::string & s) {
96     return erase(s, root, 0);
97 }
98 };
99
100 /** Example Usage */
101
102 #include <cassert>
103 using namespace std;
104
105 int main() {
106     string s[8] = {"a", "to", "tea", "ted", "ten", "i", "in", "inn"};
107     trie t;
108     for (int i = 0; i < 8; i++)
109         t.insert(s[i]);
110     assert(t.contains("ten"));
111     t.erase("tea");
112     assert(!t.contains("tea"));
113     return 0;
114 }

```

6.5.2 Radix Trie

```

1  /*
2
3  6.6.2 - Radix Tree
4
5  A radix tree, radix trie, patricia trie, or compressed trie is a
6  data structure that is used to store a dynamic set or associative
7  array where the keys are strings. Each leaf node represents a string
8  that has been inserted into the trie. Unlike simple tries, radix
9  tries are space-optimized by merging each node that is an only child
10 with its parent.
11
12 Time Complexity:  $O(n)$  for insert(), contains(), and erase(), where
13 n is the length of the string being inserted, searched, or erased.

```

```

14
15 Space Complexity: At worst  $O(l)$ , where  $l$  is the sum of all lengths
16 of strings that have been inserted so far.
17
18 */
19
20 #include <string>
21 #include <vector>
22
23 class radix_trie {
24     struct node_t {
25         std::string label;
26         std::vector<node_t*> children;
27
28         node_t(const std::string & s = "") {
29             label = s;
30         }
31     } *root;
32
33     unsigned int lcplen(const std::string & s, const std::string & t) {
34         int minsize = (t.size() < s.size()) ? t.size() : s.size();
35         if (minsize == 0) return 0;
36         unsigned int res = 0;
37         for (int i = 0; i < minsize && s[i] == t[i]; i++)
38             res++;
39         return res;
40     }
41
42     void insert(const std::string & s, node_t * n) {
43         unsigned int lcp = lcplen(s, n->label);
44         if (lcp == 0 || n == root ||
45             (lcp > 0 && lcp < s.size() && lcp >= n->label.size())) {
46             bool inserted = false;
47             std::string newstr = s.substr(lcp, s.size() - lcp);
48             for (int i = 0; i < (int)n->children.size(); i++) {
49                 if (n->children[i]->label[0] == newstr[0]) {
50                     inserted = true;
51                     insert(newstr, n->children[i]);
52                 }
53             }
54             if (!inserted)
55                 n->children.push_back(new node_t(newstr));
56         } else if (lcp < s.size()) {
57             node_t * t = new node_t();
58             t->label = n->label.substr(lcp, n->label.size() - lcp);
59             t->children.assign(n->children.begin(), n->children.end());
60             n->label = s.substr(0, lcp);
61             n->children.assign(1, t);
62             n->children.push_back(new node_t(s.substr(lcp, s.size() - lcp)));
63         }
64     }
65
66     void erase(const std::string & s, node_t * n) {
67         unsigned int lcp = lcplen(s, n->label);
68         if (lcp == 0 || n == root ||
69             (lcp > 0 && lcp < s.size() && lcp >= n->label.size())) {
70             std::string newstr = s.substr(lcp, s.size() - lcp);
71             for (int i = 0; i < (int)n->children.size(); i++) {
72                 if (n->children[i]->label[0] == newstr[0]) {

```

```

73         if (newstr == n->children[i]->label &&
74             n->children[i]->children.empty()) {
75             n->children.erase(n->children.begin() + i);
76             return;
77         }
78         erase(newstr, n->children[i]);
79     }
80 }
81 }
82 }
83
84 bool contains(const std::string & s, node_t * n) {
85     unsigned int lcp = lcplen(s, n->label);
86     if (lcp == 0 || n == root ||
87         (lcp > 0 && lcp < s.size() && lcp >= n->label.size())) {
88         std::string newstr = s.substr(lcp, s.size() - lcp);
89         for (int i = 0; i < (int)n->children.size(); i++)
90             if (n->children[i]->label[0] == newstr[0])
91                 return contains(newstr, n->children[i]);
92         return false;
93     }
94     return lcp == n->label.size();
95 }
96
97 static void clean_up(node_t * n) {
98     if (n == 0) return;
99     for (int i = 0; i < (int)n->children.size(); i++)
100         clean_up(n->children[i]);
101     delete n;
102 }
103
104 public:
105     template <class UnaryFunction>
106     void walk(node_t * n, UnaryFunction f) {
107         if (n == 0) return;
108         if (n != root) f(n->label);
109         for (int i = 0; i < (int)n->children.size(); i++)
110             walk(n->children[i], f);
111     }
112
113     radix_trie() { root = new node_t(); }
114     ~radix_trie() { clean_up(root); }
115
116     void insert(const std::string & s) { insert(s, root); }
117     void erase(const std::string & s) { erase(s, root); }
118     bool contains(const std::string & s) { return contains(s, root); }
119
120     template <class UnaryFunction> void walk(UnaryFunction f) {
121         walk(root, f);
122     }
123 };
124
125 /** Example Usage */
126
127 #include <cassert>
128 using namespace std;
129
130 string preorder;
131

```

```

132 void concat(const string & s) {
133     preorder += (s + "_");
134 }
135
136 int main() {
137     {
138         string s[8] = {"a", "to", "tea", "ted", "ten", "i", "in", "inn"};
139         radix_trie t;
140         for (int i = 0; i < 8; i++)
141             t.insert(s[i]);
142         assert(t.contains("ten"));
143         t.erase("tea");
144         assert(!t.contains("tea"));
145     }
146     {
147         radix_trie t;
148         t.insert("test");
149         t.insert("toaster");
150         t.insert("toasting");
151         t.insert("slow");
152         t.insert("slowly");
153         preorder = "";
154         t.walk(concat);
155         assert(preorder == "t_test_oast_er_ing_slow_ly");
156     }
157     return 0;
158 }

```

6.5.3 Suffix Trie

```

1  /*
2
3  6.6.3 - Suffix Tree (Ukkonen's Algorithm)
4
5  A suffix tree of a string S is a compressed trie of all the suffixes
6  of S. While it can be constructed in  $O(n^2)$  time on the length of S
7  by simply inserting the suffixes into a radix tree, Ukkonen (1995)
8  provided an algorithm to construct one in  $O(n * \text{ALPHABET\_SIZE})$ .
9
10 Suffix trees can be used for string searching, pattern matching, and
11 solving the longest common substring problem. The implementation
12 below is optimized for solving the latter.
13
14 Time Complexity:  $O(n)$  for construction of suffix_tree() and
15 per call to longest_common_substring(), respectively.
16
17 Space Complexity:  $O(n)$  auxiliary.
18
19 */
20
21 #include <cstdio>
22 #include <string>
23
24 struct suffix_tree {
25
26     static const int ALPHABET_SIZE = 38;
27

```

```

28 static int map_alphabet(char c) {
29     static const std::string ALPHABET(
30         "abcdefghijklmnopqrstuvwxyz0123456789\01\02"
31     );
32     return ALPHABET.find(c);
33 }
34
35 struct node_t {
36     int begin, end, depth;
37     node_t *parent, *suffix_link;
38     node_t *children[ALPHABET_SIZE];
39
40     node_t(int begin, int end, int depth, node_t * parent) {
41         this->begin = begin;
42         this->end = end;
43         this->depth = depth;
44         this->parent = parent;
45         for (int i = 0; i < ALPHABET_SIZE; i++)
46             children[i] = 0;
47     }
48 } *root;
49
50 suffix_tree(const std::string & s) {
51     int n = s.size();
52     int * c = new int[n];
53     for (int i = 0; i < n; i++) c[i] = map_alphabet(s[i]);
54     root = new node_t(0, 0, 0, 0);
55     node_t *node = root;
56     for (int i = 0, tail = 0; i < n; i++, tail++) {
57         node_t *last = 0;
58         while (tail >= 0) {
59             node_t *ch = node->children[c[i - tail]];
60             while (ch != 0 && tail >= ch->end - ch->begin) {
61                 tail -= ch->end - ch->begin;
62                 node = ch;
63                 ch = ch->children[c[i - tail]];
64             }
65             if (ch == 0) {
66                 node->children[c[i]] = new node_t(i, n,
67                     node->depth + node->end - node->begin, node);
68                 if (last != 0) last->suffix_link = node;
69                 last = 0;
70             } else {
71                 int aftertail = c[ch->begin + tail];
72                 if (aftertail == c[i]) {
73                     if (last != 0) last->suffix_link = node;
74                     break;
75                 } else {
76                     node_t *split = new node_t(ch->begin, ch->begin + tail,
77                         node->depth + node->end - node->begin, node);
78                     split->children[c[i]] = new node_t(i, n, ch->depth + tail, split);
79                     split->children[aftertail] = ch;
80                     ch->begin += tail;
81                     ch->depth += tail;
82                     ch->parent = split;
83                     node->children[c[i - tail]] = split;
84                     if (last != 0)
85                         last->suffix_link = split;
86                     last = split;

```

```

87         }
88     }
89     if (node == root) {
90         tail--;
91     } else {
92         node = node->suffix_link;
93     }
94 }
95 }
96 }
97 };
98
99 int lcs_begin, lcs_len;
100
101 int lcs_rec(suffix_tree::node_t * n, int i1, int i2) {
102     if (n->begin <= i1 && i1 < n->end) return 1;
103     if (n->begin <= i2 && i2 < n->end) return 2;
104     int mask = 0;
105     for (int i = 0; i < suffix_tree::ALPHABET_SIZE; i++) {
106         if (n->children[i] != 0)
107             mask |= lcs_rec(n->children[i], i1, i2);
108     }
109     if (mask == 3) {
110         int curr_len = n->depth + n->end - n->begin;
111         if (lcs_len < curr_len) {
112             lcs_len = curr_len;
113             lcs_begin = n->begin;
114         }
115     }
116     return mask;
117 }
118
119 std::string longest_common_substring
120 (const std::string & s1, const std::string & s2) {
121     std::string s(s1 + '\01' + s2 + '\02');
122     suffix_tree tree(s);
123     lcs_begin = lcs_len = 0;
124     lcs_rec(tree.root, s1.size(), s1.size() + s2.size() + 1);
125     return s.substr(lcs_begin - 1, lcs_len);
126 }
127
128 /** Example Usage */
129
130 #include <cassert>
131
132 int main() {
133     assert(longest_common_substring("bbbabca", "aababcd") == "bab");
134     return 0;
135 }

```

6.5.4 Suffix Automaton

```

1  /*
2
3  6.6.4 - Suffix Automaton
4
5  A suffix automaton is a data structure to efficiently represent the

```


6 suffixes of a string. It can be considered a compressed version of
 7 a suffix tree. The data structure supports querying for substrings
 8 within the text from with the automaton is constructed in linear
 9 time. It also supports computation of the longest common substring
 10 in linear time.

11
 12 Time Complexity: $O(n * \text{ALPHABET_SIZE})$ for construction, and $O(n)$
 13 for `find_all()`, as well as `longest_common_substring()`.

14
 15 Space Complexity: $O(n * \text{ALPHABET_SIZE})$ auxiliary.

```

16
17 */
18
19 #include <algorithm>
20 #include <queue>
21 #include <string>
22 #include <vector>
23
24 struct suffix_automaton {
25
26     static const int ALPHABET_SIZE = 26;
27
28     static int map_alphabet(char c) {
29         return (int)(c - 'a');
30     }
31
32     struct state_t {
33         int length, suffix_link;
34         int firstpos, next[ALPHABET_SIZE];
35         std::vector<int> invlinks;
36
37         state_t() {
38             length = 0;
39             suffix_link = 0;
40             firstpos = -1;
41             for (int i = 0; i < ALPHABET_SIZE; i++)
42                 next[i] = -1;
43         }
44     };
45
46     std::vector<state_t> states;
47
48     suffix_automaton(const std::string & s) {
49         int n = s.size();
50         states.resize(std::max(2, 2 * n - 1));
51         states[0].suffix_link = -1;
52         int last = 0;
53         int size = 1;
54         for (int i = 0; i < n; i++) {
55             int c = map_alphabet(s[i]);
56             int curr = size++;
57             states[curr].length = i + 1;
58             states[curr].firstpos = i;
59             int p = last;
60             while (p != -1 && states[p].next[c] == -1) {
61                 states[p].next[c] = curr;
62                 p = states[p].suffix_link;
63             }
64             if (p == -1) {

```

```

65     states[curr].suffix_link = 0;
66 } else {
67     int q = states[p].next[c];
68     if (states[p].length + 1 == states[q].length) {
69         states[curr].suffix_link = q;
70     } else {
71         int clone = size++;
72         states[clone].length = states[p].length + 1;
73         for (int i = 0; i < ALPHABET_SIZE; i++)
74             states[clone].next[i] = states[q].next[i];
75         states[clone].suffix_link = states[q].suffix_link;
76         while (p != -1 && states[p].next[c] == q) {
77             states[p].next[c] = clone;
78             p = states[p].suffix_link;
79         }
80         states[q].suffix_link = clone;
81         states[curr].suffix_link = clone;
82     }
83 }
84 last = curr;
85 }
86 for (int i = 1; i < size; i++)
87     states[states[i].suffix_link].invlinks.push_back(i);
88 states.resize(size);
89 }
90
91 std::vector<int> find_all(const std::string & s) {
92     std::vector<int> res;
93     int node = 0;
94     for (int i = 0; i < (int)s.size(); i++) {
95         int next = states[node].next[map_alphabet(s[i])];
96         if (next == -1) return res;
97         node = next;
98     }
99     std::queue<int> q;
100     q.push(node);
101     while (!q.empty()) {
102         int curr = q.front();
103         q.pop();
104         if (states[curr].firstpos != -1)
105             res.push_back(states[curr].firstpos - (int)s.size() + 1);
106         for (int j = 0; j < (int)states[curr].invlinks.size(); j++)
107             q.push(states[curr].invlinks[j]);
108     }
109     return res;
110 }
111
112 std::string longest_common_substring(const std::string & s) {
113     int len = 0, bestlen = 0, bestpos = -1;
114     for (int i = 0, cur = 0; i < (int)s.size(); i++) {
115         int c = map_alphabet(s[i]);
116         if (states[cur].next[c] == -1) {
117             while (cur != -1 && states[cur].next[c] == -1)
118                 cur = states[cur].suffix_link;
119             if (cur == -1) {
120                 cur = len = 0;
121                 continue;
122             }
123             len = states[cur].length;

```

```

124     }
125     len++;
126     cur = states[cur].next[c];
127     if (bestlen < len) {
128         bestlen = len;
129         bestpos = i;
130     }
131 }
132 return s.substr(bestpos - bestlen + 1, bestlen);
133 }
134 };
135
136 /** Example Usage */
137
138 #include <algorithm>
139 #include <cassert>
140 using namespace std;
141
142 int main() {
143     {
144         suffix_automaton sa("bananas");
145         vector<int> pos_a, pos_an, pos_ana;
146         int ans_a[] = {1, 3, 5};
147         int ans_an[] = {1, 3};
148         int ans_ana[] = {1, 3};
149         pos_a = sa.find_all("a");
150         pos_an = sa.find_all("an");
151         pos_ana = sa.find_all("ana");
152         assert(equal(pos_a.begin(), pos_a.end(), ans_a));
153         assert(equal(pos_an.begin(), pos_an.end(), ans_an));
154         assert(equal(pos_ana.begin(), pos_ana.end(), ans_ana));
155     }
156     {
157         suffix_automaton sa("bbbabca");
158         assert(sa.longest_common_substring("aababcd") == "bab");
159     }
160     return 0;
161 }

```