Algorithm Reference - Java

Bellman Ford

bellman_ford.java

```java
/*
Bellman-Ford algorithm for single-source shortest paths with negative edge weights.

Finds shortest paths from a source vertex to all other vertices, even with negative
edge weights. Can detect negative cycles.

Key operations:
- addEdge(u, v, weight): Add directed edge
- shortestPaths(source): Compute shortest paths, returns null if negative cycle detected
- shortestPath(source, target): Get shortest path between two vertices

Time complexity: O(VE)
Space complexity: O(V + E)
*/

import java.util.*;

class bellman_ford {
    static class Edge {
        int from, to, weight;

        Edge(int from, int to, int weight) {
            this.from = from;
            this.to = to;
            this.weight = weight;
        }
    }

    static class BellmanFord {
        private List<Edge> edges;
        private Set<Integer> nodes;
        private static final int INF = 999999;

        BellmanFord() {
            this.edges = new ArrayList<>();
            this.nodes = new HashSet<>();
        }

        void addEdge(int u, int v, int weight) {
            edges.add(new Edge(u, v, weight));
            nodes.add(u);
            nodes.add(v);
        }

        Map<Integer, Integer> shortestPaths(int source) {
            Map<Integer, Integer> distances = new HashMap<>();
            for (int node : nodes) {
                distances.put(node, INF);
            }
            distances.put(source, 0);

            // Relax edges V-1 times
            for (int i = 0; i < nodes.size() - 1; i++) {
                for (Edge e : edges) {
                    if (distances.get(e.from) != INF
                            && distances.get(e.from) + e.weight < distances.get(e.to)) {
                        distances.put(e.to, distances.get(e.from) + e.weight);
                    }
                }
            }

            // Check for negative cycles
            for (Edge e : edges) {
                if (distances.get(e.from) != INF
                        && distances.get(e.from) + e.weight < distances.get(e.to)) {
                    return null;
```

```java
            }
        }

        return distances;
    }

    List<Integer> shortestPath(int source, int target) {
        Map<Integer, Integer> distances = new HashMap<>();
        Map<Integer, Integer> predecessors = new HashMap<>();

        for (int node : nodes) {
            distances.put(node, INF);
        }
        distances.put(source, 0);
        predecessors.put(source, null);

        for (int i = 0; i < nodes.size() - 1; i++) {
            for (Edge e : edges) {
                if (distances.get(e.from) != INF
                        && distances.get(e.from) + e.weight < distances.get(e.to)) {
                    distances.put(e.to, distances.get(e.from) + e.weight);
                    predecessors.put(e.to, e.from);
                }
            }
        }

        for (Edge e : edges) {
            if (distances.get(e.from) != INF
                    && distances.get(e.from) + e.weight < distances.get(e.to)) {
                return null;
            }
        }

        if (!predecessors.containsKey(target)) {
            return null;
        }

        List<Integer> path = new ArrayList<>();
        Integer current = target;
        while (current != null) {
            path.add(current);
            current = predecessors.get(current);
        }
        Collections.reverse(path);
        return path;
    }
}

static void testMain() {
    BellmanFord bf = new BellmanFord();
    bf.addEdge(0, 1, 4);
    bf.addEdge(0, 2, 2);
    bf.addEdge(1, 2, -3);
    bf.addEdge(2, 3, 2);
    bf.addEdge(3, 1, 1);

    Map<Integer, Integer> result = bf.shortestPaths(0);
    assert result != null;
    assert result.get(2) == 1;
    assert result.get(3) == 3;

    List<Integer> path = bf.shortestPath(0, 3);
    assert path != null;
    assert path.get(0) == 0;
    assert path.get(path.size() - 1) == 3;
}
```

Bipartite Match

bipartite_match.java

```java
/*
Maximum bipartite matching using augmenting path algorithm.

Given a bipartite graph with left and right vertex sets, finds the maximum
number of edges such that no two edges share a vertex.

Key operations:
- addEdge(u, v): Add edge from left vertex u to right vertex v
- maxMatching(): Compute maximum matching size

Time complexity: O(V * E)
Space complexity: O(V + E)
*/

import java.util.*;

class bipartite_match {
    static class BipartiteMatch {
        private int leftSize;
        private int rightSize;
        private Map<Integer, List<Integer>> graph;
        private Map<Integer, Integer> match;
        private Set<Integer> visited;

        BipartiteMatch(int leftSize, int rightSize) {
            this.leftSize = leftSize;
            this.rightSize = rightSize;
            this.graph = new HashMap<>();
            for (int i = 0; i < leftSize; i++) {
                graph.put(i, new ArrayList<>());
            }
        }

        void addEdge(int u, int v) {
            graph.get(u).add(v);
        }

        int maxMatching() {
            match = new HashMap<>();
            int matchingSize = 0;

            for (int u = 0; u < leftSize; u++) {
                visited = new HashSet<>();
                if (dfs(u)) {
                    matchingSize++;
                }
            }

            return matchingSize;
        }

        private boolean dfs(int u) {
            for (int v : graph.get(u)) {
                if (visited.contains(v)) {
                    continue;
                }
                visited.add(v);

                // If v is not matched or we can find augmenting path from match[v]
                if (!match.containsKey(v) || dfs(match.get(v))) {
                    match.put(v, u);
                    return true;
                }
            }
            return false;
        }
```

```java
    Map<Integer, Integer> getMatching() {
        Map<Integer, Integer> result = new HashMap<>();
        for (Map.Entry<Integer, Integer> entry : match.entrySet()) {
            result.put(entry.getValue(), entry.getKey());
        }
        return result;
    }
}

static void testMain() {
    BipartiteMatch b = new BipartiteMatch(3, 3);
    b.addEdge(0, 0); // 1 -> X
    b.addEdge(1, 1); // 2 -> Y
    b.addEdge(2, 0); // 3 -> X
    b.addEdge(0, 2); // 1 -> Z
    b.addEdge(1, 2); // 2 -> Z
    b.addEdge(2, 1); // 3 -> Y

    int matching = b.maxMatching();
    if (matching != 3) throw new AssertionError("Expected 3, got " + matching);
    Map<Integer, Integer> matches = b.getMatching();
    if (matches.size() != 3) throw new AssertionError("Expected size 3, got " + matches.size());
}
```

Convex Hull

convex_hull.java

```java
/*
Andrew's monotone chain algorithm for computing the convex hull of 2D points.

Computes the convex hull (smallest convex polygon containing all points) using
a simple and robust algorithm.

Key operations:
- convexHull(points): Returns convex hull vertices in counter-clockwise order

Time complexity: O(n log n) dominated by sorting
Space complexity: O(n)
*/

import java.util.*;

class convex_hull {
    static class Point implements Comparable<Point> {
        double x, y;

        Point(double x, double y) {
            this.x = x;
            this.y = y;
        }

        @Override
        public int compareTo(Point other) {
            if (this.x != other.x) {
                return Double.compare(this.x, other.x);
            }
            return Double.compare(this.y, other.y);
        }

        @Override
        public boolean equals(Object obj) {
            if (!(obj instanceof Point)) return false;
            Point p = (Point) obj;
            return this.x == p.x && this.y == p.y;
        }

        @Override
        public int hashCode() {
            return Objects.hash(x, y);
        }
    }

    static double cross(Point o, Point a, Point b) {
        return (a.x - o.x) * (b.y - o.y) - (a.y - o.y) * (b.x - o.x);
    }

    static List<Point> convexHull(List<Point> points) {
        if (points.size() <= 1) {
            return new ArrayList<>(points);
        }

        List<Point> sorted = new ArrayList<>(points);
        Collections.sort(sorted);

        List<Point> lower = new ArrayList<>();
        for (Point p : sorted) {
            while (lower.size() >= 2
                    && cross(lower.get(lower.size() - 2), lower.get(lower.size() - 1), p) <= 0) {
                lower.remove(lower.size() - 1);
            }
            lower.add(p);
        }
```

```
    List<Point> upper = new ArrayList<>();
    for (int i = sorted.size() - 1; i >= 0; i--) {
        Point p = sorted.get(i);
        while (upper.size() >= 2
                && cross(upper.get(upper.size() - 2), upper.get(upper.size() - 1), p) <= 0) {
            upper.remove(upper.size() - 1);
        }
        upper.add(p);
    }

    lower.remove(lower.size() - 1);
    upper.remove(upper.size() - 1);
    lower.addAll(upper);

    return lower;
}

static void testMain() {
    List<Point> pts =
            Arrays.asList(
                    new Point(0, 0),
                    new Point(1, 0),
                    new Point(1, 1),
                    new Point(0, 1),
                    new Point(0.5, 0.5));
    List<Point> hull = convexHull(pts);
    assert hull.size() == 4;
    assert hull.contains(new Point(0, 0));
    assert hull.contains(new Point(1, 0));
    assert hull.contains(new Point(1, 1));
    assert hull.contains(new Point(0, 1));
    assert !hull.contains(new Point(0.5, 0.5));
}
```

Dijkstra

dijkstra.java

```java
/*
Dijkstra's algorithm for single-source shortest paths in weighted graphs.

Finds shortest paths from a source vertex to all other vertices in a graph
with non-negative edge weights.

Key operations:
- addEdge(u, v, weight): Add weighted directed edge
- shortestPaths(source): Compute shortest paths from source to all vertices
- shortestPath(source, target): Get shortest path between two vertices

Time complexity: O((V + E) log V) with binary heap
Space complexity: O(V + E)
*/

import java.util.*;

class dijkstra {
    static class Edge {
        int to;
        int weight;

        Edge(int to, int weight) {
            this.to = to;
            this.weight = weight;
        }
    }

    static class Node implements Comparable<Node> {
        int vertex;
        int distance;

        Node(int vertex, int distance) {
            this.vertex = vertex;
            this.distance = distance;
        }

        @Override
        public int compareTo(Node other) {
            return Integer.compare(this.distance, other.distance);
        }
    }

    static class Dijkstra {
        private int n;
        private Map<Integer, List<Edge>> graph;

        Dijkstra(int n) {
            this.n = n;
            this.graph = new HashMap<>();
            for (int i = 0; i < n; i++) {
                graph.put(i, new ArrayList<>());
            }
        }

        void addEdge(int u, int v, int weight) {
            graph.get(u).add(new Edge(v, weight));
        }

        Map<Integer, Integer> shortestPaths(int source) {
            Map<Integer, Integer> distances = new HashMap<>();
            for (int i = 0; i < n; i++) {
                distances.put(i, Integer.MAX_VALUE);
            }
            distances.put(source, 0);
```

```java
        PriorityQueue<Node> pq = new PriorityQueue<>();
        pq.offer(new Node(source, 0));

        while (!pq.isEmpty()) {
            Node current = pq.poll();
            int u = current.vertex;
            int dist = current.distance;

            if (dist > distances.get(u)) {
                continue;
            }

            for (Edge edge : graph.get(u)) {
                int v = edge.to;
                int newDist = dist + edge.weight;

                if (newDist < distances.get(v)) {
                    distances.put(v, newDist);
                    pq.offer(new Node(v, newDist));
                }
            }
        }

        return distances;
    }

    List<Integer> shortestPath(int source, int target) {
        Map<Integer, Integer> distances = new HashMap<>();
        Map<Integer, Integer> previous = new HashMap<>();

        for (int i = 0; i < n; i++) {
            distances.put(i, Integer.MAX_VALUE);
        }
        distances.put(source, 0);

        PriorityQueue<Node> pq = new PriorityQueue<>();
        pq.offer(new Node(source, 0));

        while (!pq.isEmpty()) {
            Node current = pq.poll();
            int u = current.vertex;
            int dist = current.distance;

            if (u == target) {
                break;
            }

            if (dist > distances.get(u)) {
                continue;
            }

            for (Edge edge : graph.get(u)) {
                int v = edge.to;
                int newDist = dist + edge.weight;

                if (newDist < distances.get(v)) {
                    distances.put(v, newDist);
                    previous.put(v, u);
                    pq.offer(new Node(v, newDist));
                }
            }
        }

        if (!previous.containsKey(target) && target != source) {
            return null;
        }

        List<Integer> path = new ArrayList<>();
        int current = target;
        while (current != source) {
            path.add(current);
            current = previous.get(current);
```

```java
        }
        path.add(source);
        Collections.reverse(path);

        return path;
    }
}

static void testMain() {
    Dijkstra d = new Dijkstra(4);
    d.addEdge(0, 1, 4);
    d.addEdge(0, 2, 2);
    d.addEdge(1, 2, 1);
    d.addEdge(1, 3, 5);
    d.addEdge(2, 3, 8);

    Map<Integer, Integer> distances = d.shortestPaths(0);
    assert distances.get(3) == 9;

    List<Integer> path = d.shortestPath(0, 3);
    assert path.equals(Arrays.asList(0, 1, 3));
}
```

Edmonds Karp

edmonds_karp.java

```java
/*
Edmonds-Karp algorithm for computing maximum flow in a flow network.

Implementation of the Ford-Fulkerson method using BFS to find augmenting paths.
Guarantees O(V * E^2) time complexity.

Key operations:
- addEdge(u, v, capacity): Add a directed edge with given capacity
- maxFlow(source, sink): Compute maximum flow from source to sink

Space complexity: O(V^2) for adjacency matrix representation
*/

import java.util.*;

class edmonds_karp {
    static class EdmondsKarp {
        private int n;
        private int[][] capacity;
        private int[][] flow;

        EdmondsKarp(int n) {
            this.n = n;
            this.capacity = new int[n][n];
            this.flow = new int[n][n];
        }

        void addEdge(int u, int v, int cap) {
            capacity[u][v] += cap;
        }

        int maxFlow(int source, int sink) {
            // Reset flow
            for (int i = 0; i < n; i++) {
                Arrays.fill(flow[i], 0);
            }

            int totalFlow = 0;

            while (true) {
                // BFS to find augmenting path
                int[] parent = new int[n];
                Arrays.fill(parent, -1);
                parent[source] = source;

                Queue<Integer> queue = new LinkedList<>();
                queue.offer(source);

                while (!queue.isEmpty() && parent[sink] == -1) {
                    int u = queue.poll();

                    for (int v = 0; v < n; v++) {
                        if (parent[v] == -1 && capacity[u][v] - flow[u][v] > 0) {
                            parent[v] = u;
                            queue.offer(v);
                        }
                    }
                }

                // No augmenting path found
                if (parent[sink] == -1) {
                    break;
                }

                // Find minimum residual capacity along the path
                int pathFlow = Integer.MAX_VALUE;
```

```java
            int v = sink;
            while (v != source) {
                int u = parent[v];
                pathFlow = Math.min(pathFlow, capacity[u][v] - flow[u][v]);
                v = u;
            }

            // Update flow along the path
            v = sink;
            while (v != source) {
                int u = parent[v];
                flow[u][v] += pathFlow;
                flow[v][u] -= pathFlow;
                v = u;
            }

            totalFlow += pathFlow;
        }

        return totalFlow;
    }

    int getFlow(int u, int v) {
        return flow[u][v];
    }
}

static void testMain() {
    EdmondsKarp e = new EdmondsKarp(4);
    e.addEdge(0, 1, 10);
    e.addEdge(0, 2, 8);
    e.addEdge(1, 2, 2);
    e.addEdge(1, 3, 5);
    e.addEdge(2, 3, 7);

    int maxFlow = e.maxFlow(0, 3);
    assert maxFlow == 12;
}
```

Fenwick Tree

fenwick_tree.java

```java
/*
Fenwick Tree (Binary Indexed Tree) implementation.

A data structure for efficient prefix sum queries and point updates on an array.

Key operations:
- update(i, delta): Add delta to element at index i - O(log n)
- query(i): Get sum of elements from index 0 to i (inclusive) - O(log n)
- range_query(l, r): Get sum from index l to r (inclusive) - O(log n)

Space complexity: O(n)

Note: Uses 1-based indexing internally for simpler bit manipulation.
*/

import java.util.function.BinaryOperator;

class fenwick_tree {
    interface Summable<T> {
        T add(T other);

        T subtract(T other);
    }

    static class FenwickTree<T> {
        private Object[] tree;
        private int size;
        private T zero;
        private BinaryOperator<T> addOp;
        private BinaryOperator<T> subtractOp;

        FenwickTree(int n, T zero, BinaryOperator<T> addOp, BinaryOperator<T> subtractOp) {
            this.size = n;
            this.zero = zero;
            this.addOp = addOp;
            this.subtractOp = subtractOp;
            this.tree = new Object[n + 1];
            for (int i = 0; i <= n; i++) {
                tree[i] = zero;
            }
        }

        // O(n log n) constructor from array
        FenwickTree(T[] values, T zero, BinaryOperator<T> addOp, BinaryOperator<T> subtractOp) {
            this(values.length, zero, addOp, subtractOp);
            for (int i = 0; i < values.length; i++) {
                update(i, values[i]);
            }
        }

        // O(n) constructor from array using prefix sums
        static <T> FenwickTree<T> fromArray(
                T[] arr, T zero, BinaryOperator<T> addOp, BinaryOperator<T> subtractOp) {
            int n = arr.length;
            FenwickTree<T> ft = new FenwickTree<>(n, zero, addOp, subtractOp);

            // Compute prefix sums
            Object[] prefix = new Object[n + 1];
            prefix[0] = zero;
            for (int i = 0; i < n; i++) {
                prefix[i + 1] = addOp.apply((T) prefix[i], arr[i]);
            }

            // Build tree in O(n): each tree[i] contains sum of range [i - (i & -i) + 1, i]
            for (int i = 1; i <= n; i++) {
                int rangeStart = i - (i & (-i)) + 1;
```

```java
            ft.tree[i] = subtractOp.apply((T) prefix[i], (T) prefix[rangeStart - 1]);
        }

        return ft;
    }

    @SuppressWarnings("unchecked")
    void update(int i, T delta) {
        if (i < 0 || i >= size) {
            throw new IndexOutOfBoundsException(
                    "Index " + i + " out of bounds for size " + size);
        }
        i++; // Convert to 1-based indexing
        while (i <= size) {
            tree[i] = addOp.apply((T) tree[i], delta);
            i += i & (-i);
        }
    }

    @SuppressWarnings("unchecked")
    T query(int i) {
        if (i < 0 || i >= size) {
            throw new IndexOutOfBoundsException(
                    "Index " + i + " out of bounds for size " + size);
        }
        i++; // Convert to 1-based indexing
        T sum = zero;
        while (i > 0) {
            sum = addOp.apply(sum, (T) tree[i]);
            i -= i & (-i);
        }
        return sum;
    }

    T rangeQuery(int l, int r) {
        if (l > r || l < 0 || r >= size) {
            return zero;
        }
        if (l == 0) {
            return query(r);
        }
        return subtractOp.apply(query(r), query(l - 1));
    }

    // Optional functionality (not always needed during competition)

    T getValue(int i) {
        if (i < 0 || i >= size) {
            throw new IndexOutOfBoundsException(
                    "Index " + i + " out of bounds for size " + size);
        }
        if (i == 0) {
            return query(0);
        }
        return subtractOp.apply(query(i), query(i - 1));
    }

    // Find smallest index >= startIndex with value > zero
    // REQUIRES: all updates are non-negative, T must be comparable
    @SuppressWarnings("unchecked")
    Integer firstNonzeroIndex(int startIndex, java.util.Comparator<T> comparator) {
        startIndex = Math.max(startIndex, 0);
        if (startIndex >= size) {
            return null;
        }

        T prefixBefore = startIndex > 0 ? query(startIndex - 1) : zero;
        T total = query(size - 1);
        if (comparator.compare(total, prefixBefore) == 0) {
            return null;
        }
```

```java
        // Fenwick lower_bound: first idx with prefix_sum(idx) > prefixBefore
        int idx = 0; // 1-based cursor
        T cur = zero; // running prefix at 'idx'
        int bit = Integer.highestOneBit(size);

        while (bit > 0) {
            int nxt = idx + bit;
            if (nxt <= size) {
                T cand = addOp.apply(cur, (T) tree[nxt]);
                if (comparator.compare(cand, prefixBefore)
                        <= 0) { // move right while prefix <= target
                    cur = cand;
                    idx = nxt;
                }
            }
            bit >>= 1;
        }

        // idx is the largest position with prefix <= prefixBefore (1-based).
        // The answer is idx (converted to 0-based).
        return idx;
    }
}

static void testMain() {
    FenwickTree<Long> f = new FenwickTree<>(5, 0L, (a, b) -> a + b, (a, b) -> a - b);
    f.update(0, 7L);
    f.update(2, 13L);
    f.update(4, 19L);
    assert f.query(4) == 39L;
    assert f.rangeQuery(1, 3) == 13L;

    // Optional functionality (not always needed during competition)

    assert f.getValue(2) == 13L;
    FenwickTree<Long> g =
            FenwickTree.fromArray(
                    new Long[] {1L, 2L, 3L, 4L, 5L}, 0L, (a, b) -> a + b, (a, b) -> a - b);
    assert g.query(4) == 15L;
}
```

Kmp

kmp.java

```java
/*
Knuth-Morris-Pratt (KMP) string matching algorithm.

Efficiently finds all occurrences of a pattern in a text string.

Key operations:
- computeLPS(pattern): Compute Longest Proper Prefix which is also Suffix array
- search(text, pattern): Find all starting positions where pattern occurs in text

Time complexity: O(n + m) where n is text length and m is pattern length
Space complexity: O(m) for the LPS array
*/

import java.util.*;

class kmp {
    static int[] computeLPS(String pattern) {
        int m = pattern.length();
        int[] lps = new int[m];
        int len = 0;
        int i = 1;

        lps[0] = 0;

        while (i < m) {
            if (pattern.charAt(i) == pattern.charAt(len)) {
                len++;
                lps[i] = len;
                i++;
            } else {
                if (len != 0) {
                    len = lps[len - 1];
                } else {
                    lps[i] = 0;
                    i++;
                }
            }
        }

        return lps;
    }

    static List<Integer> search(String text, String pattern) {
        List<Integer> result = new ArrayList<>();

        if (pattern.isEmpty()) {
            return result;
        }

        int n = text.length();
        int m = pattern.length();
        int[] lps = computeLPS(pattern);

        int i = 0; // index for text
        int j = 0; // index for pattern

        while (i < n) {
            if (text.charAt(i) == pattern.charAt(j)) {
                i++;
                j++;
            }

            if (j == m) {
                result.add(i - j);
                j = lps[j - 1];
            } else if (i < n && text.charAt(i) != pattern.charAt(j)) {
```

```java
                if (j != 0) {
                    j = lps[j - 1];
                } else {
                    i++;
                }
            }
        }

        return result;
    }

    static void testMain() {
        String text = "ababcababa";
        String pattern = "aba";
        List<Integer> matches = search(text, pattern);
        assert matches.equals(Arrays.asList(0, 5, 7));
        assert matches.size() == 3;

        // Test failure function
        int[] failure = computeLPS("abcabcab");
        assert Arrays.equals(failure, new int[] {0, 0, 0, 1, 2, 3, 4, 5});
    }
```

Kosaraju Scc

kosaraju_scc.java

```java
/*
Kosaraju's algorithm for finding strongly connected components (SCCs) in directed graphs.

A strongly connected component is a maximal set of vertices where every vertex is
reachable from every other vertex in the set. Uses two DFS passes.

Key operations:
- addEdge(u, v): Add directed edge from u to v
- findSCCs(): Find all strongly connected components

Time complexity: O(V + E)
Space complexity: O(V + E)
*/

import java.util.*;

class kosaraju_scc {
    static class KosarajuSCC {
        private Map<Integer, List<Integer>> graph;
        private Map<Integer, List<Integer>> transpose;

        KosarajuSCC() {
            this.graph = new HashMap<>();
            this.transpose = new HashMap<>();
        }

        void addEdge(int u, int v) {
            graph.putIfAbsent(u, new ArrayList<>());
            graph.putIfAbsent(v, new ArrayList<>());
            transpose.putIfAbsent(u, new ArrayList<>());
            transpose.putIfAbsent(v, new ArrayList<>());

            graph.get(u).add(v);
            transpose.get(v).add(u);
        }

        List<List<Integer>> findSCCs() {
            // First DFS pass: compute finish order
            Set<Integer> visited = new HashSet<>();
            List<Integer> finishOrder = new ArrayList<>();

            for (int node : graph.keySet()) {
                if (!visited.contains(node)) {
                    dfs1(node, visited, finishOrder);
                }
            }

            // Second DFS pass: find SCCs on transpose graph
            visited.clear();
            List<List<Integer>> sccs = new ArrayList<>();

            for (int i = finishOrder.size() - 1; i >= 0; i--) {
                int node = finishOrder.get(i);
                if (!visited.contains(node)) {
                    List<Integer> scc = new ArrayList<>();
                    dfs2(node, visited, scc);
                    sccs.add(scc);
                }
            }

            return sccs;
        }

        private void dfs1(int node, Set<Integer> visited, List<Integer> finishOrder) {
            visited.add(node);
            if (graph.containsKey(node)) {
```

```java
                for (int neighbor : graph.get(node)) {
                    if (!visited.contains(neighbor)) {
                        dfs1(neighbor, visited, finishOrder);
                    }
                }
            }
            finishOrder.add(node);
        }

        private void dfs2(int node, Set<Integer> visited, List<Integer> scc) {
            visited.add(node);
            scc.add(node);
            if (transpose.containsKey(node)) {
                for (int neighbor : transpose.get(node)) {
                    if (!visited.contains(neighbor)) {
                        dfs2(neighbor, visited, scc);
                    }
                }
            }
        }
    }

    static void testMain() {
        KosarajuSCC g = new KosarajuSCC();
        g.addEdge(0, 1);
        g.addEdge(1, 2);
        g.addEdge(2, 0);
        g.addEdge(1, 3);
        g.addEdge(3, 4);
        g.addEdge(4, 5);
        g.addEdge(5, 3);

        List<List<Integer>> sccs = g.findSCCs();
        assert sccs.size() == 2;

        // Sort SCCs for comparison
        List<List<Integer>> sorted = new ArrayList<>();
        for (List<Integer> scc : sccs) {
            List<Integer> s = new ArrayList<>(scc);
            Collections.sort(s);
            sorted.add(s);
        }
        Collections.sort(sorted, (a, b) -> Integer.compare(a.get(0), b.get(0)));

        assert sorted.get(0).equals(Arrays.asList(0, 1, 2));
        assert sorted.get(1).equals(Arrays.asList(3, 4, 5));
    }
```

Lca

lca.java

```
/*
Lowest Common Ancestor (LCA) using Binary Lifting.

Preprocesses a tree to answer LCA queries efficiently.

Key operations:
- addEdge(u, v): Add undirected edge to tree
- build(root): Preprocess tree with given root - O(n log n)
- query(u, v): Find LCA of nodes u and v - O(log n)
- distance(u, v): Find distance between two nodes - O(log n)

Space complexity: O(n log n)

Binary lifting allows us to "jump" up the tree in powers of 2, enabling
efficient LCA queries.
*/

import java.util.*;

class lca {
    static class LCA {
        private int n;
        private int maxLog;
        private Map<Integer, List<Integer>> graph;
        private int[] depth;
        private Map<Integer, Map<Integer, Integer>> up;

        LCA(int n) {
            this.n = n;
            this.maxLog = (int) Math.ceil(Math.log(n) / Math.log(2)) + 1;
            this.graph = new HashMap<>();
            this.depth = new int[n];
            this.up = new HashMap<>();

            for (int i = 0; i < n; i++) {
                graph.put(i, new ArrayList<>());
                up.put(i, new HashMap<>());
            }
        }

        void addEdge(int u, int v) {
            graph.get(u).add(v);
            graph.get(v).add(u);
        }

        void build(int root) {
            Arrays.fill(depth, 0);
            dfs(root, -1, 0);
        }

        private void dfs(int node, int parent, int d) {
            depth[node] = d;

            if (parent != -1) {
                up.get(node).put(0, parent);
            }

            for (int i = 1; i < maxLog; i++) {
                if (up.get(node).containsKey(i - 1)) {
                    int ancestor = up.get(node).get(i - 1);
                    if (up.get(ancestor).containsKey(i - 1)) {
                        up.get(node).put(i, up.get(ancestor).get(i - 1));
                    }
                }
            }
```

```java
        for (int child : graph.get(node)) {
            if (child != parent) {
                dfs(child, node, d + 1);
            }
        }
    }

    int query(int u, int v) {
        if (depth[u] < depth[v]) {
            int temp = u;
            u = v;
            v = temp;
        }

        // Bring u to the same level as v
        int diff = depth[u] - depth[v];
        for (int i = 0; i < maxLog; i++) {
            if (((diff >> i) & 1) == 1) {
                if (up.get(u).containsKey(i)) {
                    u = up.get(u).get(i);
                }
            }
        }

        if (u == v) {
            return u;
        }

        // Binary search for LCA
        for (int i = maxLog - 1; i >= 0; i--) {
            if (up.get(u).containsKey(i) && up.get(v).containsKey(i)) {
                int uAncestor = up.get(u).get(i);
                int vAncestor = up.get(v).get(i);
                if (uAncestor != vAncestor) {
                    u = uAncestor;
                    v = vAncestor;
                }
            }
        }

        return up.get(u).getOrDefault(0, u);
    }

    int distance(int u, int v) {
        int lcaNode = query(u, v);
        return depth[u] + depth[v] - 2 * depth[lcaNode];
    }
}

static void testMain() {
    LCA lca = new LCA(6);
    lca.addEdge(0, 1); // 1-2
    lca.addEdge(0, 2); // 1-3
    lca.addEdge(1, 3); // 2-4
    lca.addEdge(1, 4); // 2-5
    lca.addEdge(2, 5); // 3-6

    lca.build(0);

    assert lca.query(3, 4) == 1; // LCA(4, 5) = 2
    assert lca.query(3, 5) == 0; // LCA(4, 6) = 1
    assert lca.distance(3, 5) == 4; // distance(4, 6) = 4
}
```

Polygon Area

polygon_area.java

```java
/*
Shoelace formula (Gauss's area formula) for computing the area of a polygon.

Computes the area of a simple polygon given its vertices in order (clockwise or
counter-clockwise). Works for both convex and concave polygons.

The formula: Area = 1/2 * |sum(x_i * y_(i+1) - x_(i+1) * y_i)|

Time complexity: O(n) where n is the number of vertices.
Space complexity: O(1) additional space.
*/

class polygon_area {
    static class Point {
        double x, y;

        Point(double x, double y) {
            this.x = x;
            this.y = y;
        }
    }

    static double polygonArea(Point[] vertices) {
        if (vertices.length < 3) {
            return 0.0;
        }

        int n = vertices.length;
        double area = 0.0;

        for (int i = 0; i < n; i++) {
            int j = (i + 1) % n;
            area += vertices[i].x * vertices[j].y;
            area -= vertices[j].x * vertices[i].y;
        }

        return Math.abs(area) / 2.0;
    }

    static double polygonSignedArea(Point[] vertices) {
        if (vertices.length < 3) {
            return 0.0;
        }

        int n = vertices.length;
        double area = 0.0;

        for (int i = 0; i < n; i++) {
            int j = (i + 1) % n;
            area += vertices[i].x * vertices[j].y;
            area -= vertices[j].x * vertices[i].y;
        }

        return area / 2.0;
    }

    static boolean isClockwise(Point[] vertices) {
        return polygonSignedArea(vertices) < 0;
    }

    static void testMain() {
        // Simple square with side length 2
        Point[] square = {
            new Point(0.0, 0.0), new Point(2.0, 0.0), new Point(2.0, 2.0), new Point(0.0, 2.0)
        };
        assert Math.abs(polygonArea(square) - 4.0) < 1e-9;
```

```java
    // Triangle with base 3 and height 4
    Point[] triangle = {new Point(0.0, 0.0), new Point(3.0, 0.0), new Point(1.5, 4.0)};
    assert Math.abs(polygonArea(triangle) - 6.0) < 1e-9;

    // Test orientation
    Point[] ccwSquare = {
        new Point(0.0, 0.0), new Point(1.0, 0.0), new Point(1.0, 1.0), new Point(0.0, 1.0)
    };
    assert !isClockwise(ccwSquare);
}
```

Prefix Tree

prefix_tree.java

```java
/*
Prefix Tree (Trie) implementation for efficient string prefix operations.

Supports:
- insert(word): Add a word to the trie - O(m) where m is word length
- search(word): Check if exact word exists - O(m)
- startsWith(prefix): Check if any word starts with prefix - O(m)
- delete(word): Remove a word from the trie - O(m)

Space complexity: O(ALPHABET_SIZE * N * M) where N is number of words and M is average length
*/

import java.util.*;

class prefix_tree {
    static class TrieNode {
        Map<Character, TrieNode> children;
        boolean isEndOfWord;

        TrieNode() {
            children = new HashMap<>();
            isEndOfWord = false;
        }
    }

    static class PrefixTree {
        private TrieNode root;

        PrefixTree() {
            root = new TrieNode();
        }

        void insert(String word) {
            TrieNode node = root;
            for (char c : word.toCharArray()) {
                node.children.putIfAbsent(c, new TrieNode());
                node = node.children.get(c);
            }
            node.isEndOfWord = true;
        }

        boolean search(String word) {
            TrieNode node = root;
            for (char c : word.toCharArray()) {
                if (!node.children.containsKey(c)) {
                    return false;
                }
                node = node.children.get(c);
            }
            return node.isEndOfWord;
        }

        boolean startsWith(String prefix) {
            TrieNode node = root;
            for (char c : prefix.toCharArray()) {
                if (!node.children.containsKey(c)) {
                    return false;
                }
                node = node.children.get(c);
            }
            return true;
        }

        boolean delete(String word) {
            return deleteHelper(root, word, 0);
        }
```

```java
    private boolean deleteHelper(TrieNode node, String word, int depth) {
        if (node == null) {
            return false;
        }

        if (depth == word.length()) {
            if (!node.isEndOfWord) {
                return false;
            }
            node.isEndOfWord = false;
            return node.children.isEmpty();
        }

        char c = word.charAt(depth);
        if (!node.children.containsKey(c)) {
            return false;
        }

        TrieNode child = node.children.get(c);
        boolean shouldDeleteChild = deleteHelper(child, word, depth + 1);

        if (shouldDeleteChild) {
            node.children.remove(c);
            return !node.isEndOfWord && node.children.isEmpty();
        }

        return false;
    }
}

static void testMain() {
    PrefixTree trie = new PrefixTree();
    trie.insert("cat");
    trie.insert("car");
    trie.insert("card");

    assert trie.search("car");
    assert !trie.search("ca");
    assert trie.startsWith("car");
}
```

Priority Queue

priority_queue.java

```java
/*
Generic priority queue (min-heap) with update and remove operations.

Supports:
- push(item): Add item to heap - O(log n)
- pop(): Remove and return minimum item - O(log n)
- peek(): View minimum item without removing - O(1)
- update(old_item, new_item): Update item in heap - O(n)
- remove(item): Remove specific item - O(n)

Space complexity: O(n)
*/

import java.util.*;

class priority_queue {
    static class PriorityQueue<T extends Comparable<T>> {
        private List<T> heap;

        PriorityQueue() {
            this.heap = new ArrayList<>();
        }

        void push(T item) {
            heap.add(item);
            siftUp(heap.size() - 1);
        }

        T pop() {
            if (heap.isEmpty()) {
                throw new IllegalStateException("Heap is empty");
            }
            T item = heap.get(0);
            T last = heap.remove(heap.size() - 1);
            if (!heap.isEmpty()) {
                heap.set(0, last);
                siftDown(0);
            }
            return item;
        }

        T peek() {
            if (heap.isEmpty()) {
                return null;
            }
            return heap.get(0);
        }

        boolean contains(T item) {
            return heap.contains(item);
        }

        void update(T oldItem, T newItem) {
            int idx = heap.indexOf(oldItem);
            if (idx == -1) {
                throw new IllegalArgumentException("Item not in heap");
            }
            heap.set(idx, newItem);
            if (newItem.compareTo(oldItem) < 0) {
                siftUp(idx);
            } else {
                siftDown(idx);
            }
        }

        void remove(T item) {
```

```java
        int idx = heap.indexOf(item);
        if (idx == -1) {
            throw new IllegalArgumentException("Item not in heap");
        }
        T last = heap.remove(heap.size() - 1);
        if (idx < heap.size()) {
            T oldItem = heap.get(idx);
            heap.set(idx, last);
            if (last.compareTo(oldItem) < 0) {
                siftUp(idx);
            } else {
                siftDown(idx);
            }
        }
    }

    int size() {
        return heap.size();
    }

    boolean isEmpty() {
        return heap.isEmpty();
    }

    private void siftUp(int idx) {
        while (idx > 0) {
            int parent = (idx - 1) / 2;
            if (heap.get(idx).compareTo(heap.get(parent)) >= 0) {
                break;
            }
            Collections.swap(heap, idx, parent);
            idx = parent;
        }
    }

    private void siftDown(int idx) {
        while (true) {
            int smallest = idx;
            int left = 2 * idx + 1;
            int right = 2 * idx + 2;

            if (left < heap.size() && heap.get(left).compareTo(heap.get(smallest)) < 0) {
                smallest = left;
            }
            if (right < heap.size() && heap.get(right).compareTo(heap.get(smallest)) < 0) {
                smallest = right;
            }
            if (smallest == idx) {
                break;
            }
            Collections.swap(heap, idx, smallest);
            idx = smallest;
        }
    }
}

static void testMain() {
    PriorityQueue<Integer> p = new PriorityQueue<>();
    p.push(15);
    p.push(23);
    p.push(8);
    assert p.peek() == 8;
    assert p.pop() == 8;
    assert p.pop() == 15;
}
```

Segment Tree

segment_tree.java

```java
/*
Segment Tree for range queries and point updates.

Supports efficient range queries (sum, min, max, etc.) and point updates on an array.

Key operations:
- update(i, value): Update element at index i - O(log n)
- query(l, r): Query range [l, r] - O(log n)

Space complexity: O(4n) = O(n)

This implementation supports sum queries but can be modified for min/max/gcd/etc.
*/

import java.util.*;
import java.util.function.BinaryOperator;

class segment_tree {
    static class SegmentTree<T> {
        private Object[] tree;
        private int n;
        private T zero;
        private BinaryOperator<T> combineOp;

        SegmentTree(T[] arr, T zero, BinaryOperator<T> combineOp) {
            this.n = arr.length;
            this.zero = zero;
            this.combineOp = combineOp;
            this.tree = new Object[4 * n];
            if (n > 0) {
                build(arr, 0, 0, n - 1);
            }
        }

        private void build(T[] arr, int node, int start, int end) {
            if (start == end) {
                tree[node] = arr[start];
            } else {
                int mid = (start + end) / 2;
                int leftChild = 2 * node + 1;
                int rightChild = 2 * node + 2;

                build(arr, leftChild, start, mid);
                build(arr, rightChild, mid + 1, end);

                tree[node] = combineOp.apply((T) tree[leftChild], (T) tree[rightChild]);
            }
        }

        void update(int idx, T value) {
            update(0, 0, n - 1, idx, value);
        }

        @SuppressWarnings("unchecked")
        private void update(int node, int start, int end, int idx, T value) {
            if (start == end) {
                tree[node] = value;
            } else {
                int mid = (start + end) / 2;
                int leftChild = 2 * node + 1;
                int rightChild = 2 * node + 2;

                if (idx <= mid) {
                    update(leftChild, start, mid, idx, value);
                } else {
                    update(rightChild, mid + 1, end, idx, value);
```

```java
            }

            tree[node] = combineOp.apply((T) tree[leftChild], (T) tree[rightChild]);
        }
    }

    T query(int l, int r) {
        if (l < 0 || r >= n || l > r) {
            throw new IllegalArgumentException("Invalid range");
        }
        return query(0, 0, n - 1, l, r);
    }

    @SuppressWarnings("unchecked")
    private T query(int node, int start, int end, int l, int r) {
        if (r < start || l > end) {
            return zero;
        }

        if (l <= start && end <= r) {
            return (T) tree[node];
        }

        int mid = (start + end) / 2;
        int leftChild = 2 * node + 1;
        int rightChild = 2 * node + 2;

        T leftSum = query(leftChild, start, mid, l, r);
        T rightSum = query(rightChild, mid + 1, end, l, r);

        return combineOp.apply(leftSum, rightSum);
    }
}

static void testMain() {
    Long[] arr = {1L, 3L, 5L, 7L, 9L};
    SegmentTree<Long> st = new SegmentTree<>(arr, 0L, (a, b) -> a + b);
    assert st.query(1, 3) == 15L;
    st.update(2, 10L);
    assert st.query(1, 3) == 20L;
    assert st.query(0, 4) == 30L;
}
```

Sprague Grundy

sprague_grundy.java

```java
/*
Sprague-Grundy theorem implementation for impartial games (finite, acyclic, normal-play).

The Sprague-Grundy theorem states that every impartial game is equivalent to a Nim heap
of size equal to its Grundy number (nimber). For multiple independent games,
XOR the Grundy numbers to determine the combined game value.

API:
- GrundyEngine(moveFunction): makes it easy to plug in any game.
- grundy(state): compute nimber for a state (must be hashable).
- grundyMulti(states): XOR of nimbers for independent subgames.
- isWinningPosition(states): true iff XOR != 0.

Includes implementations for:
- Nim (single heap).
- Subtraction game (allowed moves = {1,3,4}) with period detection.
- Kayles (bowling pins) with splits into subgames via array representation.

Requirements:
- State must be hashable and canonically represented (e.g., sorted arrays).
- moveFunction must not create cycles.
*/

import java.util.*;
import java.util.function.Function;

public class sprague_grundy {

    // Minimum EXcludant: smallest non-negative integer not occurring in 'values'
    public static int mex(Collection<Integer> values) {
        Set<Integer> s = new HashSet<>(values);
        int g = 0;
        while (s.contains(g)) {
            g++;
        }
        return g;
    }

    public static class GrundyEngine<T> {
        protected final Function<T, Collection<T>> moves;
        private final Map<T, Integer> cache = new HashMap<>();

        public GrundyEngine(Function<T, Collection<T>> moveFunction) {
            this.moves = moveFunction;
        }

        public int grundy(T state) {
            if (cache.containsKey(state)) {
                return cache.get(state);
            }

            Collection<T> nextStates = moves.apply(state);
            if (nextStates.isEmpty()) {
                cache.put(state, 0);
                return 0;
            }

            List<Integer> nimbers = new ArrayList<>();
            for (T nextState : nextStates) {
                nimbers.add(grundy(nextState));
            }

            int result = mex(nimbers);
            cache.put(state, result);
            return result;
        }
```

```java
    public int grundyMulti(Collection<T> states) {
        int result = 0;
        for (T state : states) {
            result ^= grundy(state);
        }
        return result;
    }

    public boolean isWinningPosition(Collection<T> states) {
        return grundyMulti(states) != 0;
    }
}

// Wrapper class for Kayles segments with proper equals/hashCode
public static class KaylesState {
    private final int[] segments;
    private final int hashCode;

    public KaylesState(int[] segments) {
        this.segments = segments.clone();
        Arrays.sort(this.segments); // Ensure canonical form
        this.hashCode = Arrays.hashCode(this.segments);
    }

    public KaylesState(List<Integer> segments) {
        this(segments.stream().mapToInt(Integer::intValue).toArray());
    }

    public int[] getSegments() {
        return segments.clone();
    }

    @Override
    public boolean equals(Object obj) {
        if (this == obj) return true;
        if (obj == null || getClass() != obj.getClass()) return false;
        KaylesState that = (KaylesState) obj;
        return Arrays.equals(segments, that.segments);
    }

    @Override
    public int hashCode() {
        return hashCode;
    }

    @Override
    public String toString() {
        return Arrays.toString(segments);
    }
}

// Optional functionality (not always needed during competition)

public static Integer detectPeriod(List<Integer> seq, int minPeriod, Integer maxPeriod) {
    int n = seq.size();
    if (maxPeriod == null) {
        maxPeriod = n / 2;
    }
    for (int p = minPeriod; p <= maxPeriod; p++) {
        boolean ok = true;
        for (int i = 0; i < n; i++) {
            if (!seq.get(i).equals(seq.get(i % p))) {
                ok = false;
                break;
            }
        }
        if (ok) {
            return p;
        }
    }
    return null;
```

```java
    }

    public static Collection<Integer> nimMovesSingleHeap(int n) {
        List<Integer> moves = new ArrayList<>();
        for (int k = 0; k < n; k++) {
            moves.add(k); // leave 0..n-1
        }
        return moves;
    }

    public static Function<Integer, Collection<Integer>> subtractionGameMovesFactory(
            Set<Integer> allowed) {
        List<Integer> allowedSorted = new ArrayList<>(allowed);
        Collections.sort(allowedSorted);

        return n -> {
            List<Integer> moves = new ArrayList<>();
            for (int d : allowedSorted) {
                if (d <= n) {
                    moves.add(n - d);
                }
            }
            return moves;
        };
    }

    public static Collection<KaylesState> kaylesMovesHelper(KaylesState state) {
        Set<KaylesState> resultSet = new HashSet<>();
        int[] segments = state.getSegments();

        for (int idx = 0; idx < segments.length; idx++) {
            int n = segments[idx];
            if (n <= 0) continue;

            // Remove one pin at position i (0..n-1)
            for (int i = 0; i < n; i++) {
                int left = i;
                int right = n - i - 1;
                List<Integer> newSeg = new ArrayList<>();

                for (int j = 0; j < idx; j++) {
                    newSeg.add(segments[j]);
                }
                if (left > 0) newSeg.add(left);
                if (right > 0) newSeg.add(right);
                for (int j = idx + 1; j < segments.length; j++) {
                    newSeg.add(segments[j]);
                }

                resultSet.add(new KaylesState(newSeg));
            }

            // Remove two adjacent pins at position i,i+1 (0..n-2)
            for (int i = 0; i < n - 1; i++) {
                int left = i;
                int right = n - i - 2;
                List<Integer> newSeg = new ArrayList<>();

                for (int j = 0; j < idx; j++) {
                    newSeg.add(segments[j]);
                }
                if (left > 0) newSeg.add(left);
                if (right > 0) newSeg.add(right);
                for (int j = idx + 1; j < segments.length; j++) {
                    newSeg.add(segments[j]);
                }

                resultSet.add(new KaylesState(newSeg));
            }
        }

        return new ArrayList<>(resultSet);
```

```java
}

public static Function<KaylesState, Collection<KaylesState>> kaylesMovesFactory() {
    return sprague_grundy::kaylesMovesHelper;
}

public static void testMain() {
    // Test Nim with larger values
    GrundyEngine<Integer> eng = new GrundyEngine<>(sprague_grundy::nimMovesSingleHeap);
    assert eng.grundy(42) == 42;
    assert eng.grundyMulti(Arrays.asList(17, 23, 31)) == 25; // 17^23^31 = 25
    assert eng.isWinningPosition(Arrays.asList(15, 27, 36)) == true; // 15^27^36 = 48 != 0

    // Test subtraction game {1,3,4} with period 7
    GrundyEngine<Integer> eng2 =
            new GrundyEngine<>(subtractionGameMovesFactory(Set.of(1, 3, 4)));
    assert eng2.grundy(14) == 0; // 14 % 7 = 0 → grundy = 0
    assert eng2.grundy(15) == 1; // 15 % 7 = 1 → grundy = 1
    assert eng2.grundy(18) == 2; // 18 % 7 = 4 → grundy = 2

    // Test Kayles
    GrundyEngine<KaylesState> eng3 = new GrundyEngine<>(kaylesMovesFactory());
    assert eng3.grundy(new KaylesState(new int[] {7})) == 2; // K(7) = 2
    assert eng3.grundy(new KaylesState(new int[] {3, 5})) == 7; // K(3)^K(5) = 3^4 = 7
}
```

Suffix Array

suffix_array.java

```java
/*
Suffix Array construction with Longest Common Prefix (LCP) array using Kasai's algorithm.

A suffix array is a sorted array of all suffixes of a string. The LCP array stores the length
of the longest common prefix between consecutive suffixes in the suffix array.

Key operations:
- Constructor: Build suffix array and LCP array for a string
- findPattern(pattern): Find all occurrences of pattern in text

Time complexity: O(n log n) for suffix array, O(n) for LCP array
Space complexity: O(n)
*/

import java.util.*;

class suffix_array {
    static class SuffixArray {
        private String text;
        private int n;
        private int[] sa;
        private int[] lcp;

        SuffixArray(String text) {
            this.text = text;
            this.n = text.length();
            this.sa = buildSuffixArray();
            this.lcp = buildLCPArray();
        }

        private int[] buildSuffixArray() {
            Integer[] suffixes = new Integer[n];
            for (int i = 0; i < n; i++) {
                suffixes[i] = i;
            }
            Arrays.sort(suffixes, (a, b) -> text.substring(a).compareTo(text.substring(b)));

            int[] result = new int[n];
            for (int i = 0; i < n; i++) {
                result[i] = suffixes[i];
            }
            return result;
        }

        private int[] buildLCPArray() {
            if (n == 0) return new int[0];

            int[] rank = new int[n];
            for (int i = 0; i < n; i++) {
                rank[sa[i]] = i;
            }

            int[] lcp = new int[n];
            int h = 0;

            for (int i = 0; i < n; i++) {
                if (rank[i] > 0) {
                    int j = sa[rank[i] - 1];
                    while (i + h < n && j + h < n && text.charAt(i + h) == text.charAt(j + h)) {
                        h++;
                    }
                    lcp[rank[i]] = h;
                    if (h > 0) h--;
                }
            }
```

```java
        return lcp;
    }

    List<Integer> findPattern(String pattern) {
        if (pattern.isEmpty()) return new ArrayList<>();

        int m = pattern.length();
        int left = 0, right = n;

        while (left < right) {
            int mid = (left + right) / 2;
            String suffix = text.substring(sa[mid]);
            if (suffix.compareTo(pattern) < 0) {
                left = mid + 1;
            } else {
                right = mid;
            }
        }

        int start = left;
        left = start;
        right = n;

        while (left < right) {
            int mid = (left + right) / 2;
            String suffix = text.substring(sa[mid], Math.min(sa[mid] + m, n));
            if (suffix.compareTo(pattern) <= 0) {
                left = mid + 1;
            } else {
                right = mid;
            }
        }

        int end = left;

        List<Integer> result = new ArrayList<>();
        for (int i = start; i < end; i++) {
            if (sa[i] + m <= n && text.substring(sa[i], sa[i] + m).equals(pattern)) {
                result.add(sa[i]);
            }
        }

        Collections.sort(result);
        return result;
    }

    int[] getSA() {
        return sa;
    }

    int[] getLCP() {
        return lcp;
    }
}

static void testMain() {
    SuffixArray sa = new SuffixArray("banana");
    assert Arrays.equals(sa.getSA(), new int[] {5, 3, 1, 0, 4, 2});
    assert Arrays.equals(sa.getLCP(), new int[] {0, 1, 3, 0, 0, 2});

    List<Integer> positions = sa.findPattern("ana");
    assert positions.equals(Arrays.asList(1, 3));
}
```

Topological Sort

topological_sort.java

```java
/*
Topological sorting algorithms for Directed Acyclic Graphs (DAG).

Provides two implementations:
1. Kahn's algorithm (BFS-based) - detects cycles
2. DFS-based algorithm - also detects cycles

Both return a topological ordering of vertices if the graph is a DAG,
or null if a cycle is detected.

Time complexity: O(V + E)
Space complexity: O(V + E)
*/

import java.util.*;

class topological_sort {
    static class TopologicalSort {
        private int n;
        private Map<Integer, List<Integer>> graph;

        TopologicalSort(int n) {
            this.n = n;
            this.graph = new HashMap<>();
            for (int i = 0; i < n; i++) {
                graph.put(i, new ArrayList<>());
            }
        }

        void addEdge(int u, int v) {
            graph.get(u).add(v);
        }

        List<Integer> kahnSort() {
            int[] inDegree = new int[n];

            for (int u = 0; u < n; u++) {
                for (int v : graph.get(u)) {
                    inDegree[v]++;
                }
            }

            Queue<Integer> queue = new LinkedList<>();
            for (int i = 0; i < n; i++) {
                if (inDegree[i] == 0) {
                    queue.offer(i);
                }
            }

            List<Integer> result = new ArrayList<>();

            while (!queue.isEmpty()) {
                int u = queue.poll();
                result.add(u);

                for (int v : graph.get(u)) {
                    inDegree[v]--;
                    if (inDegree[v] == 0) {
                        queue.offer(v);
                    }
                }
            }

            if (result.size() != n) {
                return null; // Cycle detected
            }
```

```java
        return result;
    }

    List<Integer> dfsSort() {
        Set<Integer> visited = new HashSet<>();
        Set<Integer> recStack = new HashSet<>();
        Stack<Integer> stack = new Stack<>();

        for (int i = 0; i < n; i++) {
            if (!visited.contains(i)) {
                if (!dfsVisit(i, visited, recStack, stack)) {
                    return null; // Cycle detected
                }
            }
        }

        List<Integer> result = new ArrayList<>();
        while (!stack.isEmpty()) {
            result.add(stack.pop());
        }

        return result;
    }

    private boolean dfsVisit(
            int u, Set<Integer> visited, Set<Integer> recStack, Stack<Integer> stack) {
        visited.add(u);
        recStack.add(u);

        for (int v : graph.get(u)) {
            if (!visited.contains(v)) {
                if (!dfsVisit(v, visited, recStack, stack)) {
                    return false;
                }
            } else if (recStack.contains(v)) {
                return false; // Cycle detected
            }
        }

        recStack.remove(u);
        stack.push(u);
        return true;
    }

    boolean hasCycle() {
        return kahnSort() == null;
    }

    List<Integer> longestPath(int source) {
        List<Integer> topoOrder = kahnSort();
        if (topoOrder == null) {
            return null; // Has cycle
        }

        Map<Integer, Integer> dist = new HashMap<>();
        Map<Integer, Integer> parent = new HashMap<>();

        for (int i = 0; i < n; i++) {
            dist.put(i, Integer.MIN_VALUE);
        }
        dist.put(source, 0);

        for (int u : topoOrder) {
            if (dist.get(u) != Integer.MIN_VALUE) {
                for (int v : graph.get(u)) {
                    if (dist.get(u) + 1 > dist.get(v)) {
                        dist.put(v, dist.get(u) + 1);
                        parent.put(v, u);
                    }
                }
            }
```

```java
        }

        // Find vertex with maximum distance
        int maxDist = Integer.MIN_VALUE;
        int endVertex = -1;
        for (int i = 0; i < n; i++) {
            if (dist.get(i) > maxDist) {
                maxDist = dist.get(i);
                endVertex = i;
            }
        }

        if (endVertex == -1 || maxDist == Integer.MIN_VALUE) {
            return Arrays.asList(source);
        }

        // Reconstruct path
        List<Integer> path = new ArrayList<>();
        int current = endVertex;
        while (current != source) {
            path.add(current);
            current = parent.get(current);
        }
        path.add(source);
        Collections.reverse(path);

        return path;
    }
}

static void testMain() {
    TopologicalSort ts = new TopologicalSort(6);
    int[][] edges = {{5, 2}, {5, 0}, {4, 0}, {4, 1}, {2, 3}, {3, 1}};
    for (int[] edge : edges) {
        ts.addEdge(edge[0], edge[1]);
    }

    List<Integer> kahnResult = ts.kahnSort();
    List<Integer> dfsResult = ts.dfsSort();

    assert kahnResult != null;
    assert dfsResult != null;
    assert !ts.hasCycle();

    // Test with cycle
    TopologicalSort tsCycle = new TopologicalSort(3);
    tsCycle.addEdge(0, 1);
    tsCycle.addEdge(1, 2);
    tsCycle.addEdge(2, 0);
    assert tsCycle.hasCycle();
}
```

Two Sat

two_sat.java

```java
/*
2-SAT solver using Kosaraju's SCC algorithm on implication graph.

2-SAT (Boolean Satisfiability with 2 literals per clause) determines if a Boolean formula
in CNF with at most 2 literals per clause is satisfiable. Uses implication graph where
each variable x has nodes x and not-x, and clause (a OR b) creates edges not-a -> b
and not-b -> a.

Key operations:
- addClause(a, aNeg, b, bNeg): Add clause (a OR b)
- solve(): Returns assignment array if satisfiable, null otherwise

Time complexity: O(n + m) where n is variables and m is clauses
Space complexity: O(n + m)
*/

import java.util.*;

class two_sat {
    static class TwoSAT {
        private int n;
        private List<List<Integer>> graph;
        private List<List<Integer>> transpose;

        TwoSAT(int n) {
            this.n = n;
            this.graph = new ArrayList<>();
            this.transpose = new ArrayList<>();
            for (int i = 0; i < 2 * n; i++) {
                graph.add(new ArrayList<>());
                transpose.add(new ArrayList<>());
            }
        }

        void addClause(int a, boolean aNeg, int b, boolean bNeg) {
            int aNode = 2 * a + (aNeg ? 1 : 0);
            int bNode = 2 * b + (bNeg ? 1 : 0);
            int naNode = 2 * a + (aNeg ? 0 : 1);
            int nbNode = 2 * b + (bNeg ? 0 : 1);

            graph.get(naNode).add(bNode);
            graph.get(nbNode).add(aNode);
            transpose.get(bNode).add(naNode);
            transpose.get(aNode).add(nbNode);
        }

        boolean[] solve() {
            // Kosaraju's algorithm
            boolean[] visited = new boolean[2 * n];
            List<Integer> finishOrder = new ArrayList<>();

            for (int node = 0; node < 2 * n; node++) {
                if (!visited[node]) {
                    dfs1(node, visited, finishOrder);
                }
            }

            Arrays.fill(visited, false);
            int[] sccId = new int[2 * n];
            int currentScc = 0;

            for (int i = finishOrder.size() - 1; i >= 0; i--) {
                int node = finishOrder.get(i);
                if (!visited[node]) {
                    dfs2(node, visited, sccId, currentScc);
                    currentScc++;
```

```java
            }
        }

        // Check satisfiability
        for (int i = 0; i < n; i++) {
            if (sccId[2 * i] == sccId[2 * i + 1]) {
                return null;
            }
        }

        // Construct assignment
        boolean[] assignment = new boolean[n];
        for (int i = 0; i < n; i++) {
            assignment[i] = sccId[2 * i] > sccId[2 * i + 1];
        }

        return assignment;
    }

    private void dfs1(int node, boolean[] visited, List<Integer> finishOrder) {
        visited[node] = true;
        for (int neighbor : graph.get(node)) {
            if (!visited[neighbor]) {
                dfs1(neighbor, visited, finishOrder);
            }
        }
        finishOrder.add(node);
    }

    private void dfs2(int node, boolean[] visited, int[] sccId, int scc) {
        visited[node] = true;
        sccId[node] = scc;
        for (int neighbor : transpose.get(node)) {
            if (!visited[neighbor]) {
                dfs2(neighbor, visited, sccId, scc);
            }
        }
    }
}

static void testMain() {
    TwoSAT sat = new TwoSAT(2);
    sat.addClause(0, false, 1, false);
    sat.addClause(0, true, 1, false);
    sat.addClause(0, false, 1, true);

    boolean[] result = sat.solve();
    assert result != null;
    assert result[0] || result[1];
    assert !result[0] || result[1];
    assert result[0] || !result[1];
}
```

Union Find

union_find.java

```java
/*
Union-Find (Disjoint Set Union) data structure with path compression and union by rank.

Supports:
- find(x): Find the representative of the set containing x - O(α(n)) amortized
- union(x, y): Merge the sets containing x and y - O(α(n)) amortized
- connected(x, y): Check if x and y are in the same set - O(α(n)) amortized

Space complexity: O(n)

α(n) is the inverse Ackermann function, which is effectively constant for all practical values of n.
*/

class union_find {
    static class UnionFind {
        private int[] parent;
        private int[] rank;

        UnionFind(int n) {
            parent = new int[n];
            rank = new int[n];
            for (int i = 0; i < n; i++) {
                parent[i] = i;
                rank[i] = 0;
            }
        }

        int find(int x) {
            if (parent[x] != x) {
                parent[x] = find(parent[x]); // Path compression
            }
            return parent[x];
        }

        int union(int x, int y) {
            int rootX = find(x);
            int rootY = find(y);

            if (rootX == rootY) {
                return rootX;
            }

            // Union by rank
            if (rank[rootX] < rank[rootY]) {
                parent[rootX] = rootY;
                merge(rootY, rootX);
                return rootY;
            } else if (rank[rootX] > rank[rootY]) {
                parent[rootY] = rootX;
                merge(rootX, rootY);
                return rootX;
            } else {
                parent[rootY] = rootX;
                merge(rootX, rootY);
                rank[rootX]++;
                return rootX;
            }
        }

        boolean connected(int x, int y) {
            return find(x) == find(y);
        }

        void merge(int root, int child) {
            // Override to define custom merge behavior when sets are united
        }
```

```java
}

static class Test extends UnionFind {
    private int[] size;

    Test(int n) {
        super(n);
        size = new int[n];
        for (int i = 0; i < n; i++) {
            size[i] = 1;
        }
    }

    @Override
    void merge(int root, int child) {
        size[root] += size[child];
    }

    int getSize(int x) {
        return size[find(x)];
    }
}

static void testMain() {
    Test a = new Test(3);
    int d = a.union(0, 1);
    int e = a.union(d, 2);
    assert a.getSize(e) == 3;
    assert a.getSize(a.find(0)) == 3;
}
```