

Algorithm Reference - Java

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Bellman Ford

bellman_ford.java

```
/*
Bellman-Ford algorithm for single-source shortest paths with negative 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;
                }
            }

            return distances;
        }
    }
}
```

```

    }
}

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;
}

// Don't write tests below during competition.

static void testNegativeCycle() {
    BellmanFord bf = new BellmanFord();
    bf.addEdge(0, 1, 1);

```

```

    bf.addEdge(1, 2, -3);
    bf.addEdge(2, 0, 1);

    Map<Integer, Integer> result = bf.shortestPaths(0);
    assert result == null;
}

static void testUnreachableNodes() {
    BellmanFord bf = new BellmanFord();
    bf.addEdge(1, 2, 5);
    bf.addEdge(3, 4, 3);

    Map<Integer, Integer> result = bf.shortestPaths(1);
    assert result != null;
    assert result.get(2) == 5;
    assert result.get(3) == 999999;
}

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

    Map<Integer, Integer> result = bf.shortestPaths(0);
    assert result != null;
    assert result.get(3) == -6;
}

static void testPathReconstruction() {
    BellmanFord bf = new BellmanFord();
    bf.addEdge(0, 1, 5);
    bf.addEdge(1, 2, 3);
    bf.addEdge(0, 2, 10);

    List<Integer> path = bf.shortestPath(0, 2);
    assert path != null;
    assert path.equals(Arrays.asList(0, 1, 2));
}

static void testNegativeEdgeRelaxation() {
    BellmanFord bf = new BellmanFord();
    bf.addEdge(0, 1, 10);
    bf.addEdge(0, 2, 5);
    bf.addEdge(2, 1, -8);

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

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

    Map<Integer, Integer> result = bf.shortestPaths(0);
    assert result != null;
    assert result.get(1) == 1;
    assert result.get(2) == 999999;
}

static void testSelfLoopNegative() {
    BellmanFord bf = new BellmanFord();
    bf.addEdge(0, 0, -1);

    Map<Integer, Integer> result = bf.shortestPaths(0);
    assert result == null;
}

static void testComplexGraph() {
    BellmanFord bf = new BellmanFord();

```

```

    bf.addEdge(0, 1, 10);
    bf.addEdge(0, 4, 8);
    bf.addEdge(1, 2, 2);
    bf.addEdge(2, 3, 5);
    bf.addEdge(3, 4, 3);
    bf.addEdge(4, 3, 1);

    Map<Integer, Integer> result = bf.shortestPaths(0);
    assert result != null;
    assert result.get(3) == 9;
    assert result.get(4) == 8;
}

public static void main(String[] args) {
    testMain();
    testNegativeCycle();
    testUnreachableNodes();
    testAllNegativeEdges();
    testPathReconstruction();
    testNegativeEdgeRelaxation();
    testDisconnectedGraph();
    testSelfLoopNegative();
    testComplexGraph();
    System.out.println("All tests passed!");
}
}

```

Bipartite Match

bipartite_match.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;
        }
    }
}
```

```

    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());
}

// Don't write tests below during competition.

static void testSimpleMatching() {
    BipartiteMatch bm = new BipartiteMatch(3, 3);
    bm.addEdge(0, 0);
    bm.addEdge(1, 1);
    bm.addEdge(2, 2);

    assert bm.maxMatching() == 3;
}

static void testNoMatching() {
    BipartiteMatch bm = new BipartiteMatch(2, 2);
    assert bm.maxMatching() == 0;
}

static void testPartialMatching() {
    BipartiteMatch bm = new BipartiteMatch(3, 2);
    bm.addEdge(0, 0);
    bm.addEdge(1, 0);
    bm.addEdge(2, 1);

    assert bm.maxMatching() == 2;
}

static void testComplexMatching() {
    BipartiteMatch bm = new BipartiteMatch(5, 5);
    bm.addEdge(0, 2);
    bm.addEdge(1, 1);
    bm.addEdge(1, 3);
    bm.addEdge(2, 0);
    bm.addEdge(2, 3);
    bm.addEdge(3, 2);
    bm.addEdge(3, 4);
    bm.addEdge(4, 4);

    int matching = bm.maxMatching();
    assert matching >= 4; // Should be at least 4
}

static void testSingleVertex() {
    BipartiteMatch bm = new BipartiteMatch(1, 1);
    bm.addEdge(0, 0);

    assert bm.maxMatching() == 1;
}

```

```

static void testMultipleEdges() {
    BipartiteMatch bm = new BipartiteMatch(2, 3);
    bm.addEdge(0, 0);
    bm.addEdge(0, 1);
    bm.addEdge(0, 2);
    bm.addEdge(1, 1);
    bm.addEdge(1, 2);

    assert bm.maxMatching() == 2;
}

static void testAugmentingPath() {
    BipartiteMatch bm = new BipartiteMatch(3, 3);
    bm.addEdge(0, 0);
    bm.addEdge(0, 1);
    bm.addEdge(1, 1);
    bm.addEdge(2, 2);

    int matching = bm.maxMatching();
    assert matching == 3;

    Map<Integer, Integer> matches = bm.getMatching();
    assert matches.size() == 3;
}

public static void main(String[] args) {
    testMain();
    testSimpleMatching();
    testNoMatching();
    testPartialMatching();
    testSingleVertex();
    testMultipleEdges();
    testAugmentingPath();
    System.out.println("All tests passed!");
}
}

```


Convex Hull

convex_hull.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));
}

// Don't write tests below during competition.

static void testEmpty() {
    assert convexHull(new ArrayList<>()).isEmpty();
}

static void testSinglePoint() {
    List<Point> pts = Arrays.asList(new Point(1, 2));
    List<Point> hull = convexHull(pts);
    assert hull.size() == 1;
}

static void testTwoPoints() {
    List<Point> pts = Arrays.asList(new Point(0, 0), new Point(1, 1));
    List<Point> hull = convexHull(pts);
    assert hull.size() == 2;
}

static void testCollinearPoints() {
    List<Point> pts =
        Arrays.asList(
            new Point(0, 0), new Point(1, 1),
            new Point(2, 2), new Point(3, 3));
    List<Point> hull = convexHull(pts);
    assert hull.size() == 2;
    assert hull.contains(new Point(0, 0));
    assert hull.contains(new Point(3, 3));
}

static void testTriangle() {
    List<Point> pts = Arrays.asList(new Point(0, 0), new Point(2, 0), new Point(1, 2));
    List<Point> hull = convexHull(pts);
    assert hull.size() == 3;
}

static void testWithInteriorPoints() {
    List<Point> pts =
        Arrays.asList(

```

```

        new Point(0, 0),
        new Point(4, 0),
        new Point(4, 3),
        new Point(2, 4),
        new Point(0, 3),
        new Point(2, 2),
        new Point(2, 1));
List<Point> hull = convexHull(pts);
assert hull.size() == 5;
assert !hull.contains(new Point(2, 2));
assert !hull.contains(new Point(2, 1));
}

static void testNegativeCoordinates() {
    List<Point> pts =
        Arrays.asList(
            new Point(-1, -1), new Point(1, -1),
            new Point(1, 1), new Point(-1, 1));
    List<Point> hull = convexHull(pts);
    assert hull.size() == 4;
}

static void testLargeSquare() {
    List<Point> pts = new ArrayList<>();
    for (int i = 0; i <= 10; i++) {
        for (int j = 0; j <= 10; j++) {
            pts.add(new Point(i, j));
        }
    }
    List<Point> hull = convexHull(pts);
    assert hull.size() == 4;
    assert hull.contains(new Point(0, 0));
    assert hull.contains(new Point(10, 0));
    assert hull.contains(new Point(10, 10));
    assert hull.contains(new Point(0, 10));
}

public static void main(String[] args) {
    testMain();
    testEmpty();
    testSinglePoint();
    testTwoPoints();
    testCollinearPoints();
    testTriangle();
    testWithInteriorPoints();
    testNegativeCoordinates();
    testLargeSquare();
    System.out.println("All tests passed!");
}
}

```

Dijkstra

dijkstra.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);
        }
    }
}
```

```

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);
    }
}

```

```

        }
        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));
}

// Don't write tests below during competition.

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

    Map<Integer, Integer> distances = d.shortestPaths(0);
    assert distances.get(2) == 8;
}

static void testNoPath() {
    Dijkstra d = new Dijkstra(3);
    d.addEdge(0, 1, 1);

    Map<Integer, Integer> distances = d.shortestPaths(0);
    assert distances.get(2) == Integer.MAX_VALUE;

    List<Integer> path = d.shortestPath(0, 2);
    assert path == null;
}

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

    Map<Integer, Integer> distances = d.shortestPaths(0);
    assert distances.get(0) == 0;
    assert distances.get(1) == 3;
}

public static void main(String[] args) {
    testSimplePath();
    testNoPath();
    testSelfLoop();
    testMain();
    System.out.println("All tests passed!");
}
}

```

Edmonds Karp

edmonds_karp.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;
            }
        }
    }
}
```

```

        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;
}

// Don't write tests below during competition.

static void testSimpleFlow() {
    EdmondsKarp ek = new EdmondsKarp(3);
    ek.addEdge(0, 1, 5);
    ek.addEdge(1, 2, 3);

    assert ek.maxFlow(0, 2) == 3;
}

static void testMultiplePaths() {
    EdmondsKarp ek = new EdmondsKarp(4);
    ek.addEdge(0, 1, 10);
    ek.addEdge(0, 2, 10);
    ek.addEdge(1, 3, 10);
    ek.addEdge(2, 3, 10);

    assert ek.maxFlow(0, 3) == 20;
}

static void testBottleneck() {
    EdmondsKarp ek = new EdmondsKarp(4);
    ek.addEdge(0, 1, 100);
    ek.addEdge(1, 2, 1);
    ek.addEdge(2, 3, 100);

    assert ek.maxFlow(0, 3) == 1;
}

static void testComplexNetwork() {
    EdmondsKarp ek = new EdmondsKarp(6);
    ek.addEdge(0, 1, 16);
    ek.addEdge(0, 2, 13);

```



```

        ek.addEdge(1, 2, 10);
        ek.addEdge(1, 3, 12);
        ek.addEdge(2, 1, 4);
        ek.addEdge(2, 4, 14);
        ek.addEdge(3, 2, 9);
        ek.addEdge(3, 5, 20);
        ek.addEdge(4, 3, 7);
        ek.addEdge(4, 5, 4);

        assert ek.maxFlow(0, 5) == 23;
    }

    static void testNoPath() {
        EdmondsKarp ek = new EdmondsKarp(4);
        ek.addEdge(0, 1, 10);
        ek.addEdge(2, 3, 10);

        assert ek.maxFlow(0, 3) == 0;
    }

    static void testSingleEdge() {
        EdmondsKarp ek = new EdmondsKarp(2);
        ek.addEdge(0, 1, 42);

        assert ek.maxFlow(0, 1) == 42;
    }

    static void testZeroCapacity() {
        EdmondsKarp ek = new EdmondsKarp(3);
        ek.addEdge(0, 1, 0);
        ek.addEdge(1, 2, 10);

        assert ek.maxFlow(0, 2) == 0;
    }

    static void testMultipleEdges() {
        EdmondsKarp ek = new EdmondsKarp(3);
        ek.addEdge(0, 1, 5);
        ek.addEdge(0, 1, 5);
        ek.addEdge(1, 2, 10);

        assert ek.maxFlow(0, 2) == 10;
    }

    public static void main(String[] args) {
        testSimpleFlow();
        testMultiplePaths();
        testBottleneck();
        testComplexNetwork();
        testNoPath();
        testSingleEdge();
        testZeroCapacity();
        testMultipleEdges();
        testMain();
        System.out.println("All tests passed!");
    }
}

```

Fenwick Tree

fenwick_tree.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;

```

```

        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;
    }
}

```

```

    // 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;
}

// Don't write tests below during competition.

static void testEmpty() {
    FenwickTree<Long> ft = new FenwickTree<>(10, 0L, (a, b) -> a + b, (a, b) -> a - b);
    assert ft.query(0) == 0L;
    assert ft.query(9) == 0L;
    assert ft.rangeQuery(0, 9) == 0L;
}

static void testSingleUpdate() {
    FenwickTree<Long> ft = new FenwickTree<>(5, 0L, (a, b) -> a + b, (a, b) -> a - b);
    ft.update(2, 7L);
    assert ft.query(1) == 0L;
    assert ft.query(2) == 7L;
    assert ft.query(4) == 7L;
}

static void testFromArray() {
    Long[] arr = {1L, 2L, 3L, 4L, 5L};
    FenwickTree<Long> ft = new FenwickTree<>(arr, 0L, (a, b) -> a + b, (a, b) -> a - b);
    assert ft.query(0) == 1L;
    assert ft.query(2) == 6L;
    assert ft.query(4) == 15L;
    assert ft.rangeQuery(1, 3) == 9L;
}

static void testNegativeValues() {
    FenwickTree<Long> ft = new FenwickTree<>(4, 0L, (a, b) -> a + b, (a, b) -> a - b);
    ft.update(0, 10L);
    ft.update(1, -5L);
    ft.update(2, 3L);
}

```

```

ft.update(3, -2L);

assert ft.query(1) == 5L;
assert ft.query(3) == 6L;
assert ft.rangeQuery(1, 2) == -2L;
}

static void testLargeUpdates() {
    FenwickTree<Long> ft = new FenwickTree<>(1000, 0L, (a, b) -> a + b, (a, b) -> a - b);
    for (int i = 0; i < 1000; i++) {
        ft.update(i, (long) (i + 1));
    }
    assert ft.query(999) == 500500L;
    assert ft.rangeQuery(0, 99) == 5050L;
}

static void testBoundsChecking() {
    FenwickTree<Long> ft = new FenwickTree<>(5, 0L, (a, b) -> a + b, (a, b) -> a - b);

    // Test update bounds
    try {
        ft.update(-1, 10L);
        assert false : "Should throw IndexOutOfBoundsException for negative index";
    } catch (IndexOutOfBoundsException e) {
        // Expected
    }

    try {
        ft.update(5, 10L);
        assert false : "Should throw IndexOutOfBoundsException for index >= size";
    } catch (IndexOutOfBoundsException e) {
        // Expected
    }

    // Test query bounds
    try {
        ft.query(-1);
        assert false : "Should throw IndexOutOfBoundsException for negative index";
    } catch (IndexOutOfBoundsException e) {
        // Expected
    }

    try {
        ft.query(5);
        assert false : "Should throw IndexOutOfBoundsException for index >= size";
    } catch (IndexOutOfBoundsException e) {
        // Expected
    }

    // Test range_query bounds - should return 0 for invalid ranges
    assert ft.rangeQuery(-1, 2) == 0L;
    assert ft.rangeQuery(0, 5) == 0L;
    assert ft.rangeQuery(5, 3) == 0L;
}

static void testGetValue() {
    FenwickTree<Long> ft = new FenwickTree<>(5, 0L, (a, b) -> a + b, (a, b) -> a - b);
    ft.update(0, 5L);
    ft.update(2, 3L);
    ft.update(4, 7L);

    assert ft.getValue(0) == 5L;
    assert ft.getValue(2) == 3L;
    assert ft.getValue(4) == 7L;
}

static void testFirstNonzeroIndex() {
    FenwickTree<Long> ft = new FenwickTree<>(10, 0L, (a, b) -> a + b, (a, b) -> a - b);
    ft.update(2, 1L);
    ft.update(8, 1L);

    java.util.Comparator<Long> cmp = Long::compare;

```

```

    assert ft.firstNonzeroIndex(5, cmp) == 8;
    assert ft.firstNonzeroIndex(8, cmp) == 8;
    assert ft.firstNonzeroIndex(0, cmp) == 2;
    assert ft.firstNonzeroIndex(9, cmp) == null;
}

static void testFirstNonzeroBounds() {
    FenwickTree<Long> ft = new FenwickTree<>(10, 0L, (a, b) -> a + b, (a, b) -> a - b);
    ft.update(5, 1L);

    java.util.Comparator<Long> cmp = Long::compare;
    // Negative start_index should be clamped to 0
    assert ft.firstNonzeroIndex(-5, cmp) == 5;

    // Start from exactly where nonzero is
    assert ft.firstNonzeroIndex(5, cmp) == 5;

    // Start past all nonzero elements
    assert ft.firstNonzeroIndex(10, cmp) == null;
    assert ft.firstNonzeroIndex(100, cmp) == null;

    // Empty tree
    FenwickTree<Long> ftEmpty = new FenwickTree<>(10, 0L, (a, b) -> a + b, (a, b) -> a - b);
    assert ftEmpty.firstNonzeroIndex(0, cmp) == null;
}

static void testFromArrayMethod() {
    Long[] arr = {1L, 3L, 5L, 7L, 9L, 11L};
    FenwickTree<Long> ft = FenwickTree.fromArray(arr, 0L, (a, b) -> a + b, (a, b) -> a - b);

    // Test that prefix sums match
    long expectedSum = 0;
    for (int i = 0; i < arr.length; i++) {
        expectedSum += arr[i];
        assert ft.query(i) == expectedSum;
    }

    // Test range queries
    assert ft.rangeQuery(1, 3) == 3 + 5 + 7; // 15
    assert ft.rangeQuery(2, 4) == 5 + 7 + 9; // 21

    // Test updates
    ft.update(2, 10L); // arr[2] becomes 15
    assert ft.getValue(2) == 15L;
    assert ft.rangeQuery(1, 3) == 3 + 15 + 7; // 25
}

static void testEdgeCases() {
    FenwickTree<Long> ft = new FenwickTree<>(1, 0L, (a, b) -> a + b, (a, b) -> a - b);

    // Single element tree
    ft.update(0, 42L);
    assert ft.query(0) == 42L;
    assert ft.rangeQuery(0, 0) == 42L;
    assert ft.getValue(0) == 42L;

    // Empty range
    FenwickTree<Long> ftLarge = new FenwickTree<>(10, 0L, (a, b) -> a + b, (a, b) -> a - b);
    assert ftLarge.rangeQuery(5, 3) == 0L; // left > right
}

public static void main(String[] args) {
    testEmpty();
    testSingleUpdate();
    testFromArray();
    testNegativeValues();
    testLargeUpdates();
    testBoundsChecking();
    testGetValue();
    testFirstNonzeroIndex();
    testFirstNonzeroBounds();
    testFromArrayMethod();
}

```

```
    testEdgeCases();  
    testMain();  
    System.out.println("All tests passed!");  
}  
}
```

Kmp

kmp.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)) {
```



```

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

return result;
}

static void testMain() {
    String text = "ababcbaba";
    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("abcbcab");
    assert Arrays.equals(failure, new int[] {0, 0, 0, 1, 2, 3, 4, 5});
}

// Don't write tests below during competition.

static void testNoMatch() {
    List<Integer> result = search("ABCDEF", "XYZ");
    assert result.isEmpty();
}

static void testSingleChar() {
    List<Integer> result = search("AAAAA", "A");
    assert result.equals(Arrays.asList(0, 1, 2, 3, 4));
}

static void testEmptyPattern() {
    List<Integer> result = search("ABC", "");
    assert result.isEmpty();
}

static void testPatternLongerThanText() {
    List<Integer> result = search("AB", "ABCD");
    assert result.isEmpty();
}

static void testOverlappingMatches() {
    List<Integer> result = search("AAAA", "AA");
    assert result.equals(Arrays.asList(0, 1, 2));
}

static void testLPS() {
    int[] lps = computeLPS("AAAA");
    assert Arrays.equals(lps, new int[] {0, 1, 2, 3});

    lps = computeLPS("ABCDE");
    assert Arrays.equals(lps, new int[] {0, 0, 0, 0, 0});

    lps = computeLPS("AABAAA");
    assert Arrays.equals(lps, new int[] {0, 1, 0, 1, 2, 2});
}

static void testFullMatch() {
    List<Integer> result = search("PATTERN", "PATTERN");
    assert result.equals(Arrays.asList(0));
}

static void testMultipleOccurrences() {
    List<Integer> result = search("ABABABAB", "ABA");
    assert result.equals(Arrays.asList(0, 2, 4));
}

static void testComplexPattern() {

```

```
String text = "ABCABDABCABC";
String pattern = "ABC";
List<Integer> result = search(text, pattern);
assert result.equals(Arrays.asList(0, 6, 9));
}

public static void main(String[] args) {
    testNoMatch();
    testSingleChar();
    testEmptyPattern();
    testPatternLongerThanText();
    testOverlappingMatches();
    testLPS();
    testFullMatch();
    testMultipleOccurrences();
    testComplexPattern();
    testMain();
    System.out.println("All tests passed!");
}
}
```

Kosaraju Scc

kosaraju_scc.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)) {
                for (Integer v : graph.get(node)) {
                    if (!visited.contains(v)) {
                        dfs1(v, 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 (Integer v : transpose.get(node)) {
                    if (!visited.contains(v)) {
                        dfs2(v, visited, scc);
                    }
                }
            }
        }
    }
}
```

```

        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));
}

// Don't write tests below during competition.

static void testSingleNode() {
    KosarajuSCC g = new KosarajuSCC();
    g.addEdge(1, 1);

    List<List<Integer>> sccs = g.findSCCs();
    assert sccs.size() == 1;
    assert sccs.get(0).contains(1);
}

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

    List<List<Integer>> sccs = g.findSCCs();
    assert sccs.size() == 4;
}

static void testFullyConnected() {
    KosarajuSCC g = new KosarajuSCC();
    for (int i = 0; i < 4; i++) {
        g.addEdge(i, (i + 1) % 4);
    }
}

```

```

    }

    List<List<Integer>> sccs = g.findSCCs();
    assert sccs.size() == 1;
    assert sccs.get(0).size() == 4;
}

static void testLinearChain() {
    KosarajuSCC g = new KosarajuSCC();
    for (int i = 0; i < 4; i++) {
        g.addEdge(i, i + 1);
    }

    List<List<Integer>> sccs = g.findSCCs();
    assert sccs.size() == 5;
}

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

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

static void testComplexGraph() {
    KosarajuSCC g = new KosarajuSCC();
    g.addEdge(0, 1);
    g.addEdge(1, 2);
    g.addEdge(2, 0);
    g.addEdge(3, 4);
    g.addEdge(4, 3);
    g.addEdge(5, 6);
    g.addEdge(6, 7);
    g.addEdge(7, 5);
    g.addEdge(2, 3);
    g.addEdge(4, 5);

    List<List<Integer>> sccs = g.findSCCs();
    assert sccs.size() == 3;
}

static void testBidirectionalEdges() {
    KosarajuSCC g = new KosarajuSCC();
    g.addEdge(1, 2);
    g.addEdge(2, 1);
    g.addEdge(2, 3);
    g.addEdge(3, 2);

    List<List<Integer>> sccs = g.findSCCs();
    assert sccs.size() == 1;
    assert sccs.get(0).size() == 3;
}

static void testLargeGraph() {
    KosarajuSCC g = new KosarajuSCC();
    for (int sccId = 0; sccId < 10; sccId++) {
        int base = sccId * 5;
        for (int i = 0; i < 5; i++) {
            g.addEdge(base + i, base + (i + 1) % 5);
        }
        if (sccId < 9) {
            g.addEdge(base + 4, (sccId + 1) * 5);
        }
    }

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

```

```
    assert sccs.size() == 10;
    for (List<Integer> scc : sccs) {
        assert scc.size() == 5;
    }
}

public static void main(String[] args) {
    testMain();
    testSingleNode();
    testNoEdges();
    testFullyConnected();
    testLinearChain();
    testMultipleComponents();
    testComplexGraph();
    testBidirectionalEdges();
    testLargeGraph();
    System.out.println("All tests passed!");
}
}
```

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));  
                    }  
                }  
            }  
        }  
    }  
}
```

```

    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
}

// Don't write tests below during competition.

static void testLinearTree() {
    LCA lca = new LCA(5);
    lca.addEdge(0, 1);
    lca.addEdge(1, 2);
    lca.addEdge(2, 3);
    lca.addEdge(3, 4);
}

```



```

    lca.build(0);

    assert lca.query(0, 4) == 0;
    assert lca.query(2, 4) == 2;
    assert lca.distance(0, 4) == 4;
}

static void testSameNode() {
    LCA lca = new LCA(3);
    lca.addEdge(0, 1);
    lca.addEdge(0, 2);

    lca.build(0);

    assert lca.query(1, 1) == 1;
    assert lca.distance(1, 1) == 0;
}

static void testDeepTree() {
    int n = 100;
    LCA lca = new LCA(n);
    for (int i = 0; i < n - 1; i++) {
        lca.addEdge(i, i + 1);
    }

    lca.build(0);

    assert lca.query(50, 99) == 50;
    assert lca.distance(0, 99) == 99;
}

static void testComplexTree() {
    LCA lca = new LCA(10);
    lca.addEdge(0, 1);
    lca.addEdge(0, 2);
    lca.addEdge(1, 3);
    lca.addEdge(1, 4);
    lca.addEdge(2, 5);
    lca.addEdge(3, 6);
    lca.addEdge(3, 7);
    lca.addEdge(4, 8);
    lca.addEdge(5, 9);

    lca.build(0);

    assert lca.query(6, 7) == 3;
    assert lca.query(6, 8) == 1;
    assert lca.query(7, 9) == 0;
    assert lca.distance(6, 7) == 2;
    assert lca.distance(6, 9) == 6;
}

static void testBinaryTree() {
    LCA lca = new LCA(7);
    lca.addEdge(0, 1);
    lca.addEdge(0, 2);
    lca.addEdge(1, 3);
    lca.addEdge(1, 4);
    lca.addEdge(2, 5);
    lca.addEdge(2, 6);

    lca.build(0);

    assert lca.query(3, 6) == 0;
    assert lca.query(4, 5) == 0;
    assert lca.distance(3, 6) == 4;
}

public static void main(String[] args) {
    testLinearTree();
    testSameNode();
}

```

```
testDeepTree();
testComplexTree();
testBinaryTree();
testMain();
System.out.println("All tests passed!");
}
```

Polygon Area

polygon_area.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;
    }
}
```

```

// 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);
}

// Don't write tests below during competition.

static void testRectangle() {
    Point[] rect = {
        new Point(0.0, 0.0), new Point(5.0, 0.0), new Point(5.0, 3.0), new Point(0.0, 3.0)
    };
    assert polygonArea(rect) == 15.0;

    Point[] rectCw = {
        new Point(0.0, 0.0), new Point(0.0, 3.0), new Point(5.0, 3.0), new Point(5.0, 0.0)
    };
    assert polygonArea(rectCw) == 15.0;
}

static void testDiamond() {
    Point[] diamond = {
        new Point(0.0, 2.0), new Point(3.0, 0.0), new Point(0.0, -2.0), new Point(-3.0, 0.0)
    };
    double area = polygonArea(diamond);
    assert area == 12.0;
}

static void testSignedArea() {
    Point[] ccw = {
        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 polygonSignedArea(ccw) == 1.0;
    assert !isClockwise(ccw);

    Point[] cw = {
        new Point(0.0, 0.0), new Point(0.0, 1.0), new Point(1.0, 1.0), new Point(1.0, 0.0)
    };
    assert polygonSignedArea(cw) == -1.0;
    assert isClockwise(cw);
}

public static void main(String[] args) {
    testRectangle();
    testDiamond();
    testSignedArea();
    testMain();
    System.out.println("All tests passed!");
}
}

```

Prefix Tree

prefix_tree.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);
        }
    }
}
```

```

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");
}

// Don't write tests below during competition.

static void testEmpty() {
    PrefixTree trie = new PrefixTree();
    assert !trie.search("test");
    assert !trie.startsWith("test");
}

static void testOverlappingWords() {
    PrefixTree trie = new PrefixTree();
    trie.insert("car");
    trie.insert("card");
    trie.insert("care");
    trie.insert("careful");

    assert trie.search("car");
    assert trie.search("card");
    assert trie.search("careful");
    assert !trie.search("ca");
    assert trie.startsWith("car");
    assert trie.startsWith("care");
}

static void testDeleteNonexistent() {
    PrefixTree trie = new PrefixTree();
    trie.insert("test");
    assert !trie.delete("testing");
    assert trie.search("test");
}

```

```
public static void main(String[] args) {  
    testEmpty();  
    testOverlappingWords();  
    testDeleteNonexistent();  
    testMain();  
    System.out.println("All tests passed!");  
}  
}
```

Priority Queue

priority_queue.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) {
```



```

        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;
}

// Don't write tests below during competition.

static void testBasicOperations() {
    PriorityQueue<Integer> pq = new PriorityQueue<>();

    // Test empty queue

```

```

    assert pq.size() == 0;
    assert pq.peek() == null;

    // Add items
    pq.push(10);
    pq.push(5);
    pq.push(15);

    assert pq.size() == 3;
    assert pq.peek() == 5;

    // Pop in priority order
    assert pq.pop() == 5;
    assert pq.size() == 2;
    assert pq.pop() == 10;
    assert pq.pop() == 15;

    assert pq.size() == 0;
}

static void testUpdatePriority() {
    PriorityQueue<Integer> pq = new PriorityQueue<>();

    pq.push(10);
    pq.push(5);

    // Update to have higher priority
    pq.update(10, 3);
    assert pq.peek() == 3;
    assert pq.size() == 2;

    // Pop should now give updated value first
    assert pq.pop() == 3;
    assert pq.pop() == 5;
}

static void testRemove() {
    PriorityQueue<Integer> pq = new PriorityQueue<>();

    pq.push(10);
    pq.push(5);
    pq.push(15);

    // Remove middle priority task
    pq.remove(10);
    assert pq.size() == 2;
    assert !pq.contains(10);

    // Verify correct items remain
    assert pq.pop() == 5;
    assert pq.pop() == 15;
}

static void testContains() {
    PriorityQueue<Integer> pq = new PriorityQueue<>();

    pq.push(10);
    pq.push(5);

    assert pq.contains(10);
    assert pq.contains(5);
    assert !pq.contains(3);

    pq.remove(10);
    assert !pq.contains(10);
}

static void testEmptyOperations() {
    PriorityQueue<Integer> pq = new PriorityQueue<>();

    // Test peek on empty queue
    assert pq.peek() == null;
}

```

```

    // Test pop on empty queue
    try {
        pq.pop();
        assert false : "Should throw IllegalStateException";
    } catch (IllegalStateException e) {
        // Expected
    }
}

static void testRemoveNonexistent() {
    PriorityQueue<Integer> pq = new PriorityQueue<>();

    pq.push(10);

    try {
        pq.remove(999);
        assert false : "Should throw IllegalArgumentException";
    } catch (IllegalArgumentException e) {
        // Expected
    }
}

static void testSingleElement() {
    PriorityQueue<Integer> pq = new PriorityQueue<>();

    pq.push(42);
    assert pq.size() == 1;
    assert pq.peek() == 42;
    assert pq.pop() == 42;
    assert pq.size() == 0;
}

static void testDuplicatePriorities() {
    PriorityQueue<Integer> pq = new PriorityQueue<>();

    pq.push(10);
    pq.push(10);
    pq.push(10);

    assert pq.size() == 3;

    // All should pop eventually
    assert pq.pop() == 10;
    assert pq.pop() == 10;
    assert pq.pop() == 10;
}

static void testWithDoubles() {
    PriorityQueue<Double> pq = new PriorityQueue<>();

    pq.push(1.5);
    pq.push(0.5);
    pq.push(2.3);

    assert pq.pop() == 0.5;
    assert pq.pop() == 1.5;
    assert pq.pop() == 2.3;
}

public static void main(String[] args) {
    testBasicOperations();
    testUpdatePriority();
    testRemove();
    testContains();
    testEmptyOperations();
    testRemoveNonexistent();
    testSingleElement();
    testDuplicatePriorities();
    testWithDoubles();
    testMain();
    System.out.println("All tests passed!");
}

```

} }

Segment Tree

segment_tree.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);
                }
            }
        }
    }
}
```

```

        }

        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;
}

// Don't write tests below during competition.

static void testSingleElement() {
    Long[] arr = {42L};
    SegmentTree<Long> st = new SegmentTree<>(arr, 0L, (a, b) -> a + b);

    assert st.query(0, 0) == 42L;

    st.update(0, 100L);
    assert st.query(0, 0) == 100L;
}

static void testAllElements() {
    Long[] arr = {1L, 2L, 3L, 4L, 5L};
    SegmentTree<Long> st = new SegmentTree<>(arr, 0L, (a, b) -> a + b);

    assert st.query(0, 4) == 15L;
}

static void testNegativeValues() {
    Long[] arr = {-5L, 3L, -2L, 8L, -1L};
    SegmentTree<Long> st = new SegmentTree<>(arr, 0L, (a, b) -> a + b);

    assert st.query(0, 4) == 3L;
    assert st.query(1, 3) == 9L;

    st.update(2, 5L);
    assert st.query(0, 4) == 10L;
}

```

```

static void testMultipleUpdates() {
    Long[] arr = {1L, 1L, 1L, 1L, 1L};
    SegmentTree<Long> st = new SegmentTree<>(arr, 0L, (a, b) -> a + b);

    for (int i = 0; i < 5; i++) {
        st.update(i, (long) (i + 1));
    }

    assert st.query(0, 4) == 15L;
    assert st.query(2, 4) == 12L;
}

static void testLargeArray() {
    Long[] arr = new Long[1000];
    for (int i = 0; i < 1000; i++) {
        arr[i] = (long) (i + 1);
    }

    SegmentTree<Long> st = new SegmentTree<>(arr, 0L, (a, b) -> a + b);

    assert st.query(0, 999) == 500500L;
    assert st.query(0, 99) == 5050L;

    st.update(500, 1000L);
    assert st.query(500, 500) == 1000L;
}

static void testEmpty() {
    Long[] arr = {};
    SegmentTree<Long> st = new SegmentTree<>(arr, 0L, (a, b) -> a + b);
    // Empty tree should not crash
}

public static void main(String[] args) {
    testSingleElement();
    testAllElements();
    testNegativeValues();
    testMultipleUpdates();
    testLargeArray();
    testEmpty();
    testMain();
    System.out.println("All tests passed!");
}
}

```

Sprague Grundy

sprague_grundy.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;  
        }  
    }  
}
```



```

    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;
}

```

```

}

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);
}

```

```

}

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; //  $17 \oplus 23 \oplus 31 = 25$ 
    assert eng.isWinningPosition(Arrays.asList(15, 27, 36)) == true; //  $15 \oplus 27 \oplus 36 = 48 \neq 0$ 

    // 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; //  $14 \% 7 = 0 \rightarrow \text{grundy} = 0$ 
    assert eng2.grundy(15) == 1; //  $15 \% 7 = 1 \rightarrow \text{grundy} = 1$ 
    assert eng2.grundy(18) == 2; //  $18 \% 7 = 4 \rightarrow \text{grundy} = 2$ 

    // 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; //  $K(3) \oplus K(5) = 3 \oplus 4 = 7$ 
}

// Don't write tests below during competition.

public static void testNimExtended() {
    GrundyEngine<Integer> eng = new GrundyEngine<>(sprague_grundy::nimMovesSingleHeap);
    // Known: grundy(n) = n for all n in Nim
    for (int n = 0; n < 64; n++) {
        assert eng.grundy(n) == n;
    }
}

public static void testSubtractionGamePeriod() {
    // Allowed moves = {1,3,4}. Classic periodic sequence.
    GrundyEngine<Integer> eng =
        new GrundyEngine<>(subtractionGameMovesFactory(Set.of(1, 3, 4)));

    List<Integer> seq = new ArrayList<>();
    for (int n = 0; n < 200; n++) {
        seq.add(eng.grundy(n));
    }

    // For {1,3,4} the period is 7: [0,1,0,1,2,3,2] ...
    Integer p = detectPeriod(seq, 1, 50);
    assert p != null && p == 7;

    List<Integer> base = seq.subList(0, p);
    // Check repetition
    for (int i = 0; i < seq.size(); i++) {
        assert seq.get(i).equals(base.get(i % p));
    }

    // Winning N: those with grundy(n) != 0
    List<Integer> wins = new ArrayList<>();
    for (int n = 0; n < 30; n++) {
        if (seq.get(n) != 0) {
            wins.add(n);
        }
    }
    List<Integer> expected = Arrays.asList(1, 3, 4, 5, 6, 8, 10, 11, 12, 13);
    assert wins.subList(0, 10).equals(expected);
}

public static void testSumOfIndependentSubgames() {
    // Same subtraction game. Combined position = multiple independent heaps (ints).
    GrundyEngine<Integer> eng =
        new GrundyEngine<>(subtractionGameMovesFactory(Set.of(1, 3, 4)));

```

```

    // Build some positions
    List<Integer> A = Arrays.asList(5, 7); // grundy(5)=3, grundy(7)=2 → XOR=1 → winning
    List<Integer> B = Arrays.asList(8, 9); // Let's compute what g(8) and g(9) are:
    int GA = eng.grundyMulti(A);
    int GB = eng.grundyMulti(B);
    assert GA != 0;
    assert GB == (eng.grundy(8) ^ eng.grundy(9));
    assert eng.isWinningPosition(A) == true;
    assert eng.isWinningPosition(B) == (GB != 0);
}

public static void testKaylesSmall() {
    GrundyEngine<KaylesState> eng = new GrundyEngine<>(kaylesMovesFactory());

    // Known first values for K(n) (reasonably small n)
    List<Integer> vals = new ArrayList<>();
    for (int n = 0; n < 15; n++) {
        vals.add(eng.grundy(new KaylesState(new int[] {n})));
    }

    // Not trivial pattern; we check a few hand-picked facts (from direct computation):
    List<Integer> expected = Arrays.asList(0, 1, 2, 3, 1, 4, 3, 2, 1, 4);
    assert vals.subList(0, 10).equals(expected);

    // Splits: (n,) can end in (a,b) → XOR rule implicit in recursion.
    // Extra sanity: composite segments
    assert eng.grundy(new KaylesState(new int[] {2, 2}))
        == (eng.grundy(new KaylesState(new int[] {2}))
            ^ eng.grundy(new KaylesState(new int[] {2})));
}

public static void testLongApplicationScan() {
    /*
    Typical competition application:
    - Given a parameter N, derive for which N the position is winning.
    - Use period if it exists.
    Here we use subtraction game {1,3,4}.
    */
    GrundyEngine<Integer> eng =
        new GrundyEngine<>(subtractionGameMovesFactory(Set.of(1, 3, 4)));
    int N = 500;
    List<Integer> seq = new ArrayList<>();
    for (int n = 0; n <= N; n++) {
        seq.add(eng.grundy(n));
    }

    Integer period = detectPeriod(seq, 1, 100);
    assert period != null && period == 7;

    // Winning N up to 60:
    List<Integer> winningN = new ArrayList<>();
    for (int n = 0; n <= 60; n++) {
        if (seq.get(n) != 0) {
            winningN.add(n);
        }
    }

    // Spot-check the first few values
    List<Integer> expected = Arrays.asList(1, 3, 4, 5, 6, 8, 10, 11, 12, 13, 15, 17);
    assert winningN.subList(0, 12).equals(expected);
}

public static void testCycleGuardNote() {
    /*
    Theory requirement: no cycles. This test is 'meta' and documents the assumption.
    We do NOT build a cyclic moves function here; we just note the requirement.
    */
    assert true;
}

public static void test() {
    testNimExtended();
}

```

```
        testSubtractionGamePeriod();
        testSumOfIndependentSubgames();
        testKaylesSmall();
        testLongApplicationScan();
        testCycleGuardNote();
    }

    public static void main(String[] args) {
        testMain();
        test();
        System.out.println("All Sprague-Grundy tests passed!");
    }
}
```

Suffix Array

suffix_array.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--;  
                }  
            }  
        }  
    }  
}
```

```

        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));
}

// Don't write tests below during competition.

static void testEmptyString() {
    SuffixArray sa = new SuffixArray("");
    assert sa.getSA().length == 0;
    assert sa.getLCP().length == 0;
    assert sa.findPattern("a").isEmpty();
}

```

```

static void testSingleChar() {
    SuffixArray sa = new SuffixArray("a");
    assert sa.getSA().length == 1;
    assert sa.getSA()[0] == 0;
}

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

static void testPatternNotFound() {
    SuffixArray sa = new SuffixArray("hello");
    assert sa.findPattern("world").isEmpty();
}

static void testPatternAtEnd() {
    SuffixArray sa = new SuffixArray("hello");
    assert sa.findPattern("lo").equals(Arrays.asList(3));
}

static void testOverlappingPatterns() {
    SuffixArray sa = new SuffixArray("aabaabaa");
    List<Integer> positions = sa.findPattern("aa");
    Collections.sort(positions);
    assert positions.equals(Arrays.asList(0, 3, 6));
}

static void testEntireString() {
    String text = "programming";
    SuffixArray sa = new SuffixArray(text);
    assert sa.findPattern(text).equals(Arrays.asList(0));
}

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

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

static void testPalindrome() {
    SuffixArray sa = new SuffixArray("racecar");
    List<Integer> positions = sa.findPattern("r");
    Collections.sort(positions);
    assert positions.equals(Arrays.asList(0, 6));
}

static void testLongPattern() {
    String text = "thequickbrownfoxjumpsoverthelazydog";
    SuffixArray sa = new SuffixArray(text);
    assert sa.findPattern("jumps").equals(Arrays.asList(16));
    List<Integer> thePos = sa.findPattern("the");
    Collections.sort(thePos);
    assert thePos.equals(Arrays.asList(0, 25));
}

public static void main(String[] args) {
    testMain();
    testEmptyString();
    testSingleChar();
}

```



```
        testRepeatedChars();
        testPatternNotFound();
        testPatternAtEnd();
        testOverlappingPatterns();
        testEntireString();
        testLCPCalculation();
        testAllUniqueChars();
        testPalindrome();
        testLongPattern();
        System.out.println("All tests passed!");
    }
}
```

Topological Sort

topological_sort.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
            }
        }
    }
}
```

```

        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);
                    }
                }
            }
        }
    }

```

```

    }

    // 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();
}

// Don't write tests below during competition.

static void testSimpleDAG() {
    TopologicalSort ts = new TopologicalSort(4);
    ts.addEdge(0, 1);
    ts.addEdge(0, 2);
    ts.addEdge(1, 3);
    ts.addEdge(2, 3);

    List<Integer> result = ts.kahnSort();
    assert result != null;
    assert result.get(0) == 0;
    assert result.get(3) == 3;
}

static void testCycle() {
    TopologicalSort ts = new TopologicalSort(3);
    ts.addEdge(0, 1);
    ts.addEdge(1, 2);
    ts.addEdge(2, 0);
}

```

```

    assert ts.kahnSort() == null;
    assert ts.dfsSort() == null;
    assert ts.hasCycle();
}

static void testSingleVertex() {
    TopologicalSort ts = new TopologicalSort(1);
    List<Integer> result = ts.kahnSort();
    assert result != null;
    assert result.equals(Arrays.asList(0));
}

static void testDisconnected() {
    TopologicalSort ts = new TopologicalSort(4);
    ts.addEdge(0, 1);
    ts.addEdge(2, 3);

    List<Integer> result = ts.kahnSort();
    assert result != null;
    assert result.size() == 4;
}

static void testLongestPath() {
    TopologicalSort ts = new TopologicalSort(6);
    ts.addEdge(0, 1);
    ts.addEdge(0, 2);
    ts.addEdge(1, 3);
    ts.addEdge(2, 3);
    ts.addEdge(3, 4);
    ts.addEdge(3, 5);

    List<Integer> path = ts.longestPath(0);
    assert path != null;
    assert path.get(0) == 0;
    assert path.size() >= 3;
}

static void testSelfLoop() {
    TopologicalSort ts = new TopologicalSort(2);
    ts.addEdge(0, 0);

    assert ts.kahnSort() == null;
    assert ts.hasCycle();
}

public static void main(String[] args) {
    testSimpleDAG();
    testCycle();
    testSingleVertex();
    testDisconnected();
    testLongestPath();
    testSelfLoop();
    testMain();
    System.out.println("All tests passed!");
}
}

```

Two Sat

two_sat.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  $\neg x$ , and clause  $(a \text{ OR } b)$  creates edges  $\neg a \rightarrow b$   
and  $\neg b \rightarrow a$ .
```

Key operations:

- addClause(a, aNeg, b, bNeg): Add clause $(a \text{ OR } b)$
- 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++;  
                }  
            }  
        }  
    }  
}
```

```

    }
}

// 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];
}

// Don't write tests below during competition.

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

    boolean[] result = sat.solve();
    assert result == null;
}

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

    boolean[] result = sat.solve();
    assert result != null;
}

```

```

    assert result[0];
}

static void testImplicationChain() {
    TwoSAT sat = new TwoSAT(4);
    sat.addClause(0, true, 1, false);
    sat.addClause(1, true, 2, false);
    sat.addClause(2, true, 3, false);

    boolean[] result = sat.solve();
    assert result != null;
    if (result[0]) assert result[1];
    if (result[1]) assert result[2];
    if (result[2]) assert result[3];
}

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

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

static void testLargeSatisfiable() {
    TwoSAT sat = new TwoSAT(10);
    for (int i = 0; i < 9; i++) {
        sat.addClause(i, false, i + 1, false);
    }

    boolean[] result = sat.solve();
    assert result != null;
    for (int i = 0; i < 9; i++) {
        assert result[i] || result[i + 1];
    }
}

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

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

static void testComplexSystem() {
    TwoSAT sat = new TwoSAT(5);
    sat.addClause(0, false, 1, false);
    sat.addClause(1, true, 2, false);
    sat.addClause(2, true, 3, true);
    sat.addClause(3, false, 4, false);
    sat.addClause(4, true, 0, true);

    boolean[] result = sat.solve();
    assert result != null;
    assert result[0] || result[1];
    assert !result[1] || result[2];
    assert !result[2] || !result[3];
    assert result[3] || result[4];
    assert !result[4] || !result[0];
}

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

    boolean[] result = sat.solve();

```



```
    assert result != null;
    assert (result[0] && !result[1]) || (!result[0] && result[1]);
}

public static void main(String[] args) {
    testMain();
    testUnsatisfiable();
    testSingleVariable();
    testImplicationChain();
    testMutualImplication();
    testLargeSatisfiable();
    testContradictoryImplications();
    testComplexSystem();
    testXorConstraint();
    System.out.println("All tests passed!");
}
}
```

Union Find

union_find.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` - $O(\alpha(n))$ amortized
- `union(x, y)`: Merge the sets containing `x` and `y` - $O(\alpha(n))$ amortized
- `connected(x, y)`: Check if `x` and `y` are in the same set - $O(\alpha(n))$ amortized

Space complexity: $O(n)$

$\alpha(n)$ 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  
        }  
    }  
}
```

```

}

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;
}

// Don't write tests below during competition.

static void testSingleElement() {
    Test uf = new Test(1);
    assert uf.find(0) == 0;
    assert uf.getSize(0) == 1;
}

static void testUnionSameSet() {
    Test uf = new Test(2);
    uf.union(0, 1);
    // Unioning again should be safe
    int root = uf.union(0, 1);
    assert uf.find(0) == uf.find(1);
    assert uf.getSize(root) == 2;
}

static void testMultipleUnions() {
    Test uf = new Test(10);
    // Chain union: 0-1-2-3-4-5-6-7-8-9
    for (int i = 0; i < 9; i++) {
        uf.union(i, i + 1);
    }

    // All should have same root
    int root = uf.find(0);
    for (int i = 0; i < 10; i++) {
        assert uf.find(i) == root;
    }

    assert uf.getSize(root) == 10;
}

static void testUnionOrderIndependence() {
    // Test that union order doesn't affect final result
    Test uf1 = new Test(3);
    uf1.union(0, 1);
    uf1.union(1, 2);
    int root1 = uf1.find(0);

    Test uf2 = new Test(3);

```

```

    uf2.union(2, 1);
    uf2.union(1, 0);
    int root2 = uf2.find(0);

    assert uf1.getSize(root1) == uf2.getSize(root2);
    assert uf1.getSize(root1) == 3;
}

```

```

static void testDisconnectedSets() {
    Test uf = new Test(4);

    uf.union(0, 1);
    uf.union(2, 3);

    assert uf.connected(0, 1);
    assert uf.connected(2, 3);
    assert !uf.connected(0, 2);

    assert uf.getSize(uf.find(0)) == 2;
    assert uf.getSize(uf.find(2)) == 2;
}

```

```

static void testLargeSet() {
    Test uf = new Test(100);

    // Union in pairs
    for (int i = 0; i < 100; i += 2) {
        uf.union(i, i + 1);
    }

    // Now we have 50 sets of size 2
    int uniqueRoots = 0;
    boolean[] seenRoots = new boolean[100];
    for (int i = 0; i < 100; i++) {
        int root = uf.find(i);
        if (!seenRoots[root]) {
            seenRoots[root] = true;
            uniqueRoots++;
        }
    }
    assert uniqueRoots == 50;

    // Union all pairs together
    for (int i = 0; i < 100; i += 4) {
        if (i + 2 < 100) {
            uf.union(i, i + 2);
        }
    }

    // Now we have 25 sets of size 4
    uniqueRoots = 0;
    seenRoots = new boolean[100];
    for (int i = 0; i < 100; i++) {
        int root = uf.find(i);
        if (!seenRoots[root]) {
            seenRoots[root] = true;
            uniqueRoots++;
        }
    }
    assert uniqueRoots == 25;
}

```

```

public static void main(String[] args) {
    testSingleElement();
    testUnionSameSet();
    testMultipleUnions();
    testUnionOrderIndependence();
    testDisconnectedSets();
    testLargeSet();
    testMain();
    System.out.println("All tests passed!");
}

```

} }