Notes:

- Many of the algorithms below can be accomplished by either modifying the graph and applying a known algorithm or slightly modifying a known algorithm. Try thinking of these first as they will save you a lot of work, and writing :) I don’t expect long answers, but be precise.

- You will be graded on efficiency!

- If not specified in the problem, you may assume whatever graph representation makes your algorithm more efficient (adjacency list or adjacency matrix). State which one you are using.
1. **[5 points]** Write pseudocode for an algorithm which, given an undirected graph $G$ and a particular edge $e$ in it, determines whether $G$ has a cycle containing $e$. What is the runtime of this algorithm?

2. **[8 points]** Often there are multiple shortest paths between nodes of a graph. Write pseudocode for an algorithm that given an undirected, unweighted graph $G$ and nodes $u, v \in V$, outputs the number of distinct shortest paths from $u$ to $v$. What is the running time?

3. **[5 points]** Given a directed graph $G = (V, E)$ with positive edge weights and a particular node $v_i \in V$, give an efficient algorithm for finding the shortest paths between all pairs of nodes, with the one restriction that these paths must all pass through $v_i$. Give the runtime of your algorithm. Points will be deducted for an inefficient algorithm.

   *Hint:* Look at how we determined if a graph was strongly connected.

4. **[5 points]** If a graph does not have a negative cycle, when calculating the shortest paths from a given vertex using the Bellman-Ford algorithm, we can stop early and do not need to do all $|V| - 1$ iterations and will still have a correct answer for all the shortest paths from that vertex. Describe how to modify the Bellman-Ford algorithm to stop early when all of the distances are already correct.

5. **[6 points]** Given an undirected graph $G$ with nonnegative edge weights $w_e \geq 0$. Suppose you have calculated the minimum spanning tree of $G$ and also the shortest paths to all nodes from a particular node $s \in V$. Now, suppose that each edge weight is increased by 1, i.e. the new weights are $w'_e = w_e + 1$.

   (a) **(3 points)** Does the minimum spanning tree change? Give an example where it does or prove that it cannot change.

   (b) **(3 points)** Do the shortest paths from $s$ change? Given an example where it does or prove that it cannot change.