INSTRUCTIONS: Be clear and concise. Write your answers in the space provided. Use the backs of pages, and/or the scratch page at the end, for your scratchwork. All graphs are assumed to be simple. Good luck!

You may freely use or cite the following subroutines from class:

- **explore**\((G, s)\)
  This returns three arrays of size \(|V|\): \texttt{pre}, \texttt{post}, and \texttt{visited}.

- **dfs**\((G)\)
  This returns three arrays of size \(|V|\): \texttt{pre}, \texttt{post}, and \texttt{cc}. If the graph has \(k\) connected components, then the \texttt{cc} array assigns each node a number in the range 1 to \(k\).

- **scc**\((G)\)
  This returns an array \texttt{scc} of size \(|V|\). If the graph has \(k\) strongly connected components, then the \texttt{scc} array assigns each node a number in the range 1 to \(k\).

- **bfs**\((G, s)\), **dijkstra**\((G, \ell, s)\), **bellman-ford**\((G, \ell, s)\)
  These all return two arrays of size \(|V|\): \texttt{dist} and \texttt{prev}.

- **dag-sp**\((G, \ell, s)\)
  This returns two arrays of size \(|V|\): \texttt{dist} and \texttt{prev}. The array \texttt{dist} contains the shortest paths from \(s\) to all other reachable nodes in \(G\). The algorithm is similar to **dag-lp** which instead returns the longest paths. These only work on directed acyclic graphs with and without negative edges.

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1^We recall from class/text the following time complexities. (1) **dfs/explore**: \(O(|V| + |E|)\). (2) **scc**: \(O(|V| + |E|)\). (3) **bfs**: \(O(|V| + |E|)\). (4) **dijkstra**: \(O((|V| + |E|) \log |V|)\) assuming a simple binary heap implementation of the priority queue. (5) **bellman-ford**: \(O(|V| \cdot |E|)\) (6) **dag-sp**: \(O(|V| + |E|)\).
1. (10 points) For the directed graph below with non-negative edges, list the order in which nodes are processed by each of the following algorithms. Start all algorithms from node A and ignore edge lengths if they are not commonly used by an algorithm (e.g., \texttt{dfs}). Break any ties alphabetically (alphabetically-lowest first).

![Graph Diagram]

- \texttt{dfs}
- \texttt{bfs}
- \texttt{dijkstra}
- \texttt{dag-sp}
2. **Short answer.** For true/false questions state whether the claim is true or false. If true, give a brief justification. If false, justify by providing a counterexample. *No points will be given for simply writing “true” or “false” without any justification!*

(a) (2 1/2 points) The running-time of a divide-and-conquer algorithm is characterized by the following recurrence: \( T(n) = 4T(n/2) + \log n \). Provide a tight big-O bound for the running-time of this algorithm.

(b) (2 1/2 points) True/False: For any directed graph \( G = (V, E) \) if all edge lengths are distinct (no two edge lengths are the same) then the shortest path between two nodes \( s \) and \( t \) is unique.
(c) (2 1/2 points) True/False: Given two nodes $s, t$, the shortest (simple) cycle containing $s$ and $t$ must also contain a shortest $s$-$t$ path.

(d) (2 1/2 points) True/False: Given a directed graph $G = (V, E)$ and node $s \in G$, with all nodes in $V$ reachable from $s$. We run the Bellman-Ford algorithm in $G$, starting from node $s$, and the stored $\text{dist}$ values do not change from the $(|V|/2 - 1)^{st}$ iteration to the $(|V|/2)^{st}$ iteration. Then, $G$ cannot have any negative cycles.
3. (10 points) You are given a nonempty array $A$ with $n$ distinct integer-valued elements. The values in the array increase monotonically from $A_1$ to an element $A_i$, and then decrease monotonically from $A_i$ to $A_n$. The element $A_i$ is called the *peak* element of $A$. In other words:

$$A_1 < A_2 < \ldots < A_i > A_{i+1} > A_{i+2} > \ldots > A_n$$

In the following example the *peak* element is $A_4 = 5$:

$$[-7, -1, 4, 5, 2, 0, -10, -23]$$

Design a divide-and-conquer algorithm to find the *peak* element $A_i$. Briefly explain your algorithm, give a recurrence characterizing its time complexity, apply the master theorem to provide a big-$O$ running-time, and provide pseudo-code.
4. Given a connected, directed graph $G = (V, E)$, we say that $v \in V$ is a root node in $G$ if, for all $u \in V, u \neq v$, there exists a directed $v$-$u$ path in $G$.

(a) (2 points) Give an example with no more than four (4) nodes of a connected, directed acyclic graph (DAG) with no root node.

(b) (4 points) Suppose that you are given a connected, directed graph $G$ and a known root node $r$. Give an efficient algorithm to find all other root nodes in $G$. (Possibly useful observation: if there is a directed path in $G$ from a node $u$ to $r$, then $u$ is also a root node.) Briefly explain and justify your algorithm, analyze the time complexity, and provide pseudo-code.
(c) (4 points) Suppose that you are given a connected, directed graph $G$ that may or may not have any root nodes. Explain (with pseudo-code if you wish) how to determine all of $G$’s root nodes, or indicate that no root nodes exist, in time $O(|V| + |E|)$. Clearly state any algorithms from class that you use in your solution.