

# CSL-531: Dynamic Graph Algorithms

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Notes for the course *Dynamic Graph Algorithms* instructed  
by Dr. Shahbaz Khan at IIT Roorkee, Spring, 2026.

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This course will be graded through the following components:

- **MTE:** 30%
- **CWS:** 30%
- **ETE:** 40%

Both the MTE and the ETE will be written examinations. The CWS component will be based on announced quizzes, tutorial session and a course project. The goal of the course is:

1. to be able to **Design** dynamic graph algorithms using standard design techniques and **prove** its correctness.
2. to be able to **Analyze** dynamic graph algorithms using standard analysis techniques and **prove** its tightness.
3. to be able to **Prove** the hardness of a given dynamic graph problem by **reducing** it to a standard hard problem.

## 1.1 Introduction to Dynamic Graph Algorithms

**Definition 1.1. Dynamic Graphs** are graphs that *change* with time. A *change* in a graph refers to **graph updates**, that are *online* sequences of insertion or deletion of edges or vertices.

Therefore we can model a dynamic graph as a sequence of updates on a static graph. Formally, we can view this as

$$G_0 \xrightarrow{\Delta_1} G_1 \xrightarrow{\Delta_2} G_2 \xrightarrow{\Delta_3} \dots$$

where each  $\Delta_i$  is an update to the graph. Suppose we are interested in computing some quantity  $\mathcal{X}$  of the graph  $G$  for which there exists a known static graph algorithm **X**. Upon each update  $\Delta_i$  to  $G$ , we can trivially compute  $\mathcal{X}$  for the new graph  $G'$  by updating  $G$  and running **X** on it. The goal of a **dynamic graph algorithm** is to reuse previous computations to update the quantity  $\mathcal{X}$  *much faster* than a static graph algorithm.

Most graphs in real world are dynamic. The sizes of parameters for these graphs are significantly large and thus, recomputing solutions on such graphs from scratch is impractical. This motivates us to look for dynamic variants of static graph algorithms. However, we are only interested in dynamic graph algorithms that perform *better* than the best static graph algorithms that exist for the problem.

## 1.2 Classification of DGAs

Dynamic Graph Algorithms (DGAs) can be classified into

1. **Incremental** (only insertions)
2. **Decremental** (only deletions)
3. **Fully Dynamic** (both insertions and deletions)

It is worth mentioning that in case of weighted graphs, we might want to consider incrementing and decrementing the weights as graph updates too. However, any increment or decrement to the weight of an edge could be modelled as a deletion followed by an insertion. Therefore, we limit the definition of graph updates to

**Definition 1.2.** A dynamic graph  $G(V, E)$  supports the following **graph updates**

- Insertion of edges
- Deletion of edges
- Insertion of vertices
- Deletion of vertices

To analyse the performance of algorithms, we need to equip ourselves with some theory on time complexity analysis.

### 1.3 Time Complexity Analysis

Some key notations on time complexities.

**Definition 1.3.** For functions  $f$  and  $g$ , we have

1.  $f(n) = \mathcal{O}(g(n))$ , if there exists positive real numbers  $M$  and  $n_0$  such that,

$$|f(n)| \leq Mg(n), \quad \forall n \geq n_0$$

2.  $f(n) = o(g(n))$ , if for every positive real number  $M$ , there exists  $n_0$  such that,

$$|f(n)| \leq Mg(n), \quad \forall n \geq n_0$$

3.  $f(n) = \Omega(g(n))$ , if there exists positive real numbers  $M$  and  $n_0$  such that,

$$|f(n)| \geq Mg(n), \quad \forall n \geq n_0$$

4.  $f(n) = \omega(g(n))$ , if for every positive real number  $M$ , there exists  $n_0$  such that,

$$|f(n)| \geq Mg(n), \quad \forall n \geq n_0$$

5.  $f(n) = \Theta(g(n))$ , if there exists positive real numbers  $M_1, M_2$  and  $n_0$  such that,

$$M_1g(n) \leq |f(n)| \leq M_2g(n), \quad \forall n \geq n_0$$

A common way to establish a tight bound while analysing an algorithm is to find a worst-case example, which helps us establish a lower bound. In dynamic graphs, we commonly deal with the following.

1. **Preprocessing Time:** Initial time to preprocess the graph.
2. **Update Time:** Time taken after each update to reconstruct the data structure.
3. **Query Time:** Time taken to answer query on the updated structure.

## 1.4 Update-Query Tradeoff

There is often a trade-off between how fast updates are processed with how fast queries can be answered. Suppose a static algorithm has time complexity  $\mathcal{O}(T)$ . The extremes of the update-query tradeoff occur when we adopt the following approaches.

- **Eager Approach**

- $\mathcal{O}(T)$  update time.
- $\mathcal{O}(1)$  query time.

- **Lazy Approach**

- $\mathcal{O}(1)$  update time.
- $\mathcal{O}(T)$  query time.

The above approaches are feasible when queries are more frequent, and when updates are more frequent, respectively. Usually when we design an algorithm, we aim to find a sweet spot between these extremes depending on the constraints and requirements of the problem. At times, even when the worst-case bound is proven to be tight, improving the amortized bound is still considered an improvement.

### Example 1.4

DSU (**Disjoin Set Union**) is a popular example of a dynamic graph algorithm. It supports two operations, **Join** and **Find**, both of which achieve an amortized time complexity of  $\mathcal{O}(\alpha(n))$ . Here,  $\alpha(n)$  is the **inverse ackermann function**. Suppose we consider an incremental dynamic graph model that has  $m$  edge updates. One might think that the total time complexity of this algorithm would be  $\mathcal{O}(m\alpha(n))$ . However, we can only have  $n - 1$  edges in the final graph. Therefore, the total time complexity must be  $\mathcal{O}(n\alpha(n))$  and the amortized time complexity achieved per update is

$$\mathcal{O}\left(\frac{n\alpha(n)}{m}\right)$$

## 1.5 Time Complexity Bounds

So far, we have given an informal discussion of the ideal performance of a dynamic algorithm. Now we consider various scenarios and analyse them in detail.

Consider a problem  $\mathcal{P}$  having a best static algorithm  $T_s(n)$ . Now consider a dynamic algorithm  $T_d(n)$  for the problem  $\mathcal{P}$ .

### 1.5.1 Upper Bound on $T_d(n)$

Since we cannot have  $T_d(n)$  perform worse than  $T_s(n)$ , therefore

$$T_d(n) = \mathcal{O}(T_s(n))$$

### 1.5.2 Lower Bound on $T_d(n)$

1. If  $T_d(n)$  is an incremental algorithm, then consider a graph with size  $\mathcal{O}(n)$  constructed with  $m$  incremental updates. Applying  $T_d(n)$  at every incremental update and summing up, we get

$$mT_d(n) = \Omega(T_s(n)) \implies T_d(n) = \Omega\left(\frac{T_s(n)}{m}\right)$$

2. If  $T_d(n)$  is a decremental algorithm
3. If  $T_d(n)$  is fully dynamic

**Question 1.5.** Think about the lower bound on  $T_d(n)$  in the case of a decremental, and fully dynamic algorithm.

**Question 1.6.** Does there exist a dynamic algorithm for an **NP-hard** problem that lies in **P**?

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In this lecture, we elaborate on our discussion of the lower bounds of  $T_d(n)$ .

Here is the premise of our discussion. Given a problem  $\mathcal{P}$  and the best known static algorithm to solve  $\mathcal{P}$  called  $T_s(n)$ , we wish to analyse the time complexity of a dynamic algorithm  $T_d(n)$  for solving  $\mathcal{P}$ .

**Lemma 2.1 (Upper Bound on  $T_d(n)$ )**

For any problem  $\mathcal{P}$ , it always holds that

$$T_d(n) = \mathcal{O}(T_s(n))$$

*Proof.* If the time complexity of the dynamic algorithm  $T_d(n)$  exceeds that of the static algorithm  $T_s(n)$ , then there is no use in developing the dynamic algorithm. In such a case, one could simply use  $T_s(n)$  to recompute the desired quantity after every update.  $\square$

## 2.1 $T_d(n)$ is Incremental

Suppose  $T_d(n)$  is an incremental dynamic algorithm for  $\mathcal{P}$ , meaning that  $T_d(n)$  only supports incremental updates. We consider the following two types of incremental updates.

### 2.1.1 Edge Updates

Let  $G(n, m)$  be a graph on  $n$  vertices and  $m$  edges. We would like to analyse the bounds on  $T_d(n)$  when considering **edge insertions** to  $G$ .

1. *Upper Bound.* By **lemma 2.1**, we immediately obtain an upper bound on  $T_d(n)$  given by

$$T_d(n) = \mathcal{O}(T_s(n))$$

2. *Lower Bound.* Consider a graph with  $n$  vertices and no edges. Constructing this graph takes  $\mathcal{O}(1)$  time, and we assume that computing  $\mathcal{P}$  on this graph also takes  $\mathcal{O}(1)$  time. To obtain the target graph  $G$ , we must perform  $m$  edge insertions. Applying the dynamic algorithm  $T_d(n)$  after each edge update yields a valid *static* algorithm to compute  $\mathcal{P}$ . Since  $T_s(n)$  is the best known algorithm for static computation of  $\mathcal{P}$  on  $G$ , therefore we must have

$$\mathcal{O}(1) + mT_d(n) = \Omega(T_s(n))$$

which implies

$$T_d(n) = \Omega\left(\frac{T_s(n)}{m}\right)$$

### 2.1.2 Vertex Updates

Let  $G(n, m)$  be a graph on  $n$  vertices and  $m$  edges. Now we would like to analyse the bounds on  $T_d(n)$  when considering **vertex insertions** to  $G$ .

1. *Upper Bound.* By [lemma 2.1](#), we have

$$\boxed{T_d(n) = \mathcal{O}(T_s(n))}$$

2. *Lower Bound.* If each update on  $G$  inserts a singleton vertex *without* any edges, then assuming that no nontrivial recomputation is required for  $\mathcal{P}$ , we obtain the lower bound

$$\boxed{T_d(n) = \Omega(1)}$$

If instead, each update on  $G$  adds a singleton vertex *with* edges, then computing the lower bound for  $T_d(n)$  in a similar fashion to that for [edge insertions](#), we obtain

$$\mathcal{O}(1) + nT_d(n) = \Omega(T_s(n))$$

which implies

$$\boxed{T_d(n) = \Omega\left(\frac{T_s(n)}{n}\right)}$$

## 2.2 $T_d(n)$ is Decremental

We now assume that  $T_d(n)$  is a decremental algorithm for  $\mathcal{P}$ . We first want to solve the problem on a trivial case and then apply a sequence of graph updates to obtain the given graph.

For incremental algorithms, we started with an empty graph. Similarly, for decremental algorithms, we would require a graph from which we could perform a sequence of decremental graph updates and obtain the given graph. A **complete graph** is a suitable choice since, every graph on  $n$  vertices is a subgraph of the complete graph on  $n$  vertices.

Suppose that we can solve  $\mathcal{P}$  on a complete graph trivially, in  $\mathcal{O}(1)$  time. If the update operation consists of **edge deletions**, then constructing the complete graph requires  $\mathcal{O}(n^2)$  time, and we would require  $\mathcal{O}(n^2)$  edge deletions to transform it to  $G$ . This implies that

$$\mathcal{O}(n^2) + \mathcal{O}(n^2)T_d(n) = \Omega(T_s(n))$$

From here, we can derive lower bounds on  $T_d(n)$  depending upon  $T_s(n)$ . For example,

$$T_s(n) = \mathcal{O}(n^2) \implies T_d(n) = \Omega(1)$$

and,

$$T_s(n) = \omega(n^2) \implies T_d(n) = \Omega\left(\frac{T_s(n)}{n^2}\right)$$

However, solving  $\mathcal{P}$  on a complete graph is not always trivial. For example, the **Traveling Salesman Problem** is exponential on a complete graph. Hence, a general treatment of the time complexity of decremental algorithms is difficult, and we instead analyse specific problems to obtain more meaningful bounds.

### 2.2.1 Decremental MST (Minimum Spanning Tree)

Let  $T_d(n)$  be a decremental algorithm for computing the **Minimum Spanning Tree** of a graph  $G$  on  $n$  vertices, and let  $T_s(n)$  be the best known static algorithm to compute the MST.

**Definition 2.2.** The **Minimum Spanning Tree** of a connected, weighted, undirected graph  $G$  is a subset of edges that connects all the vertices of  $G$  and has the minimum sum of weights.

Suppose we consider **edge deletions** for our algorithm. We could obtain a lower bound on  $T_d(n)$  by the following method. Introduce a dummy vertex  $v'$  and connect it to every vertex  $v \in G$  with edges of extremely small weights. Let the resulting graph be  $G'$ . To construct  $G'$  from  $G$ , we require  $\mathcal{O}(n)$  time. The minimum spanning tree of  $G'$  is trivial because it contains all the edges connecting  $v'$ . Deleting these  $n$  edges recovers  $G$ , and we obtain

$$\mathcal{O}(n) + nT_d(n) = \Omega(T_s(n))$$

and hence

$$T_d(n) = \Omega\left(\frac{T_s(n)}{n}\right)$$

If instead we considered **vertex deletions** for our algorithm, then

$$\mathcal{O}(n) + T_d(n) = \Omega(T_s(n))$$

which implies

$$T_d(n) = \Omega(T_s(n))$$

Using **lemma 2.1**, we obtain

$$T_d(n) = \Theta(T_s(n))$$

This tells us that we have a tight bound and there is no asymptotic benefit in designing a decremental algorithm for computing the MST that supports only vertex deletions.

### 2.2.2 Decremental BFS Tree

Let  $T_d(n)$  be a decremental algorithm to compute the **BFS Tree** on a graph  $G$  with  $n$  vertices, and  $T_s(n)$  be the best known static algorithm to compute the BFS Tree.



**Definition 2.3.** The **BFS Tree** of an unweighted graph  $G$  is the spanning tree produced by running the BFS algorithm on  $G$ .

Let's say we allow **edge deletions**. Observe that we can trivially compute the BFS Tree on a complete graph in  $\mathcal{O}(n)$  time. Hence, we could add dummy edges to  $G$  to transform it to a complete graph on  $n$  vertices in  $\mathcal{O}(n^2)$  time. Moreover, we require  $\mathcal{O}(n^2)$  edge deletions to transform the complete graph back to  $G$ . Therefore

$$\mathcal{O}(n^2) + \mathcal{O}(n^2)T_d(n) = \Omega(T_s(n))$$

and hence

$$T_d(n) = \Omega\left(\frac{T_s(n)}{n^2}\right)$$

### 2.2.3 Decremental Traveling Salesman Problem

Let  $T_d(n)$  be a decremental algorithm to compute the **Traveling Salesman Problem** on a graph  $G$  with  $n$  vertices, and  $T_s(n)$  be the best known algorithm to compute this problem.

**Definition 2.4.** Given a complete, weighted, undirected graph  $G$  and a source vertex  $s$ , the **Traveling Salesman Problem** asks for a minimum weight cycle starting and ending on  $s$  that visits all the vertices in graph  $G$ , exactly once.

Suppose we allow **vertex deletions** for our algorithm. Add  $n$  dummy vertices to the graph  $G$  and for each dummy vertex  $v$ , connect all the vertices in  $G$  to  $v$  with extremely small weights. Let the resulting graph be  $G'$ . In this graph, computing the minimum weight cycle that visits all the vertices is trivial. It is just a cycle that alternates between each vertex of  $G$  and the dummy vertices. Constructing  $G'$  takes  $\mathcal{O}(n^2)$  time, and computing the minimum weight cycle requires  $\mathcal{O}(n)$  time. Further, we require  $n$  vertex deletions to transform  $G'$  to  $G$ . Hence

$$\mathcal{O}(n^2) + nT_d(n) = \Omega(T_s(n))$$

and therefore

$$T_d(n) = \Omega\left(\frac{T_s(n)}{n}\right)$$

If instead we allow **edge deletions** for our algorithm, then we would have to relax the constraint on the Traveling Salesman Problem for  $G$  to be a complete graph, so that every edge deletion results in valid subproblem. We construct graph  $G'$  again, but in this case we require  $\mathcal{O}(n^2)$  edge deletions to transform  $G'$  to  $G$ . Therefore

$$\mathcal{O}(n^2) + \mathcal{O}(n^2)T_d(n) = \Omega(T_s(n))$$

and hence

$$T_d(n) = \Omega\left(\frac{T_s(n)}{n^2}\right)$$

### 2.3 $T_d(n)$ is Fully Dynamic

For fully dynamic algorithms, it is difficult to make general statements. However, since incremental and decremental algorithms are special cases of fully dynamic algorithms, any lower bound for these special cases also yields a (possibly weaker) lower bound for fully dynamic algorithms.

**Remark 2.5** — There cannot exist a polynomial time dynamic algorithm for an **NP-hard** problem, because if such an algorithm existed then we could apply it in an incremental fashion to obtain a polynomial time static algorithm to solve the problem, contradicting NP-hardness.

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We begin our discussion with some general comments on *hardness* of problems.

**Lemma 3.1**

The **fully dynamic version** of a problem is at least as hard as the **partially dynamic version**.

*Proof.* Suppose there exists a problem  $\mathcal{P}$  for which the partially dynamic version is *harder* than the fully dynamic version. Consider an algorithm  $A$  that solves the problem  $\mathcal{P}$  in the fully dynamic version. Then the same algorithm can be used to solve the problem in the partially dynamic version with equal efficiency. This is because the fully dynamic version of  $\mathcal{P}$  allows all types of updates. If we were to restrict the sequence of updates to only increments or decrements, we would have the partially dynamic version. This contradicts our assumption that the partially dynamic version is harder than the fully dynamic version.  $\square$

**Lemma 3.2**

A problem  $\mathcal{P}$  on **directed graphs** is at least as hard as if it were on **undirected graphs**.

*Proof.* An undirected graph can be modelled as a directed graph by replacing each of its undirected edge  $e(u, v)$  by two directed edges  $d(u, v)$  and  $d(v, u)$ . Therefore, an algorithm  $A$  that solves  $\mathcal{P}$  on directed graphs can also be used to solve  $\mathcal{P}$  on undirected graphs. Hence, the problem  $\mathcal{P}$  on directed graphs is at least as hard as it is on undirected graphs.  $\square$

**Lemma 3.3**

If  $T_1$  and  $T_2$  are the **amortized** and **worst-case** time complexities of a problem  $\mathcal{P}$ , then

$$T_1 \leq T_2$$

*Proof.* This follows from

$$T_1 = \frac{\text{Total Time}}{\# \text{Updates}} \leq \frac{T_2 \times \# \text{Updates}}{\# \text{Updates}} = T_2$$

$\square$

We now discuss the classic **single source reachability problem**, which is defined on directed graphs and asks if there exists a path from node  $s$  to  $t$  in a directed graph  $G$ . The undirected version of this problem is called the **connectivity problem**. We

are interested in designing an incremental algorithm for the single source reachability problem.

### 3.1 Static Single Source Reachability

Consider the *static single source reachability problem*.

#### **Problem 3.1** (Static Single Source Reachability)

Given a directed graph  $G(V, E)$  and a source vertex  $s \in V$ , design an algorithm to determine which vertices are reachable from  $s$ .

This problem can be solved using either a **depth first search** (DFS) or a **breadth first search** (BFS) traversal starting from  $s$ , which computes a **reachability tree**  $T$  rooted at  $s$ . We maintain an array  $R$  of size  $n = |V|$ , where

$$R[u] = \begin{cases} 1, & \text{if } u \text{ is reachable from } s \\ 0, & \text{otherwise} \end{cases}$$

Initially, all entries of  $R$  are set to 0. After computing the reachability tree  $T$ , we set  $R[u] = 1$  for every vertex  $u \in T$ . Subsequently, **reachability queries** can be answered in constant time by checking if  $R[u] = 1$ .

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#### **Algorithm 1** Static Single Source Reachability

---

**Require:** Graph  $G(V, E)$ , source vertex  $s \in V$

**Ensure:** Array  $R$  where  $R[u] = 1$  if and only if  $u$  is *reachable* from  $s$

```

1: for all  $u \in V$  do
2:    $R[u] \leftarrow 0$ 
3: end for
4: Run DFS or BFS from  $s$ , obtaining a reachability tree  $T$ 
5: for all  $u \in T$  do
6:    $R[u] \leftarrow 1$ 
7: end for
8: return  $R$ 

```

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#### **Algorithm 2** Reachability Query

---

**Require:** Array  $R$ , vertex  $u$

**Ensure:** **true** if  $u$  is *reachable* from  $s$ , otherwise **false**

```

1: if  $R[u] = 1$  then
2:   return true
3: else
4:   return false
5: end if

```

---

**Remark 3.4** — Since we use a DFS/BFS, it takes  $O(n + m)$  time for the algorithm to complete and each reachability query can be answered in  $O(1)$  time. The algorithm uses  $O(n)$  additional space for the array  $R$ .

## 3.2 Incremental Single Source Reachability

We now consider the *incremental* version of the problem.

### Problem 3.2 (Incremental Single Source Reachability)

Given a directed graph  $G(V, E)$  having  $n$  vertices and  $m$  edges with a source vertex  $s \in V$ , design an **incremental algorithm** that computes all vertices reachable from  $s$  under edge insertions to  $G$ .

We are interested in maintaining the set of vertices reachable from the source vertex  $s$ , under edge insertions to the directed graph  $G$ . We begin with a few definitions before designing an algorithm for the problem.

### 3.2.1 Definitions

**Definition 3.5.** Let  $G(V, E)$  be a directed graph. Then we use  $\rightsquigarrow$  to denote that there exists a directed path from  $u$  to  $v$  in  $G$  and this is defined as the *reachability relation*. A vertex  $u$  is said to be *reachable* from  $s$  in  $G$ , if  $s \rightsquigarrow u$ . Similarly, a vertex  $u$  is said to be *unreachable* from  $s$  in  $G$ , if there does not exist a path from  $s$  to  $u$ .

**Definition 3.6.** Let  $G(V, E)$  be a directed graph with source vertex  $s$ . A vertex  $w$  is said to be **newly reachable** from  $s$ , if after inserting  $e(u, v)$  to  $G$ , the vertex  $w$ , which was previously unreachable from  $s$ , becomes reachable from  $s$ .

### 3.2.2 Algorithm

Consider the insertion of a directed edge  $e(u, v)$  to  $G$ . This edge insertion can only increase the set of vertices reachable from  $s$ . It can never remove any reachable vertex.

If  $v$  is already reachable from  $s$ , then the insertion of  $e$  has no effect. Similarly, if  $u$  is not reachable from  $s$ , then adding an outgoing edge from  $u$  cannot introduce any new reachable vertices.

However, if  $u$  is reachable from  $s$  and  $v$  is not, then adding  $e$  makes  $v$  reachable from  $s$ . Moreover, every vertex reachable from  $v$  that was previously unreachable from  $s$  also becomes reachable from  $s$ . Therefore, we should **perform a graph traversal** starting from  $v$  and add all vertices that are reachable from  $v$  and previously unreachable from  $s$  to our data structure.

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**Algorithm 3** Incremental Single Source Reachability

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**Require:** Graph  $G(V, E)$ , source vertex  $s \in V$

**Ensure:** Array  $R$  where  $R[u] = 1$  if and only if  $u$  is *reachable* from  $s$

```
1: function UPDATE( $u, v$ )
2:   if  $R[u] = 1$  and  $R[v] = 0$  then
3:      $R[v] \leftarrow 1$ 
4:     for all  $(v, w) \in E$  do
5:       UPDATE( $v, w$ )
6:     end for
7:   end if
8: end function
```

---

### 3.2.3 Correctness

We will now prove the **correctness of the algorithm**. Essentially, we want to show that the algorithm correctly identifies all vertices that become newly reachable from  $s$  after an edge insertion.

#### Lemma 3.7

Let  $G(V, E)$  be a directed graph with a source vertex  $s$ . Adding a directed edge  $e(u, v)$  to  $G$  can never decrease the set of reachable vertices from  $s$ .

*Proof.* Define  $G' = (V, E \cup \{e(u, v)\})$ . Clearly, every edge  $e \in G(E)$  also belongs to  $G'(E)$ . Therefore, any path  $p$  in  $G$  also belongs to  $G'$ . Suppose  $Q$  is the set of vertices reachable from  $s$  in  $G$ . For every vertex  $v \in Q$ , let  $p$  be the path from  $s$  to  $v$ . Since  $p$  also belongs to  $G'$ , therefore  $v$  is reachable from  $s$  in  $G'$ . Therefore, every vertex reachable from  $s$  in  $G$  remains reachable from  $s$  in  $G'$ . Hence, adding a directed edge cannot decrease the set of reachable vertices from  $s$ .  $\square$

#### Lemma 3.8 (Reachability is Transitive)

Let  $G(V, E)$  be a directed graph. Then the reachability relation  $\rightsquigarrow$  is transitive. That is,  $\forall u, v, w \in G(V)$

$$u \rightsquigarrow v \text{ and } v \rightsquigarrow w \implies u \rightsquigarrow w$$

*Proof.* Given that  $u \rightsquigarrow v$  and  $v \rightsquigarrow w$ , we know that there exist directed paths  $p_1$  and  $p_2$  in  $G$  that connect  $u$  to  $v$  and  $v$  to  $w$ . Concatenating these paths to form a new path  $p = p_1 \cup p_2$  implies that  $p$  is the directed path from  $u$  to  $w$  implying that  $u \rightsquigarrow w$ .  $\square$

**Lemma 3.9**

Let  $G(V, E)$  be a directed graph with a source vertex  $s$ . Adding a directed edge  $e(u, v)$  to  $G$  will increase the set of reachable vertices from  $s$  *if and only if*  $u$  is reachable from  $s$  and  $v$  is not.

*Proof.* If  $u$  is reachable from  $s$  and  $v$  is not, then adding a directed edge from  $u$  to  $v$  makes  $v$  reachable. Hence, the set of reachable vertices increases.

To prove the other direction, define  $G' = (V, E \cup \{e(u, v)\})$ . Suppose  $v$  is reachable from  $s$  in  $G$ . If adding the edge  $e$  made a vertex  $w$  newly reachable, then there exists a path  $p$  from  $s$  to  $w$  in  $G'$ , but not in  $G$ . Since every edge  $e \in G(E)$  also belongs to  $G(E')$ , hence  $p$  must contain  $e(u, v)$ . We can conclude from here that  $w$  must be reachable from  $v$  in  $G$ . Using [lemma 3.8](#), and  $v$  being reachable from  $s$  and  $w$  from  $v$  in  $G$  implies that  $w$  is reachable from  $s$ , contradicting the fact that  $w$  is newly reachable. Hence, no such  $w$  exists.

Similarly, if  $u$  is not reachable from  $s$  and adding  $e$  to  $G$  makes a vertex  $w$  newly reachable, then there exists a path  $p$  from  $s$  to  $w$  in  $G'$ , but not in  $G$ . Since every edge  $e \in G(E)$  also belongs to  $G(E')$ , hence  $p$  must contain  $e(u, v)$ . However this implies that  $u$  is reachable from  $s$ , contradicting our assumption. Hence, no such  $w$  exists and the set of reachable vertices from  $s$  does not increase.  $\square$

**Main Proof.** We now show that [Algorithm 3](#) correctly computes the set of newly reachable vertices when a directed  $e(u, v)$  is added to  $G$ . For the sake of contradiction, assume there exists a vertex  $w$  which is newly reachable vertex and is not computed by the algorithm.

By definition,  $w$  is reachable from  $s$  in  $G'$  but not in  $G$ . Hence there must exist a path  $p$  in  $G' = (V, E \cup \{e(u, v)\})$  from  $s$  to  $w$  such that  $p$  does not exist in  $G$ . Since all the edges  $e \in G(E)$  also belongs to  $G'(E)$ , therefore the path  $p$  must contain  $e(u, v)$ . Thus,  $w$  is reachable from  $v$  in  $G'$ .

Now consider the path from  $v$  to  $w$ . Consider any vertex  $x$  on this path, such that  $x \neq v, w$ . Clearly  $x$  is reachable from  $s$  in  $G'$ . Furthermore, we can say that  $x$  must be newly reachable too. If  $x$  was previously reachable then,  $w$  must have been previously reachable too because the path from  $x$  to  $w$  exists in  $G$ . Therefore, every vertex on this path is newly reachable.

The algorithm first identifies  $v$  as newly reachable and then performs a traversal that marks every previously unreachable vertex reachable from  $v$ . By induction on the length of the path, the algorithm must discover every vertex on the path from  $v$  to  $w$ , including  $w$  itself.

This contradicts our assumption that  $w$  is not computed by the algorithm. Hence, no newly reachable vertex is missed, and the algorithm is correct.  $\square$

**3.2.4 Time Complexity Analysis**

For [Algorithm 3](#), we show that the

1. **Worst-case time complexity** is  $\mathcal{O}(m + n)$ .

*Proof.* If a vertex  $u$  is newly reachable, then we perform  $(1 + \deg u)$  operations on it. Thus, the total running time of the algorithm is

$$\sum_{u \in Q} (1 + \deg u) = \mathcal{O}(m + n)$$

where  $Q$  is the set of newly reachable vertices. □

2. **Amortized time complexity** is  $\mathcal{O}(1)$ .

*Proof.* Since the algorithm reduces edges  $e(u, v)$  of the form

$$(R[u] = 1, R[v] = 0) \mapsto (R[u] = 1, R[v] = 1)$$

hence, each edge could be reduced *atmost once*. Thus, the number of operations are bounded by  $m$  and the amortized time complexity turns out to be

$$\frac{1}{m} \sum_{\substack{v \in V \\ R[v]=1}} (1 + \deg v) = \frac{\mathcal{O}(m + n)}{m} = \mathcal{O}(1)$$

□