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Capstone Project Phase A – 61998

**Citation networks evolution using Dynamic Network Embeddings**

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# Abstract

Citation networks are modeled as a series of graphs. In these graphs, nodes represent articles, and edges indicate citations from one article to another. Each graph corresponds to a snapshot at a specific timestamp. These networks evolve with the addition of new research and references. Identifying public opinion leaders, whether articles or subjects, is essential for understanding research influence and emerging trends. Advanced programming techniques are necessary to analyze these dynamic networks effectively.

Dynamic network embeddings offer a powerful approach for analyzing evolving networks by transforming graphs into vectors within a shared vector space. By employing methods such as dynamic Bernoulli embeddings and sequential random walks, this research aims to model temporal changes effectively. Through tasks such as link prediction and evolving node detection, the approach demonstrates its capability to identify influential works and emerging research areas in citation networks.

In conclusion, dynamic network embedding methods provide a robust framework for uncovering key insights in citation networks, driving a deeper understanding of research trends and influence over time.

# Introduction

Highly cited articles are instrumental in shaping the direction of research discourse. Spanning a vast array of diverse subjects, are often published in response to the popularity of certain subjects. By detecting such works, citation networks provide valuable insights into the evolution of research priorities and the propagation of knowledge.

 As shown in Figure 1, highly cited articles serve as central nodes within citation networks, connecting diverse knowledge domains and facilitating interdisciplinary collaboration. These central articles play a crucial role in driving innovation, highlighting significant research areas, and influencing funding priorities toward emerging fields. Their impact extends beyond individual research areas, shaping the evolution of disciplines and driving transformative shifts across the broader academic landscape. Over time, their influence grows as they continue to guide future research directions and inspire new discoveries.

**Figure 1: Illustration of highly cited articles as central nodes in a citation graph, highlighting their role in connecting diverse domains of knowledge and fostering interdisciplinary collaboration.**

Static analysis methods are techniques that analyze networks by assuming a fixed structure, where nodes and edges remain unchanged over time. Traditional static analysis methods, such as DeepWalk and Node2vec models, are limited in capturing the dynamic nature of evolving networks. By treating the network as a static graph, these methods provide only a snapshot at a specific timestamp, ignoring crucial temporal variations. As a result, these approaches fail to account for critical changes such as the emergence of new influential nodes or the shifting importance of edges over time. This static perspective makes it difficult to analyze trends, predict future interactions, or understand temporal patterns in the network's structure. For instance, while DeepWalk model uses random walks to learn embeddings, it assumes a fixed structure, ignoring how nodes and edges evolve. Similarly, Node2vec model introduces flexibility in embedding generation but still lacks the ability to incorporate temporal dynamics, leading to incomplete representations of the network's evolution.

Dynamic networks address the limitations of static analysis by modeling nodes and edges that change over time. Unlike static networks, dynamic networks capture how structures evolve, providing critical insights into temporal interactions. By tracking these changes, dynamic networks enable the analysis of trends, the identification of emerging patterns, and the understanding of how relationships develop over time.

Dynamic network embedding enhances this framework by generating low-dimensional representations of nodes that capture both structural relationships and temporal changes. Using specialized techniques, these embeddings ensure proximity preservation by keeping similar nodes close in the embedding space, while also ensuring temporal continuity by minimizing unnecessary drift for stable nodes over time. This approach enables researchers to identify influential articles in citation networks, shaping funding decisions, academic hiring, and research prioritization.

Analysing citation dynamic networks over time provides significant contributions to understanding the evolution of scientific knowledge and research priorities. This allows for the detection of the identification of influential works at different stages of their lifecycle. For instance, articles that may initially receive limited attention can later emerge as central nodes, influencing research trajectories and fostering innovation. By capturing these temporal patterns, dynamic network analysis enables a more nuanced understanding of how scientific ideas propagate, evolve, and gain prominence over time.

The benefits of dynamic citation network analysis extend beyond academic insights. It provides actionable intelligence for decision-makers such as funding agencies, institutions, and policymakers. By identifying rising areas of influence and predicting future research directions, these analyses can guide the allocation of resources toward high-potential fields.

Additionally, tracking changes in the importance of nodes and edges helps in evaluating the long-term impact of research contributions, improving strategies for academic hiring, grant distribution, and collaborative initiatives. Ultimately, dynamic citation network analysis fosters a deeper understanding of scientific progress, facilitating data-driven decisions that enhance innovation and accelerate the advancement of knowledge.

# Background

## Dynamic Network Background

Dynamic networks are structured systems where the connections (edges) between entities (nodes) evolve over time, reflecting changes in relationships or interactions. Unlike static networks with fixed topologies, dynamic networks are represented by a series of time-dependent snapshots or continuous-time models, capturing the temporal variation in their structure. These changes may include the addition or removal of nodes, the strengthening or weakening of connections, or shifts in the network's overall topology. However, in citation networks, edges are only added over time and not removed, as citations represent permanent references once established.

**Definition 1 (Dynamic Networks): A dynamic network is a series of graphs Γ = {G1,...,GT } and Gt = (Vt,Et), where T is the number of graphs, Vt is a node set and Et includes all temporal edges within the timespan [St,St+1]. Each ei = (u,v,si) ∈ Et is a temporal edge between the node u ∈ Vt and the node v ∈ Vt at the timestamp si ∈ [St,St+1].**

Two critical factors in dynamic networks are the **proximity between nodes** and the **temporal continuity of nodes over time** :

* **Proximity between nodes** refers to the measure of how closely connected two nodes are within the network at a certain timestamp graph. The proximitycan be influenced by direct connections (e.g. a temporal edge between two nodes) or indirect relationships (e.g., shared temporal neighbours or paths).
* **Temporal continuity of stable nodes** involves maintaining consistent representations of nodes that remain relatively unchanged across time. This is crucial for capturing the evolution of nodes and their roles within the network without introducing unnecessary distortions. For example, consider an article in a specific scientific field that continues to be cited over decades. The node representing this article remains stable in terms of its role in the network, consistently attracting citations as new research builds upon its findings.

## Citation Dynamic Network Specificities

Citation networks exhibit unique and complex properties that distinguish them from other types of dynamic networks:

* **Irreversibility of Edges:** A citation, once established, is permanent and unidirectional. This reflects the enduring nature of knowledge transfer, where older foundational works remain integral to the evolving research landscape.
* **Node Longevity:** Articles often remain relevant for years or even decades after publication. This longevity reflects their continued influence as foundational works or seminal contributions in a specific domain. Articles with sustained citation activity serve as anchors in the evolving structure, providing stability in the dynamic embedding space.
* **Citation Burstiness:** Citations are unevenly distributed over time. Articles may experience sudden surges in citations due to emerging trends, paradigm shifts, or groundbreaking discoveries. These bursts are crucial for identifying trending publications and tracking shifts in research focus.
* **Hierarchical Structure of Influence:** Citation networks often exhibit a hierarchical flow of influence, where older, highly cited works act as "roots," and newer works branch out to build upon these foundations. Over time, articles may accumulate more citations, further reinforcing their importance in the network hierarchy.
* **Field-Specific Dynamics:** Different research fields exhibit distinct citation behaviors. For instance, fast-evolving fields such as artificial intelligence (AI) and bioinformatics experience rapid bursts of citations, while fields like mathematics or physics may have longer citation cycles where articles remain influential for extended periods.

Understanding these characteristics is crucial for designing methods tailored to citation network analysis. By accounting for the permanence of edges, the longevity of influential nodes, and the bursty nature of citation events, dynamic embedding methods can better capture the evolving structure and influence of articles within citation networks. These insights allow researchers to identify emerging trends, track the propagation of knowledge, and recognize the enduring impact of foundational works.

## Random Walk

A random walk is a stochastic process that generates a path consisting of successive steps on a mathematical space, such as a graph. At each step, the next node is randomly selected from the neighbours of the current node.

Random walks are widely used for efficiently exploring graph structures, analysing connectivity, and identifying communities. Additionally, they enable effective sampling of large networks, especially when global computations are impractical or computationally expensive.

Basic random walk algorithm on graph:

**Input:**

* : A graph with nodes V and edges E.
* : stating node
* : length of the walk
* : Edge weights (optional)

**Output:**

* : A sequence representing the random walk.

**Steps:**

1. Set
2. For to L:
   1. Set
   2. If graph is unweighted:
      1. Select uniformly at random from N
   3. Else:
      1. For each Compute the probably :
      2. Select based on the probability distribution.
   4. Append to
   5. Set as
3. Return

The random walk length (L) is a key parameter that directly influences the behaviour, outcome, and efficiency of graph exploration and the tasks that depend on the random walk, such as graph traversal, connectivity analysis, and node embedding generation:

* **Short walks** in a random walk process focus on exploring the local neighbourhood of a starting node and capturing immediate connectivity. These walks are particularly suitable for tasks requiring fine-grained, localized relationships, such as detecting tightly connected communities or performing micro-level analysis.
* **Long walks** explore a broader region of the graph, capturing global structures and distant connectivity patterns. This makes them useful for understanding macro-level graph properties, such as identifying how nodes are connected across different clusters or detecting bridge nodes that link communities.

Random walks are considered as efficient tools for exploring dynamic networks due to their localized and adaptable nature. They allow real-time updates as networks evolve, enabling tasks like community detection, anomaly detection, node embedding, and influence propagation in changing environments. By leveraging their flexibility and scalability, random walks provide a robust solution for understanding the complex temporal behavior of dynamic networks.

## Word2Vec and its Inspiration for Dynamic Network Embeddings

Word2Vec is a neural network-based method used to learn continuous vector representations of words by leveraging their context within a corpus. Words that appear in similar contexts are mapped to nearby points in the vector space, capturing semantic relationships between words.

Two key approaches in Word2Vec are:

* **Continuous Bag-of-Words (CBOW):** Predicts a target word based on its surrounding context words.
* **Skip-Gram Model:** Predicts context words given a target word.

These models learn embeddings by maximizing the likelihood of observing context words around a target word, using positive and negative sampling to make the computation efficient. The proximity of word embeddings in the learned vector space reflects semantic similarity.

Dynamic network embeddings draw direct inspiration from Word2Vec. Instead of modeling words and their contexts, dynamic embeddings model nodes in a network and their temporal contexts:

* **Nodes as Words:** Nodes represent entities (e.g., articles in citation networks), analogous to words in Word2Vec.
* **Node Contexts:** Random walks generate sequences of nodes, capturing the local structure of the network over time. These sequences act as temporal contexts similar to word co-occurrences.
* **Proximity Learning:** The embeddings preserve node proximity within each snapshot of the dynamic network, like how Word2Vec preserves word similarity.
* **Temporal Evolution:** While Word2Vec assumes a static corpus, dynamic embeddings introduce a temporal dimension to track changes in node relationships and positions over time.

The core idea of learning context-based embeddings to capture relationships is retained in dynamic network embeddings but adapted to represent evolving structures. This adaptation enables dynamic embeddings to model temporal continuity, ensuring that stable nodes maintain consistent representations while allowing for significant embedding drift in trending nodes.

## Detecting Trending Articles in Citation Networks

To detect a trending article in a dynamic citation network using the Dynamic Network Embedding approach, we analyze how the node embeddings (representing articles) evolve over time. A trending article exhibits distinct and measurable behaviors that reflect its increasing importance and impact within the network:

* **Rapid Increase in Degree:** A trending article receives a sudden and notable rise in citations (edges) within a short time window. This rapid increase signifies growing recognition of the article's relevance and its influence on subsequent research. Such articles often address emerging topics, present groundbreaking methods, or offer significant insights that capture the attention of the academic community.
* **Significant Embedding Drift:** The position of the article in the embedding space changes substantially between consecutive timesteps. This drift occurs as the article attracts citations from diverse or unexpected areas, signaling its expansion beyond its original domain. Embedding drift highlights the article's evolving role and its capacity to influence interdisciplinary research or spawn new lines of inquiry.
* **Centrality Growth:** Over time, the article becomes more central within the citation network. Centrality measures, such as betweenness, closeness, or eigenvector centrality, indicate how influential a node is within the network. An article experiencing centrality growth acts as a "hub" connecting multiple research areas, fostering collaborations, and serving as a foundation for subsequent work.

These behaviors collectively provide a comprehensive view of an article's trajectory within the evolving citation network. By tracking degree growth, embedding drift, and centrality changes, researchers can identify not only articles gaining influence but also emerging research themes and fields. Combining these metrics offers a robust, multi-dimensional method for detecting trending articles and understanding their evolving impact on the research landscape.

# Approach

# Testing Plan

# References