

# Dynamic Subgraph Matching via Cost-Model-based Vertex Dominance Embeddings (Technical Report)

## ABSTRACT

In many real-world applications such as social network analysis, knowledge graph discovery, biological network analytics, and so on, graph data management has become increasingly important and has drawn much attention from the database community. While many graphs (e.g., Twitter, Wikipedia, etc.) are usually involving over time, it is of great importance to study the *dynamic subgraph matching* problem, a fundamental yet challenging graph operator, over dynamic graphs with a stream of edge updates. In this paper, we formulate the problems of *snapshot dynamic subgraph matching* (S-DSM) and *continuous dynamic subgraph matching* (C-DSM), which conduct subgraph matching queries over snapshots of dynamic graphs or continuously monitor subgraph matching results over dynamic graphs, respectively. To efficiently tackle S-DSM and C-DSM problems, in this paper, we carefully design a novel *vertex dominance embedding* approach, which effectively encodes vertex labels that can be incrementally maintained upon graph updates. Inspire by low pruning power for high-degree vertices, we propose a new *degree grouping* technique over basic subgraph patterns in different degree groups (i.e., groups of star substructures), and devise *degree-aware star substructure synopses* (DAS<sup>3</sup>) to effectively facilitate our designed *vertex dominance* and *range pruning strategies*. We develop efficient algorithms to incrementally maintain dynamic graphs and answer S-DSM and C-DSM queries. Through extensive experiments, we confirm the efficiency of our proposed approaches over both real and synthetic graphs.

## KEYWORDS

Dynamic Subgraph Matching, Vertex Dominance Embedding

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## 1 INTRODUCTION

For the past few decades, the *subgraph matching* problem has been extensively studied as a fundamental operator in the graph data management [13, 38, 46, 61, 67, 72] for many real-world applications such as social network analysis, knowledge graph discovery, and pattern matching in biological networks. Given a large-scale data

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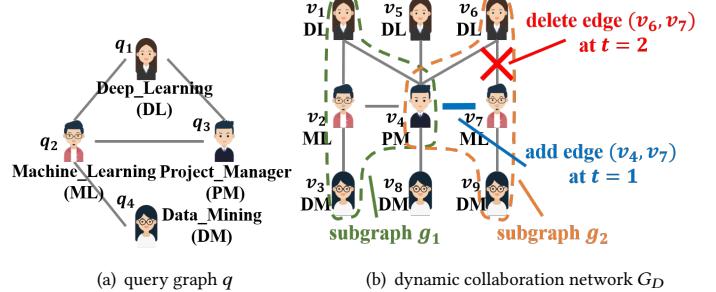


Figure 1: An example of the subgraph matching in dynamic collaboration networks  $G_D$ .

graph  $G$ , a subgraph matching query finds all the subgraphs of  $G$  that are isomorphic to a given query graph  $q$ .

While many previous works [8–10, 26, 30, 35, 53, 58] usually considered the subgraph matching over static graphs, real-world graph data are often dynamic and change over time. For example, in social networks, friend relationships among users may subject to changes (e.g., adding or breaking up with friends); similarly, in collaboration networks, people may start to collaborate on some project and then suddenly stop the collaboration for years. In these scenarios, it is important, yet challenging, to conduct the subgraph matching over such a large-scale, dynamic data graph  $G_D$ , upon updates (e.g., edge insertions/deletions). In other words, we need to continuously monitor subgraphs (e.g., user communities or collaborative teams) in  $G_D$  that follow query graph patterns  $q$ .

Below, we give an example of the subgraph matching over dynamic collaboration networks in the expert team search application.

**EXAMPLE 1. (Monitoring Project Teams in Dynamic Collaboration Networks [19])** Due to numerous requests from departments/companies for recruiting (similar) project teams, a job search advisor may want to monitor the talent market (especially teams of experts) in dynamically changing collaboration networks.

Consider a toy example of a collaboration network  $G_D$  in Figure 1. Figure 1(a) shows a desirable expert team pattern  $q$ , which is represented by a graph of 4 experts  $q_1 \sim q_4$ , where each expert vertex  $q_i$  is associated with one's skill/role keyword (e.g.,  $q_1$  with keyword "Deep\_Learning" and  $q_3$  with "Project\_Manager"), and each edge indicates that two experts had the collaboration before (e.g., edge  $(q_1, q_3)$ ).

Figure 1(b) provides an example of a dynamic collaboration network  $G_D$ , where edges are inserted or deleted over time. For example, a new edge  $(v_4, v_7)$  is inserted at timestamp  $t = 1$ , implying that two experts  $v_4$  and  $v_7$  start to collaborate with each other in a team. Similarly, at timestamp  $t = 2$ , an existing edge  $(v_6, v_7)$  is removed from the graph  $G_D$ , which may indicate that experts  $v_6$  and  $v_7$  have not collaborated with each other for a certain period of time (e.g., two years).

In this example, the job search advisor can register a dynamic subgraph matching query over  $G_D$  to continuously identify subgraphs of  $G_D$  that match with the query graph pattern  $q$ . At timestamp  $t = 1$ ,

subgraphs  $g_1$  and  $g_2$  are the subgraph matching answers, whereas at timestamp  $t = 2$ , subgraph  $g_1$  is the only answer (since the deletion of edge  $(v_6, v_7)$  invalidates the subgraph  $g_2$ ). ■

Dynamic subgraph matching has many other real applications. For example, in the application of anomaly detection for online shopping [49], the interactions (e.g., purchases, views, likes, etc.) among users/products over time form a dynamic social/transaction graph, and it is important to detect some abnormal events such as fraudulent activities (i.e., query graph patterns) over such a dynamically changing graph.

Inspired by the examples above, we formulate two query types over dynamic graphs, named *snapshot dynamic subgraph matching* (S-DSM) and *continuous dynamic subgraph matching* (C-DSM), which conduct the subgraph matching over snapshots of dynamic graphs or continuously monitor subgraph matching results, resp. **Prior Works:** Due to NP-completeness of the subgraph isomorphism [15, 21, 22], dynamic subgraph matching is not tractable. To tackle this problem, several exact algorithms have been proposed [14, 20, 33, 34, 37, 40, 43], which consist of three categories: *recomputation-based* [20], *direct-incremental* [37], and *index-based incremental algorithms* [14, 33, 34, 40, 43]. The recomputation-based algorithms re-compute all the subgraph matching answers at each timestamp from scratch, the direct-incremental algorithms incrementally calculate new matching results from dynamic graphs upon updates, and index-based incremental algorithms incrementally maintain matching results via auxiliary indexes built over initial query answers.

**Our Contributions:** Our work falls into the category of the direct-incremental algorithm. Different from existing works that directly use structural information (e.g., vertex label and neighbors' label set) to filter out vertex candidates, we design a novel and effective *vertex dominance embedding* technique for candidate vertex/subgraph retrieval. Specifically, our proposed vertex dominance embeddings can be incrementally maintained in dynamic graphs, and transform our S-DSM/C-DSM problem into a *dominating region search* problem in the embedding space with no false dismissals. To enhance the pruning power of our embeddings for high-degree vertices, we propose a new *degree grouping* approach for vertex embeddings over basic subgraph patterns in different degree groups (i.e., groups of star substructures). We also devise a cost model to further guide the vertex embeddings to effectively achieve high pruning power. Finally, we develop algorithms to incrementally maintain dynamic graphs and answer S-DSM and C-DSM queries efficiently.

Specifically, in this paper, we make the following contributions:

- (1) We formally define *snapshot* and *continuous dynamic subgraph matching* problems (i.e., S-DSM and C-DSM, respectively) in Section 2, and propose a general framework for S-DSM and C-DSM query answering in Section 3.
- (2) We carefully design incremental vertex dominance embeddings to facilitate dynamic subgraph matching in Section 4.
- (3) We devise a degree grouping technique to enhance the pruning power of vertex embeddings, and construct *degree-aware star substructure synopses* (DAS<sup>3</sup>) to support the dynamic subgraph matching in Section 5.
- (4) We design effective synopsis pruning strategies, and develop effective S-DSM/C-DSM processing algorithms in Section 6.

**Table 1: Symbols and Descriptions**

Symbol	Description
$G$	a static graph
$G_D$	a dynamic graph
$\Delta G_t$	a set of graph updates at timestamp $t$
$G_t$	a snapshot graph of $G_D$ at timestamp $t$
$e+$ (or $e-$ )	an insertion (or deletion) of edge $e$
$q$	a query graph
$Q$	a set of query graph patterns
$x_i$	a SPUR vector of vertex $v_i$
$y_i$	a SPAN vector of vertex $v_i$ 's 1-hop neighbors
$o(v_i)$ (or $o(g_{v_i})$ , $o(s_{v_i})$ )	a vertex dominance embedding vector

- (5) We present a novel cost-model-guided vertex embeddings to further improve the pruning power of dynamic subgraph matching in Section 7.
- (6) We demonstrate through experiments the efficiency and effectiveness of our S-DSM and C-DSM processing algorithms over real/synthetic graphs in Section 8.

In addition, Section 9 reviews previous works on dynamic graph management and graph embeddings. Finally, Section 10 concludes this paper.

## 2 PROBLEM DEFINITION

This section formally defines the dynamic graph data model and subgraph matching queries over a dynamic graph. Table 1 depicts the commonly used symbols and their descriptions in this paper.

### 2.1 Static Graph Model

We first give the model for a static undirected, vertex-labeled graph,  $G$ , below.

**DEFINITION 1. (*Static Graph*,  $G$ )** A static graph,  $G$ , is represented by a triple  $(V(G), E(G), L(G))$ , where  $V(G)$  is a set of vertices  $v_i$ ,  $E(G)$  is a set of edges  $e_{i,j} = (v_i, v_j)$  between vertices  $v_i$  and  $v_j$ , and  $L(G)$  is a mapping function from each vertex  $v_i \in V(G)$  to a label  $l(v_i)$ . ■

The static graph model (as given in Definition 1) has been widely used in various real-life applications to reflect relationships between different entities, for example, social networks [1], Semantic Web [29], transportation networks [50], biological networks [36], citation networks [70], and so on.

**The Graph Isomorphism:** Next, we define the classic graph isomorphism problem between two graphs.

**DEFINITION 2. (*Graph Isomorphism*)** Given two graphs  $G_1$  and  $G_2$ , graph  $G_1$  is isomorphic to graph  $G_2$  (denoted as  $G_1 \equiv G_2$ ), if there exists a bijection mapping function  $M : V(G_1) \Rightarrow V(G_2)$ , such that:

- i)  $\forall v_i \in V(G_1)$ , we have  $L(v_i) = L(M(v_i))$ , and;
- ii)  $\forall e_{i,j} \in E(G_1)$ , edge  $e_{M(v_i), M(v_j)} = (M(v_i), M(v_j)) \in E(G_2)$  holds. ■

In Definition 2, the graph isomorphism problem checks whether graphs  $G_1$  and  $G_2$  exactly match with each other.

**The Subgraph Matching Problem:** The subgraph isomorphism (or subgraph matching) problem is defined as follows.

**DEFINITION 3. (*Subgraph Matching*)** Given graphs  $G$  and  $g$ , a subgraph matching problem identifies subgraphs  $g'$  of  $G$  (i.e.,  $g' \subseteq G$ ) such that  $g$  and  $g'$  are isomorphic. ■

Note that, the subgraph matching problem is NP-complete [21].

## 2.2 Dynamic Graph Model

Real-world graphs are often continuously evolving and updated. Examples of such dynamic graphs include social networks with updates of friend relationships among users, bibliographical networks with new collaboration relationships, and so on. In this subsection, we provide the data model for dynamic graphs with update operations below.

**DEFINITION 4. (*Dynamic Graph*,  $G_D$ )** A dynamic graph,  $G_D$ , consists of an initial graph  $G_0$  (as given by Definition 1) and a sequence of graph update operations  $\Delta\mathcal{G} = \{\Delta G_1, \Delta G_2, \dots, \Delta G_t, \dots\}$  on  $G$ . Here,  $\Delta G_t$  is a graph update operator, in the form of  $(e+, t)$  or  $(e-, t)$ , which indicates either an insertion (+) or a deletion (-) of an edge  $e$  at timestamp  $t$ , respectively. ■

**Snapshot Graph**,  $G_t$ : From Definition 4, after applying to initial graph  $G$  all the graph update operations up to the current timestamp  $t$  (i.e.,  $\Delta G_1, \Delta G_2, \dots$ , and  $\Delta G_t$ ), we can obtain a snapshot of the dynamic graph  $G_D$ , denoted as  $G_t$ .

**Discussions on the Edge Insertion:** For the edge insertion  $(e+, t)$  in Definition 4, there are three cases:

- both ending vertices of  $e$  exist in the graph snapshot  $G_{t-1}$ ;
- one ending vertex of  $e$  exists in  $G_{t-1}$  and the other one is a new vertex, and;
- both ending vertices of  $e$  are new vertices.

We will later discuss how to deal with the three cases of edge insertions above for dynamic graph maintenance and incremental query answering.

## 2.3 Subgraph Matching Queries Over Dynamic Graphs

In this subsection, we define a dynamic subgraph matching query over a snapshot of large-scale dynamic graph  $G_D$ , which obtains all subgraphs,  $g$ , in  $G_D$  that match with a given query graph  $q$ .

**DEFINITION 5. (*Snapshot Dynamic Subgraph Matching*, S-DSM)** Given a dynamic graph  $G_D$ , a query graph  $q$ , and a timestamp  $t$ , a snapshot dynamic subgraph matching (S-DSM) query retrieves a set,  $A(q, t)$ , of subgraphs  $g$  from the snapshot  $G_t$  of dynamic graph  $G_D$  that are isomorphic to the query graph  $q$  (denoted as  $g \equiv q$ ). ■

In Definition 5, the S-DSM problem is a subgraph matching query over a snapshot graph  $G_t$  at timestamp  $t$ , which is one-time only. The S-DSM query (as given in Definition 5) has many real-world applications, for example, finding communities (for social events) that match with a query graph pattern over a dynamic social network.

Next, we define a continuous subgraph matching query over dynamic graph  $G_D$ , which monitors subgraph matching answers for a set,  $Q$ , of registered query graph patterns.

**DEFINITION 6. (*Continuous Dynamic Subgraph Matching*, C-DSM)** Given a dynamic graph  $G_D$ , a set,  $Q$ , of registered query graph patterns  $q$ , and a timestamp  $t$ , a continuous dynamic subgraph matching (C-DSM) query maintains a subgraph matching answer set  $A(q, t)$  for each query graph pattern  $q \in Q$ , such that  $g \equiv q$  holds for any subgraph  $g \in A(q, t)$ .

Alternatively, for each  $q \in Q$ , the C-DSM problem incrementally computes an update,  $\Delta A(q, t)$ , to answer set  $A(q, t - 1)$ , upon the change  $\Delta G_t$  to  $G_{t-1}$ . ■

Different from a one-time S-DSM query, the C-DSM query (given in Definition 6) continuously maintains a subgraph matching answer set  $A(q, t)$  (w.r.t. each query graph pattern  $q \in Q$ ) over dynamic graph  $G_D$  (upon incremental updates) for a long period of time. The C-DSM problem is quite useful in real applications such as cyber-attack event detection and credit card fraud detection.

## 2.4 Challenges

The subgraph matching problem in a static large data graph has been proven to be NP-complete [21]. Thus, it is even more challenging to design effective techniques for answering (snapshot and continuous) dynamic subgraph matching queries as well. Due to frequent updates to the data graph, it is non-trivial how to effectively maintain the large-scale dynamic graph that can support efficient snapshot dynamic subgraph matching (i.e., S-DSM query). Moreover, for the C-DSM query with registered query patterns, it is also challenging to continuously and efficiently monitor subgraph matching answer sets, upon fast graph updates.

In order to tackle S-DSM and C-DSM problems, in this paper, we will propose a novel and effective vertex dominance embedding technique over dynamic graphs, which transforms the subgraph matching to a dominance search problem in a graph-node-embedding space. Our proposed embedding technique can guarantee the subgraph matching with no false dismissals. Furthermore, we also design effective pruning, indexing, and incremental maintenance mechanisms to facilitate efficient and scalable dynamic subgraph matching.

## 3 THE DYNAMIC SUBGRAPH MATCHING FRAMEWORK

In this section, we illustrate a general framework for dynamic subgraph matching in Algorithm 1, which consists of two stages, *graph maintenance* and *subgraph matching stages*.

Specifically, for the graph maintenance stage, we first pre-process initial data graph  $G_0$  by constructing a set of  $m$  graph synopses,  $Syn_j$ , over vertex embeddings  $o(v_i)$  with degree grouping (lines 1-2). Then, for each graph update operation  $\Delta G_t \in \Delta\mathcal{G}$ , we incrementally maintain the dynamic graph  $G_t$  and synopses  $Syn_j$  (lines 3-5).

In the subgraph matching stage, we consider both S-DSM query processing over snapshot dynamic graph  $G_t$  (lines 6-11) and C-DSM query answering over continuously changing dynamic graph  $G_t$  (lines 12-16).

For a one-time S-DSM query with a query graph  $q$ , we first obtain query vertex embeddings  $o(q_i)$  from vertices  $q_i \in V(q)$  (line 7). Then, for each query vertex  $q_i$ , we find and store candidate vertices in a set  $q_i.cand\_set$  by accessing  $Syn_j$  (line 8). After that, we enumerate candidate subgraphs  $g$  by assembling candidate vertices in  $q_i.cand\_set$  (line 9), and refine/return matching subgraphs  $g$  in an S-DSM answer set  $A(q, t)$  (lines 10-11).

Moreover, to answer the C-DSM query, for each graph update operation  $\Delta G_t \in \Delta\mathcal{G}$ , we check the updated vertices in  $\Delta G_t$ , update the candidate vertex sets  $q_i.cand\_set$ , and monitor the changes  $\Delta A(q, t)$  in  $A(q, t)$  (lines 12-14). Next, we obtain  $A(q, t)$  by applying

**Algorithm 1: The Dynamic Subgraph Matching Framework**


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**Input:** i) a dynamic data graph  $G_D$  ii) a query graph  $q$ , and; iii) current timestamp  $t$

**Output:** subgraphs  $g$  ( $\subseteq G$ ) that are isomorphic to  $q$

// Graph Maintenance Stage

- 1 generate a vertex embedding vector  $o(v_i)$  for each vertex  $v_i \in G_0$
- 2 build  $m$  synapses,  $Syn_j$ , over vertex embeddings with degree grouping
- 3 **for** each graph update  $\Delta G_t \in \Delta G$  **do**
- 4   obtain  $G_t$  by applying the graph update  $\Delta G_t$  over  $G_{t-1}$
- 5   maintain synapses  $Syn_j$  by updating the corresponding vertex embeddings

// Subgraph Matching Stage

// S-DSM Query Answering

- 6 **for** each query graph  $q$  **do**
- 7   compute a query embedding vector  $o(q_i)$  of each vertex  $q_i \in V(q)$
- 8   find candidate vertex sets  $q_i.cand\_set$  for query vertices  $q_i$  by accessing synapses  $Syn_j$
- 9   enumerate candidate subgraphs  $g$  from candidate vertices in  $q_i.cand\_set$
- 10   obtain an answer set,  $A(q, t)$ , of matching subgraphs  $g$  ( $\equiv q$ )
- 11   **return**  $A(q, t)$

// C-DSM Query Answering

- 12 **for** each graph update  $\Delta G_t \in \Delta G$  **do**
- 13   update candidate vertex sets  $q_i.cand\_set$  by checking the updated vertices in  $\Delta G_t$
- 14   compute answer changes  $\Delta A(q, t)$  from the new candidate sets  $q_i.cand\_set$
- 15   apply changes  $\Delta A(q, t)$  to  $A(q, t - 1)$  and obtain the latest subgraph answers in  $A(q, t)$
- 16   **return**  $A(q, t)$

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changes  $\Delta A(q, t)$  to  $A(q, t - 1)$ , and return the  $A(q, t)$  as the C-DSM query answer set (lines 15–16).

## 4 INCREMENTAL VERTEX DOMINANCE EMBEDDINGS

In this section, we will present our vertex dominance embeddings, which can be incrementally maintained, preserve dominance relationships between basic subgraph patterns (i.e., star subgraphs), and support efficient subgraph matching over dynamic graphs.

### 4.1 Preliminaries and Terminologies

We first introduce two terms of basic subgraph patterns (used for our proposed vertex dominance embedding), that is, *unit star subgraphs* and *star substructures*:

- **Unit Star Subgraph  $g_{v_i}$ :** A unit star subgraph  $g_{v_i}$  is defined as a (star) subgraph in  $G_t$  containing a center vertex  $v_i$  and its one-hop neighbors.

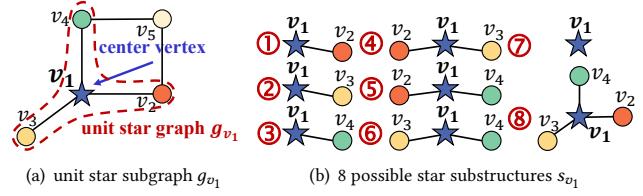


Figure 2: Illustration of unit star subgraph and star substructures.

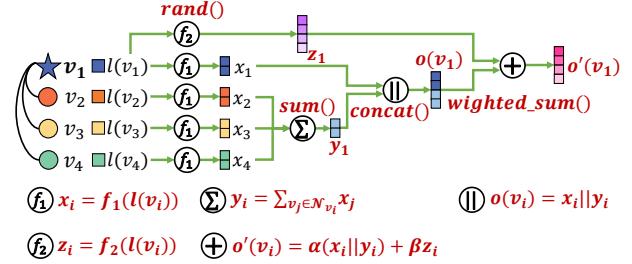


Figure 3: Illustration of vertex dominance embedding  $o(v_1)$  and the optimized vertex dominance embedding  $o'(v_1)$ .

- **Star Substructure  $s_{v_i}$ :** A star substructure  $s_{v_i}$  is defined as a (star) subgraph of the unit star subgraph  $g_{v_i}$  in  $G_t$  (i.e.,  $s_{v_i} \subseteq g_{v_i}$ ), which shares the same center vertex  $v_i$ .

As an example in Figure 2(a), the unit star subgraph  $g_{v_1}$  in data graph  $G_t$  contains a center vertex  $v_1$  and its 1-hop neighbors  $v_2, v_3$ , and  $v_4$ . Figure 2(b) illustrates 8 (=  $2^3$ ) possible star substructures  $s_{v_1}$  ( $\subseteq g_{v_1}$ ), which are centered at vertex  $v_1$  and with different combinations of  $v_1$ 's 1-hop neighbors.

### 4.2 Vertex Dominance Embedding

In this subsection, we discuss how to obtain an embedding vector,  $o(v_i)$ , for each vertex  $v_i$ , which embeds labels of vertex  $v_i$  and its 1-hop neighbors (i.e., unit star subgraph or star substructure). Specifically, the embedding vector  $o(v_i)$  consists of two portions, a Seeded Pseudo Random (SPUR) vector  $x_i$  and a SPUR Aggregated Neighbor (SPAN) vector  $y_i$ .

**Seeded Pseudo Random (SPUR) Vector,  $x_i$ :** In the dynamic graph  $G_D$ , each vertex  $v_i$  is associated with a label  $l(v_i)$ , which can be encoded by a nonnegative integer. By treating the vertex label  $l(v_i)$  as the seed, we can generate a *Seeded Pseudo Random* (SPUR) vector,  $x_i$ , of arity  $d$  via a pseudo-random number generator  $f_1(\cdot)$ . That is, we have:

$$x_i = f_1(l(v_i)). \quad (1)$$

We denote  $x_i[j]$  as the  $j$ -th element in SPUR vector  $x_i$ , where  $1 \leq j \leq d$  and  $x_i[j] > 0$ .

Note that, since our randomized SPUR vector  $x_i$  is generated based on the seed (i.e., label  $l(v_i)$  of each vertex  $v_i$ ), vertices with the same label will have the same SPUR vector.

In the example of Figure 3, vertices  $v_1 \sim v_4$  are associated with labels  $l(v_1) \sim l(v_4)$ , respectively. We generate their corresponding SPUR vectors,  $x_1 \sim x_4$ , via a randomized function  $f_1(\cdot)$  in Eq. (1).

**SPUR Aggregated Neighbor (SPAN) Vector,  $y_i$ :** Next, for each vertex  $v_i$ , we consider its 1-hop neighbors,  $v_j \in N_{v_i}$ , in a star

subgraph pattern (i.e., the unit star subgraph  $g_{v_i}$  or star substructure  $s_{v_i}$ ), and sum up their corresponding SPUR vectors  $x_j$  to generate a *SPur Aggregated Neighbor* (SPAN) vector  $y_i$ :

$$y_i = \sum_{\forall v_j \in N_{v_i}} x_j, \quad (2)$$

where  $N_{v_i}$  is a set of 1-hop neighbors of  $v_i$ , and  $x_j$  are the SPUR vectors of 1-hop neighbors of  $v_i$ .

Taking Figure 3 as an example, the SPAN vector of the vertex  $v_1$  is calculated by  $y_1 = x_2 + x_3 + x_4$ .

**Vertex Dominance Embedding,  $o(v_i)$ :** We define the *vertex dominance embedding* vector,  $o(v_i)$ , of each vertex  $v_i$ , by concatenating its SPUR vector  $x_i$  and SPAN vector  $y_i$ :

$$o(v_i) = x_i \parallel y_i, \quad (3)$$

where  $\parallel$  is the concatenation operation of two vectors, and  $x_i$  and  $y_i$  are given in Eqs. (1) and (2), respectively.

Intuitively, vertex dominance embedding  $o(v_i)$  encodes label features of a star subgraph pattern (i.e.,  $g_{v_i}$  or  $s_{v_i}$ ) containing center vertex  $v_i$  and its 1-hop neighbors. To distinguish embeddings  $o(v_i)$  from different star subgraph patterns, we also use notations  $o(g_{v_i})$  or  $o(s_{v_i})$ .

As shown in Figure 3, the vertex dominance embedding of vertex  $v_1$  can be computed by  $o(v_1) = x_1 \parallel y_1$ .

### 4.3 Properties of Vertex Dominance Embedding

**The Dominance Property of Vertex Embeddings:** From Eq. (3), the vertex dominance embedding  $o(v_i)$  is a combination of SPUR and SPAN vectors. Given any unit star subgraph  $g_{v_i}$  and its star substructure  $s_{v_i}$  (i.e.,  $s_{v_i} \subseteq g_{v_i}$ ), their vertex dominance embeddings always satisfy the *dominance* [11] (or equality) condition:  $o(s_{v_i})[j] \leq o(g_{v_i})[j]$ , for all dimensions  $1 \leq j \leq 2d$ , which is denoted as  $o(s_{v_i}) \leq o(g_{v_i})$  (including the case where  $o(s_{v_i}) = o(g_{v_i})$ ).

The reason for the property above is as follows. Since star patterns  $s_{v_i}$  and  $g_{v_i}$  have the same center vertex  $v_i$ , the vertex embeddings,  $o(s_{v_i})$  and  $o(g_{v_i})$ , for  $s_{v_i}$  and  $g_{v_i}$ , respectively, must share the same SPUR vector  $x_i$ . Moreover, since  $s_{v_i} \subseteq g_{v_i}$  holds, 1-hop neighbors of vertex  $v_i$  in  $s_{v_i}$  and  $g_{v_i}$  must satisfy the condition that  $N_{v_i}(s_{v_i}) \subseteq N_{v_i}(g_{v_i})$ . As the SPAN vectors are defined as the summed SPUR aggregates of 1-hop neighbors in  $N_{v_i}(s_{v_i})$  and  $N_{v_i}(g_{v_i})$ , respectively, we have the dominance relationship between SPAN vectors  $y_i(s_{v_i})$  and  $y_i(g_{v_i})$  (i.e.,  $y_i(s_{v_i}) \leq y_i(g_{v_i})$ ).

**LEMMA 4.1. (The Dominance Property of Vertex Embeddings)** Given a unit star subgraph  $g_{v_i}$  centered at vertex  $v_i$  and any of its star substructures  $s_{v_i}$  (i.e.,  $s_{v_i} \subseteq g_{v_i}$ ), their vertex dominance embeddings satisfy the condition that:  $o(s_{v_i}) \leq o(g_{v_i})$  (including  $o(s_{v_i}) = o(g_{v_i})$ ) in the embedding space.

**PROOF.** For a given unit star subgraph  $g_{v_i}$  centered at vertex  $v_i$  and any of its star substructures  $s_{v_i}$  (i.e.,  $s_{v_i} \subseteq g_{v_i}$ ), since they share the same center vertex  $v_i$  (i.e., with the same label  $l(v_i)$ ), they must have the same SPUR vector  $x_i$ .

Moreover, since  $s_{v_i} \subseteq g_{v_i}$  holds, we also have  $N_{v_i}(s_{v_i}) \subseteq N_{v_i}(g_{v_i})$ , where  $N_{v_i}(s_{v_i})$  (or  $N_{v_i}(g_{v_i})$ ) is a set of  $v_i$ 's 1-hop neighbors in subgraph  $s_{v_i}$  (or  $g_{v_i}$ ). Thus, for SPAN vectors  $y_i(s_{v_i})$  and  $y_i(g_{v_i})$  of  $s_{v_i}$  and  $g_{v_i}$ , respectively, it must hold that:  $y_i(s_{v_i})[k] \leq y_i(g_{v_i})[k]$  for all dimensions  $k$  (since we have  $y_i(s_{v_i})[k] = \sum_{\forall v_j \in N_{v_i}(s_{v_i})} x_j[k] \leq$

$\sum_{\forall v_j \in N_{v_i}(g_{v_i})} x_j[k] = y_i(g_{v_i})[k]$ ). In other words, their SPAN vectors satisfy the condition that  $y_i(s_{v_i}) \leq y_i(g_{v_i})$ . Therefore, for  $s_{v_i} \subseteq g_{v_i}$ , their vertex dominance embeddings satisfy the condition that:  $o(s_{v_i}) = (x_i \parallel y_i(s_{v_i})) \leq (x_i \parallel y_i(g_{v_i})) = o(g_{v_i})$  (including  $o(s_{v_i}) = o(g_{v_i})$ ) in the embedding space, which completes the proof.  $\square$

**The Usage of the Vertex Embedding Property:** Note that, a star substructure  $s_{v_i} (\subseteq g_{v_i})$  can be a potential query unit star subgraph  $s_{q_i}$  from the query graph  $q$  (containing a center query vertex  $q_i$  and its 1-hop neighbors) for dynamic subgraph matching.

During the subgraph matching, given a query embedding vector  $o(q_i)$  of query vertex  $q_i$ , we can identify those candidate matching vertices  $v_i$  in dynamic graph  $G_D$  with embeddings  $o(v_i)$  dominated by  $o(q_i)$ . This way, we can convert the dynamic subgraph matching problem into a dominance search problem in the embedding space.

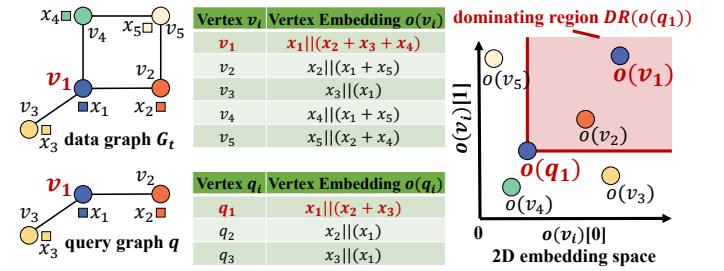


Figure 4: An example of vertex dominance embeddings in S-DSM ( $\parallel$  is the concatenation operation of two vectors).

**EXAMPLE 2.** Figure 4 shows an example of using our vertex dominance embedding for subgraph matching between a snapshot graph  $G_t$  and a query graph  $q$ . Based on Eq. (3), we can obtain the embedding for each vertex in  $G_t$  or  $q$ . For example, vertices  $v_1$  and  $q_1$  have the embeddings  $o(v_1) = x_1 \parallel (x_2 + x_3 + x_4)$  and  $o(q_1) = x_1 \parallel (x_2 + x_3)$ , respectively.

Since vertex  $q_1$  in  $q$  matches with vertex  $v_1$  in (a subgraph of)  $G_t$ , we can see that  $o(q_1)$  is dominating  $o(v_1)$  in a 2D embedding space (based on the property of vertex dominance embedding), which implies that  $g_{q_1}$  is potentially a subgraph of (i.e., matching with)  $g_{v_1}$ . Moreover, although  $o(v_2)$  is dominated by  $o(q_1)$ ,  $g_{v_2}$  does not match  $g_{q_1}$ . Thus, in this case, vertex  $v_2$  is a false positive during the subgraph candidate retrieval.

On the other hand, since  $o(q_1)$  is not dominating  $o(v_3)$  in the 2D embedding space, query vertex  $q_1$  cannot match with vertex  $v_3$  in graph  $G_t$ . ■

**Ease of Incremental Updates for Vertex Dominance Embeddings:** In the dynamic graph  $G_D$ , our proposed vertex dominance embedding  $o(v_i)$  can be incrementally maintained, upon graph update operations in  $\Delta G_t$ .

Specifically, any edge insertion ( $e+, t$ ) or deletion ( $e-, t$ ) (as given in Definition 4) will affect the embeddings of two ending vertices,  $v_i$  and  $v_j$ , of edge  $e = (v_i, v_j)$ . We consider an incremental update of the embedding vector  $o(v_i)$  for vertex  $v_i$  as follows.

- When  $v_i$  is a newly inserted vertex, we obtain its embedding vector  $o(v_i)$  from scratch (i.e.,  $o(v_i) = x_i \parallel x_j$ ), and;

- When  $v_i$  is an existing vertex in dynamic graph  $G_D$ , for an insertion (or deletion) operator of edge  $e = (v_i, v_j)$ , we update the SPAN vector,  $y_i$ , in  $o(v_i)$  with  $(y_i + x_j)$  (or  $(y_i - x_j)$ ), where  $x_j$  is the SPUR vector of vertex  $v_j$ .

The case of updating the embedding of vertex  $v_j$  is similar and thus omitted.

Note that, for each graph update (i.e., edge insertion ( $e+$ ,  $t$ ) or deletion ( $e-$ ,  $t$ )), the time complexity of incrementally updating vertex dominance embedding vectors is given by  $O(d)$ , where  $d$  is the dimension of SPUR/SPAN vectors.

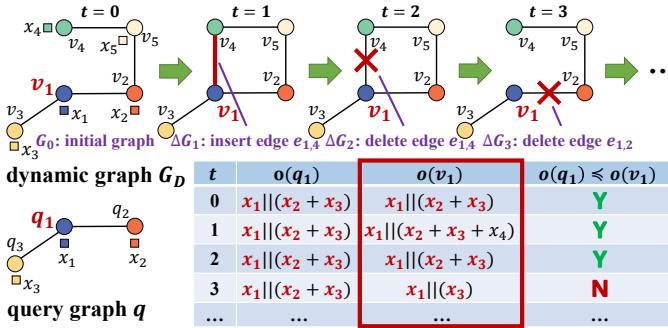


Figure 5: An example of vertex embeddings for C-DSM.

**EXAMPLE 3.** Figure 5 illustrates an example of using our vertex dominance embeddings to conduct the subgraph matching over dynamic graph  $G_D$  over time  $t$  from 0 to 3, where  $q$  is a given query graph. Consider two vertices  $v_1$  and  $q_1$  in graphs  $G_D$  and  $q$ , respectively. At timestamp  $t = 0$ , their vertex embeddings satisfy the dominance relationship, that is,  $o(q_1) \leq o(v_1)$ , thus, vertex  $v_1$  is a candidate matching with  $q_1$ .

At timestamp  $t = 1$ , a new edge  $e_{1,4}$  is inserted (i.e.,  $\Delta G_1$ ), and the vertex embedding  $o(v_1)$  changes from  $x_1||(x_2+x_3)$  to  $x_1||(x_2+x_3+x_4)$  (by including new neighbor  $v_4$ 's SPUR vector  $x_4$ ). Since  $o(q_1) \leq o(v_1)$  still holds,  $v_1$  remains a candidate matching with  $q_1$ .

At timestamp  $t = 2$ , since edge  $e_{1,4}$  is deleted (i.e.,  $\Delta G_2$ ), the vertex embedding  $o(v_1)$  changes back to  $x_1||(x_2+x_3)$ . At timestamp  $t = 3$ , edge  $e_{1,2}$  is deleted (i.e.,  $\Delta G_3$ ), and  $o(v_1)$  is updated with  $x_1||(x_3)$  (by removing the expired neighbor  $v_2$ 's SPUR vector  $x_2$ ). In this case,  $o(q_1) \leq o(v_1)$  does not hold, and vertex  $v_1$  fails to match with  $q_1$ . ■

#### 4.4 Embedding Optimization with Base Vector $z_i$

Figure 6 shows the distributions of 2D SPUR and SPAN vectors,  $x_i$  and  $y_i$ , respectively, in vertex dominance embedding  $o(v_i)$  over Yeast graph [58] (with 3,112 vertices and 12,519 edges). We can see that, in Figure 6(a), the SPUR vectors  $x_i$  generated by a seeded randomized function are distributed uniformly in the embedding space, whereas the SPAN vectors (i.e., the summed SPUR vectors)  $y_i$  are more clustered along the reverse diagonal line in Figure 6(a).

As mentioned in Section 4.3, given a query vertex  $q_i$ , we can use its embedding vector  $o(q_i)$  as a query point to find the dominated embedding vectors  $o(v_i)$  ( $= x_i || y_i$ ) in the 4D embedding space. Due to the scattered SPUR/SPAN vectors in the embedding space, it is very likely that some false alarms of embedding vectors  $o(v_i)$  are included as candidate matching vertices (i.e., dominated by  $o(q_i)$ ).

In order to further enhance the pruning power, our goal is to update our vertex dominance embedding vector from  $o(v_i)$  to  $o'(v_i)$ , such that the number of candidate vertices dominated by  $o(q_i)$  is reduced (i.e., as small as possible). Specifically, we have the optimized embedding  $o'(v_i)$ , given by:

$$o'(v_i) = \alpha(x_i || y_i) + \beta z_i = \alpha o(v_i) + \beta z_i, \quad (4)$$

where  $\alpha$  and  $\beta$  are positive constants ( $\alpha \ll \beta$ ), and  $z_i = f_2(l(v_i))$  is a random base vector of size  $(2d)$ , generated by a pseudo-random function  $f_2(\cdot)$  with  $l(v_i)$  as the seed. Please refer to Figure 3 on how to compute this optimized vertex dominance embedding.

Note that, since the base vector  $z_i$  is generated only based on the label  $l(v_i)$  of center vertex  $v_i$ , different star subgraphs with the same center vertex label  $l(v_i)$  will result in the same base vector  $z_i$ . Therefore, the new (optimized) vertex embedding vector  $o'(v_i)$  in Eq. (4) still follows the dominance relationship, that is,  $o'(q_i) \leq o'(v_i)$  holds, if a query star pattern  $s_{q_i}$  is a subgraph of unit star subgraph  $g_{v_i}$  (i.e.,  $s_{q_i} \subseteq g_{v_i}$  and  $l(q_i) \equiv l(v_i)$ ).

**LEMMA 4.2. (The Dominance Property of the Optimized Vertex Embeddings)** Given a unit star subgraph  $g_{v_i}$  centered at vertex  $v_i$  and any of its star substructures  $s_{v_i}$  (i.e.,  $s_{v_i} \subseteq g_{v_i}$ ), their optimized vertex embeddings (via base vector  $z_i$ ) satisfy the condition that:  $o'(s_{v_i}) \leq o'(g_{v_i})$  (including  $o'(s_{v_i}) = o'(g_{v_i})$ ).

**PROOF.** Given a unit star subgraph  $g_{v_i}$  centered at vertex  $v_i$  and any of its star substructures  $s_{v_i}$  (i.e.,  $s_{v_i} \subseteq g_{v_i}$ ), since they have the same center vertex  $v_i$  (with the same vertex label), their base vectors have the same values, i.e.,  $z_i(s_{v_i}) = z_i(g_{v_i})$ , or equivalently  $\beta z_i(s_{v_i}) = \beta z_i(g_{v_i})$  (for  $\beta > 0$ ).

Due to the property of vertex dominance embeddings (as given in Lemma 4.1), we have  $o(s_{v_i}) \leq o(g_{v_i})$ , or equivalently  $\alpha o(s_{v_i}) \leq \alpha o(g_{v_i})$  (for  $\alpha > 0$ ).

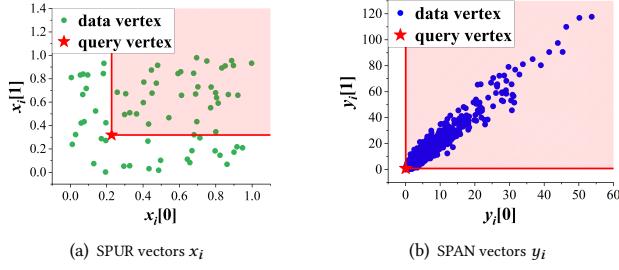
Therefore, we can derive that  $\alpha o(s_{v_i}) + \beta z_i(s_{v_i}) \leq \alpha o(g_{v_i}) + \beta z_i(g_{v_i})$ , or equivalently  $o'(s_{v_i}) \leq o'(g_{v_i})$  (including  $o'(s_{v_i}) = o'(g_{v_i})$ ), which completes the proof. □

**Discussions on How to Design a Base Vector,  $z_i$ :** To improve the pruning power, we would like to make the distribution of the updated vertex embeddings in Eq. (4) more dispersed along diagonal line (or plane), so that fewer false alarms (dominated by  $o'(q_i)$ ) can be obtained during dynamic subgraph matching.

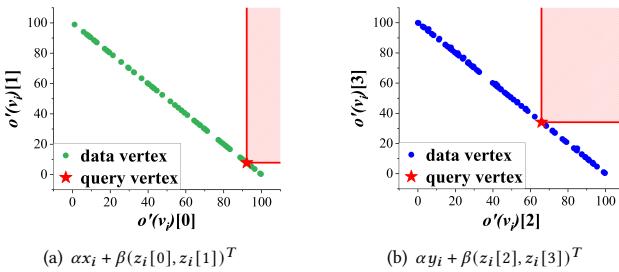
In this paper, we propose to design the base vector  $z_i$  as a random vector distributed on the unit diagonal line/hyperplane ( $L_1$ -norm) in the first quadrant. That is, we can normalize  $z_i$  to  $\frac{z_i}{\|z_i\|_1}$ , where  $\|\cdot\|_1$  is  $L_1$ -norm. Moreover, since constant  $\alpha$  is far smaller than  $\beta$ ,  $\alpha(x_i || y_i)$  can be considered as noises added to the scaled base vector  $\beta z_i$ . Thus, vertex embedding vectors  $o'(v_i)$  ( $= \alpha(x_i || y_i) + \beta z_i$ ) in Eq. (4) are still distributed close to a diagonal line (or hyperplane) in the first quadrant.

We would like to leave interesting topics of using other base vectors  $z_i$  (e.g.,  $L_2$ -norm) as our future work.

Figure 7 shows the distributions of the updated 2D SPUR and SPAN vectors (from  $o'(v_i)$ ), by adding a base vector  $z_i$ , where  $z_i$  is given by  $L_1$ -norm. Since we have  $\alpha \ll \beta$  in Eq. (4), we can see that after adding  $\alpha(x_i || y_i)$  to the scaled base vector  $\beta z_i$ , the previous embedding vector  $o(v_i)$  (as shown in Figure 6) is re-located close to diagonal lines in Figure 7. This way, we can reduce the number



**Figure 6: An example of SPUR/SPAN vector distributions in vertex dominance embedding  $o(v_i)$ .**



**Figure 7: An example of  $o'(v_i)$  distributions with  $L_1$ -norm diagonal-line base vector  $z_i$  ( $\alpha = 0.01, \beta = 100$ ).**

of vertex false alarms dominated by  $o(q_i)$  in both SPUR and SPAN spaces.

## 5 DEGREE-AWARE STAR SUBSTRUCTURE SYNOPSIS

In this section, we will build effective synopses over embeddings of star substructures of different degrees in dynamic graph  $G_t$ , which can be incrementally updated and support efficient S-DSM and C-DSM query processing.

### 5.1 Vertex Embedding via Degree Grouping

Note that, for the subgraph matching over a dynamic graph  $G_t$ , those vertices  $v_i \in V(G_t)$  with high degrees  $\deg(v_i)$  are less likely to be pruned in the embedding space. This is because, for high degrees, the SPAN vectors in  $o'(v_i)$  tend to have large values. Thus,  $o'(v_i)$  is more likely to be dominated by query embedding vector  $o'(q_i)$ , and treated as candidate vertices for the refinement (i.e.,  $v_i$  cannot be pruned).

To enhance the pruning power for high-degree vertices, in this subsection, we propose a novel and effective *degree grouping* technique, which separately maintains vertex embeddings,  $o'(v_i)$ , for star substructures  $s_{v_i}$  of different (lower) degree groups (instead of unit star subgraphs  $g_{v_i}$ ) in  $G_t$ .

**Equi-Frequency Degree Grouping:** One straightforward way to perform the degree grouping is to let each single degree value be a degree group. However, since vertex degrees in real-world graphs usually follow the power-law distribution [2, 5, 6, 16, 45], only a small fraction of vertices have high degrees. In other words, only a few unit star subgraphs  $g_{v_i}$  have star substructures  $s_{v_i}$  of very

high degrees, which is not space- and time-efficient to maintain in a dynamic graph  $G_t$ .

Inspired by this, in this paper, we propose to maintain vertex embeddings for star substructures with  $m$  degree groups (of different degree intervals). We assume that the degree statistics of the initial graph  $G_0$  are similar to that in  $G_t$ .

This way, we obtain the *probability mass function* of vertex degrees in  $G_0$  is  $pmf(\delta) = \frac{freq(deg(v_i) \geq \delta)}{|V(G_0)|}$ , where  $freq(deg(v_i) \geq \delta)$  is the number of vertices  $v_i \in V(G_0)$  whose degrees are greater than or equal to a degree value  $\delta$ . Our goal is to divide the degree interval,  $[1, deg_{max}]$ , into  $m$  degree groups  $\mathcal{B} = \{B_1, B_2, \dots, B_m\}$ , such that each *degree bucket*  $B_j (= (\delta_{j-1}, \delta_j])$  contains the same (or similar) mass in the distribution of  $pmf(\delta)$  (for  $\delta \in B_j$ ).

### 5.2 The Construction of Degree-Aware Star Substructure Synopses (DAS<sup>3</sup>)

Based on the degree grouping, we will construct  $m$  *degree-aware star substructure synopses* (DAS<sup>3</sup>),  $Syn_j$  (for  $1 \leq j \leq m$ ), which are essentially  $m$  grid files [24], respectively, that store (aggregated) vertex embeddings for star substructures in specific degree groups. **Data Structure of DAS<sup>3</sup> Synopses:** Specifically, each DAS<sup>3</sup> synopsis  $Syn_j$  partitions the embedding data space into cells,  $C$ , of equal size. Each grid cell  $C$  is associated with a list,  $C.list$ , of vertices  $v_i$ . Each vertex  $v_i \in C.list$  contains the following aggregates:

- an *embedding upper bound* vector,  $v_i.UB_\delta$ , for all star substructures  $s_{v_i}$  with center vertex degrees  $\delta \in (\delta_{j-1}, \delta_j]$ , and;
- a list of MBRs,  $v_i.MBR_\delta$  (for  $\delta \in (\delta_{j-1}, \delta_j]$ ), that minimally bound all embedding vectors,  $o'(s_{v_i})$ , of star substructures  $s_{v_i}$  with degrees equal to  $\delta$ .

To facilitate the access of cells in DAS<sup>3</sup> synopsis  $Syn_j$  efficiently, we sort all cells in descending order of their keys  $C.key$ . Here, for each cell  $C$ , we use  $C.CUB$  to denote its maximal corner point (i.e., taking the maximum value of the cell interval on each dimension). The key,  $C.key$ , is defined as  $\|C.CUB\|_2$ , where  $\|Z\|_2 = \sum_{i=1}^d Z[i]^2$  for a  $d$ -dimensional vector  $Z$ .

Note that, if a query vertex embedding  $o(q_i)$  dominates  $C.CUB$ , then the key  $\|o(q_i)\|_2$  of query vertex embedding  $o(q_i)$  must be smaller than or equal to the cell key  $C.key$ . Thus, with such a sorted list of cells, we can efficiently access all cells that are fully or partially dominated by a given query vertex embedding  $o(q_i)$ .

**DAS<sup>3</sup> Synopsis Construction:** Each DAS<sup>3</sup> synopsis  $Syn_j$  corresponds to a degree group  $B_j$  ( $1 \leq j \leq m$ ) with degree interval  $(\delta_{j-1}, \delta_j]$ .

We build the DAS<sup>3</sup> synopsis  $Syn_j$  as follows. For each vertex  $v_i$  with degree  $\deg(v_i) > \delta_{j-1}$  in  $G_t$  and for each degree value  $\delta$  ( $\in (\delta_{j-1}, \delta_j]$ ), we obtain all its star substructures,  $s_{v_i}$ , with degrees of center vertex  $v_i$  equal to  $\delta$ , compute their embedding vectors  $o'(s_{v_i})$ , and use a *minimum bounding rectangle* (MBR),  $v_i.MBR_\delta$ , to minimally bound these embedding vectors.

Let  $v_i.UB_\delta$  is the maximum corner point of the MBR  $v_i.MBR_\delta$  (by taking the upper bound of the MBR on each dimension). Then, for vertex  $v_i$ , we insert vertex  $v_i$  into the vertex list,  $C.list$ , of a cell  $C \in \mathcal{I}_j$ , into which corner point  $v_i.UB_{ub,\delta}$  falls, where degree upper bound  $ub_\delta = \min\{\deg(v_i), \delta_j\}$ . Intuitively, this corner point

$v_i.UB_{ub,\delta}$  is the one most likely to be dominated by a query vertex embedding  $o'(q_i)$  in this degree group  $B_j$ .

Moreover, we also associate corner point  $v_i.UB_{ub,\delta}$  with the list of MBRs,  $v_i.MBR_\delta$  (for each  $\delta \in (\delta_{j-1}, ub_\delta]$ ), in synopsis  $Syn_j$ , which can be used for further pruning for a specific degree in interval  $(\delta_{j-1}, \delta_j]$ .

**Discussions on MBR Computations and Incremental Maintenance:** Note that, the MBRs,  $v_i.MBR_\delta$ , mentioned above minimally bound embedding vectors  $o'(v_i)$  for all star substructures  $s_{v_i}$ . Since there are an exponential number of possible star structures (i.e.,  $2^{deg(v_i)}$ ), it is not efficient to enumerate all star substructures, compute their embedding vectors, and obtain the MBRs. Therefore, in this paper, we propose a sorting-based method to obtain  $v_i.MBR_\delta$  without enumerating all star substructures with degree  $\delta$ .

Specifically, for each vertex  $v_i$ , we maintain  $d$  sorted lists, each of which,  $v_i.spur\_list_k$  (for  $1 \leq k \leq d$ ), contains the  $k$ -th elements,  $y_j[k]$ , of SPUR vectors  $y_j$  (obtained from  $v_i$ 's 1-hop neighbors  $v_j \in N(v_i)$ ) in ascending order.

For a degree  $\delta$  in the degree group  $B_j = (\delta_{j-1}, \delta_j]$ , we obtain lower and upper bounds of MBR  $v_i.MBR_\delta$ , that is,  $v_i.MBR_\delta[2k]$  and  $v_i.MBR_\delta[2k+1]$ , respectively, as follows:

$$v_i.MBR_\delta[2k] = \sum_{deg \in [1, \delta]} v_i.spur\_list_k[deg], \quad (5)$$

$$v_i.MBR_\delta[2k+1] = \sum_{deg \in [deg(v_i) - \delta + 1, deg(v_i)]} v_i.spur\_list_k[deg], \quad (6)$$

where  $deg(v_i)$  is the degree of vertex  $v_i$  in  $G_t$  (or the size of the sorted list  $v_i.spur\_list_k$ ).

Intuitively, Eqs. (5) and (6) give the lower/upper bounds of the MBR  $v_i.MBR_\delta$  on the  $k$ -th dimension, by summing up the first  $\delta$  and the last  $\delta$  values, respectively, in the sorted list  $v_i.spur\_list_k$ .

**The Time Complexity of the MBR Maintenance:** The time complexity of sorting the  $k$ -th dimension of SPUR vectors (for  $1 \leq k \leq d$ ) is given by  $O(d \cdot deg(v_i) \cdot log(deg(v_i)))$ , which is much less than that of enumerating all star substructures (i.e.,  $O(d \cdot 2^{deg(v_i)})$ ).

For the maintenance of a sorted list  $v_i.spur\_list_k$  in dynamic graph  $G_t$ , upon edge insertion or deletion (or insertion/deletion of a 1-hop neighbor  $v_j$ ), we can use a binary search to locate where we need to insert into (or remove from)  $v_i.spur\_list_k$  elements  $y_j[k]$  in the SPUR vector  $y_j$ . Therefore, the time complexity of incrementally maintaining  $d$  sorted lists  $v_i.spur\_list_k$  is given by  $O(d \cdot log_2(deg(v_i)))$ .

## 6 S-DSM AND C-DSM QUERY PROCESSING

In this section, we illustrate query processing algorithms based on vertex dominance embeddings in DAS<sup>3</sup> synopses to efficiently answer S-DSM and C-DSM queries.

### 6.1 Synopsis Pruning Strategies

Given a query vertex  $q_i$  in the query graph  $q$  and SAS<sup>3</sup> synopses  $Syn_j$ , we would like to obtain candidate vertices  $v_i$  from synopsis  $Syn_j$  which may match with the query vertex  $q_i$ , where  $deg(q_i)$  falls into the degree group  $B_j = (\delta_{j-1}, \delta_j]$ .

In this subsection, we present two effective pruning methods over index  $Syn_j$ , named *embedding dominance pruning* and *MBR range pruning*, which are used to rule out false alarms of cells/vertices.

**Embedding Dominance Pruning:** We first provide the embedding dominance pruning method, which filters out those cells/vertices in synopsis  $Syn_j$  that are not dominated by a given query embedding vector  $o'(q_i)$ .

**LEMMA 6.1. (Embedding Dominance Pruning)** *Given a query embedding vector  $o'(q_i)$  of the query vertex  $q_i$ , any cell  $C$  or vertex  $v_i$  can be safely pruned, if  $o'(q_i)$  does not dominate any portion of cell  $C$  or embedding upper bound vector  $v_i.UB_\delta$ .*

**PROOF.** If a query vertex  $q_i$  in query graph  $q$  matches with a data vertex  $v_i$  in a subgraph of the data graph, then their vertex dominance embeddings must hold that  $o'(q_i) \leq o'(v_i)$ . Therefore, if  $o'(q_i)$  does not dominate the cell  $C$ , then  $o'(q_i)$  cannot dominate any vertex  $o'(v_i)$  inside cell  $C$ , and all vertices in cell  $C$  (or cell  $C$ ) can be safely pruned.

Moreover, if  $o'(q_i)$  does not dominate embedding upper bound vector  $v_i.UB_\delta$ , i.e.,  $v_i.UB_\delta \notin DR(o'(q_i))$ , then  $o'(q_i)$  does not dominate any star substructure  $s_{v_i}$  with center vertex  $v_i$  and the corresponding degree group. In other words,  $q_i$  does not match with  $v_i$ . Thus, vertex  $v_i$  can be safely pruned.  $\square$

**MBR Range Pruning:** Next, we give an effective *MBR range pruning* method, which further utilizes the MBR ranges,  $v_i.MBR_\delta$ , of star substructure embeddings and prunes vertices  $v_i$  that do not fall into the MBRs.

**LEMMA 6.2. (MBR Range Pruning)** *Given a query embedding  $o'(q_i)$  of the query vertex  $q_i$  and a vertex  $v_i$  in a cell of DAS<sup>3</sup> synopsis  $Syn_j$  (for  $deg(q_i) \in (\delta_{j-1}, \delta_j]$ ), vertex  $v_i$  can be safely pruned, if it holds that  $o'(q_i) \notin v_i.MBR_{deg(q_i)}$ .*

**PROOF.** The MBR  $v_i.MBR_{deg(q_i)}$  minimally bounds vertex embeddings for all possible star substructures  $s_{v_i}$  with center vertex  $v_i$  and degree  $deg(q_i)$ . Thus, if query vertex  $q_i \in V(q)$  and its 1-hop neighbors match with some star substructures with the same degree  $deg(q_i)$ , then its query embedding vector  $o'(q_i)$  must fall into this MBR  $v_i.MBR_{deg(q_i)}$ . Therefore, if this condition does not hold, i.e.,  $o'(q_i) \notin v_i.MBR_{deg(q_i)}$ , then  $q_i$  does not match with  $v_i$ , and  $v_i$  can be safely pruned, which completes the proof.  $\square$

### 6.2 S-DSM Query Answering

Algorithm 2 illustrates the S-DSM query answering algorithm over a snapshot  $G_t$  of a dynamic subgraph  $G_D$ , by traversing the synopses over vertex dominance embeddings. Specifically, given a query graph  $q$ , we first obtain vertex dominance embeddings  $o'(q_i)$  for each query vertex  $q_i \in V(q)$  (line 1), and then traverse DAS<sup>3</sup> synopses,  $Syn_j$ , to retrieve vertex candidate sets  $q_i.cand\_set$  (lines 2-8). Next, we generate a query plan  $Q$ , which is an ordered list of connected query vertices that can be used to join their corresponding candidate vertices (lines 9-10). Finally, we assemble candidate vertices into candidate subgraphs, and refine candidate subgraphs by the *left-deep join based method* [37, 53] by invoking function  $Refinement(\cdot)$ , and return S-DSM answers in  $A(q, t)$  (lines 11-13).

**The Synopsis Search:** For each query vertex  $q_i \in V(q)$ , we first need to find a synopsis  $Syn_j$  that matches the degree group of  $q_i$  (i.e.,  $deg(q_i) \in (\delta_{j-1}, \delta_j]$  must hold; line 3).

---

**Algorithm 2: The Algorithm for Answering Snapshot Dynamic Subgraph Matching (S-DSM) Query**


---

**Input:** i) a snapshot graph  $G_t$  at current timestamp  $t$ ; ii) a DAS<sup>3</sup> synopsis  $Syn_j$  on  $G_t$ , and; iii) a query graph  $q$

**Output:** a set,  $A(q, t)$ , of subgraph matching results

```

1 compute vertex dominance embeddings  $o'(q_i)$  for all query
  vertices  $q_i \in V(q)$ 
// traverse DAS3 synopses  $Syn_j$  to retrieve
  candidate vertices
2 for each query vertex  $q_i \in V(q)$  do
3   obtain a synopsis  $Syn_j$  such that  $\deg(q_i) \in (\delta_{j-1}, \delta_j]$ 
4   for each cell  $C \in Syn_j$  with  $C.key \geq ||o'(q_i)||_2$  do
5     for each candidate vertex  $v_i \in C.list$  do
6       if  $o'(q_i) \leq v_i.UB_\delta$  then
7         if  $o'(q_i) \in v_i.MBR_{\deg(q_i)}$  then
8            $q_i.cand\_set \leftarrow q_i.cand\_set \cup \{v_i\}$ 
           // Lemmas 6.1 and 6.2
// generate a query plan  $Q$ 
9 select a query vertex  $q_i$  with the smallest candidate set size
   $|q_i.cand\_set|$  as the first query vertex in an ordered list  $Q$ 
10 iteratively select a neighbor  $q_k$  of  $q_i \in Q$  with minimum
   $|q_k.cand\_set|$  and append  $q_k$  to  $Q$ , until all query vertices
  in  $V(q)$  have been added to  $Q$ 
// assemble and refine candidate subgraphs
11  $A(q, t) \leftarrow \emptyset$ 
12 invoke Refinement( $q, Q, G_t, A(q, t), \emptyset, 0$ ) to obtain actual
  S-DSM query answers in  $A(q, t)$ 
13 return  $A(q, t)$ ;

```

---

As mentioned in Section 5.2, cells,  $C$ , in the DAS<sup>3</sup> synopsis  $Syn_j$  are sorted in descending order of their keys  $C.key$ . We thus only need to search for those cells  $C \in Syn_j$  satisfying the condition that  $C.key \geq ||o'(q_i)||_2$  (line 4). Then, for each candidate vertex  $v_i \in C.list$ , we apply our proposed embedding dominance and MBR range pruning strategies (as discussed in Lemmas 6.1 and 6.2, respectively), and obtain the candidate vertex set,  $q_i.cand\_set$ , for the query vertex  $q_i$  (lines 5-8).

**Query Plan Generation:** After obtaining candidate vertices, we generate a query plan  $Q$  for refinement. Intuitively, we would like to reduce the size of intermediate join results. Therefore, we first initialize  $Q$  with a query vertex  $q_i \in V(q)$  having the minimum candidate set size  $|q_i.cand\_set|$  (line 9), and then iteratively add to  $Q$  the one,  $q_k$ , that is connected with those selected query vertices in  $Q$  and having the smallest  $|q_k.cand\_set|$  value (line 10).

**Refinement:** Algorithm 3 uses a *left-deep join based method* [37, 53] to assemble candidate vertices in  $q_i.cand\_set$  into candidate subgraphs, and obtain the actual matching subgraph answer set  $A(q, t)$  (i.e., lines 11-13 of Algorithm 2).

Specifically, we maintain a vertex vector  $M$  that will store vertices of the subgraph  $g$  matching with ordered query vertices in  $Q$ . To enumerate all matching subgraphs, each time we recursively expand partial matching results by including a new candidate vertex  $u$  as  $M[n]$  that maps with the  $n$ -th query vertex  $Q[n]$ . If we find all vertices in  $M$  mapping with  $Q$  (i.e., recursion depth  $n = |Q|$ ), then

---

**Algorithm 3: Refinement**


---

**Input:** i) a query graph  $q$ ; ii) a sorted list (query plan)  $Q$ ; iii) a snapshot graph  $G_t$ ; iv) matching results set  $A$ ; v) a sorted list,  $M$ , of vertices matching with query vertices in  $Q$ , and; vi) the recursion depth  $n$

**Output:** a set,  $A$ , of subgraph matching results

```

1 if  $n = |Q|$  then
2    $A \leftarrow A \cup \{M\}$ 
3   return;
4 else
5    $S_{cand} = \emptyset$ 
6   if  $n = 0$  then
7      $S_{cand} \leftarrow S_{cand} \cup Q[0].cand\_set$ 
8   else
9     for each candidate vertex  $u \in Q[n].cand\_set$  and
       $u \notin M$  do
10       if edges  $(M[i], u)$  exist in  $E(G_t)$  for all edges
         $(Q[i], Q[n]) \in E(q)$  (for  $0 \leq i < n$ ) then
11          $S_{cand} \leftarrow S_{cand} \cup \{u\}$ 
12 for each candidate vertex  $u \in S_{cand}$  do
13    $M[n] = u$ 
14   Refinement( $q, Q, G_t, A, M, n + 1$ );

```

---

we can add  $M$  to the answer set  $A$  (lines 1-3). Otherwise, we will find a vertex candidate set  $S_{cand}$  from  $Q[n].cand\_set$ , such that each vertex  $u$  in  $S_{cand}$  has the same edge connections to that in  $M$  as that in  $Q$  (lines 5-11). Next, for each vertex  $u \in S_{cand}$ , we treat it as vertex  $M[n]$  matching with  $Q[n]$ , and recursively call function Refinement(·) with more depth  $n + 1$  (lines 13-17).

After the recursive function Refinement(·) has been executed, the answer set  $A$  (or  $A(q, t)$  in Algorithm 3) will contain a set of actual subgraph matching results.

**Complexity Analysis:** In Algorithm 2, since we need to access each query vertex  $q_i$  and its 1-hop neighbors  $N_{q_i}$ , the time complexity of computing vertex dominance embeddings  $o'(q_i)$  (line 1) is given by  $O(|V(q)| + |E(q)|)$ .

For the synopsis traversal (lines 2-8), assume that  $PP_C$  is the pruning power of the cells' key value and  $PP_v$  is the pruning power in each cell's point list. Thus, the synopsis traversal cost is  $O(|V(q)| \cdot (1 - PP_C)K^d \cdot (1 - PP_v)|C.list|)$ , where  $K^d$  is the number of cells and  $|C.list|$  is the number of vertices in the cell  $C$ .

Next, for the greedy-based query plan generation (lines 9-10), we need to iteratively select a neighbor of vertices in the query plan  $Q$ , which requires  $O(|V(q)|^2)$  cost.

Finally, we invoke the recursive function Refinement(·) to find actual subgraph matching results (lines 11-13), with the worst-case time complexity  $O(\prod_{i=0}^{|V(q)|-1} |q_i.cand\_set|)$ .

Therefore, the overall time complexity of Algorithm 2 is given by:  $O(|V(q)| + |E(q)| + |V(q)| \cdot (1 - PP_C)K^d \cdot (1 - PP_v)|C.list| + \prod_{i=0}^{|V(q)|-1} |q_i.cand\_set| + |V(q)|^2)$ .

### 6.3 C-DSM Query Answering

In this subsection, we illustrate the C-DSM query answering algorithm in Algorithm 4. Given a dynamic graph  $G_{t-1}$  at timestamp

( $t - 1$ ), a registered query graph  $q$ , and a graph update operation  $\Delta G_t$  at timestamp  $t$ , C-DSM algorithm aims to find an updated subgraph matching answer set,  $A(q, t)$ , at timestamp  $t$ .

Specifically, if the graph update operation  $\Delta G_t$  is an insertion of edge  $e = (v_i, v_j)$ , we will calculate an incremental update,  $\Delta A(q, t)$ , of new subgraph matching results (lines 1-11).

**Edge Insertion:** For the insertion of an edge  $e = (v_i, v_j)$ , we will first find matching edge(s)  $(q_i, q_j)$  in the query graph with the same keywords (line 3). Then, we will check whether or not edges  $(v_i, v_j)$  and  $(q_i, q_j)$  match each other, by applying the *embedding dominance* and *MBR range pruning* strategies (described in Section 6.1; lines 4-5). If the answer is yes, then we will generate a new query plan  $Q'$  starting from query vertices  $q_i$  and  $q_j$  (note: the remaining ones are obtained from  $Q$ , similar to line 10 of Algorithm 2; line 7), initialize the first two matching vertices  $v_i$  and  $v_j$  in a sorted list  $M'$  (lines 8-9), and invoke the function  $\text{Refinement}(\cdot)$  with parameters of new query plan  $Q'$ , incremental answer set  $\Delta A(q, t)$ , the initialized sorted list  $M'$ , and recursion depth  $n = 2$  (as two matching vertices have been found; line 10). After that, we can update the answer set  $A(q, t)$  with  $A(q, t - 1) \cup \Delta A(q, t)$  (line 11).

**Edge Deletion:** When  $\Delta G_t$  is an edge deletion operation  $(e-, t)$ , we can simply remove those existing subgraph matching answers  $g \in A(q, t - 1)$  which contain the deleted edge  $e$ , and obtain the updated answer set  $A(q, t)$  (lines 12-16).

Finally, we return the latest C-DSM query answer set  $A(q, t)$  at timestamp  $t$  (line 17).

**Complexity Analysis:** In Algorithm 4, for the edge insertion operation, we check all query edges, generate a new query plan  $Q'$ , and refine new candidate subgraphs with the new edge (lines 1-11). Therefore, the worst-case time complexity is given by  $O((|V(q)|^2 + \prod_{i=2}^{|V(q)|-1} |Q'[i].cand\_set|) \cdot |E(q)|)$ .

For the edge deletion operation (lines 12-16), since we delete matching results from  $A(q, t - 1)$  that contain the deleted edge, by using the hash file to check the edge existence with  $O(1)$  cost, the time complexity is given by  $O(|A(q, t - 1)|)$ .

## 7 COST-MODEL-GUIDED EMBEDDING OPTIMIZATION

In this section, we will design a novel cost model for evaluating the pruning power of our proposed vertex dominance embedding technique. Then, we will utilize this cost model to guide the embeddings and achieve better performance of dynamic subgraph matching.

### 7.1 Cost Model for Dynamic Subgraph Matching via Vertex Embeddings

In this subsection, we will propose a cost model to evaluate the performance of our dynamic subgraph matching (or the pruning power of using vertex dominance embeddings).

Specifically, we estimate the number,  $\text{Cost}_{\text{DSM}}$ , of candidate vertices  $v_i$  (to retrieve and refine) whose embedding vectors  $o'(v_i)$  are dominated by query embedding vector  $o'(q_i)$  (given by Lemma 6.1). That is, we have:

$$\text{Cost}_{\text{DSM}} = \sum_{v_i \in V(G_t)} \prod_{j=1}^{2d} \Pr\{o'(q_i)[j] \leq o'(v_i)[j]\}, \quad (7)$$

---

### Algorithm 4: The Query Answering Algorithm for Continuous Dynamic Subgraph Matching Query

---

```

Input: i) a dynamic graph  $G_{t-1}$  at previous timestamp
       ( $t - 1$ ); ii) a graph update operation  $\Delta G_t$ ; iii) a
       registered query graph  $q$ , and; iv) matching result set
        $A(q, t - 1)$  at timestamp ( $t - 1$ )
Output: an updated set,  $A(q, t)$ , of subgraph matching
       results at timestamp  $t$ 
// edge insertion operation  $\Delta G_t = (e+, t)$ 
1 if  $\Delta G_t = (e+, t)$  for edge  $e = (v_i, v_j)$  then
2    $\Delta A(q, t) \leftarrow \emptyset$ 
3   for each query edge  $(q_i, q_j) \in E(q)$  with keywords
      matching with that of  $(v_i, v_j)$  do
        // check whether  $(v_i, v_j)$  matches  $(q_i, q_j)$ 
4       if  $o'(q_i) \leq o'(v_i)$  and  $o'(q_j) \leq o'(v_j)$  then
5         if  $o'(q_i) \in v_i.\text{MBR}_{\text{deg}}(q_i)$  and
             $o'(q_j) \in v_j.\text{MBR}_{\text{deg}}(q_j)$  then
6           // Lemmas 6.1 and 6.2
7           generate a query plan  $Q'$  by using  $q_i$  and  $q_j$ 
           as the first two query vertices and the
           remaining ones from  $Q$ 
8            $M'[0] = v_i$ 
9            $M'[1] = v_j$ 
10          invoke  $\text{Refinement}(q, Q', G_t, \Delta A(q, t), M', 2)$ 
           to incrementally obtain new matching
           results in  $\Delta A(q, t)$ 
11          $A(q, t) \leftarrow A(q, t - 1) \cup \Delta A(q, t)$ 
12 else
13   // edge deletion operation  $\Delta G_t = (e-, t)$  for
     edge  $e = (v_i, v_j)$ 
14    $A(q, t) = A(q, t - 1)$ 
15   for each subgraph answer  $g \in A(q, t - 1)$  do
16     if edge  $(v_i, v_j)$  exists in  $E(g)$  then
17        $A(q, t) \leftarrow A(q, t) - \{g\}$ 
17 return  $A(q, t)$ 

```

---

where  $2d$  is the dimension of the embedding vector  $o'(\cdot)$ , and  $\Pr\{\cdot\}$  is a probability function.

**Analysis of the Cost Model:** We consider  $o'(v_i)[j]$  as a random number generated from a random variable, with mean  $\mu_{o'(v_i)[j]}$  and variance  $\sigma_{o'(v_i)[j]}^2$ . Moreover,  $o'(q_i)[j]$  can be considered as a constant. We have the following equation:

$$\begin{aligned}
 & \Pr\{o'(q_i)[j] \leq o'(v_i)[j]\} \\
 = & \Pr\{o'(q_i)[j] - o'(v_i)[j] \leq 0\} \\
 = & \Pr\left\{\frac{(o'(q_i)[j] - o'(v_i)[j]) - (\mu_{o'(v_i)[j]} - \mu_{o'(v_i)[j]})}{\sigma_{o'(v_i)[j]}^2}\right\} \\
 & \leq \frac{-(o'(q_i)[j] - \mu_{o'(v_i)[j]})}{\sigma_{o'(v_i)[j]}^2} \}.
 \end{aligned} \quad (8)$$

By applying *Central Limit Theorem* (CLT) [69] to Eq. (8), we have:

$$\Pr\{o'(q_i)[j] \leq o'(v_i)[j]\} \approx \Phi\left(\frac{\mu_{o'(v_i)}[j] - o'(q_i)[j]}{\sigma_{o'(v_i)}^2[j]}\right), \quad (9)$$

where  $\Phi(\cdot)$  is the *cumulative density function* (cdf) of *standard normal distribution*.

We substitute Eq. (9) into Eq. (7) and obtain:

$$Cost_{DSM} = |V(G_t)| \cdot \prod_{j=1}^{2d} \Phi\left(\frac{\mu_{o'(v_i)}[j] - o'(q_i)[j]}{\sigma_{o'(v_i)}^2[j]}\right). \quad (10)$$

## 7.2 Design of Cost-Model-Based Vertex Dominance Embeddings

Eq. (10) estimates the (worst-case) query cost for one query vertex  $q_i$  during the dynamic subgraph matching. Intuitively, our goal is to design vertex embeddings  $o'(\cdot)$  that minimizes the cost model  $Cost_{DSM}$  (given in Eq. (10)).

Note that,  $\Phi(\cdot)$  in Eq. (10) is a monotonically increasing function. Therefore, if we can minimize the term  $\frac{\mu_{o'(v_i)}[j] - o'(q_i)[j]}{\sigma_{o'(v_i)}^2[j]}$  in Eq. (10), then low query cost  $Cost_{DSM}$  can be achieved. In other words, guided by our proposed cost model (to minimize the query cost  $Cost_{DSM}$ ), **our target is to design/select a “good” distribution of vertex dominance embeddings  $o'(v_i)$  with:**

- (1) **low mean**  $\mu_{o'(v_i)}[j]$ , and;
- (2) **high variance**  $\sigma_{o'(v_i)}^2[j]$ .

In this paper, unlike standard vertex dominance embeddings generated by *Uniform* random function  $f_1(\cdot)$  (as discussed in Section 4.2), we choose to use a (seeded) *Zipf* random function to produce SPUR vectors  $x_i$  in vertex embeddings  $o'(v_i)$  (or in turn generate SPAN vectors  $y_i = \sum x_j$ ). The *Zipf* distribution exactly follows our target of finding a random variable with low mean and high variance, which can achieve low query cost, as guided by our proposed cost model  $Cost_{DSM}$  (given in Eq. (7)). We would like to leave the interesting topic of studying other low-mean/high-variance distributions as our future work.

**Discussions on the Seeded Zipf Generator:** We consider two distributions, *Uniform* and *Zipf*, each of which is divided to  $b$  buckets with the same area. This way, we create a 1-to-1 mapping between buckets in a *Uniform* distribution and that in a *Zipf* distribution. Given a seeded pseudo-random number,  $r$ , from the *Uniform* distribution, we can first find the bucket this *Uniform* random number falls into, obtain its corresponding bucket in the *Zipf* distribution, and compute its proportional location  $r'$  in the *Zipf* bucket. As a result,  $r'$  is the random number that follows the *Zipf* distribution.

**Integration of the Cost-Model-Based Vertex Embeddings into our Dynamic Subgraph Matching Framework:** In light of our cost model above, we design a novel cost-model-based vertex dominance embedding, denoted as  $o'_C(v_i)$ , for each vertex  $v_i$ , that is:

$$o'_C(v_i) = \alpha(x'_i || y'_i) + \beta z_i, \quad (11)$$

where  $x'_i = f_Z(l(v_i))$  is the newly designed SPUR vector generated by a seeded *Zipf* random generator  $f_Z(\cdot)$ , and  $y'_i = \sum_{v_j \in N_{v_i}} x'_j$ .

Note that, since the SPAN vector  $y'_i$  in Eq. (11) is given by  $\sum_{v_j \in N_{v_i}} x'_j$ , its distribution still follows the property of low mean and high variance to achieve low query cost.

## 8 EXPERIMENTAL EVALUATION

### 8.1 Experimental Settings

To evaluate the effectiveness and efficiency of our S-DSM/C-DSM approaches, we conduct experiments on a Ubuntu server equipped with an Intel Core i9-12900K CPU and 128GB memory. Our approach is implemented in C++. Our source code and real/synthetic graph data sets are available at URL: <https://anonymous.4open.science/r/DSM-0D2E>.

**Real/Synthetic Graph Data Sets:** We evaluate our S-DSM/C-DSM approaches over both real and synthetic graphs.

**Real-world graphs.** We test five real-world graph data used by previous works [8, 9, 26, 27, 30, 39, 41, 51, 53, 58, 60, 73], which can be classified into three categories: i) biology networks (Yeast and HPRD); ii) bibliographical/social networks (DBLP and Youtube), and; iii) citation networks (US Patents). Statistics of these real graphs are summarized in Table 2.

**Synthetic graphs.** We generate synthetic graphs via NetworkX [25], and produce small-world graphs following the Newman-Watts-Strogatz model [68]. Parameter settings of synthetic graphs are depicted in Table 3. For each vertex  $v_i$ , we generate its label  $l(v_i)$  by randomly picking up an integer within  $[1, |\Sigma|]$ , following the *Uniform*, *Gaussian*, or *Zipf* distribution. Accordingly, we obtain 3 types of graphs, denoted as *Syn-Uni*, *Syn-Gau*, and *Syn-Zipf*, resp.

The insertion (or deletion) rate is defined as the ratio of the number of edge insertions (or deletions) to the total number of edges in the raw graph data. Following the literature [14, 40, 43, 59], we set the insertion rate to 10% by default (i.e., the initial graph  $G_0$  contains 90% edges, and the remaining 10% edges arrive as the insertion stream).

**Query Graphs:** Similar to previous works [3, 8, 9, 26, 27, 39, 51, 59, 60], for each graph  $G_D$ , we randomly extract/sample 100 connected subgraphs as query graphs, where parameters of query graphs  $q$  (e.g.,  $|V(q)|$  and  $avg\_deg(q)$ ) are depicted in Table 3.

**Baseline Methods:** We compare our S-DSM/C-DSM approaches (using the cost-model-based vertex dominance embeddings  $o'_C(v_i)$ , as discussed in Section 7) with five representative baseline methods of dynamic subgraph matching as follows:

- (1) **Graphflow (GF)** [37] is a direct-incremental algorithm that enumerates updates of matching results without any auxiliary data structure.
- (2) **SJ-Tree (SJ)** [14] is an index-based incremental method that evaluates the join query with binary joins using the index.
- (3) **TurboFlux (TF)** [40] is an index-based incremental method that stores matches of paths in  $q$  without materialization and evaluates the query with the vertex-at-a-time method.
- (4) **SymBi (Sym)** [43] is an index-based incremental method that prunes candidate vertex sets using all query edges.
- (5) **IEDyn (IED)** [33, 34] is an index-based incremental method that supports acyclic queries and can achieve constant delay enumeration under the setting of graph homomorphism.

We used the code of baseline methods from [59], which is implemented in C++ for a fair comparison.

**Evaluation Metrics:** In our experiments, we report the efficiency of our S-DSM/C-DSM approaches and baseline methods, in terms of the *wall clock time*. In particular, the S-DSM efficiency includes the

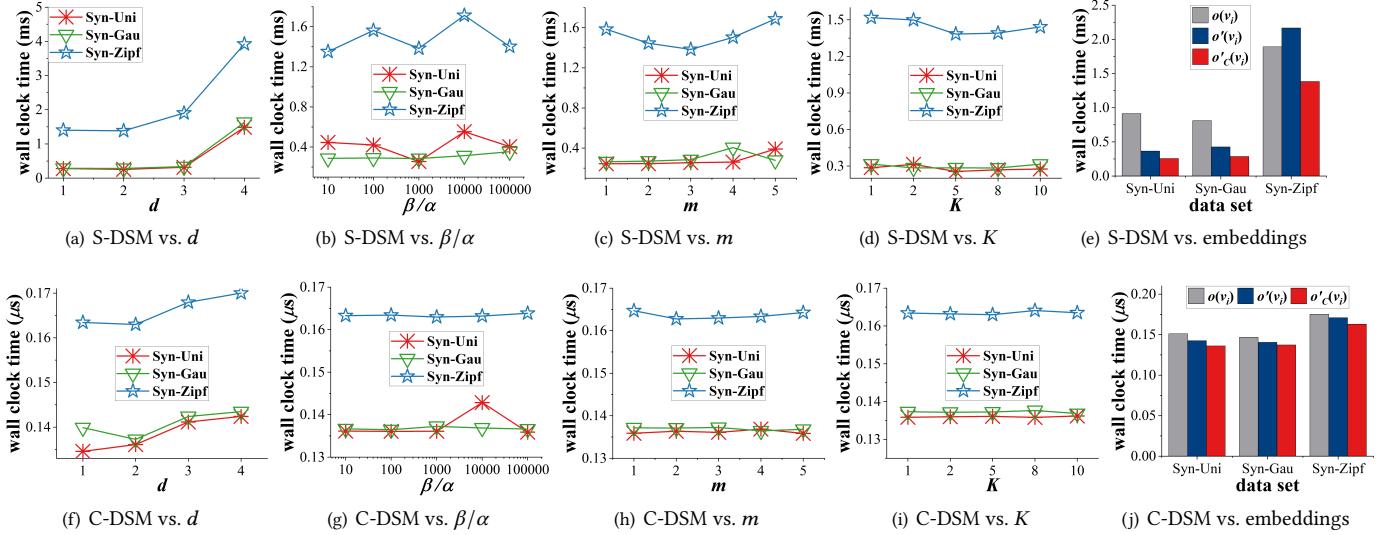
Figure 8: The S-DSM/C-DSM efficiency w.r.t parameters  $d$ ,  $\beta/\alpha$ ,  $m$ ,  $K$ , and embedding design strategies.

Table 2: Statistics of real-world graph data sets.

Data Sets	$ V(G) $	$ E(G) $	$ \Sigma $	$avg\_deg(G)$
Yeast (ye)	3,112	12,519	71	8.0
HPRD (hp)	9,460	34,998	307	7.4
DBLP (db)	317,080	1,049,866	15	6.6
Youtube (yt)	1,134,890	2,987,624	25	5.3
US Patents (up)	3,774,768	16,518,947	20	8.8

Table 3: Parameter settings.

Parameters	Values
the dimension, $d$ , of the SPUR/SPAN vector	1, 2, 3, 4
the ratio, $\beta/\alpha$	10, 100, <b>1,000</b> , 10,000, 100,000
the number, $m$ , of degree groups	1, 2, 3, 4, 5
the number, $K$ , of cell intervals in each dimension of $Syn_j$	1, 2, 5, 8, 10
the number, $ \Sigma $ , of distinct labels	5, 10, 15, 20, 25
the average degree, $avg\_deg(q)$ , of the query graph $q$	2, 3, 4
the size, $ V(q) $ , of the query graph $q$	5, 6, 8, 10, 12
the average degree, $avg\_deg(G_D)$ , of dynamic graph $G_D$	3, 4, 5, 6, 7
the size, $ V(G_D) $ , of the dynamic data graph $G_D$	10K, 30K, <b>50K</b> , 80K, 100K, 500K, 1M

time costs of filtering, refinement, and synopsis updates, whereas the C-DSM efficiency includes the time costs of filtering, refinement, and embedding updates, for each C-DSM query at each timestamp. We also evaluate the *pruning power* of our *embedding dominance pruning* and *MBR range pruning* strategies (as mentioned in Section 6.1), which is defined as the percentage of vertices that can be ruled out by our pruning methods. For all the experiments, we take an average of each metric over 100 runs (w.r.t. 100 query graphs, resp.).

Table 3 depicts parameter settings in our experiments, where default parameter values are in bold. For each set of experiments, we vary the value of one parameter while setting other parameters to their default values.

## 8.2 Parameter Tuning

In this subsection, we tune parameters for our S-DSM/C-DSM approaches over synthetic graphs.

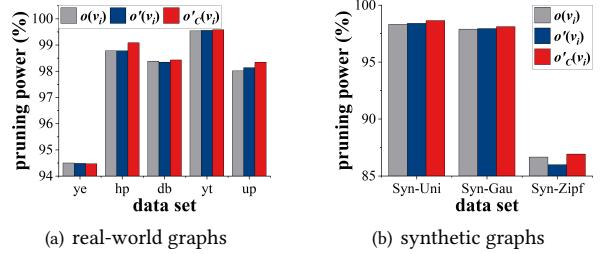
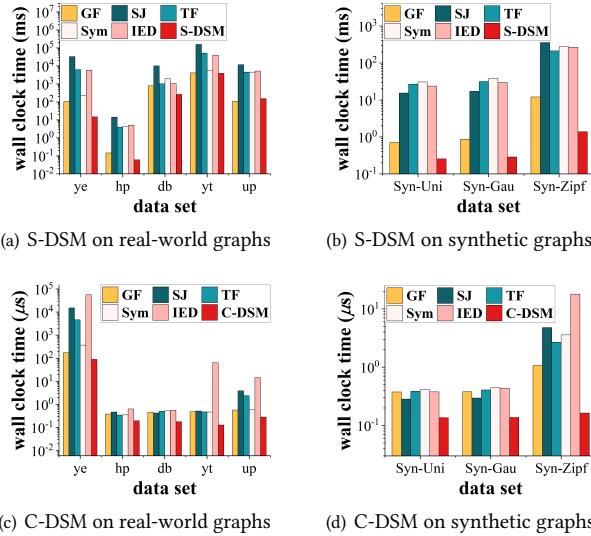


Figure 9: The S-DSM pruning power w.r.t different design strategies of vertex dominance embeddings.

**The S-DSM/C-DSM Efficiency w.r.t. SPUR/SPAN Vector Dimension  $d$ :** Figures 8(a) and 8(f) illustrate the S-DSM/C-DSM performance by varying the dimension,  $d$ , of the SPUR/SPAN vector from 1 to 4, where other parameters are set by default. With higher embedding dimension  $d$ , the pruning power of our proposed pruning strategies in higher dimensional space increases. On the other hand, the access of synopses with larger  $d$  may also incur higher costs due to the "dimensionality curse" [7]. Thus, from figures, for larger  $d$ , the wall clock time of S-DSM/C-DSM first decreases and then increases over most synthetic graphs (except for C-DSM on *Syn-Uni*). Nonetheless, the time cost remains low (i.e., 0.25 ~ 3.92 ms for S-DSM and 0.13 ~ 0.17  $\mu$ s for C-DSM) for different  $d$  values.

**The S-DSM/C-DSM Efficiency w.r.t.  $\beta/\alpha$  Ratio:** Figures 8(b) and 8(g) vary the ratio,  $\beta/\alpha$ , from 10 to 100,000 for the optimized (or cost-model-based) vertex dominance embeddings  $o'(v_i)$  (or  $o'_c(v_i)$ ), where other parameters are set to their default values. In the figures, we can see that our S-DSM/C-DSM approaches are not very sensitive to the ratio  $\beta/\alpha$ . For different  $\beta/\alpha$  ratios, the query cost remains low (i.e., 0.25 ~ 1.71 ms for S-DSM and 0.14 ~ 0.16  $\mu$ s for C-DSM).



**Figure 10: The S-DSM/C-DSM efficiency on real/synthetic graphs, compared with baseline methods.**

**The S-DSM/C-DSM Efficiency w.r.t. # of Degree Groups,  $m$ :** Figures 8(c) and 8(h) report the performance of our S-DSM/C-DSM approaches, by varying the number,  $m$ , of degree groups from 1 to 5, where other parameters are set by default. More degree groups will result in high pruning power of pruning strategies, however, higher synopsis maintenance cost. For S-DSM, the time cost over *Syn-Zipf* first decreases and then increases when  $m$  increases. Moreover, there are some fluctuations for *Syn-Uni* and *Syn-Gau* (e.g., when  $m = 4$  or 5). Since the C-DSM algorithm does not use synopses  $Syn_j$ , the C-DSM performance is not very sensitive to  $m$ . For all  $m$  values, the time cost remains low (i.e.,  $0.24 \sim 1.69$  ms for S-DSM and  $0.14 \sim 0.16$   $\mu$ s for C-DSM).

**The S-DSM/C-DSM Efficiency w.r.t. # of Cell Intervals on Each Dimension,  $K$ :** Figures 8(d) and 8(i) evaluate the effect of the number,  $K$ , of cell intervals on each dimension on the S-DSM/C-DSM performance, where  $K$  varies from 1 to 10, and other parameters are set by default. When  $K$  becomes larger, more vertices in synopsis cells can be pruned, however, more cells need to be accessed. Therefore, for S-DSM, with the increase of  $K$ , the time cost first decreases and then increases. For C-DSM, since it does not rely on synopses, the C-DSM performance is not sensitive to  $K$ . Nonetheless, for different  $K$  values, the query cost remains low (i.e.,  $0.25 \sim 1.52$  ms for S-DSM and  $0.14 \sim 0.16$   $\mu$ s for C-DSM).

**The S-DSM/C-DSM Efficiency w.r.t. Vertex Dominance Embedding Design Strategy:** Figures 8(e) and 8(j) test the S-DSM/C-DSM performance with different designs of vertex dominance embeddings,  $o(v_i)$  (in Eq. (3)),  $o'(v_i)$  (in Eq. (4)), and  $o'_C(v_i)$  (in Eq. (11)), where default values are used for parameters. In the figures, we can see that, the optimized vertex embeddings  $o'(v_i)$  (via the base vector  $z_i$ ) incur smaller time cost than  $o(v_i)$  in most cases (except for S-DSM over *Syn-Zipf*), whereas the cost-model-based vertex embeddings  $o'_C(v_i)$  consistently achieve the lowest time. For different vertex embeddings, the query cost remains low (i.e.,  $0.25 \sim 2.17$  ms for S-DSM and  $0.14 \sim 0.18$   $\mu$ s for C-DSM).

The experimental results on real-world graphs are similar and thus omitted here. In subsequent experiments, we will set parameters  $d = 2$ ,  $\beta/\alpha = 1,000$ ,  $m = 3$ , and  $K = 5$ , and use the cost-model-based vertex embeddings  $o'_C(v_i)$  (given by Eq. (11)).

### 8.3 The S-DSM/C-DSM Effectiveness Evaluation

In this subsection, we report the pruning power of our proposed pruning strategies (as discussed in Section 6.1) for S-DSM over real/synthetic graphs. The case of C-DSM is similar and thus omitted.

**The S-DSM Pruning Power on Real/Synthetic Graphs:** Figure 9 shows the pruning power of S-DSM queries over real/synthetic graphs with different embedding designs  $o(v_i)$ ,  $o'(v_i)$ , and  $o'_C(v_i)$ , where all parameters are set by default. In figures, we can see that for all real/synthetic graphs, the pruning power of our proposed vertex embedding designs can reach as high as  $94.47\% \sim 99.58\%$  for real-world graphs and  $85.99\% \sim 98.65\%$  for synthetic graphs, which confirms the effectiveness of our embedding-based pruning strategies. Our cost-model-based vertex embedding strategy  $o'_C(v_i)$  always achieves the highest pruning power (i.e.,  $86.93\% \sim 99.58\%$ )

### 8.4 The S-DSM/C-DSM Efficiency Evaluation

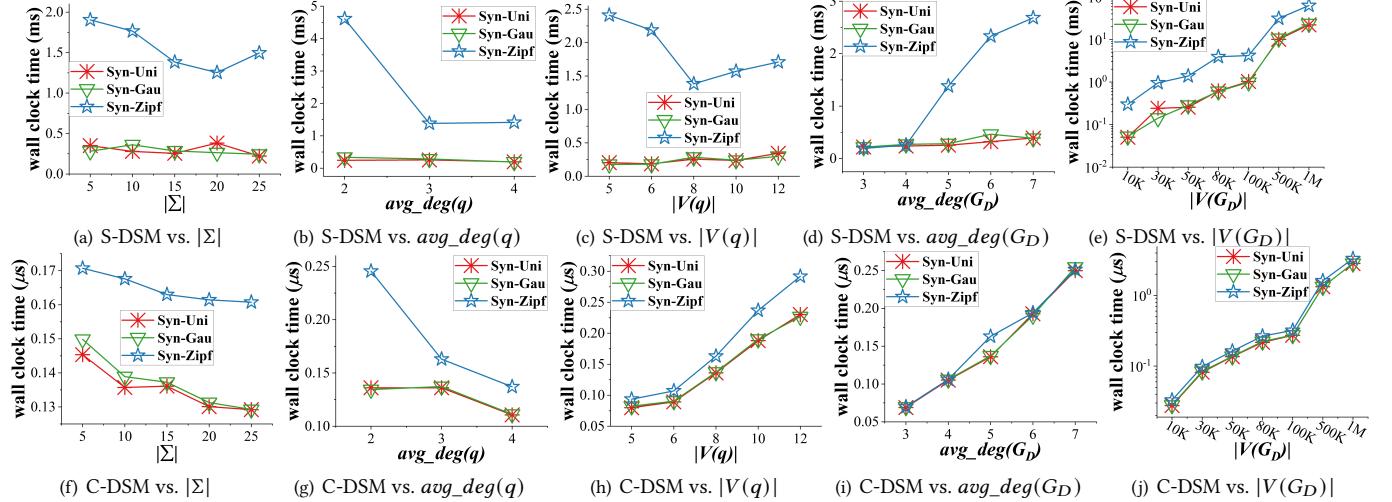
In this subsection, we report the efficiency of our S-DSM/C-DSM approaches over real/synthetic graphs.

**The S-DSM Efficiency on Real/Synthetic Graphs:** Figures 10(a) and 10(b) compare the efficiency of our S-DSM approach with that of 5 state-of-the-art baseline methods over both real-world and synthetic graphs, where all parameters are set to default values. From the figures, our S-DSM approach outperforms baseline methods (e.g., SJ, TF, and IED) on all real/synthetic graphs (mostly by 1-2 orders of magnitude), except for the GF baseline on the *up* with comparable performance. Overall, for all real/synthetic graphs (even for *up* with  $1.65M$  vertices), the time cost of our S-DSM approach remains low (i.e.,  $< 3.87$  sec).

**The C-DSM Efficiency on Real/Synthetic Graphs:** Figures 10(c) and 10(d) compare the performance of our C-DSM approach with that of 5 baselines for both real/synthetic graphs, where default values are used for all parameters. From the figures, our C-DSM approach always performs better than baselines. Especially, for some real data sets (e.g., *ye*, *yt*, and *up*) and *Syn-Zipf*, C-DSM can achieve better performance than baselines by 1-2 orders of magnitude. For all real/synthetic graphs (even for *up* with  $1.65M$  edge insertions), the time cost of our C-DSM approach remains low ( $< 0.09$  ms).

To evaluate the robustness of our S-DSM/C-DSM approaches, in the sequel, we vary the parameter values on synthetic graphs (e.g.,  $|\Sigma|$ ,  $|V(q)|$ ,  $avg\_deg(q)$ ,  $|V(G_D)|$ , and  $avg\_deg(G_D)$ ). To better illustrate the trends of curves, we omit the results of the baselines below.

**The S-DSM/C-DSM Efficiency w.r.t. # of Distinct Vertex Labels,  $|\Sigma|$ :** Figures 11(a) and 11(f) show the wall clock time of our S-DSM/C-DSM approaches, where  $|\Sigma|$  varies from 5 to 25, and other parameters are set to default values. When the number,  $|\Sigma|$ , of distinct vertex labels increases, the pruning power also increases (i.e., with fewer candidate vertices). Moreover, the query cost is also affected by vertex label distributions. Overall, the S-DSM/C-DSM



**Figure 11: The S-DSM/C-DSM efficiency w.r.t. parameters  $|\Sigma|$ ,  $\text{avg\_deg}(q)$ ,  $|V(q)|$ ,  $\text{avg\_deg}(G_D)$ , and  $|V(G_D)|$ .**

query cost remains low for different  $|\Sigma|$  values (i.e.,  $0.22 \sim 1.91$  ms for S-DSM and  $0.13 \sim 0.17$   $\mu$ s for C-DSM).

**The S-DSM/C-DSM Efficiency w.r.t. Average Degree,  $\text{avg\_deg}(q)$ , of the Query Graph  $q$ :** Figures 11(b) and 11(g) examine the S-DSM/C-DSM performance by varying the average degree,  $\text{avg\_deg}(q)$ , of the query graph  $q$  from 2 to 4, where other parameters are set to default values. Higher degree  $\text{avg\_deg}(q)$  of  $q$  incurs higher pruning power of query vertices. Therefore, when  $\text{avg\_deg}(q)$  increases, the S-DSM/C-DSM time cost decreases. For different  $\text{avg\_deg}(q)$  values, the S-DSM/C-DSM query cost remains low (i.e.,  $0.19 \sim 4.61$  ms for S-DSM and  $0.11 \sim 0.25$   $\mu$ s for C-DSM).

**The S-DSM/C-DSM Efficiency w.r.t. Query Graph Size  $|V(q)|$ :** Figures 11(c) and 11(h) illustrate our S-DSM/C-DSM performance, by varying the query graph size,  $|V(q)|$ , from 5 to 12, where default values are used for other parameters. When the number,  $|V(q)|$ , of vertices in query graph  $q$  increases, fewer candidate subgraphs are expected to match with larger query graph  $q$ . On the other hand, larger query graph size  $|V(q)|$  will cause higher query costs of finding candidates for more query vertices, through synopsis traversal and refinement. Thus, the wall clock time is influenced by these two factors. Nevertheless, the query time remains small for different query graph sizes (i.e.,  $< 2.41$  ms for S-DSM and  $< 0.29$   $\mu$ s for C-DSM).

**The S-DSM/C-DSM Efficiency w.r.t. Average Degree,  $\text{avg\_deg}(G_D)$ , of Dynamic Graph  $G_D$ :** Figures 11(d) and 11(i) present our S-DSM/C-DSM performance with different average degrees,  $\text{avg\_deg}(G_D)$ , of dynamic graph  $G_D$ , where  $\text{avg\_deg}(G_D) = 3 \sim 7$ , and default values are used for other parameters. Intuitively, higher degree  $\text{avg\_deg}(G_D)$  in data graph  $G_D$  incurs lower pruning power and more candidate vertices. Thus, when  $\text{avg\_deg}(G_D)$  becomes higher, the wall clock time also increases, especially for *Syn-Zipf* (due to its skewed vertex label distribution). Nevertheless, the S-DSM/C-DSM query time remains small for different  $\text{avg\_deg}(G_D)$  values (i.e.,  $0.2 \sim 2.68$  ms for S-DSM and  $0.07 \sim 0.25$   $\mu$ s for C-DSM).

**The S-DSM/C-DSM Scalability Test w.r.t. Dynamic Graph Size  $|V(G_D)|$ :** Figures 11(e) and 11(j) test the scalability of our S-DSM/C-DSM approaches with different dynamic graph sizes,  $|V(G_D)|$ , from  $10K$  to  $1M$ , where default values are assigned to other parameters. A larger dynamic graph incurs more matching candidate vertices (and, in turn, candidate subgraphs). From figures, the time costs of both S-DSM and C-DSM increase linearly with the increase of graph size  $|V(G_D)|$ , nonetheless, remains low (i.e.,  $0.05 \sim 63.07$  ms for S-DSM and  $0.02 \sim 3.32$   $\mu$ s for C-DSM), which confirms the scalability of our S-DSM/C-DSM approaches for large graph sizes.

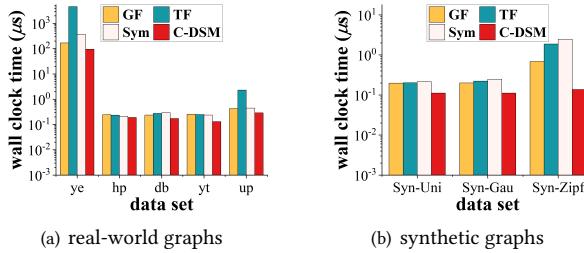
## 8.5 The C-DSM Performance Upon Edge Deletions

In this subsection, we report the efficiency of our C-DSM approach in the case of edge deletions over both real and synthetic graphs. Similar to the settings of edge insertions, we set the deletion rate to 10% (i.e., the initial graph  $G_0$  contains all edges and deletion operations of 10% edges arrive in the stream). Note that, since SJ and IED baseline methods do not support the edge deletion [59], we only compare our C-DSM approach with GF, TF, and SYM.

**The C-DSM Efficiency on Edge-Deletion-Only Real/Synthetic Graphs:** Figure 12 compares the efficiency of our C-DSM approach with that of GF, TF, and SYM baseline methods over both real and synthetic graphs, where all parameters are set to their default values. From the figure, we can find that our C-DSM approach can always outperform the other three baseline methods. Overall, for all real/synthetic data sets (even for *up* with  $1.65M$  edge deletions), the wall clock time of our C-DSM approach remains low (i.e.,  $< 0.09$  ms).

## 9 RELATED WORK

**Dynamic Subgraph Matching:** Existing works on exact dynamic subgraph matching [14, 20, 33, 34, 37, 40, 43] can be classified into three categories: the *recomputation-based* [20], *direct-incremental*



**Figure 12: The C-DSM efficiency on edge-deletion-only real/synthetic dynamic graphs, compared with baseline methods.**

[37], and *index-based incremental algorithms* [14, 33, 34, 40, 43]. For the recomputation-based category, IncIsoMatch [20] extracted a snapshot subgraph  $g_S \subseteq G_t$  surrounding the updated edges at the timestamp  $t$ , conducted the subgraph matching over this snapshot subgraph  $g_S$  (w.r.t. query graph  $q$ ), and updated the answer set  $A(q, t-1)$  at timestamp  $(t-1)$  with new subgraph matching answers by removing redundant subgraphs. For the direct-incremental approach, GraphFlow [37] computed incremental results over the dynamic graph by using a multi-way join from the updated edge.

Moreover, index-based incremental methods construct an index over the initial subgraph matching answers, and obtain incremental results from the index (instead of the data graph). For example, SJ-Tree [14] modeled a dynamic subgraph query as a multi-way join and organized all partial join results in an index to serve the query. TurboFlux [40] built a tree index in which each node contains candidates of a query vertex, and dynamically maintained the index to keep the consistency with each snapshot of the dynamic graph. SymBi [43] improved the pruning power by constructing a graph index and designing an adaptive ordering method. IEDyn [33, 34] maintained an index for candidate vertex sets and their connection edges, which can achieve constant delay enumeration for acyclic queries with graph homomorphism. In contrast, our work designs a novel and effective *vertex dominance embedding* technique for candidate vertex/subgraph retrieval, which can effectively prune vertex/subgraph candidates and improve query efficiency.

In addition, there are also some studies that consider specific query graph topologies, such as paths [47, 57], cycles [49], and cliques [44]. Due to the high computation cost of finding exact matching results, several approximate algorithms [12, 18, 20, 31, 54] have been proposed. Different from these works, our paper focuses on the exact subgraph matching query over the dynamic graph, given general query graphs (i.e., with arbitrary query graph structures).

**Graph Embeddings:** Prior works on graph embedding usually transform graphs or nodes to  $d$ -dimensional embedding vectors for different downstream tasks, such as graph classification, vertex classification, link prediction, and so on. Several graph embedding methods used heuristic rules to encode a graph or its nodes, such as DeepWalk [48], LINE [62], SDNE [63], Node2vec [23], and Struc2vec [52]. These methods are designed for static graphs, which generate graph or node embeddings for fixed graph structures. Thus, we cannot directly use them for a dynamic graph task.

Recently, the graph representation learning via *graph neural networks* (GNNs) has exhibited success in various graph-related applications [28, 32, 55, 56, 64–66]. With different network architectures, some previous works [4, 17, 42, 71] proposed to use GNNs to generate graph embeddings for the graph matching. However, these works either cannot guarantee the accuracy of tasks over unseen test graph data [4, 42] (due to the limitation of neural networks), or cannot efficiently and incrementally maintain embeddings in dynamic graphs with continuous updates [17, 71]. In contrast, our vertex dominance embedding technique does not use learning-based graph embedding, which can guarantee exact subgraph matching over dynamic graphs without false dismissals and enable incremental embedding maintenance over dynamic graphs upon updates.

## 10 CONCLUSIONS

In this paper, we formulate and tackle the problems of snapshot and continuous dynamic subgraph matching (i.e., S-DSM and C-DSM, resp.), which obtain subgraphs (matching with a given query graph) over a snapshot of a large-scale dynamic graph, or continuously monitor the matching subgraph answers over time, respectively. We propose a general framework for efficiently processing S-DSM and C-DSM queries, based on our carefully-designed vertex dominance embeddings. We also provide an effective degree grouping technique and pruning strategies to facilitate our efficient algorithms of retrieving/maintaining subgraph query answers. Most importantly, we devise an effective cost model for guiding the design of vertex embeddings and further enhance the pruning power of our subgraph matching query processing. Through extensive experiments, we evaluate the performance of our S-DSM and C-DSM approaches over real/synthetic dynamic graphs.

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