



Mayura: Exploiting Similarities in Motifs for Temporal Co-Mining

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ABSTRACT

Temporal graphs serve as a critical foundation for modeling evolving interactions in domains ranging from financial networks to social media. Mining temporal motifs is essential for applications such as fraud detection, cybersecurity, and dynamic network analysis. However, conventional motif mining approaches treat each query independently, incurring significant redundant computations when similar substructures exist across multiple motifs. In this paper, we propose Mayura, a novel framework that unifies the mining of multiple temporal motifs by exploiting their inherent structural and temporal commonalities. Central to our approach is the *Motif-Group Tree (MG-Tree)*, a hierarchical data structure that organizes related motifs and enables the reuse of common search paths, thereby reducing redundant computation. We propose a co-mining algorithm that leverages the MG-Tree and develop a flexible runtime capable of exploiting both CPU and GPU architectures for scalable performance. Empirical evaluations on diverse real-world datasets demonstrate that Mayura achieves substantial improvements over the state-of-the-art techniques that mine each motif individually, with an average speed-up of 2.4× on the CPU and 1.7× on the GPU, while maintaining the exactness required for high-stakes applications.

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The source code, data, and/or other artifacts have been made available at
<https://github.com/singam-sanjay/Mayura>.

1 INTRODUCTION

Temporal graphs have become a fundamental abstraction for modeling dynamic interactions in domains ranging from financial transaction networks to social media ecosystems [4, 11, 42, 43, 48, 57]. These graphs capture not only topological relationships but also the temporal evolution of interactions, enabling the analysis of complex phenomena such as information diffusion, fraud patterns, and network dynamics. With the advent of large-scale temporal datasets—exceeding billions of edges in domains like blockchain transactions and communication networks—the need for efficient analytical primitives has never been more critical [16]. Traditional

graph mining techniques, designed for static graphs, fail to account for the temporal ordering and time-window constraints inherent in real-world systems, necessitating specialized approaches for temporal pattern discovery [10, 17, 18, 30, 31, 41, 44, 47, 55].

A cornerstone of analyzing relationships in temporal graph is temporal motif mining, which identifies and enumerates sequences of time-constrained edges whose structure is governed by a motif (e.g., 3-cycles) [33]. These motifs can represent meaningful relationships in the underlying temporal graph, such as a pattern of suspicious transactions between bank accounts within a short period of time, thus helping with fraud detection in financial networks [14]. Applications of temporal mining also include cybersecurity threat analysis [13, 29], social behavior modeling [4, 57], and monitoring energy disaggregation in electrical grids [40]. Existing systems focus on mining individual motifs, while real-world workloads often need to process queries with multiple motifs that overlap structurally and temporally. For instance, anti-money laundering investigations [2, 5, 11, 43] often require simultaneous detection of multiple transaction patterns across shared subsets of edges. Current approaches thus incur redundant computations as they need to repeatedly traverse the graph for each motif.

While multi-query optimization (MQO) techniques for static graphs and approximate temporal mining offer partial solutions, they prove inadequate because the techniques used to exploit similarities are not applicable to temporal motif mining [19, 34]. Approximate counting [26, 32, 35, 37, 54] sacrifices accuracy for performance, which cannot be used in high-stakes domains like finance, where the exact identification of crime is necessary.

This paper addresses aforementioned limitations by proposing **Mayura**, the first system to enable efficient co-mining of temporal motifs. Mayura accomplishes this by using a data-structure called the *Motif-Group Tree (MG-Tree)*, a hierarchical representation of motifs that captures edge-level commonalities, enabling shared search path exploration and eliminating redundant computations. The temporal mining algorithm is then adapted to search for matches guided by the MG-Tree instead of a single motif. Mayura supports efficient co-mining on both CPUs and GPUs, balancing the workload across multiple threads (and warps) and exploiting the hierarchical parallelism exposed by the MG-Tree. Mayura also generates code that optimizes execution for a specific MG-tree to improve instruction throughput and reduce the architectural resource footprint.

Co-mining presents several critical system-level challenges that must be addressed to maximize the efficacy of this approach. Load balancing emerges as a fundamental challenge due to the inherent irregularity of graph workloads, where different search paths exhibit vastly different computational requirements, necessitating sophisticated work distribution strategies. Co-mining on the GPU presents additional challenges. The irregularity of the graph workload makes the GPU implementation susceptible to control-flow

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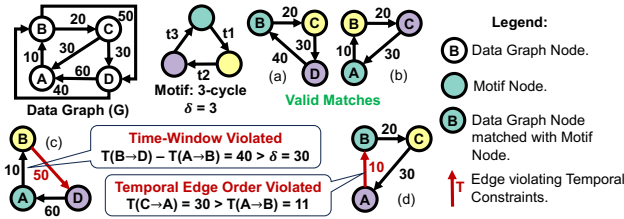


Figure 1: Example of mining a 3-cycle motif within a temporal Data Graph (G). Data vertices (e.g. ⑤) in the matches are color-coded (⑤) to their corresponding motif vertex (●).

divergence, leading to serialized execution and lower performance, requiring the control-flow to be more streamlined than the baseline. The GPU also poses a resource bottleneck with limited register capacity per thread when maintaining context for multiple motifs simultaneously, leading to reduced occupancy and suboptimal hardware utilization, and must be addressed by careful selection of instructions to minimize register usage.

Our comprehensive evaluation demonstrates Mayura’s significant performance improvements across diverse temporal datasets. On a 40-core Intel Xeon CPU, Mayura achieves average speedups between 1.8-3.7× over multiple datasets, with peak acceleration of 8.8× over a bipartite graph. On an NVIDIA A40 GPU, Mayura achieves average speedups between 1.3-3.1× over many datasets, and 7.6× maximum speedup despite architectural constraints. These gains stem from Mayura’s core contributions: dynamic instruction counts reduce by 1.6-4.5× through the MG-Tree-guided search space pruning and code optimization, while motif-specific code generation alleviates 87-94% of warp divergence penalties on the GPU. These results validate that strategic co-mining of temporal motifs enables significant efficiency gains while preserving exactness for critical applications. Mayura makes the following contributions.

- (1) **The MG-Tree:** A hierarchical data-structure that captures structural and temporal similarities across motifs, helping unearth shared search paths.
- (2) **Temporal Co-Mining Algorithm:** The first exact algorithm capable of simultaneously mining multiple motifs.
- (3) **Multi-Backend Runtime:** A unified execution framework supporting both CPU and GPU backends.
- (4) **GPU-Specific Code Optimizations:** Predicated execution, register-bound context mapping and expression simplification to reduce warp divergence and improve occupancy.
- (5) **Hierarchical Parallelization:** Two complementary GPU optimizations—*sibling-splitting* and *multi-offload* that expose parallelism across the MG-tree hierarchy.

2 BACKGROUND

2.1 Problem definition

A **Temporal Graph** is defined as an ordered collection of *temporal edges*, where each *temporal edge* is a directed connection between two vertices with an associated timestamp. Formally, a temporal graph $G = (V_G, E_G)$ is a set of vertices V_G connected by a list of n temporal edges $E_G = (u_i, v_i, t_i)_{i=1}^n | u_i, v_i \in V_G$, where u_i

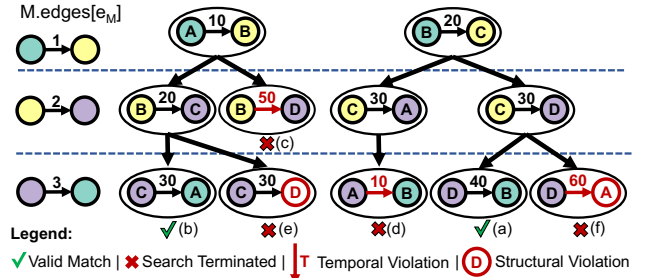


Figure 2: Search-Tree to mine a 3-cycle in Data Graph G in Fig. 1. Labeled leaf nodes (a-d) are search-paths of corresponding valid/invalid matches in Fig. 1.

and v_i are the source and destination vertices of the edge (u_i, v_i) , respectively, and $t_i \in \mathbb{R}^+$ is the edge’s timestamp. The edges are chronologically ordered with unique timestamps. Additionally, both vertices and edges have optional discrete or continuous attributes (e.g., node/edge types).

A **δ -Temporal Motif** $M = (V_M, E_M)$ is defined as an ordered sequence of m edges, where $E_M = (u_i, v_i, t_i)_{i=1}^m | u_i, v_i \in V_M$, that occur within a specified time window of length $\delta \in \mathbb{R}^+$ [29]. The edges of G that match with M must be temporally ordered ($t_1 < t_2 < \dots < t_m$) and the entire sequence must occur within a time-window δ , i.e. ($t_m - t_1 \leq \delta$). The label of a motif-edge in all figures indicates the edge’s relative order.

Temporal Motif Mining identifies all instances of a δ -temporal motif in a temporal graph, yielding either a full enumeration of matches or their total count. We adopt a strict isomorphism-based definition: one-to-one vertex correspondences between motif and subgraph [56]; and do not consider alternative notions such as edge-set mapping [23], event-sequence matching across snapshots [46], or edge-homomorphism [7]. We use “mining” to denote identifying instances of a pattern, rather than novel-pattern discovery [9].

Temporal motif mining parallels SQL query execution: treat the temporal graph as a database, with the motif and time-window as the query. It can be expressed with nested JOIN operations to enforce isomorphism, and WHERE clauses to enforce temporal constraints.

The Walk-Through Example in Fig. 1 illustrates the different aspects of temporal motif mining introduced above. The temporal data graph G has four vertices (A-D) and seven edges marked with timestamps using the same unit, e.g., seconds. The motif’s vertices are color-coded to map with their corresponding data graph vertex in a match, with the timestamp of edges indicating their relative temporal order: $T(\text{green} \rightarrow \text{yellow}) < T(\text{yellow} \rightarrow \text{purple}) < T(\text{purple} \rightarrow \text{green})$. Given G , a 3-cycle query motif and a time-window $\delta = 30$, Fig. 1(a)-(d) illustrates different sub-graphs that are valid and invalid matches, along with the rationale for their classification. The difference in the timestamp between the first and the last edges is 2 for 1(a) and 1(b), making them valid matches ($2 < \delta = 30$). Fig. 1(c) violates the time-window with the second edge occurring more than 30 time-steps after the first edge. Fig. 1(d) violates the temporal ordering constraint: $T(\text{yellow} \rightarrow \text{purple}) = 30 > T(\text{purple} \rightarrow \text{green}) = 10$.

Algorithm 1 Temporal Motif Mining Algorithm

```
1: Inputs : Temporal Data Graph  $G$ , Motif  $M$  : and Time-Window size  $\delta$ 
2: Output Variables : count  $\leftarrow 0$ ; matches  $\leftarrow \emptyset$ ;
3: Book-Keeping Context :  $e\_stack[:] \leftarrow 0$ ;  $m2g[:] \leftarrow -1$ ;  $g2m[:] \leftarrow -1$ ;  $incnt[:] \leftarrow 0$ ;

4: procedure TEMPORALMINING(TemporalGraph  $G$ , Motif  $M$ , Int  $\delta$ )
5:   MATCHEDGE( $G, M, \delta, 0$ ); return count, matches;  $\triangleright$  Start by matching first motif edge.

6: function MATCHEDGE(TemporalGraph  $G$ , Motif  $M$ , Int  $\delta$ , Int  $e_M$ )
7:   if  $e_M = |E(M)|$  then  $\triangleright$  Match Found when  $e_M$  reaches number of motif edges.
8:     count  $\leftarrow$  count + 1; matches.append( $e\_stack$ ); return
9:    $u_M, v_M \leftarrow M.edges[e_M]$ ;  $u_G \leftarrow m2g[u_M]$ ;  $v_G \leftarrow m2g[v_M]$   $\triangleright$  Get  $u_G \leftrightarrow u_M$  map.
10:  cand  $\leftarrow (u_G \neq -1) ? \mathcal{N}(u_G) : G.edges$   $\triangleright$  All edges are candidates for unmapped  $u_G$ .
11:  for  $edge_G \in$  cand do
12:    if  $e_M > 0$  and ( $edge_G.t < e\_stack[e_M-1].t$  or  $edge_G.t - e\_stack[0].t > \delta$ ) then
13:      continue  $\triangleright$  Ensure Temporal Edge-Order and Time-Window Constraints.
14:    if  $v_G \neq -1$  and  $edge_G.v \neq v_G$  then continue  $\triangleright$  Ensure Structural Constraints.
15:     $e\_stack.append(edge_G)$ ;
16:    ROLLONEDGE( $u_M, v_M, edge_G.u, edge_G.v$ )  $\triangleright$  Book-keep ( $u_M, v_M$ ) to  $edge_G$  map.
17:    MATCHEDGE( $G, M, \delta, e_M + 1$ )  $\triangleright$  Expand Search-Tree to match next  $M$  edge recursively.
18:     $e\_stack.pop()$ ; ROLLBACKEDGE( $edge_G.u, edge_G.v$ );  $\triangleright$  Remove  $edge_G$ 's mapping.

19: function ROLLONEDGE(Int  $u_M$ , Int  $v_M$ , Int  $u_G$ , Int  $v_G$ )
20:   $m2g[u_M] \leftarrow u_G$ ;  $g2m[u_G] \leftarrow u_M$ ;  $m2g[v_M] \leftarrow v_G$ ;  $g2m[v_G] \leftarrow v_M$ 
21:   $incnt[u_G] \leftarrow incnt[u_G] + 1$ ;  $incnt[v_G] \leftarrow incnt[v_G] + 1$ 

22: function ROLLBACKEDGE(Int  $u_G$ , Int  $v_G$ )
23:   $u_G, v_G \leftarrow edge$ ;  $incnt[u_G] \leftarrow incnt[u_G] - 1$ ;  $incnt[v_G] \leftarrow incnt[v_G] - 1$ 
24:  if  $incnt[u_G] = 0$  then  $u_M \leftarrow g2m[u_G]$ ;  $g2m[u_G] \leftarrow m2g[u_M] = -1$ 
25:  if  $incnt[v_G] = 0$  then  $v_M \leftarrow g2m[v_G]$ ;  $g2m[v_G] \leftarrow m2g[v_M] = -1$ 
```

2.2 Algorithmic Prior Work

Temporal motif mining approaches fall into two categories: exact algorithms that enumerate all matches through subgraph isomorphism with temporal constraints [29, 33, 56], and approximate methods that estimate counts via sampling or sketching [26, 32, 35, 37, 54]. Exact methods are crucial for applications requiring complete enumeration, such as fraud detection [14] or insider threat identification [13, 29]. *Our work focuses on exact algorithms*, with approximate techniques discussed briefly in § 8.

Paranjape *et al.* [33] formalized δ -temporal motif mining and proposed a two-phase algorithm: 1) enumerating static isomorphic subgraphs, then 2) verifying temporal constraints. The first step uses existing static subgraph / pattern mining methods that identify matches that are structurally equivalent to the motif, ignoring temporal constraints. This potentially leads to unnecessary computational overhead, as structurally compliant candidates may not satisfy temporal requirements [56]. Subsequent work by Mackey *et al.* [29] improved efficiency by pruning temporally invalid candidates before expanding the entire subgraph. Everest [56] adapted this approach for GPUs with a state-of-art warp-level parallelization of candidate exploration. The essence of Mackey's algorithm [29] is captured in Algorithm 1. It uses book-keeping variables (line 3) for motif-to-graph edge mapping: "m2g"/"g2m" for vertex mapping, "e_stack" for temporally ordered matched edges, and "incnt" for tracking edge counts per vertex. Mining follows a depth-first search tree where nodes represent candidates for each motif-edge (Fig. 2).

Algorithm 1 begins by mapping the first motif edge (line 5, $e_M = 0$), considering all edges in the data graph as potential candidates due to the absence of pre-existing vertex mappings. It recursively expands the search tree in a depth-first manner (line 17), pruning candidates based on temporal and structural constraints (line 13-14). Upon finding complete matches, it records them by updating a counter or enumerating the match into a list (line 8). Fig. 2(c,d) illustrate the search tree being pruned due to temporal violations,

corresponding to the invalid matches Fig. 1(c,d). Search paths terminating at Fig. 2(e,f) illustrate structural violations since the last edge must finish the cycle by ending at the first vertex (A for (e) and B for (f)). The algorithm can be parallelized over candidates for the first edge, but becomes challenging for subsequent edges due to the sequential nature of candidate generation (line 11). Everest [56] extends Algo. 1 to GPUs by storing the candidate list as a range of edges and distributes among threads within a warp.

3 A CASE FOR MULTI-QUERY EXECUTION

This section motivates the need for efficient multi-query execution and evaluates the effectiveness of existing techniques in addressing the challenges of temporal motif mining.

Modern analytical workloads increasingly require concurrent execution of multiple queries across domains ranging from financial fraud detection to social network analysis. Anti-money laundering systems must simultaneously track diverse transaction patterns [2, 5, 11, 43], while social platforms analyze user engagement through parallel interaction queries [4, 57]. Traditional single-query optimization proves inadequate for these workloads due to *redundant computations across overlapping queries*.

3.1 Collective Queries in Traditional Databases

The challenge of multi-query optimization (MQO) has been studied since Sellis' seminal work on identifying common subexpressions [39], though optimal planning remains NP-hard [38]. Contemporary approaches fall into two categories: 1) physical optimizations that make the underlying system more efficient (*e.g.*, shared data access patterns via scan-sharing [3, 8] or resource-aware scheduling [1, 6]), and 2) algebraic transformations that algorithmically reduce the amount of work [49]. Ren and Wang [34] pioneered MQO for isomorphic-pattern mining, by reducing redundant computations by identifying shared structures across queries. Subgraph Morphing [19], a hybrid approach combining algebraic and physical optimizations, decomposes query patterns into alternative patterns that are less computationally expensive to mine.

3.2 Opportunity: Commonality in Temporal Motif Queries

Building upon insights gleaned from prior work, we explore potential ways to identify and reduce redundant computation. The techniques proposed previously [19, 34] could be adapted to exploit structural similarities among temporal queries, but not without challenges. Ren and Wang [34] can be used to first identify isomorphic-matches with query motifs and then filtered to comply with temporal constraints, leading to unnecessary exploration of a large search-space [33]. Subgraph Morphing [19] exploits symmetry in graph isomorphism to reduce redundant searches, may produce matches that violate temporal constraints in the context of temporal motif mining (*e.g.*, Fig. 1(b) and (d)). This issue is exacerbated when two vertices have multiple edges between them, leading to a combinatorial explosion in the number of potential matches requiring a large memory footprint for enumeration.

Given the challenges associated with efficiently adapting existing techniques for temporal motif mining, we allude to an approach specifically tailored to this domain. Consider Fig. 3, which illustrates

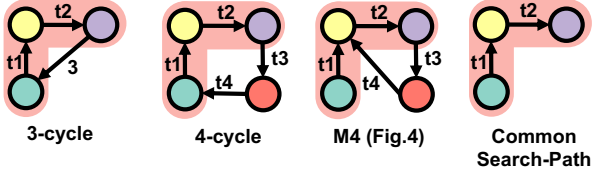


Figure 3: Common search-path between 3-cycle, 4-cycle and M4 motifs.

the 3-cycle, 4-cycle, and M4 motifs (Fig. 1). Observe that the motifs share the same first two edges, $t_1 \rightarrow t_2$ and $t_2 \rightarrow t_3$, indicating that the ideal mining algorithm must visit these edges in the search-tree for either a 3-cycle or a 4-cycle before proceeding to expand to the third edge. This observation suggests that we can eliminate redundant computation along the common path. By prioritizing edge traversal in a chronological order, we establish a natural heuristic that favors exploring common paths before diverging into specific motif searches. In subsequent section, we generalize this concept to accommodate more temporally and structurally complex common paths, laying the foundation for our efficient co-mining approach.

4 MAYURA DESIGN

This section presents the design of Mayura, outlining its core objectives, workflow, key algorithmic components and the runtime for CPU/GPU backend. We introduce the Motif-Group Tree (MG-Tree) generation algorithm and the co-mining algorithm, which form the foundation of our approach.

4.1 Design Goals

Mayura is designed with three primary objectives to address the challenges in multi-query execution for temporal motif mining.

Efficient Motif Co-Mining. While existing approaches to temporal motif mining have focused on optimizing mining a single motif, our observation in §3.2 presents an opportunity to identify redundant computations when mining multiple motifs. We aim to minimize these redundant computations by exploiting structural and temporal similarities among motifs within the query set, reducing the overall workload associated with mining multiple motifs.

Multi-Backend Support. To ensure broad accessibility, one of our goals is to support seamless operation on both GPU and CPU platforms. Recognizing the memory constraints associated with GPUs and that not all users have access to high-performance GPUs, our design allows users the flexibility to execute motif mining tasks on CPU resources when necessary.

High Performance Optimizations. While co-mining presents clear opportunities for performance improvements, its implementation introduces specific challenges that must be addressed. For instance, the additional context and control-flow introduced to enable co-mining on GPU threads can potentially reduce performance due to the additional register footprint and warp-divergence from threads in the same warp mining different motifs. Our goal is to address these challenges (§5), ensuring that the system not only capitalizes on the benefits of co-mining but also maintains high performance throughout the mining process.

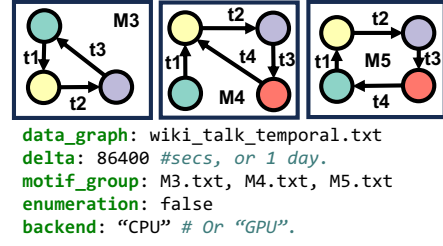


Figure 4: Example User Query.

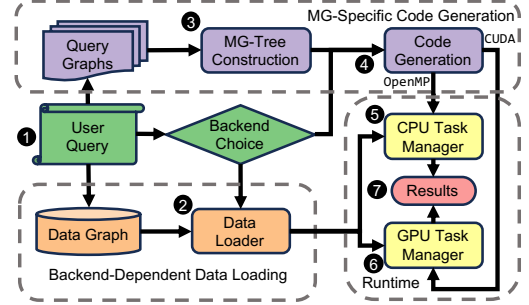


Figure 5: Overview of Mayura's workflow.

4.2 Mayura Workflow

Our system takes as input a user query (Fig. 4) that specifies the temporal data graph to mine (Fig. 5 ①), a group of motifs (*i.e.*, motif group), time-window δ , backend choice (CPU or GPU), and whether matches need to be counted or enumerated. The output is either the per-motif count or enumeration. The workflow of Mayura is structured into three distinct phases: Compile-Time, Data-Loading and Runtime, visualized by Fig.5. The Compile-Time phase generates and compiles the code that implements the co-mining algorithm, while the Data-Loading phase operates concurrently to load the dataset into (CPU/GPU) memory. The Runtime phase executes the compiled code to mine the loaded dataset.

Data-Loading and Compile-Time Phases consists of mechanisms for 1) Data Preprocessing ②, 2) Motif-Group Tree (MG-Tree) Construction ③, and 3) Backend-Specific Code Generation and Compilation ④. The temporal data graph specified by the query ① is preprocessed from an edge-list format (u_i, v_i, t_i) to an adjacency-list format stored in a CSR-like structure, with edges sorted in ascending order of timestamps ②. The system constructs a hierarchical representation of the query motifs in the motif group, *i.e.*, the MG-Tree, capturing structural and temporal similarities ③. The system then generates optimized code tailored to the specific MG-Tree and backend, utilizing C++ with OpenMP for CPU execution or CUDA C for GPU execution ④.

Runtime Phase dispatches the compiled code and preprocessed data to the appropriate backend's task manager (⑤ for CPU, ⑥ for GPU). To address the inherent load imbalance in graph workloads, both CPU and GPU task managers implement sophisticated load balancing strategies (§4.5). Upon completion, the system aggregates the results, providing either motif counts or enumerations as specified in the query ⑦.

4.3 Motif-Group Tree Construction

We propose a hierarchical data structure called Motif-Group Tree (MG-Tree) that captures structural and temporal similarities among query motifs to facilitate efficient co-mining. By grouping motifs that share overlapping edges (with the same relative order) in a hierarchical structure, the MG-Tree enables the co-mining algorithm to reuse computations along the shared search paths and eliminating redundant work. This hierarchical structure also exposes algorithmic parallelism to improve concurrency. While the MG-Tree is not the first to exploit structural similarities to accelerate matching [20, 51], we are the first to propose such a solution for temporal mining. We define the MG-Tree by defining its composition and the constraints that define the relationship between parent and children nodes,

MG-TREE DEFINITION: For a group of temporal motifs $MG = \{M_1, M_2, \dots, M_k\}$, the MG-Tree MGT is defined as a tree of Nodes that capture the similarities among motifs in MG , rooted at N_{root} .

Node Composition: Any Node $N \in MGT$ is composed of the following 3 members: C_N , $Children(N)$ and Q_N ,

C_N : A motif with edges common across all descendants $C_{N_{desc}}$, i.e. a prefix for $C_{N_{desc}}$ with their first $|C_N|$ edges being equal to C_N .

$N_{child} \in Children(N)$: Immediate descendants constructed by extending C_N , where C_N is the longest non-trivial prefix of $C_{N_{child}}$.

Q_N : The reference to a query motif $M_i \in MG$ when C_N is equivalent to M_i , else is \emptyset . $\forall M_i \in MG, \exists N \in MGT \mid Q_N = M_i$

Root Node: $N_{root} \in MGT$ whose common motif $C_{N_{root}}$ has edges common across all motifs in MG .

The MG-Tree construction algorithm (Algo. 2) begins by invoking the **CONSTRUCTMGTREE** procedure on the motif group MG . For the sake of brevity and simplicity, we refer to the temporal order of a motif edge as its timestamp. A TMap is generated for each motif, mapping timestamps to the corresponding edges. Nodes with children are known as Intermediate Nodes (Intr.), and those without are Leaf Nodes. Members of the motif group are populated as leaf Nodes in the MG-Tree, with their C_N and Q_N references set to the member (line 9). Upon reaching a leaf Node N during co-mining, the search is limited to mine only Q_N . The algorithm then proceeds in a recursive manner to build the MG-Tree, starting from the first edge in all motifs (line 7). The motifs are grouped together based on the source and destination of the edges at timestamp T (line 21). Motifs in singleton groups are inserted as a list of children into their parent Node (p_gid). Undivided groups, i.e., all motifs in the input group have the same edge at $T - 1$ and T , end up reusing the node created at $T - 1$ (or potentially before) (line 31). A new Intr. Node is created for all other groups, representing motifs encountered during the search process but not necessarily counted or enumerated like Q_N . The algorithm also eliminates redundant work when C_N is identical to a Q_N in the child_group. The new Intr. Node is then added as a child to its parent (line 38). The MG-Tree for each child group is recursively constructed and attached to the final MG-Tree (line 36), with the recursion terminating at Leaf Nodes.

Walkthrough Example: Consider the motif group $[M3, M4, M5]$ from Fig. 4 as an input to the algorithm. Fig. 6 visualizes the construction of the MG-Tree in Fig. 7. After setting up TMap and the MG-Tree with leaf Nodes, **CREATETREE** is invoked on the motif

group. Since all motifs have the same edge at $T = 1$, i.e., $\text{green} \rightarrow \text{yellow}$, the child_group reuses N_{root} at $c_gid = 0$, referred to as Intermediate Node I1. N_{root} 's C_N is set to contain the single edge, $\text{green} \rightarrow \text{yellow}$, and the Q_N is left empty since none of motifs resemble C_N . With the recursive call to **CREATETREE**, all the motifs end up being grouped together at $T = 2$ as well since they still share an edge, $\text{yellow} \rightarrow \text{purple}$. The C_N for I1 is reset to $\text{green} \rightarrow \text{yellow} \rightarrow \text{purple}$. At $T = 3$, M3 is grouped separately from M4 and M5 since its edge, $\text{purple} \rightarrow \text{green}$, is different from that of M4 and M5, $\text{purple} \rightarrow \text{red}$. M3 is added as a child for I1. A new Intr. Node, I2, is created for M4 and M5 with the C_N , $\text{green} \rightarrow \text{yellow} \rightarrow \text{purple} \rightarrow \text{red}$. With I2 as a parent Node, **CREATETREE** is called on $[M4, M5]$ and ends up separating them since they have different edges at $T = 4$, and are added as children to I2. Observe that if we had to build an MG-tree only for $[M4, M5]$, it would have been the tree rooted at I2. This hierarchical representation enables the exploitation of similarities between motifs at various granularities, reducing the overall computational workload.

Algorithm 2 MG-Tree Construction

```

Initialize Context
1: TMap  $\leftarrow \emptyset$ ; mg_tree  $\leftarrow \emptyset$ ; unique_gid  $\leftarrow 0$ 
Input: List of unique motifs; Output: MG-Tree MGT
2: procedure CONSTRUCTMGTREE(List[Motif] MG)
3:   for  $M \in MG$  do  $\triangleright$  Generate tmaps and insert tree-nodes
4:     TMap[M]  $\leftarrow$  GRAPHToTMAP(M); INSERTMOTIF(M);
5:   root_gid  $\leftarrow$  GETNEWUNIQUEGID()  $\triangleright$  Create MG_Tree_Node at gid 0
6:   Nroot  $\leftarrow$  MGT[root_gid]; Children(Nroot).clear();  $C_{Nroot} \leftarrow Q_{Nroot} \leftarrow \emptyset$ 
7:   CREATETREE(1, GETNEWUNIQUEGID(), MG)
8:   return mg_tree

9: function INSERTMOTIF(Motif M)  $\triangleright$  Query-Motifs are MG-Tree's leaves
10:   $N \leftarrow$  MGT[M.name];  $C_N \leftarrow Q_N \leftarrow M$ ; Children(N)  $\leftarrow \emptyset$ 

11: function GRAPHToTMAP(Motif M)  $\triangleright$  Maps specific timestamp to a static edge
12:  tmap  $\leftarrow \emptyset$ ;
13:  for  $e \in E(M)$  do tmap[e.t]  $\leftarrow (e.u, e.v)$ 
14:  return tmap

15: function GETNEWUNIQUEGID()  $\triangleright$  Generate unique ID number for constituent motif groups
16:  new_gid  $\leftarrow$  unique_gid; unique_gid  $\leftarrow$  unique_gid + 1; return STR(new_gid)

17: function CREATETREE(Time T, Str p_gid, List[Motif] motif_group)
18:  edge_group  $\leftarrow \emptyset$ ; Nparent  $\leftarrow$  MGT[p_gid]
19:  for  $M \in$  motif_group do  $\triangleright$  Group graphs based on edge at T
20:    if |TMap[M]| < T then pass  $\triangleright$  Ignore graphs that are too small
21:    edges  $\leftarrow$  TMap[M];  $e \leftarrow$  edges[T]; edge_group[e]  $\leftarrow$  edge_group[e]  $\cup \{M\}$ 
22:  for ( $e$ , child_group)  $\in$  edge_group do
23:     $q_n \leftarrow \emptyset$ 
24:    for  $M \in$  child_group do  $\triangleright$  Check if a constituent query motif
25:      if |E(M)| = T then  $\triangleright$  is equivalent to the group's
26:         $Q_{Nparent} \leftarrow M$ ; break  $\triangleright$  parent motif
27:  if |child_group| = 1 then  $\triangleright$  Singleton groups do not need a
28:    INSERTCHILD(p_gid, child_group[0])  $\triangleright$  new Node.
29:  else
30:    if motif_group = child_group then
31:      c_gid  $\leftarrow$  p_gid  $\triangleright$  Reuse gid if motif_group was not split up
32:    else
33:      c_gid  $\leftarrow$  GETNEWUNIQUEGID()
34:      common_edges  $\leftarrow$  TMap[motif_group[RANDOM(1, |motif_group|)]] [1:T+1]
35:       $N \leftarrow$  MGT[c_gid];  $C_N \leftarrow$  MOTIF(common_edges);  $Q_N \leftarrow \emptyset$ 
36:      INSERTCHILD(p_gid, c_gid); CREATETREE(T+1, c_gid, child_group)

37: function INSERTCHILD(Str p_gid, Str child_id)
38:  if p_gid  $\neq$  child_id then  $\triangleright$  Avoid self-loops if motif_group is intact
39:    mg_tree[p_gid].children  $\leftarrow$  mg_tree[p_gid].children  $\cup \{child\_id\}$ 

```

4.4 Mayura Co-Mining Algorithm

The co-mining algorithm extends the temporal motif mining algorithm (Algo. 1) by using the MG-Tree, instead of a single motif,

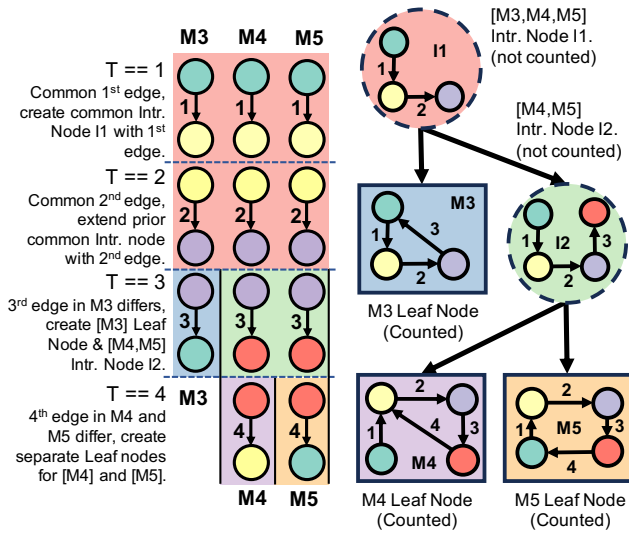


Figure 6: Visualizing MG-Tree Construction.

Figure 7: MG-Tree of motifs in Fig. 4.

to guide the expansion of the search tree. The pseudo-code of the algorithm is outlined in Algo 3, focusing only on its modifications from Algo. 1. The core mechanism for mining a single motif-edge remains unchanged (lines 12- 14). The algorithm begins by mining $C_{N_{root}}$. Upon detecting a match for C_N , it is counted if the Node also represents a query motif (line. 6). Subsequently, the algorithm moves onto mining the children of N by using C_N 's match as a partial match (line.13). By expressing co-mining in this recursive manner, we are able to reuse most of the mechanisms used in Algo 1.

Algorithm 3 Co-Mining Algorithm

Inputs: Data Graph G , root of MG-Tree and time-window δ
Outputs: Counts and matches of motifs in MG-Tree.

```

1: procedure TEMPORALCoMINING(TemporalGraph  $G$ , Node  $N_{root}$ , Int  $\delta$ )
2:   CoMATCHEDGE( $G$ ,  $N_{root}$ ,  $\delta$ , 0); return count, matches;  $\triangleright$  Start by matching first motif edge.

3: function CoMATCHEDGE(TemporalGraph  $G$ , Node  $N$ , Int  $\delta$ , Int  $e_M$ )
4:    $M \leftarrow C_N$   $\triangleright M$  is local and does not affect other calls to CoMATCHEDGE
5:   if  $e_M = |E(M)|$  then  $\triangleright$  Match Found when  $e_M$  reaches number of motif edges.
6:     if  $Q_N \neq \emptyset$  then  $\triangleright$  Add match when  $Q_N$  is assigned
7:        $count[Q_N] \leftarrow count[Q_N] + 1$ ;  $matches[Q_N].append(e\_stack)$ ;
8:     for  $C_{N_{child}} \in Children(N)$  do
9:        $\triangleright$  Expand search-tree into mining child motif with  $e\_stack$  as partial match.
10:      CoMATCHEDGE( $G$ ,  $C_{N_{child}}$ ,  $\delta$ ,  $e_M$ )  $\triangleright$  NOTE: Edge  $e_M$  is yet to be mined
11:   return  $\triangleright$  After exploring child motifs, find more matches of  $M$  to expand the search-tree.
12:   ...  $\triangleright$  Unmodified MATCHEDGE pseudocode from lines 9 to 16 in Algorithm 1
13:   CoMATCHEDGE( $G$ ,  $node$ ,  $\delta$ ,  $e_M + 1$ )  $\triangleright$  Expand Search-Tree to match next edge in  $M$ .
14:   ...  $\triangleright$  Remaining MATCHEDGE and other pseudocode from line 18 in Algorithm 1

```

Walkthrough Example: Fig. 8 illustrates a small portion of the search-tree explored by the Algo. 3 when mining the motif group [M3,M4,M5] on the Data Graph G in Fig. 1. The background colors correspond to that of the corresponding motif in the MG-tree (Fig. 7) being explored by the search-tree. The motif edges on the sides of the tree at each level indicate the motif edge being mined at that particular level. Since the search tree is for an MG-Tree, different motif edges can be mined at the same level for different sibling Nodes. The search tree starts with identifying matches for Node

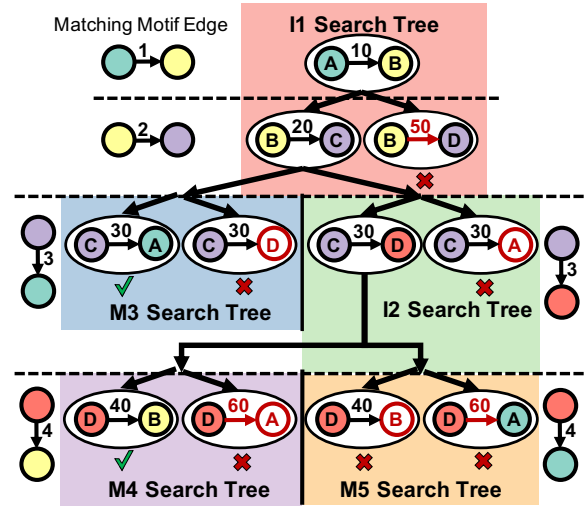


Figure 8: Search-Tree to mine motifs M3,M4 and M5 reflects the hierarchical structure of their MG-Tree (Fig. 6).

I1 (top two levels). With matches of I1 as partial matches, the search-tree expands into mining the M3 leaf Node and I2 Intr. Node, eventually terminating at the leaf Nodes: M3,M4 or M5.

4.5 Mayura Runtime

The system initiates the runtime phase by enabling the backend specified by the user. This backend receives the MG-Tree, δ , and pointers to the temporal data graph located within its memory. Both CPU and GPU backends parallelize the co-mining algorithm across multiple threads, employing task managers to handle work-scheduling and load-balancing. While global inputs such as the MG-Tree and δ are shared, the search-tree context (e.g., vertex maps, counters) is maintained locally within each thread to eliminate contention and maximize parallelism.

The CPU task-manager distributes candidate edges for the first edge across all threads, and utilizes dynamic task scheduling for load balancing. The GPU task-manager employs a two-level policy, which distributes these candidate edges across warps and then splits the search-tree within a warp [56]. This policy is also used to load-balance across threads within a warp (intra-warp) and the across warps (inter-warp). Such a multi-granular policy is necessary given the higher thread count and lower computational capability of individual GPU threads compared to CPU threads. Intra-warp balancing involves periodic polling of idle threads and candidate redistribution using warp-level primitives. Similarly, inter-warp load balancing redistributes the candidates by polling for idle warps across the GPU. Active threads' search contexts are dumped and then redistributed across all warps on the GPU before resuming mining. Fig. 9 visualizes the runtime-context held within a thread, the CPU Runtime's load-balancing across CPU threads, and the GPU runtime with its two-tiered balancing 1) within a warp at epoch #e and #e+1, and 2) across warps between two epochs.

Visualizing Intra-Warp Load-balancing: Fig. 10 illustrates the intra-warp load balancing mechanism during co-mining the

MG-Tree in Fig. 7, displaying the search-tree and candidates for the second edge in I1 and third edge in M3 or I2. Initially, a warp with four threads has only one active thread (Thread 0) processing candidates (E5-E7) for leaf node M3 (Stage 1.a). The load balancer redistributes these candidates across threads 0-2 to maximize parallelism (Stage 1.b). At a later point, when thread 0 runs out of candidates for M3, it transitions to mining sibling Node I2 and generates a new candidate list (E12...E15). Unlike thread 0, threads 1 and 2 are restricted from mining any sibling of M3 (*i.e.*, I2) in order to prevent double-counting of matches, since thread 0 has already started working on candidates for I2. Subsequent load balancing (Stage 2.a) redistributes I2 candidates from Thread 0 across all four threads, achieving full warp utilization (Stage 2.b)

Visualizing Inter-Warp Load Balancing: Fig. 11 demonstrates the inter-warp load-balancing strategy, the second part of the two-level load-balancing strategy, when mining the MG-Tree in Fig. 7. Upon detecting a threshold number of idle warps, the system interrupts the mining process to make all active threads save their context (*i.e.*, search-tree, book-keeping variables *etc.*) and exit. In Fig. 10, an active thread is saving its context to the fifth position in the context array located in global memory. This context indicates that the thread is currently exploring candidates for the last edge in M3 (E10,E11,E12), with (E1,E2,E3) and (E4-E7) as candidates for the first and second edge of I2 respectively. Inter-warp load-balancing punctuates periods/epochs of continuous mining with gaps to redistribute the workload. While the search-tree is duplicated across warps with the same source context, the candidates are partitioned across warps. It is possible that different threads in the same warp are assigned to work on search-trees distributed from different contexts. To prevent double counting, the edges that form the search tree are exclusively explored on one thread, with these considered as only a part of the search tree in other threads. For instance, the threads in warp #1 and #2 immediately skip E10 to process E11 and E12 respectively. In addition to skipping E10, the thread in warp #3 also skips E4 as a candidate for the second edge in I2 and moves to considering E6.

Implementing Load-Balancing: Mayura periodically monitors the load-balance rather than continuously calculating the balance factor, owing to the high latency of thread-level synchronization operations. Intra-warp load balancing (Fig. 10) monitors thread status every (say) INTRA_INTRVL iterations, with threads voting to redistribute work when idle threads coexist with active ones. Inter-warp load balancing (Fig. 11) uses global memory to track warp idleness across the GPU every (say) INTER_INTRVL iterations, triggering redistribution when a threshold of idle warps is detected. Since global memory access is more expensive than warp-level synchronization, inter-warp monitoring occurs at longer intervals ($INTER_INTRVL > INTRA_INTRVL$), creating the two-tier load balancing strategy visualized in the figures 10 and 11.

Cost of Co-Mining: Mayura does not allocate CPU memory co-mining while allocating a relatively small amount of GPU memory (0.1%-2.5%) to offload contexts during inter-warp load-balancing. Mayura's CPU backend replicates the baseline parallelization scheme and does not incur additional synchronization cost. However, the GPU backend needs to communicate an additional parameter (compared to the GPU baseline) with other threads in the warp to

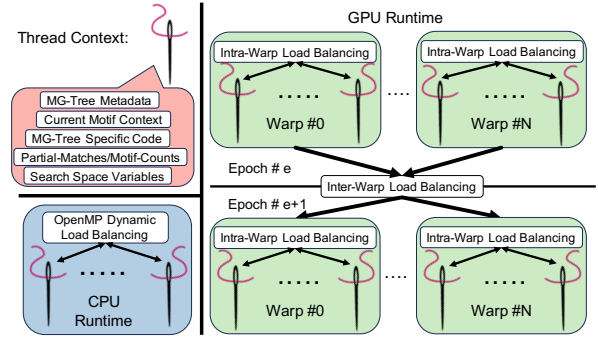


Figure 9: Visualizing Thread Context and Load-Balancing on the CPU and GPU at runtime.

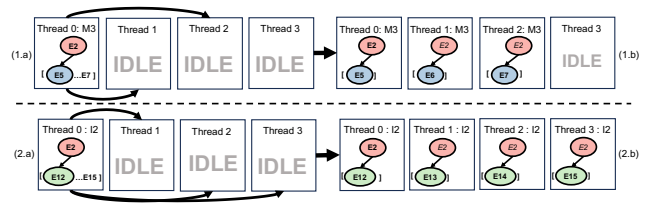


Figure 10: Intra-Warp Load-Balancing distributing candidates across idle warps. Only the source thread (*i.e.*, 0) is allowed to explore sibling Nodes.

prevent duplicate exploration of sibling Nodes. This design allows *Mayura* to mine many more motifs simultaneously while incurring little to no memory or synchronization overhead.

Limiting sibling node exploration to a single thread for correctness underutilizes available parallelism across sibling nodes. While splitting the candidates and the search tree across threads could mitigate this, it may increase load balancing latency. Furthermore, GPU threads face constraints like register limits and reduced performance from control-flow divergence. The additional context and control logic (Algo. 3) required to enable co-mining thus become an overhead, potentially reducing performance gains. We can alleviate these drawbacks by minimizing the context and streamlining the control-flow by tuning the source code to the MG-Tree. §5 discusses optimization strategies to address these challenges.

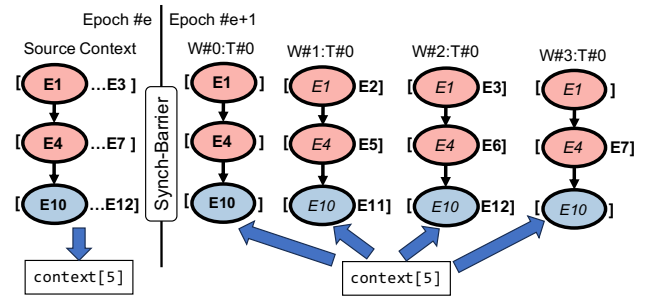


Figure 11: Inter-Warp Load-Balancing distributing candidates across warps from contexts dumped in the previous epoch.

5 MAYURA DESIGN OPTIMIZATIONS

The co-mining algorithm introduced in §4 achieves theoretical efficiency gains by exploiting structural and temporal commonalities across motifs via the MG-Tree. However, practical implementation on modern hardware architectures requires addressing critical performance bottlenecks unique to CPUs and GPUs. This section presents a suite of optimizations such as optimized code-generation and load-balancing that bridge the gap between algorithmic innovation and real-world execution efficiency.

5.1 Motif-Group Specific Code-generation

5.1.1 CPU Code-generation. We generate specialized loops for each level of the MG-Tree search hierarchy. While the baseline implementation based on prior work [29, 56] uses recursive function calls with uniform loop structures, this approach confounds modern branch predictors due to varying iteration ranges across recursion levels. The code-generation phase for the CPU (Fig. 4, ④) unrolls the recursive search into distinct nested loops, each explicitly optimized for its corresponding MG-Tree level.

5.1.2 GPU Code-generation. GPUs present unique optimization challenges due to their Single Instruction Multiple Thread (SIMD) architecture and constrained register resources. Unlike CPUs that excel at handling complex control flow through speculative execution and sophisticated branch predictors, GPUs require fundamentally different optimizations to avoid performance pitfalls like warp divergence (threads in a warp executing different code paths) and register pressure (exceeding limited per-thread register capacity). Our GPU code generation strategy employs three synergistic optimizations to address these challenges while maintaining the algorithmic benefits of co-mining.

Register-Bound Context Mapping. Fig. 12(a) illustrates a portion of the code that enforces structural constraints by ensuring that the new candidate vertex, V , has not been matched before by comparing V with all vertices upto $V[mV-1]$, where mV is the number vertices that have been mapped and V is the array of vertices. We store these values (and the most of the context) in thread-local memory since the code has to flexibly work with any motif group with different number of vertices, edges, and motifs. This flexibility results in costing latency since the GPU incurs a memory operation to the shared or global memory. Given the MG-tree, we can replace the dynamic-array based context with fixed registers (e.g., $V0-V3$) like in Fig. 12(b), effectively hard-coding the mapping state for known motif sizes and eliminating memory accesses to the context.

In GPU architectures, warps execute instructions in lockstep across all 32 threads. Divergent control flow serializes execution, forcing subsets of threads to wait at synchronization points until all warp lanes complete their current path. The synchronization overhead, of tracking divergent paths and maintaining thread masks, incurs substantial latency, leading to a phenomenon known as warp divergence. While replacing loops with the switch-case in Fig. 12(b) reduces total branches, divergence persists when threads in a warp have different values for mV .

Predicated Control-Flow. Modern GPUs support predicated execution, where instruction execution is conditional on a Boolean

value stored in predicate registers. This mechanism enables thread-specific control flow without explicit branching—instructions execute as no-ops (NOPs) when their associated predicate evaluates to false, thus eliminating warp-divergence and streamlining control-flow. As shown in Fig. 12(c), we utilize this feature to predicate the structural constraint checks based on the value of mV . The figure also contains two examples of predicated instructions in NVIDIA SASS, a low-level assembly language for NVIDIA GPUs. The first instruction is unconditionally executed since it is predicated on the always-true predicate PT, and the second one is dependent on a previously set predicate register P1. While predication avoids branch divergence, its application is limited by two constraints: 1) only arithmetic/logic operations can be predicated, and 2) predication is more effective with short code blocks, since longer predicated blocks incur higher latencies by issuing instructions from both the if-then and else parts even when the threads do not diverge.

Expression Simplification. Rewriting multiple statements in Fig. 12(c) as a single boolean expression exposes further opportunities for the compiler. The predicated logic to test a specific vertex represents an implication from the value of mV to a check on the vertex, i.e., $A \rightarrow B$, and can be simplified to a boolean expression resembling $\neg A \vee B$. These transformations enables the compiler to fuse multiple logical operations into 8-bit LookUp-Table (LUT) instructions, as illustrated in Fig. 12(d). This reduces the instruction count since multiple operations were replaced by a single LUT instruction and also reduces register pressure since registers are no longer required to hold as many intermediate values of an expression as before, this improving occupancy.

In summary, by taking advantage of the compile-time knowledge of the maximum context size from the MG-Tree, and strategically applying optimizations across the code base, Mayura mitigates warp divergence, alleviates register pressure, and minimizes instruction counts. This synergy between algorithmic design and hardware awareness enables a more efficient exploitation of computational resources, yielding significant performance improvements.

5.2 GPU-Specific Load-balancing

While the two-tier load-balancing scheme effectively exploits parallelism across search-tree candidates, it under-utilizes parallelism available across Nodes in the MG-Tree. We address this limitation using two complementary optimizations: *sibling-splitting* for intra-warp parallelism and *multi-offloading* for inter-warp parallelism.

Sibling-Splitting for Intra-Warp Parallelism. Fig. 13 demonstrates the sibling-splitting optimization during intra-warp load balancing. The detection of idle threads triggers the load-balancing similar to §4.5 (Stage 1.a). For all the active threads, the system checks whether the Node being mined has an unexplored sibling according to the order determined in Algo. 2. For thread 0 mining M3 in Fig. 13, the unexplored sibling would be I2. Threads with such sibling Nodes 1) nominate an idle thread participating in the to mine the sibling (I2 \rightarrow thread 3), and 2) distributes the candidates of its search-tree across other threads (threads 0 - 2). Thread 3 then obtains the candidate list for I2 while retaining the search-tree for I2's parent Node, I1. This approach enables the exploration of sibling Nodes in parallel, increasing the availability of candidates to reduce the number of idle threads.

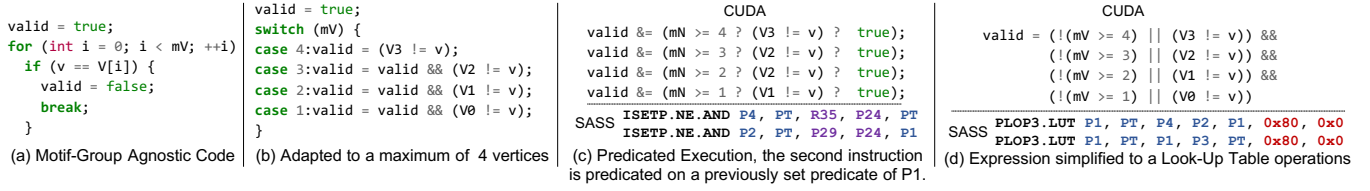


Figure 12: Optimization to reduce warp-divergence and streamline control-flow.

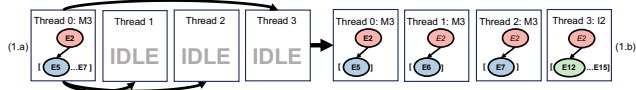


Figure 13: Sibling-Splitting for Intra-Warp Load-balancing.

Multi-Offload for Inter-Warp Parallelism is an optimization enabling concurrent exploration of Nodes across the MG-Tree hierarchy by decomposing the search context across multiple levels. Fig. 14 illustrates this approach during inter-warp load balancing, where a thread was mining for M3 with candidates for both edges in parent I1 before being interrupted to offload its context. Since siblings can be mined independent of each other, the optimization exposes this parallelism by creating separate contexts for candidates of each sibling (context[5] for M3, context[6] for I2) while preserving the search tree of their parent (I1). Since siblings are not part of the original search-tree, the candidate lists for a sibling is generated before its context is offloaded into global memory (e.g., for I2 in Fig. 14). The same process is repeated for the parent Node and its siblings until the root Node is reached, with the search tree being trimmed to reflect the shallower depth in the MG-tree.

In the case of Fig. 14, a context is created that only contains I1’s candidates (saved in context[8]). Note that all child Nodes have been explored with E4 a candidate for the second edge in I1, the I1-only context skips E4 and moves onto E5. This hierarchical decomposition exposes parallelism across as many levels as possible in the MG-tree with a given context by offloading multiple contexts for siblings in each level. When resuming mining in the next epoch in Fig. 14, the decomposed contexts are able to keep eight threads busy instead of just four threads without the optimization (Fig. 11). Observe that Sibling-Splitting paired with inter-warp load balancing has a similar effect to that of Multi-Offload: by starting the search for siblings at an early stage, sibling-splitting creates multiple contexts from a single context, albeit constrained to the same level, and these multiple contexts are offloaded during load-balancing.

Additional Resource Footprint. While the above optimizations expose additional parallelism in the workload, they can introduce trade-offs that must be carefully managed. As intra-warp load balancing is invoked frequently, we constrain sibling-splitting to explore only one sibling at a time to minimize the overhead of exploring multiple siblings. The multi-offload strategy, while effective in distributing work, can incur additional instructions to offload multiple contexts. Our experiments reveal that these optimizations incur negligible overheads: dynamic instruction counts increase by $\leq 6\%$ and occupancy is reduced by $\leq 1\%$. These results confirm

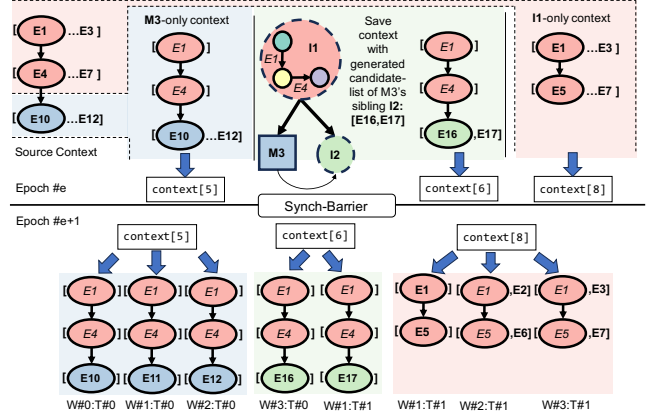


Figure 14: Optimization for Inter-Warp Load-balancing.

the practicality of our approach, as the performance benefits of enhanced parallelism outweigh the modest resource costs (§7).

6 EVALUATION METHODOLOGY

The Baselines compared against Mayura’s CPU and GPU implementations respectively are the work proposed by Mackey et.al. [29] and Everest [56]. Both baselines distribute the search space for a single query across multiple threads (intra-query parallelism).

The Hardware Setup consists of a server with an Intel Xeon Platinum 8380 CPU (40 cores, 80 threads) with 1TB of main memory, and an NVIDIA A40 GPU with 48GB GDDR6 memory.

Five Datasets of real-world temporal graphs spanning social networks, blockchain transactions, and internet traffic (Table 1) were used to evaluate Mayura. Since the equinox (eqx) dataset captures the exchange of internet packets between computers of two cities, making it a bipartite graph. Due to memory capacity limitations of our GPU, we subsample the massive eqx dataset to 37.5% of its original edges while preserving temporal characteristics.

Eight Queries were created by combining fourteen motifs, of which M1 - M11 are counted and M12 - M14 are only intermediates, which were used in prior work [23, 29, 37, 56], and are illustrated in Fig. 15. The queries cover three categories:

- (1) **Depth-focused:** Deepening MG-Trees (D1-D2).
- (2) **Fanout-focused:** Widening MG-Trees (F1-F3).
- (3) **Complex Heterogenous:** Variety of sizes and overlap (C1-C3).

To capture the notion of similarity among motifs, we define the Similarity Metric (SM) for a motif group MG and its MG-Tree as,

$$SM(MG, MG-Tree) = 1 - \frac{\sum_{M \in MG-Tree} (||E_M|| - ||E_{M.parent}||)}{\sum_{M \in MG} ||E_M||}$$

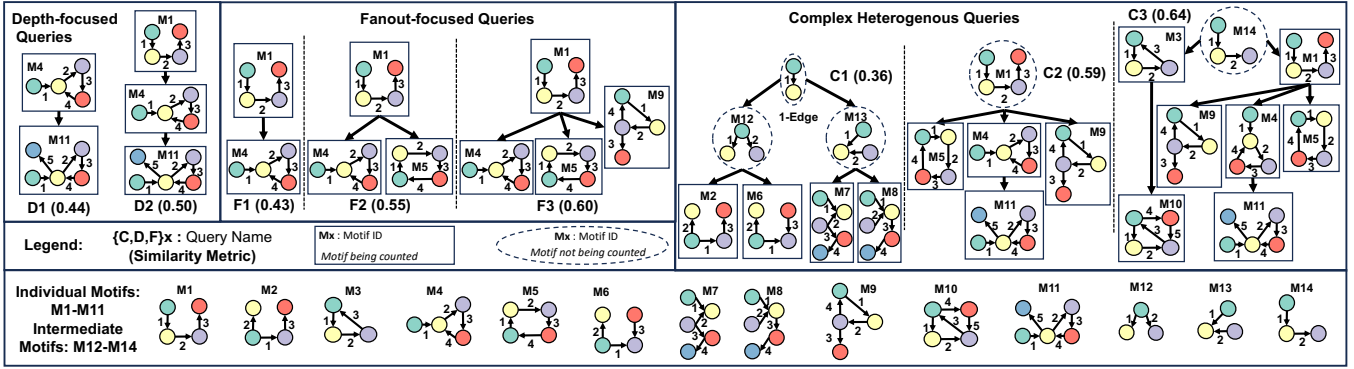


Figure 15: MG-Trees of Motif Groups, with respective (SM).

Graph	#Vertices	#Temporal Edges	# Static Edges	Time Span	δ Window
wiki-talk (wtt) [24]	1,140,149	7,833,140	2,787,968	6.24 years	1 day
stackoverflow (sxo) [24]	2,601,977	63,497,050	34,875,685	7.6 years	1 day
reddit-reply (trr) [25]	8,901,033	646,044,687	435,290,421	10.1 years	10 h
ethereum (eth) [22]	66,323,478	628,810,973	186,064,655	3.58 years	1 h
equinix (eqx) [37]	6,208,412	872,124,829	29,766,272	23.46 mins	3.6 ms

Table 1: Temporal graph datasets used for evaluation.

where $|E_M|$ is edge count of motif M . The denominator sums all edge counts across MG ; the numerator tallies each Node’s extra edges beyond its parent. Greater shared structure lowers the numerator, boosting SM. Higher SM indicates more reusable search paths in the MG-Tree, though actual speedups also depend on hardware utilization and load balancing. We choose dataset-specific δ values that reflect meaningful temporal windows and limit runtimes [56].

7 EVALUATION RESULTS

High Level Summary: Mayura’s co-mining and optimizations deliver significant speedups on both CPU and GPU. Figures 16 and 17 show absolute runtimes, while Figures 18 and 19 report per-query speedups (with “Geomean” giving the dataset-wide geometric mean). On the CPU, individual speedups span $1.05\times$ – $8.37\times$, with co-mining alone achieving a $2.35\times$ average gain and code-generation lifting this to $2.46\times$. On the GPU, speedups span $0.82\times$ – $7.59\times$, with co-mining alone yielding $1.48\times$ on average, with all optimizations reaching $1.73\times$ on average. While the absolute time saving for the experiments on the GPU, spanning shorter runtimes (milliseconds to minutes), may appear modest at best, the speedups remain practically significant in high-throughput analytical environments where thousands of such queries are executed daily [21, 27, 50, 53]. These benefits correlate with similarity among motifs in a motif-group (SM): highly similar groups see the greatest gains, while low-overlap groups (e.g. C1) show smaller improvements or occasional GPU regressions due to resource constraints. Mining C1 on the eth dataset on the CPU exceeded the time-limit of 24 hours and has been omitted from our comparisons.

Mayura effectively exploits structural similarities among motifs. D2 experiences higher speedups than D1, as mining M4 implicitly mines M1. This trend is consistently observed across F1-F3 and C2-C3, where the expansion of the MG-tree to include more structurally similar motifs correlates with improved speedups.

Dataset characteristics significantly influence performance gains. On the CPU, every dataset benefits from co-mining and most gain further from code generation. The bipartite eqx dataset exhibits exceptionally high speedups on CPU and GPU, because its disjoint partitions forbid the existence of motifs that need to connect vertices in the same partition. Consider D1, where M1 is feasible with the mapping: $(\text{blue}, \text{red}) \in \text{part.}\#0$, $(\text{yellow}, \text{red}) \in \text{part.}\#1$. Proceeding to M4 fails to match as yellow is not connected to red (both $\in \text{part.}\#1$), pruning the search of all descendants (i.e., M11) and eliminating redundant searches incurred when mining them individually. wtt, trr, and eth datasets benefit from all GPU optimizations, although the extent varies by motif-group. sxo’s performance peaks at the cgs optimization, suggesting a well-balanced workload that obviates inter-warp load balancing. eth and trr show smaller speedups due to high motif-match density ($\sigma = |\text{matches}| \div |E_G|$), which enlarges candidate sets, prolongs Node exploration, and delays sibling transitions, effectively serializing the MG-Tree search and diminishing gains from co-mining. In contrast, eqx’s bipartite structure aggressively prunes the search space, enabling superior performance.

Performance Analysis: We profiled key CPU (Fig. 20a) and GPU (Fig. 20b) architectural metrics for D2, F3 and C3 on wtt, comparing pure co-mining, co-mining with optimizations, and each baseline. The GPU Baseline’s “#Active Threads per Warp” and “Occupancy” metrics (*) are time-weighted averages across the individual baseline kernels. The error bars indicate the extent to which the optimized kernels outperform / under-perform the baseline kernels. On the CPU, co-mining with/without code-generation reduces dynamic instruction count, indicating that the system is performing less work to achieve the same outcome. CPU code-generation’s efficacy is reflected in the higher branch-instruction throughput. On the GPU, co-mining also lowers instruction counts but its efficacy diminishes as motif groups grow, due to lower occupancy and higher warp divergence. Our control-flow optimizations partly offset this by raising active-thread counts per warp, yet the inherent complexity limits gains from multi-offload and sibling-splitting. In an experiment to evaluate the efficacy of improving the occupancy at the cost of increased memory operations, we chose C3 since it has the lowest occupancy. Offloading counters to memory improved the occupancy from 44% to 70% but yielded only marginal

D1 (0.44)				D2 (0.5)				F1 (0.43)			
wtt	1.6	1.0	0.9	2.2	1.0	0.9		1.2	0.6	0.6	
sxo	11.5	5.3	5.1	16.3	5.4	5.1		10.5	5.2	5.1	
trr	708.0	498.0	461.0	832.0	502.0	461.0		320.0	194.0	180.0	
eth	591.0	467.0	449.0	661.0	468.0	451.0		168.0	91.1	89.3	
eqx	103.0	46.6	49.7	154.0	46.6	49.6		103.0	46.7	49.8	
F2 (0.55)				F3 (0.6)				C1 (0.36)			
wtt	1.8	0.6	0.6	2.4	0.7	0.6		24.7	17.0	15.5	
sxo	16.2	5.8	5.5	21.6	6.2	5.8		32.8	22.7	21.4	
trr	499.0	225.0	207.0	660.0	249.0	229.0		44.7k	43.8k	42.6k	
eth	264.0	115.0	112.0	362.0	143.0	139.0		TO	TO	TO	
eqx	154.0	46.7	49.7	206.0	46.5	49.6		216.0	57.4	56.9	
C2 (0.59)				C3 (0.64)				b c cg			
wtt	2.7	1.0	1.0	5.0	1.3	1.2		b	c	cg	
sxo	22.5	6.2	5.8	42.9	8.5	8.0					
trr	1.05k	0.55k	0.51k	1.80k	0.86k	0.81k					
eth	785.0	522.0	496.0	1.79k	1.24k	1.19k					
eqx	206.0	46.7	49.3	411.0	46.7	49.1					

Figure 16: CPU Timings (seconds).

D1 (0.44)				D2 (0.5)				F1 (0.43)			
wtt	1.52	1.70		2.27	2.39			2.13	2.12		
sxo	2.17	2.25		3.04	3.20			2.00	2.08		
trr	1.42	1.54		1.66	1.80			1.65	1.78		
eth	1.27	1.32		1.41	1.47			1.84	1.88		
eqx	2.21	2.07		3.30	3.10			2.21	2.07		
F2 (0.55)				F3 (0.6)				C1 (0.36)			
wtt	2.97	3.03		3.61	3.75			1.45	1.59		
sxo	2.78	2.95		3.48	3.74			1.44	1.53		
trr	2.22	2.41		2.65	2.88			1.02	1.05		
eth	2.30	2.36		2.53	2.60			TO	TO		
eqx	3.30	3.10		4.43	4.15			3.76	3.80		
C2 (0.59)				C3 (0.64)				Geomean			
wtt	2.66	2.71		3.91	4.04			2.42	2.53		
sxo	3.64	3.85		5.06	5.38			2.77	2.92		
trr	1.91	2.05		2.09	2.24			1.76	1.89		
eth	1.50	1.58		1.44	1.50			1.70	1.76		
eqx	4.41	4.18		8.80	8.37			3.69	3.50		
	c	cg		c	cg			c	cg		

Figure 18: Breakdown of performance improvements of different optimizations on the CPU, compared to the baseline.

performance improvements, underscoring the trade-off between occupancy and memory access efficiency in GPU implementations.

Memory Footprint: The CPU implementation incurs negligible memory overhead (100KB-180KB variation), which is effectively noise in the context of the smallest dataset’s 3GB footprint. The GPU backend allocates additional global memory for inter-warp load-balancing, ranging from 14MB (F3) to 20MB (D3) depending on the motif group. These overheads remain relatively small when compared to the overall dataset: between 0.1% for the largest dataset (trr) and 2.5% for the smallest dataset (wtt). Mayura thus enables co-mining with minimal increase in memory footprint.

GPU Footprint: The larger context required for co-mining increases per-thread register usage, reducing available parallelism (i.e. active blocks) due to GPU register file constraints, creating a performance trade-off with increasing motifs (Table 2).

Effect of δ : We evaluated Mayura’s performance under varying temporal constraints ($\delta/2$, δ , and $2 * \delta$) by mining D2, F3, and C3 on the wtt dataset. The results show that shorter time-windows

D1 (0.44)				D2 (0.5)				F1 (0.43)			
wtt	0.05	0.04	0.03	0.04	0.03	0.03		0.04	0.03	0.02	0.02
sxo	0.41	0.22	0.20	0.20	0.20	0.20		0.30	0.22	0.20	0.20
trr	33.10	23.90	17.80	17.70	17.70	17.70		18.70	14.70	13.40	13.40
eth	20.30	22.30	15.90	15.80	15.40	15.40		3.15	2.82	2.65	2.45
eqx	0.57	0.28	0.28	0.28	0.28	0.28		0.57	0.28	0.29	0.29
F2 (0.55)				F3 (0.6)				C1 (0.36)			
wtt	0.06	0.04	0.03	0.03	0.03	0.03		0.88	1.38	1.19	1.12
sxo	0.52	0.37	0.34	0.34	0.34	0.34		1.32	1.40	1.39	1.38
trr	32.50	24.90	22.50	22.50	22.50	22.50		0.79k	0.90k	0.81k	0.80k
eth	5.19	4.38	3.98	3.83	3.73	3.73		3.05k	3.57k	2.97k	2.94k
eqx	0.85	0.28	0.29	0.29	0.29	0.29		4.04	2.29	2.39	2.39
C2 (0.59)				C3 (0.64)				b c cg cgs cgsm			
wtt	0.18	0.17	0.17	0.15	0.12	0.12		b	c	cg	cgs
sxo	0.84	0.49	0.45	0.44	0.44	0.44					
trr	58.40	42.30	36.10	36.00	34.50	34.50					
eth	24.50	23.80	20.80	19.50	17.60	17.60					
eqx	1.14	0.28	0.29	0.29	0.28	0.28					

Figure 17: GPU Timings (seconds).

D1 (0.44)				D2 (0.5)				F1 (0.43)			
wtt	1.35	1.48	1.74	1.81	1.64	1.79	2.19	2.20	1.19	1.31	1.62
sxo	1.87	2.02	2.03	2.03	2.28	2.49	2.50	2.50	1.38	1.47	1.48
trr	1.38	1.86	1.87	1.87	1.57	2.13	2.14	2.14	1.27	1.40	1.40
eth	0.91	1.28	1.28	1.32	0.94	1.33	1.33	1.38	1.12	1.19	1.29
eqx	2.06	2.00	2.01	2.01	3.09	3.01	3.01	3.01	2.06	1.99	1.99
F2 (0.55)				F3 (0.6)				C1 (0.36)			
wtt	1.34	1.59	1.72	1.74	0.98	1.00	1.12	1.44	0.64	0.74	0.79
sxo	1.39	1.54	1.54	1.54	1.51	1.59	1.62	1.62	0.94	0.95	0.95
trr	1.31	1.44	1.44	1.44	1.38	1.46	1.47	1.51	0.88	0.98	0.98
eth	1.18	1.30	1.36	1.39	1.21	1.25	1.32	1.42	0.85	1.03	1.04
eqx	3.07	2.98	2.98	2.98	4.06	3.92	3.92	3.93	1.76	1.69	1.69
C2 (0.59)				C3 (0.64)				Geomean			
wtt	1.05	1.08	1.17	1.54	0.98	1.19	1.27	1.34	1.11	1.23	1.39
sxo	1.72	1.87	1.92	1.92	1.91	2.11	2.13	2.13	1.58	1.69	1.71
trr	1.38	1.62	1.62	1.69	1.39	1.57	1.58	1.64	1.31	1.52	1.55
eth	1.03	1.18	1.26	1.39	0.87	0.87	0.96	1.01	1.01	1.17	1.22
eqx	4.05	3.97	3.97	4.00	7.69	7.57	7.57	7.59	3.12	3.03	3.03
	c	cg	cgs	cgsm	c	cg	cgs	cgsm	c	cg	cgs

Figure 19: Breakdown of performance improvements of different optimizations on the GPU, compared to the baseline.

#Motifs	#Registers	#Blocks	Reduction in #Blocks
1	44	1092	0%
4	55	1008	8%
8	67	756	31%

Table 2: Impact of co-mining on GPU register utilization and thread occupancy

yield greater speedups on both CPU(Fig. 21a) and GPU(Fig. 21b). Larger δ values expand candidate sets and widen search trees across multiple levels, causing load imbalances when work is undistributed across compute units. This particularly affects the CPU backend, which only balances at the top level, while the GPU’s finer-grained load-balancing across all search-tree levels mitigates these effects.

Heuristic for Co-Mining: Co-mining’s efficacy can depend on the structure of the data-graph, S.M of the motif group and δ . Bipartite data-graphs always see gains since cross-partition query

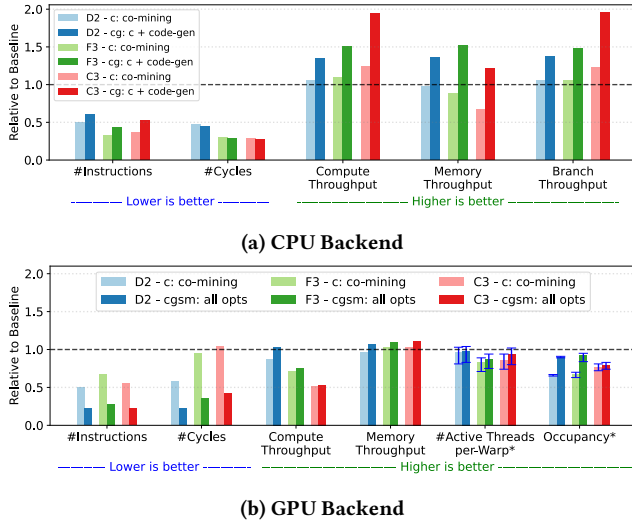


Figure 20: Architectural Metrics for mining D2, F3 and C3 on wtt, relative to the baseline.

```

1 if is_bipartite(data_graph):
2     co_mining = True
3 elif platform == "GPU" and SM < 0.44:
4     co_mining = False
5 else:
6     choose_smaller(delta)
7     co_mining = True

```

Listing 1: Heuristic for Co-Mining

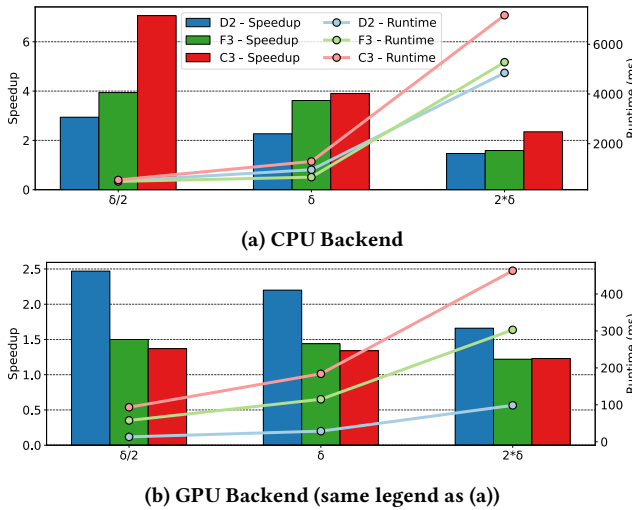


Figure 21: Effect of scaling δ on Speedup and Runtime.

motifs prune searches. On GPUs, co-mining surpasses the baseline only when $S.M. \geq 0.44$ (Table 2). A user with flexibility to choose δ could reduce the time-window to improve performance (Fig. 21). Based on our evaluation results, we propose a heuristic (Lst. 1) that determines whether co-mining would be beneficial.

8 RELATED WORK

Multi-Query Optimization (MQO): GEQO [15] pioneered ML-based identification of semantically equivalent subexpressions, while Ma *et al.* [28] extended MQO to continuous subgraph matching in dynamic graphs. MapReduce adaptations [52] demonstrated MQO’s versatility across paradigms. While these approaches focus on relational queries or subgraph processing, Mayura extends the concept of MQO to the domain of temporal graph mining.

Static Graph Mining systems count matches of a pattern based on the structure of the query pattern [10, 17, 18, 30, 31, 41, 44, 45, 55]. Notable contributions include Arabesque [47], which introduced a distributed framework for graph mining, and Peregrine [17, 18], which optimized pattern-aware exploration. G2Miner [10] further advanced the field by synthesizing pattern-specific code for GPUs, akin to Everest and Mayura. While these systems have advanced the state-of-the-art in static graph mining, they do not address the unique challenges posed by temporal motif mining.

Temporal Motif Mining adds complexity by enforcing edge order within a time window. Prior work falls under two categories: (1) *Exact* methods, such as Mackey’s chronological edge-matching [29] and Everest’s GPU-accelerated approach [56], which we build upon with co-mining; (2) *Approximate* techniques that sample edges [54], paths [32], or time intervals [26, 36, 37] to estimate counts in minutes rather than days. Oden [36] handles multiple motifs sharing the same structure. However, most systems remain CPU-only [12, 32], are optimized for a few motifs [12], or sacrifice accuracy for speed [26, 36, 37, 54]. In contrast, Mayura efficiently co-mines diverse motifs on both CPU and GPU without loss of exactness.

Hierarchical Indices: FERRARI [51] and PRAGUE [20] also exploit hierarchical structures like the MG-Tree, but differ fundamentally from Mayura. Their ADVISE [51] and SPIG [20] indices are built at runtime to record matches of fragments of a single evolving query, while the MG-Tree is a compile-time hierarchy over distinct temporal motifs. Unlike ADVISE/SPIG, which store all fragment matches and incur large memory/computational overheads when filtering for temporal constraints (§2.1), the MG-Tree expands matches only when structural and temporal constraints are satisfied, avoiding these overheads.

9 CONCLUSION

Mayura addresses the critical challenge of efficiently mining multiple temporal motifs by introducing a novel co-mining paradigm that exploits structural and temporal similarities across query patterns. Our framework introduces the Motif-Group Tree (MG-Tree), a hierarchical data structure that systematically organizes motifs. Experimental results demonstrate significant performance improvements, with overall speedup of 2.5 \times on the CPU and 1.7 \times on the GPU across diverse datasets. The effectiveness of our approach hinges on the MG-tree exploiting motif similarity to reduce redundant work and exploiting parallelism in the workload. Architectural bottlenecks posed by enabling co-mining were mitigated by optimizing code-generation. These advancements not only enhance temporal graph analytics but also underscore the importance of hardware-aware co-design for scalable motif mining.

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