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某些变量用符号表示

待办：完善实验统计，补足图和数据部分。

数据驱动的并发点对点查询系统

摘要

随着图处理技术在地图导航、网络分析等领域的大范围应用，大量点对点查询任务在同一个底层图上并发运行，对图查询系统的吞吐量提出了极高的要求。然而已有的图计算系统要么聚焦于优化单次点对点查询的速度，而忽略了并发点对点查询的吞吐量。要么沿袭点对多点算法的并发执行思路，忽略了点对点算法的优化潜力。由于冗余的数据访问开销和计算开销，现有方案在执行并发点对点查询时整体吞吐量很差。

本文提出了GraphCPP，它是第一个并发执行点对点查询任务的图遍历系统，通过数据访问共享和热路径计算共享提高并发查询任务的吞吐量。GraphCPP有两个创新之处。首先，基于不同查询任务的遍历路径大量重叠的观察，GraphCPP提出了一个数据驱动的缓存执行机制，通过细粒度的图分块调度，实现了并发任务之间的**数据共享**，提高了数据访问效率； 其次，由于不同任务对相同的热顶点和热路径频繁计算，GraphCPP提出了一个双层级计算共享机制，它通过对热顶点和热路径的计算共享来加速未知查询的收敛。为了展示GraphCPP的效率，我们在xx等数据集上，将其与最先进的点对点查询系统和并发图计算系统进行对比。结果表明，GraphCPP仅产生xx的预处理开销和xx的存储开销，但是整体吞吐量相较于SGraph、Tripoline、Pnp、Glign，分别提高了xx-xx倍。

（无需翻译：参考了GraphM和OSDI22文章）

索引关键词: graph process, point-to-point graph queries, concurrent jobs, data access similarity，computational similarity

GraphCPP: A Data-Driven Graph Processing System for Concurrent Point-to-Point Queries

Abstract

With the widespread adoption of graph processing technology in fields such as map navigation and network analysis, a considerable number of point-to-point query tasks run concurrently on the same underlying graph, imposing a high demand on the throughput of graph query systems. However, existing graph computing systems either focus on optimizing the speed of individual point-to-point queries, neglecting the throughput of concurrent point-to-point queries, or follow the concurrent execution approach of point-to-all algorithms, overlooking the optimization potential of point-to-point algorithms. Due to redundant data access overhead and computational expenses, existing solutions exhibit poor overall throughput when executing concurrent point-to-point queries.

This paper introduces GraphCPP, the first graph traversal system designed for concurrent execution of point-to-point query tasks. It enhances the throughput of concurrent query tasks through data access sharing and hot path computation sharing. GraphCPP is novel in two ways. Firstly, based on the observation that traversal paths for different query tasks overlap significantly, GraphCPP proposes a data-driven caching execution mechanism. Through fine-grained graph chunk scheduling, this mechanism enables data sharing among concurrent tasks, thereby enhancing data access efficiency. Secondly, recognizing the frequent computation of the same hot vertices and paths by distinct tasks, GraphCPP proposes a dual-level computation sharing mechanism. This mechanism accelerates the convergence of unknown queries by sharing computed values of hot vertices and paths. In our evaluation on datasets such as xx, we compare GraphCPP with state-of-the-art point-to-point query systems and concurrent graph processing systems. The results demonstrate that GraphCPP incurs only xx preprocessing overhead and xx storage overhead, achieving a throughput improvement of xx-xx times compared to SGraph, Tripoline, Pnp, and Glign.

Index term: graph process, point-to-point graph queries, concurrent jobs, data locality

前言

通常，大规模的并发点对点查询任务会在同一底层图上执行，比如在物流运输中，谷歌地图通过找到两个地点之间的最佳路径来实现；在社交网络分析中，Facebook会通过查找两个用户之间的关系链为用户推荐可能的朋友；而在金融风险分析中，支付宝则会分析风险是如何从一个实体传播到另一个实体。这些热门应用程序提出了在同一底层图上执行大规模并发点对点查询的需求。与传统的图查询方法不同，点对点查询专门针对两个特定顶点之间的关联顶点进行分析，而不需要考虑整个图或其大规模子集的复杂查询。这种有针对性的查询策略使得点对点查询算法和点对多点查询算法存在显著差异，同时也为点对点查询提供了巨大的优化潜力。然而，目前通用的并发图计算系统通常采用常规方式执行点对点查询，忽略了对其遍历过程的优化。现有的点对点查询解决方案主要关注加速单次查询的效率，却忽略了对并发查询的优化。要实现高效执行并发点对点查询任务，需要克服两个关键挑战。

首先，在执行并发点对点查询任务时，如果不考虑数据访问相似性，就会导致对重叠数据的冗余访问。具体而言，不同查询任务从不同的起点开始，沿不同的路径到达各自的终点。由于图的幂律分布特性，这些查询路径自然会在一些热门路径上形成重叠（在第x节展示了重叠率约为30%）。然而，由于不同查询任务访问的数据重叠部分各不相同，它们会沿着不同的路径访问重叠的图数据。因此，现有的查询系统采用保守的策略，让每个任务负责访问其所需的数据。这意味着每个任务的数据访问是完全独立的，即使它们的遍历路径高度重合，例如一对查询的路径是另一对查询的路径的子集，仍然需要重复加载重叠部分的数据，无法享受重用缓存中数据的好处。

其次，除了重复访问外，不同查询任务还需要重复计算热门路径的距离值。同样由于图数据往往具有幂律分布的特点，少量热门顶点会频繁出现在不同查询的最佳路径中（在第x节展示了对高度顶点的计算约占30%）。由于不同查询任务之间不会共享计算，它们会重复计算连接热顶点的热路径。此外，热门顶点往往是具有大量邻居顶点的高度顶点，对于它们的重复遍历常常导致计算开销的爆炸式增长。尽管一些已有的系统尝试采用全局索引[xxxx]的方式来实现计算共享，但由于昂贵的计算开销、存储开销、更新开销限制了计算共享的效率和精确度。

Generally, large-scale concurrent point-to-point query tasks are executed on the same underlying graph. For instance, in logistics, Google Maps determines the optimal route between two locations; in social network analysis, Facebook recommends potential friends to users by exploring the relationship chain between two users; and in financial risk analysis, Alipay analyzes how risk propagates from one entity to another. These popular applications highlight the demand for executing large-scale concurrent point-to-point queries on the same underlying graph. Unlike traditional graph query methods, point-to-point queries specifically analyze associated vertices between two specific vertices, without the need to consider complex queries for the entire graph or its large-scale subsets. This targeted query strategy results in significant differences between point-to-point query algorithms and point-to-multipoint query algorithms, offering substantial optimization potential for point-to-point queries. However, current general-purpose concurrent graph computing systems typically employ conventional methods to execute point-to-point queries, overlooking optimizations for their traversal processes. Existing point-to-point query solutions primarily focus on accelerating the efficiency of individual queries, neglecting optimization for concurrent queries. Overcoming two key challenges is essential to efficiently execute concurrent point-to-point query tasks.

Firstly, when executing concurrent point-to-point query tasks, failure to consider data access similarity results in redundant access to overlapping data. Specifically, different query tasks initiate from distinct starting points and traverse different paths to reach their respective endpoints. Due to the power-law distribution characteristics of graphs, these query paths naturally overlap on some popular routes (as demonstrated in Section x, with an overlap rate of approximately 30%). However, since the overlapping portions of data accessed by different query tasks vary, they traverse along different paths to access overlapping graph data. Consequently, existing query systems adopt a conservative strategy, assigning each task the responsibility of accessing its required data. This implies that data access for each task is entirely independent, even if their traversal paths highly overlap. For example, if the path of one query pair is a subset of the path of another query pair, it still necessitates reloading data from the overlapping portions, preventing the benefits of reusing cached data.

Secondly, in addition to redundant access, different query tasks also need to redundantly compute distance values for popular paths. Similarly, due to the power-law distribution characteristics of graph data, a few popular vertices frequently appear in optimal paths for different queries (as illustrated in Section x, with calculations for highly connected vertices constituting approximately 30%). As different query tasks do not share computations, they redundantly calculate the hot paths connecting popular vertices. Moreover, popular vertices often possess a large number of neighboring vertices, and the repetitive traversal of these vertices leads to an explosive growth in computational expenses. Although some existing systems attempt to implement computation sharing through a global index [xxxx], the efficiency and accuracy of computation sharing are restricted due to the expensive computational, storage, and update costs.为了应对上述挑战，本文提出了一个数据驱动的并发点对点查询系统，称为GraphCPP。它通过数据共享机制和计算共享机制，提高了并发点对点查询系统的吞吐量。

在GraphCPP中，我们提出了一种数据驱动的缓存执行机制，将传统的“任务→数据”的调度方式改为“数据→任务”的调度方式，进而实现多任务之间重叠图结构数据访问的共享。在这种执行机制下，GraphCPP会首先确定数据的调度顺序：它将图结构数据从逻辑上划分为LLC级别的细粒度分块。接着根据查询任务活跃顶点集所处的图分块将查询任务与其相关的图分块联系起来，关联任务数量越多的分块优先级越高更可能被优先调度。任务的活跃顶点每轮都会变化，共享分块的关联任务数也需要每轮更新；为了实现“数据→任务”的调度方式，GraphCPP采用了一种关联任务触发机制。在按照优先级顺序将图分块加载到LLC后，利用每一轮统计得到的任务与数据分块的关联信息，触发当前当前分块的关联任务批量执行，实现了对共享数据的高效访问；

其次，GraphCPP提出了一个包含全局索引和核心子图索引的双层级的计算共享机制。它将图中具有大量连接边的顶点称为热顶点，将热顶点之间的路径称为热路径。虽然热顶点和热路径的数量较少，但是在不同查询任务的遍历路径中频繁出现。1）全局索引机制。全局索引维护了少量热顶点到其它顶点的索引信息，这些热顶点充当了不同查询路径的中介节点，通过它可以为绝大多数查询提供可供剪枝的路径值。通过全局索引，可以实现第一层计算共享。2）核心子图机制。核心子图主要维护图中连接热顶点的热路径。注意，核心子图中热顶点数比全局索引中的热顶点数大一个数量级，从而可以实现更大的覆盖范围。具体地，它首先要从原始图数据中筛选高度数的热顶点，接着从每次查询的收敛结果中提取出热路径，将热路径的值保存在核心子图中。在查询过程中，核心子图就像一个高速公路网，借助它可以从一个热顶点出发遍历到其他热顶点的过程，相当于从该热顶点进入高速公路，借助高速公路网上的快速通道（热路径），快速到达其他高速站点（热顶点）。虽然核心子图维护了更多的热顶点，但是因为其值维护热顶点之间的热路径，其整体规模远小于图的规模，且热路径的值无需计算就可得到，因此其带来的额外开销是很少的。

GraphCPP两层级的计算共享机制减少了冗余计算。

最后，GraphCPP还通过预测不同查询任务的遍历路径，驱动高度重叠的相似查询任务批量执行，进一步提高了并发查询的性能。

To address the challenges mentioned above, this paper proposes a data-driven concurrent point-to-point query system called GraphCPP. It enhances the throughput of concurrent point-to-point query systems through data sharing and computation sharing mechanisms.

In GraphCPP, we firstly introduce a data-driven caching execution mechanism that transforms the traditional "task→data" scheduling approach into a "data→task" scheduling approach, thereby enabling the sharing of overlapping graph structure data among multiple tasks. Under this execution mechanism, GraphCPP first determines the scheduling order of data: it logically partitions graph structure data into fine-grained chunks at the LLC level. Subsequently, it associates query tasks with the relevant graph chunks based on the graph block where the active vertices of the query tasks reside. The higher the number of associated tasks, the higher the priority for scheduling that chunk. As the set of active vertices changes in each round, and the number of associated tasks for shared chunks needs updating in each round, GraphCPP adopts an associated task-triggering mechanism to achieve "data→task" scheduling. After loading the graph chunks into the LLC in priority order, the system utilizes the associated information obtained in each round to trigger the batch execution of associated tasks for the current chunk, efficiently accessing shared data.

GraphCPP proposes a dual-level computation sharing mechanism that incorporates a global index and a core subgraph index. It identifies vertices in the graph with a significant number of connecting edges as hot vertices and the paths between these hot vertices as hot paths. Despite the limited quantity of hot vertices and hot paths, they frequently appear in the traversal paths of different query tasks. 1) Global Index Mechanism: The global index maintains information about a small number of hot vertices and their connections to other vertices. These hot vertices serve as intermediary nodes for various query paths, providing pruning values for the majority of queries. Through the global index, the first level of computation sharing is achieved. 2) Core Subgraph Mechanism: The core subgraph primarily maintains hot paths connecting hot vertices in the graph. Notably, the number of hot vertices in the core subgraph is an order of magnitude larger than that in the global index, enabling a broader coverage. Specifically, it starts by filtering highly connected hot vertices from the original graph data. Subsequently, it extracts hot paths from the convergence results of each query, storing their values in the core subgraph. During the query process, the core subgraph functions like a highway network, facilitating traversal from one hot vertex to another. This process is akin to entering a highway from a hot vertex and utilizing the fast lanes (hot paths) on the highway network to swiftly reach other high-speed stations (hot vertices). Despite maintaining more hot vertices, the core subgraph's overall scale is significantly smaller than that of the entire graph. Additionally, the values in the core subgraph, representing hot paths between hot vertices, can be obtained without computation, resulting in minimal additional overhead during the query process.

Lastly, GraphCPP further enhances the performance of concurrent queries by predicting the traversal paths of different query tasks and driving the batch execution of highly overlapping similar query tasks.

本文主要做出了如下贡献：

1. 分析了现有图计算系统处理并发点对点查询任务时的性能瓶颈，并提出利用并发查询任务之间的数据访问相似性和计算相似性来提高并发任务吞吐量。
2. 开发了GraphCPP，一个动态图上数据驱动的并发处理点对点查询系统，实现了并发任务之间的数据共享和计算共享，并提出了一个相似任务批量执行策略。
3. 我们将GraphCPP与当前最先进的点对点查询系统和并发图计算系统进行对比，该工作负载包六个真实图表上的六个应用程序。我们的实验表明, GraphCPP性能平均提高了xx~xx的钱.

This paper makes the following contributions:

We analyze the performance bottlenecks of existing graph processing systems when handling concurrent point-to-point query tasks and propose leveraging the similarities in data access and computation among concurrent tasks to enhance throughput.

We develop GraphCPP, a dynamic graph-driven concurrent processing system for point-to-point queries. It achieves data sharing and computation sharing among concurrent tasks and introduces a strategy for batch execution of similar tasks.

we compare GraphCPP with state-of-the-art point-to-point query systems and concurrent graph processing systems, using a workload that includes six real-world graphs and six applications. Our experiments demonstrate that, GraphCPP improves their performance by 1.73∼13 times.

背景和动机

**Table 1: Profiling performance analysis of conducting 10,000 point-to-point queries on LiveJournal graph using existing graph query systems.**

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| System | Pnp | | | Tripoline | | | SGraph | | |
| Concurrent number | 1 | 128 | 512 | 1 | 128 | 512 | 1 | 218 | 512 |
| Instructions (×10^14) | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| LLC loads (×10^12) | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| LLC miss ratio | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Runtime (hour) | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

大多数现有的解决方案[xxxx]聚焦于加速单次查询的速度，然而实际应用场景中，有大量图查询任务在同一个底层图上并发运行。例如，中国地理信息产业协会[x]的统计表明，百度地图[xx]、高德地图[xx]、腾讯地图[xx]、华为地图[xx]等企业建设的位置服务开放平台日均位置服务请求次数最高达1600亿次[xx]。大量并发点对点查询需求对图遍历系统的吞吐量提出了极高的要求。然而如表1所示所示，我们证明现有系统在处理大规模并发查询时吞吐量很差。这种坏结果出现的原因是并发任务之间存在对图结构数据大量的冗余访问和冗余计算。为了定性地分析上述问题，我们在XXXXX（机器配置），选取了XXXXX（现有最佳方案），在XXXXX（图数据集上），进行并行点对点查询的性能评测。

本章分为三个部分，我们首先介绍了并发点对点查询中的一些概念；其次分析了当前点对点查询方案处理并发任务时的性能瓶颈；最后展示了我们根据观察分析获得的启发。

BACKGROUND AND MOTIVATION

Most existing solutions [xxx] are primarily focused on accelerating the speed of individual queries. However, in practical scenarios, there is a significant number of graph query tasks concurrently running on the same underlying graph. For instance, statistics from the China Geographical Information Industry Association indicate that location service open platforms constructed by companies such as Baidu Maps, Gaode Maps, Tencent Maps, and Huawei Maps receive a daily average of up to 160 billion location service requests. The substantial demand for concurrent point-to-point queries poses a high requirement for the throughput of graph traversal systems. However as illustrated in Figure 2, we demonstrate that existing systems exhibit low throughput when handling large-scale concurrent queries. The root cause of this undesirable outcome is the significant redundancy in data access and computation among concurrent tasks. To qualitatively analyze the aforementioned issues, we conducted performance evaluations on parallel point-to-point queries using XXXXX (machine configuration), selecting XXXXX (the current best solution) on XXXXX (graph dataset).

Preliminaries

定义一：（图）我们使用G=(V,E)来表示有向图（无向图中的边被视作双向边），其中V是顶点的集合，E是由V中顶点组成的有向边的集合（无向图中的边可以被拆分为两个不同方向上的有向边）。我们使用|V|，|E|分别表示顶点的数目以及边的数目。在分布式环境中，还存在图分区问题，我们使用Pi=(VPi,EPi)来表示有向图的第i个图分区，使用VPi表示图分区中顶点的集合，EPi是由VPi中顶点组成的有向边的集合。

定义二：（点对点查询）我们使用qi=(si，di)表示任务i对应的查询任务。其中si和di分别表示查询qi对应的源顶点和目的顶点。假如以为si和di输入，在图上执行点对点查询算法，可以得到一条收敛的路径，它就是si和di之间的最佳路径。点对点查询和普通查询的区别在于前者可以通过剪枝来减少不必要的遍历。剪枝时会将两点之间的路径的值当做剪枝的阈值，称为界限。不断遍历新的路径更新界限，当界限收敛，代表找到了一条最佳路径。

定义三：（核心子图）我们使用Gcore=(Vhot,Ehot,Indexhot)来表示核心子图，其中Vhot是热顶点的集合，Ehot是将热路径抽象为边后边的集合,Indexhot是热路径值的集合。此处，热顶点指高度数顶点，热路径是连接热顶点对的一条最佳路径。

**Preliminaries**

Definition 1: (Graph) We use G=(V, E) to denote a directed graph, where V is the set of vertices, and E is the set of directed edges formed by vertices in V (for undirected graphs, edges can be split into two directed edges with different directions). We use |V| and |E| to represent the number of vertices and edges, respectively.

Definition 2: (Point-to-Point Query) We use qi=(si, di) to denote the query corresponding to task i, where si and di represent the source and destination vertices of query qi, respectively. If the execution of the point-to-point query algorithm on the graph yields a convergent path for qi, this path is referred to as the optimal path between si and di.

The distinction between point-to-point queries and regular queries lies in the former's ability to reduce unnecessary traversals through pruning. Pruning involves using the value of the path between two points as a threshold, referred to as the bound. Iteratively traversing new paths updates the bound, and when the bound converges, it signifies the discovery of an optimal path.

Definition 5: (Core Subgraph) We use Gcore=(Vhot,Ehot,Indexhot) to represent the core subgraph, where Vhot is the set of hot vertices (with many connecting edges), Ehot abstracts the hot paths between vertices in Vhot as edges, and Indexhot represents the path values corresponding to Ehot.

|  |  |  |  |
| --- | --- | --- | --- |
| **图1** | 图2 | | 图3 |
| 图4 | 图5 | 图6 | |

并发点对点查询任务的性能瓶颈

在本节，我们在gemini系统的基础上实现了当前最先进的点对点查询系统SGraph的并发版本SGraph-C，并通过 Twitter评估了SGraph-C执行并发点对点查询的性能。以定量地说明现有并发点对点查询方案的性能瓶颈。

**并发任务的****冗余数据访问开销。**我们观察到当并发点对点查询任务在同一个底层图上执行图遍历时，体现出来很明显的数据访问相似性。如图1，并发任务之间存在很大比例的访问重叠，特别地，相似任务的重叠比例更高(more details are given in Sectionxx)。然而在传统的“任务->数据”调度模式下，不同任务独立执行查询，因此它们会相互争用有限的缓存来存储各自所需要的图数据分块，哪怕这些数据分块是重叠的。这会导致严重的缓存抖动并降低处理并发点对点查询的性能。表1表明，随着并发数目的增大，查询任务的缓存未命中率也急剧增大。并且虽然并发执行的整体效果优于线性执行，但是由于前面提到的冗余数据访问开销，随着查询任务数量额增加每个任务的平均查询时间显著增加。注意，并发方式的总执行时间是这些作业执行时间的最大值，而顺序方式是所有作业执行时间的总和。

**Performance Bottlenecks in Concurrent Point-to-Point Query Tasks**

In this section, we have developed the concurrent version SGraph-C based on the Gemini system, which is currently at the forefront of pairwise query systems. We evaluated the performance of SGraph-C in executing concurrent pairwise queries through Twitter, aiming to quantitatively illustrate the performance bottlenecks of existing concurrent pairwise query solutions.  
The redundant data access overhead of concurrent tasks is evident. We observe that when concurrent pairwise query tasks execute graph traversal on the same underlying graph, a significant portion of their traversal paths exhibits clear data access similarities. As shown in Figure 3x, our data indicates that there is a substantial overlap in data access among concurrent tasks, with a higher overlap ratio for similar tasks (more details are provided in Section xx). However, in the traditional "task->data" scheduling mode, different tasks independently execute queries, leading to competition for limited cache space to store their respective graph data chunks, even when these data chunks overlap. This results in severe cache thrashing and a reduction in the performance of processing concurrent pairwise queries. Table 1 illustrates that, with an increase in the number of concurrent tasks, the cache miss rate for query tasks sharply rises. Although the overall performance of concurrent execution surpasses linear execution, the average query time per task significantly increases with the growing number of query tasks due to the mentioned redundant data access overhead. It is essential to note that the total execution time in the concurrent mode is the maximum among the execution times of these tasks, while in the sequential mode, it is the sum of all task execution times.

**并发任务的冗余计算开销。**由于图数据呈现幂律分布，查询任务的遍历路径中包含大量热门顶点。如图2所示，尽管热门顶点仅占总顶点数的一小部分（约XX%），但它们却频繁出现在多个任务的遍历路径中（约XX%）。此外，图数据中热门顶点的共享程度与其在路径中的比例呈正相关。因此，不同的查询任务可能会反复计算热门顶点之间的路径，凸显了并发任务之间的计算相似性。在一个图快照周期内，相同顶点对的路径计算结果保持一致，这意味着并发任务中存在大量冗余计算。同时，由于热门顶点通常具有大量出边和入边，与普通顶点相比，它们带来的计算开销更大。

一些现有的解决方案试图通过建立全局索引机制[x]来利用计算相似性。然而，全局索引机制存在天然缺陷。首先，全局索引需要记录高度顶点与所有其他顶点的路径值。当图的规模非常庞大时，建立索引的计算开销和存储开销会急剧增加，如图3和图4所示。这种增加与全局索引顶点数的增加成正比。其次，在动态图处理中，每轮图更新都会引起新的边添加和边删除。现有方案采用增量更新方式来更新全局索引。然而，如果受影响的顶点位于某一条最佳路径上，那么从受直接影响的顶点到终点这段路径上的所有顶点的全局索引值都需要重新计算。如果共享的数据部分发生了图更新，其影响将进一步扩大，如图5所示。随着图更新比例的增加，需要重新计算的全局索引的比例也在不断增加。最后，不同图数据集的数据分布情况各异，很难选择一个合适的索引顶点数目在索引的覆盖范围和索引本身的开销之间取得平衡。如图6所示，即使在不同的数据集上选择相同的索引顶点数，其固有开销和计算共享的有效性也存在显著差异。综上所述，全局索引机制本身会引起昂贵的开销，并且对于不同的数据集，所需开销的波动较大。因此，现有系统通常保守地选择全局索引的数量（例如，在Tripoline和SGraph中都选择16个顶点），以避免引入昂贵的开销，但这也限制了全局索引的覆盖范围，无法实现高效的计算共享。

Due to the power-law distribution of graph data, the traversal paths of query tasks involve a substantial number of popular vertices. As illustrated in Figure 2, despite popular vertices constituting only a small fraction of the total vertices (approximately XX%), they frequently appear in the traversal paths of multiple tasks (about XX%). Additionally, the degree of sharing among popular vertices in graph data is positively correlated with their proportion in paths. Consequently, different query tasks may redundantly calculate paths between popular vertices, highlighting the computational similarity between concurrent tasks. Within a graph snapshot period, the calculation results for paths between identical vertex pairs remain consistent, indicating a significant redundancy in computations among concurrent tasks. Moreover, due to the typically higher number of outbound and inbound edges associated with popular vertices, their computational overhead is considerably larger compared to regular vertices.

Some existing solutions aim to exploit computational similarity through a global indexing mechanism [x]. However, this mechanism inherently suffers from three key drawbacks: 1) The computational and storage costs of establishing a global index, which records path values between highly connected vertices and all others, escalate sharply with the graph's increasing scale, as depicted in Figures 3 and 4. This escalation is directly proportional to the number of vertices in the global index. 2) In dynamic graph processing, incremental updates are employed to refresh the global index following each round of graph updates. However, if affected vertices lie on an optimal path, the global index values for all vertices along the path from the directly impacted vertex to the endpoint must be recalculated. The impact of graph updates is further amplified if the shared data segment undergoes modifications, as shown in Figure 5. The percentage of the global index requiring recalculation continues to rise with an increasing proportion of graph updates. 3)Diverse data distribution patterns across different datasets make it challenging to select an optimal number of index vertices to balance index coverage and associated overhead. Figure 6 illustrates significant variations in inherent costs and the effectiveness of shared computations, even when the same number of index vertices is selected across different datasets.

In conclusion, the global indexing mechanism itself incurs substantial costs, and these costs fluctuate significantly across different datasets. Existing systems often conservatively opt for a limited number of global index vertices (e.g., 16 vertices in Tripoline and SGraph) to avoid introducing expensive overhead. However, this choice also restricts the coverage of the global index, hindering efficient computation sharing.

我们的启发

通过上述的观察，我们得到了以下启发：

观察1：不同查询任务的遍历路径有很大部分是重叠的，这表明数据访问模式存在相似性。然而，现有解决方案在同时支持点对点查询和任务间数据共享方面存在不足，导致数据访问冗余。这一观察促使了一种高效的、细粒度的数据共享机制的开发。通过允许不同任务在不同时间共享对相同数据的访问，该机制旨在减少数据访问成本，并提高并发查询的吞吐量。

观察2：在原始图中，由热点顶点和路径组成的核心子图经常被不同任务遍历，突显了不同查询任务之间的计算相似性。现有的图遍历系统要么忽视计算相似性[xx pnp]，要么采用昂贵的全局索引机制[xx Tripoline]，限制了计算共享的效果。这一观察启发了建立一种轻量级、双层索引机制，以在不同查询任务之间共享重叠的热路径的计算结果。

**Our Motivation**

Based on the above observations, we have gained the following insights:

Observation 1: A significant portion of traversal paths in different query tasks displays substantial overlap, indicating a similarity in data access patterns. However, existing solutions fall short in concurrently supporting point-to-point queries and facilitating data sharing among tasks, resulting in redundant data access. This observation motivates the development of an efficient, fine-grained data-sharing mechanism. By allowing various tasks to share access to the same data at different times, this mechanism aims to reduce data access costs and enhance the throughput of concurrent queries.

Observation 2: The core subgraph, consisting of hot vertices and paths in the original graph, is frequently traversed by various tasks, highlighting computational similarity among different query tasks. Existing graph traversal systems either neglect computational similarity [xx pnp] or employ a costly global indexing mechanism [xx Tripoline], limiting the effectiveness of computational sharing. This observation inspires the creation of a lightweight, dual-layered indexing mechanism to share computational results of overlapping hot paths across different query tasks.

系统概述

系统架构

为了提高并发点对点查询的执行效率，在对并发点对点查询的计算细节进行仔细研究后，我们提出了一个数据驱动的高效并发点对点查询系统-GraphCPP。我们系统的关键思想是实现并发点对点查询任务之间的数据共享和计算共享。如下图所示，为了实现这个目标，GraphCPP包含了一个高效地数据驱动的缓存执行机制，利用并发任务之间的数据相似性，实现了重叠数据的共享访问。以及一个双层级计算共享机制，共享不同查询任务对相同热顶点和热路径的计算。此外，它还通过预测不同查询的遍历路径，驱动路径重叠的相似查询批量执行，进一步利用了数据相似性。

数据访问共享机制。它负责利用并发任务的数据访问相似性实现图结构数据的细粒度共享。首先，它像其它分布式图计算系统[13-16]一样将原始图数据划分为粗粒度的图分区，交由不同的机器并行处理。然后使用一个细粒度的分块管理器将粗粒度的图分区划分为细粒度的图分块。接着执行图分块-任务之间的关联机制：假如一个查询任务qi在某个图分块bi存在活跃顶点，那么就认为qi和bi之间存在关联关系。分块优先级调度机制会根据不同图分块包含关联任务的数量，优先调度有更多关联任务的图分块到LLC。关联任务触发器会根据LLC中活跃图分块信息，以及图分块-任务的关联信息，筛选出所有有关联关系的任务在共享图分块上批量执行。

计算共享机制。它负责借助双层级索引信息（包含全局索引和核心子图索引）利用并发查询任务之间的计算相似性实现路径计算的共享。1）**预处理阶段**：它首先统计原始图数据中所有顶点的度数信息， 将原始图的顶点按照度数由大到小排序，选择度数排名位于[1,k]的顶点作为全局索引顶点，选择度数排名位于[k+1,k+m]的顶点作为核心子图索引顶点；2）**索引建立阶段**：一方面，全局索引需要在查询开启前计算。对于不同算法，需要执行不同的点对多点查询算法计算全局索引顶点与图中所有顶点的最佳路径值（例如对于PPSP任务，需要执行SSSP算法）。 GraphCPP Overview

**system architecture**

To enhance the efficiency of concurrent point-to-point queries, we introduce GraphCPP—a meticulously designed, data-driven system tailored for concurrent query tasks. Developed after a thorough examination of the computational intricacies inherent in such queries, GraphCPP aims to foster data and computation sharing among concurrent point-to-point tasks. As depicted in the figure below, GraphCPP incorporates an efficient data-driven caching execution mechanism, leveraging data similarity among concurrent tasks to facilitate shared access to overlapping data. Additionally, it introduces a dual-level computation sharing mechanism, enabling computations for identical hot vertices and paths to be shared across different query tasks. Furthermore, GraphCPP employs path prediction for various queries, promoting the bulk execution of similar queries with overlapping paths and maximizing the utilization of data similarity.

{\bf{Data Access Sharing Mechanism}}. This mechanism aims to achieve precise sharing of graph structure data by leveraging data access similarities among concurrent tasks. The process unfolds as follows: initially, similar to other distributed graph computing systems [13-16], it partitions the original graph data into coarse-grained segments, distributing them for parallel processing across different machines. Subsequently, a fine-grained chunk manager further divides these coarse-grained segments into fine-grained graph chunks. The next step involves establishing connections between query tasks and graph data chunks. Specifically, if a query task (qi) has active vertices in a graph chunk (bi), a relationship between qi and bi is established. Following this, a graph chunk priority scheduling mechanism prioritizes graph chunks with a higher number of associated tasks for loading into the Last Level Cache (LLC). Consequently, the system filters out all query tasks linked to graph chunks present in the LLC, allowing them to be executed in batches on the shared graph chunks.

{\bf{Calculation Sharing Mechanism}}. It is responsible for leveraging dual-level index information (including global index and core subgraph index) to utilize computational similarity between concurrent query tasks for shared path computation. 1) Preprocessing Phase: It first gathers degree information for all vertices in the original graph data, sorts the vertices in descending order based on their degrees, and selects vertices ranked from 1 to k as global index vertices and vertices ranked from k+1 to k+m as core subgraph index vertices. 2) Index Building Phase: On one hand, before queries start, it executes a point-to-all query algorithm to compute the best path values from global index vertices to all vertices in the graph (e.g., for PPSP tasks, it requires executing SSSP algorithm). For directed graphs, it calculates both the outbound and inbound path values for global index vertices, while for undirected graphs, only one calculation is needed. On the other hand, GraphCPP dynamically maintains the core subgraph through a runtime method. Specifically, any segment of a best path between a vertex pair corresponds to the best path between the corresponding vertices. Therefore, the core subgraph does not need precomputation for hot paths but dynamically explores hot paths after each query, adding them to the core subgraph structure. 3) Computation Sharing Phase: Global index vertices typically act as intermediaries for numerous paths, so at the beginning of a query, using global index vertices can compute the path value for a reachable path. This path may not necessarily be the best path between query vertex pairs but can provide a reference for pruning queries. Moreover, in pruning traversal based on upper bound + lower bound, global index can estimate the path value for query paths earlier, allowing earlier pruning of unsuitable paths. Using global index constitutes the first level of computation sharing. The core subgraph maintains best path values between hot vertices, serving as a highway network between query tasks. When a query task traverses hot vertices in the core subgraph, it connects to the highway. Leveraging the core subgraph, it can quickly reach the exit vertex from the entrance vertex without recalculating the path value for this hot path segment. Using the core subgraph constitutes the second level of computation sharing.

对于有向图，需要分别计算全局索引的出边路径值和入边路径值，对于无向图则只需要计算一次；另一方面：核心子图则通过一个运行时方法来动态维护。具体地，一段最佳路径上的任意一段子路径，都是一条最佳路径。因此核心子图无需对热路径进行预计算，而是在每次查询结束后，执行热路径探测机制发掘一条最佳路径中的热路径，并将其加入到核心子图结构中。3）计算共享阶段：全局索引顶点一般充当大量路径的中介枢纽顶点，因此在查询开始时，使用全局索引顶点可以计算出一条可达路径的路径值。这条路径不一定是查询顶点对之间的最佳路径，但是可以对剪枝查询提供参考。此外在基于上界+下界的剪枝遍历中，还可以借助全局索引预估查询路径的路径值，更早对不合适路径进行剪枝。使用全局索引是第一层次的计算共享；核心子图维护了热顶点之间的最佳路径值，它充当了查询任务之间的高速公路。当查询任务遍历到核心子图中的热顶点，相当于接入了高速公路，它可以借助核心子图从入口顶点快速到达核心子图的出口顶点，而无需重复计算这段热路径的路径值。使用核心子图是第二层次的计算共享。

整体执行流程

算法1展示了GraphCPP处理并发查询任务的整体执行流程。假设我们已经完成分区，在第一行我们得到在分布式系统中属于当前计算节点的所有图分块的集合B以及所有查询任务的集合Q，并为他们分配一段内存空间。在第二行，我们进入一个循环处理过程，查询会迭代进行直至收敛。GraphCPP将调用ChooseNextSharingBlock来更新查询任务与图分块之间的关联关系，并选择当前优先级最高(有着最多关联任务)的图分块bi。通过统计每个任务的关联分块（即任务在当前分块存在活跃顶点），我们可以确定与当前图分块bi相关联的所有查询任务（第四行）。接下来，我们将bi加载到缓存，并并行处理所有相关联的查询操作qi（第五行）,这一步体现了数据共享的思想，即一次数据访问，多个查询任务共享。接着我们调用GraphCPPCompute在当前分块上执行点对点查询操作qi（Details are given in section.xx）。迭代查询任务执行BSP模型，每一轮迭代会生成新的活跃顶点集，并更新为一个新的查询任务（第六行）。如果新查询依然与当前的图分块bi存在关联，将qi添加到Qbi，然后返回第五行继续在图分块bi上查询。否则，代表新任务与当前图分块没有关联关系，需要将其保存在查询任务集合中，此时任务被挂起。

|  |
| --- |
| Algorithm 1: Concurrent Point-to-Point Queries |
| 1: function OverallWorkflow  2 MallocBuffers( *B*, *Q* ) //*B* is the set of graph blocks, and *Q* is the set of query tasks  3: While has\_active( *B* ) do：  4: *bi* ← ChooseNextSharingBlock( )  5: *Qbi* ← ChooseAssociatedQueries( *bi* )  6: Parallel\_for\_each *qi* ∈ *Qbi* do: // Execute queries in *Q* in parallel, which is associated with block *bi*  7: new\_query =GraphCPPCompute( *qi*, *bi* ) // The implementation function for point-to-point queries returns the active vertex set after one round of task iteration.  8: if(has Associated( ( *bi* , new\_query ) ):  9: *Qbi*.Push( new\_query )  10: else:  11: *Q*.Push( new\_query ) |
|  |

Algorithm 1 outlines the comprehensive execution process of GraphCPP in handling concurrent query tasks. Assuming partitioning is completed, in the first line, we acquire the set \(B\), which includes all graph blocks on the current computing node, and the set \(Q\), which includes all query tasks on the current computing node. Each of them is allocated a segment of memory. In the second line, we enter a loop processing phase, and queries iterate until convergence is achieved. GraphCPP invokes \texttt{ChooseNextSharingBlock} to update the association between query tasks and graph blocks and selects the graph block \(b\_i\) with the highest priority (having the most associated tasks). By tallying the associated blocks for each task (i.e., tasks with active vertices in the current block), we can determine all query tasks related to the current graph block \(b\_i\) (fourth line). Next, we load \(b\_i\) into the cache and parallelly process all associated query operations \(q\_i\) (fifth line). This step embodies the idea of data sharing, i.e., multiple query tasks sharing the result of a single data access. Subsequently, we invoke \texttt{GraphCPPCompute} to perform point-to-point query operations \(q\_i\) on the current block (details are provided in Section \ref{section:xx}). Iterative query task execution follows the Bulk Synchronous Parallel (BSP) model, where each iteration generates a new set of active vertices and updates to form a new query task (sixth line). If the new query remains associated with the current graph block \(b\_i\), we add \(q\_i\) to \(Q\_{b\_i}\) and return to the fifth line to continue querying on the graph block \(b\_i\). Otherwise, it signifies that the new task is not associated with the current graph block, and it needs to be saved in the query task set; at this point, the task is suspended.

上述算法展示了GraphCPP中的整体工作流程，其在下面的章节，我们将详细介绍数据访问共享和计算共享两个优化机制。

The presented algorithm illustrates the overall workflow of GraphCPP. In the subsequent sections, we will delve into the detailed explanations of two optimization mechanisms: data access sharing and compute sharing.

数据访问共享机制

在2.2节中我们观察到并发任务之间的图结构数据访问存在很大一部分重叠，在现有处理机制下，这部分重叠数据并不能被共享利用，我们观察到，对于图上的点对点查询任务来说，数据的访问顺序并不会影响结果的正确性，并基于此提出了数据共享机制。该机制的核心思想是将原本的“任务→数据”线性任务调度顺序，改为“数据→任务”细粒度并发任务调度顺序，来利用并发查询任务之间的数据相似性，分摊数据访问开销，提高缓存利用效率，进而提高系统吞吐量。接下来我们从两个问题出发描述如何实现数据访问共享，并在最后描述了一个进一步利用数据访问相似性的措施。

一、如何确定共享的数据部分？

1，确定共享图分块粒度。分布式内存图计算系统需要将数据载入缓存以提升数据访问效率，所以理想情况下共享图分块的数据要能完整地载入LLC，从而避免访问分块不同部分带来的频繁换入换出。但是图分块的粒度也不能过于小，否则会增加任务处理的同步开销。我们使用公式x来确定合适的共享图分块大小。其中BS表示待确定的共享图分块的图结构数据的大小，GS表示分块所属的图分区的图结构数据的大小，|V|表示分区上图的顶点总数，VS表示存储一个顶点的状态信息平均所需的空间大小，N表示并发查询的任务数，LLCS是LLC缓存空间的大小，RS是预留的冗余空间的大小，可以用来存放索引等数据。公式x右侧的两项分别表示图结构数据和任务特定数据（其大小与图分块的规模和并发查询任务数成正比）。公式右侧表示减去缓存预留空间后，每个任务剩下的可使用空间的大小。通过这个公式，我们求得了在适应LLC容量前提下，每个共享图分块的最大粒度。

**Data Access Sharing Mechanism**

In Section 2.2, we observed a significant overlap in graph structure data access among concurrent tasks. Under the existing processing mechanism, this overlapping data cannot be shared and utilized. However, for point-to-point query tasks on the graph, the order of data access does not affect the correctness of the results. The core idea of our data sharing mechanism is to transform the original "task → data" linear task scheduling order into a "data → task" fine-grained concurrent task scheduling order. This allows us to leverage data similarity among concurrent query tasks, distribute data access overhead, enhance cache utilization efficiency, and consequently, improve system throughput. We will address two key questions in the following sections: 1) How to determine the shared data segments? 2) How to implement data sharing among multiple tasks? Finally, we will describe additional measures to further exploit data access similarity.

A. How to Determine Shared Data Segments?

1.Determine the granularity of shared graph block. Distributed memory graph computing systems need to load data into the cache to improve data access efficiency. Ideally, the data of shared graph should be able to fit entirely into the Last Level Cache (LLC), thereby avoiding the frequent swapping in and out of block parts. However, the granularity of graph blocks should not be too small, as it would increase the synchronization overhead of task processing. We employ formula x to determine an appropriate size for shared graph blocks. In this formula, BS represents the size of the graph structure data for the to-be-determined shared graph block, GS denotes the size of the graph structure data for the partition to which the block belongs, signifies the total number of vertices on the partition, VS stands for the average space needed to store the status information of a vertex, N represents the number of concurrently queried tasks, LLCS denotes the size of the LLC cache space, and RS refers to the reserved redundant space，which can be used to store data such as indexes. The two terms on the right side of formula x respectively represent the graph structure data and task-specific data (whose size is proportional to the scale of the graph block and the number of concurrently queried tasks). The right side of the formula indicates the size of the available space for each task after deducting the reserved cache space. Through this formula, we determine the maximum granularity of each shared graph block under the condition of accommodating the LLC capacity.

2，逻辑划分。确定好共享图分块的粒度后，GraphCPP就可以在图预处理的过程中，采用逻辑划分的方式，将分布式系统上粗粒度的图分区划分为细粒度的共享图分块。代码2展示了GraphCPP划分图分块的过程：

|  |
| --- |
| Algorithm 2: Logical Partition Algorithm. |
| 1: function Partition(Pi , block\_table) // block\_table records the set of graph blocks owned by graph partition Pi.  3: block\_map = null  4: for each e ∈ Pi do: //e is an edge in partition Pi  5: if e.src in block\_map:  6: block\_map [e.src]++  7: else:  8: block\_map[e.src]=1  9: end if  11: if block\_map.size（）≥ SC:  12: block\_table.push(block\_map)  13: block\_map.cear( )  14: end if  15: end for |

2. Logical Partitioning. Once the granularity of shared graph blocks is established, GraphCPP can proceed with the logical partitioning during the graph preprocessing phase. This process involves subdividing coarse-grained graph partitions on the distributed system into finer-grained shared graph blocks. Pseudocode for partitioning graph blocks in GraphCPP is presented in Listing X:

逻辑分区函数接收两个参数，一个是以边表形式记录的图分区结构数据Pi ，一个是该分区所拥有的图分块集合block\_table（第一行）。在第二行，我们通过一个字典结构block\_map来统计图分块信息，它的key记录边的源顶点ID，value记录该顶点对应的出边的数目。第四行，GraphCPP循环遍历分区中的每一条边。如果该边已经被加载到当前的分区，将分区对应的出边数量加一(第6行)。如果该顶点是第一次加入到字典中，将分区的出边数置为1（第8行）。每次遍历完一条边都会判断当前分块是否已满（第11行），若分块已满，将当前分块加入图分块集合block\_table（第12行），并清空记录的分块信息（第13行）。这样当分区中的所有数据遍历完一遍，分区的每一条边都被划归到某一个图分块，我们就得到了从逻辑上划分完成的图分块的集合。

The logical partition function takes two parameters: one is the graph partition structure data Pi recorded in edge table format, and the other is the set of graph blocks B owned by the partition (Line 1). In Line 2, we utilize a dictionary structure called block\_table to collect information about graph blocks. Its key records the source vertex ID of an edge, and its value records the number of outgoing edges corresponding to that vertex. In Line 4, GraphCPP iterates through each edge in the partition. If the edge has already been loaded into the current partition, the count of outgoing edges for that partition is incremented (Line 6). If the vertex is added to the dictionary for the first time, the count of outgoing edges for the partition is set to 1 (Line 8). After processing each edge, there is a check to determine if the current block is full (Line 11). If the block is full, the current block is added to the block\_set (Line 12), and the recorded block information is cleared (Line 13). This way, when all the data in the partition has been traversed, and each edge in the partition is assigned to a specific graph block, we obtain the collection of logically partitioned graph blocks.

二、如何实现多任务间的数据共享

建立共享分块-查询任务的关联。通过之前的步骤，我们用逻辑划分的方式，实现了细粒度的图分块。我们使用block\_table来维护逻辑分块信息，其中每个分块附加上了一个标签信息。执行查询时，每个任务qi在迭代计算过程中会维护一个活跃顶点集Setact,i，它遵循以下更新策略：1，初始时Setact,i仅包含查询源顶点Si。2，按照点对点查询算法的流程，从Setact,i中的活跃顶点出发查询新的顶点，处理后的顶点会被从活跃顶点集中移除。 3，如果一个顶点的状态在本轮中被改变，且它没有被剪枝，则该顶点被加入到Setact,i等待下一轮处理。通过上述更新策略，我们可以轻松追踪每一轮迭代各个任务的活跃顶点集。接下来借助block\_table可以查询活跃顶点所在的图分块。进一步地，我们可以统计每个图分块有哪些关联任务。由于点对点查询采用基于剪枝的遍历策略，每一轮执行中活跃顶点的数量并不多，所以可以以较低的开销建立查询任务与所属分块的关联。

2，确定分区调度的优先级。对共享图分块的访问开销可以被分摊到多个任务中，因此分块的关联的任务数量越多，共享带来的收益越大。由于在上一步已经获得了共享分块和查询任务的映射关系，因此通过遍历block\_table，我们可以快速获得每个图分块的优先级。

3，触发关联任务并发执行。确定图分块优先级后，我们优选高优先级的共享分块加载到LLC中，接着根据共享分块-查询任务的关联关系推导出所有在当前图分块活跃的查询任务，并采用批量计算的方式执行这些任务。如算法X所示，活跃任务执行一轮后会产生新的活跃顶点，倘若新的活跃顶点仍然与当前的共享分块相关联，查询任务会继续执行。共享分块会始终停留在LLC，直到与该分块关联的所有查询任务都被处理完毕，才会换出。

B. Achieving Data Sharing Among Multiple Tasks

Establishing the Association between Shared Blocks and Query Tasks. Through the previous steps, we achieved fine-grained graph partitioning in a logical manner. We use the \texttt{block\_table} to maintain information about logical blocks, with each block appended with a label. As this is only a logical partitioning, the data remains contiguous on the physical storage medium. Therefore, it is easy to determine the partition in which a vertex is located based on its ID. During query execution, each task $q\_i$ maintains an active vertex set $Set\_{act,i}$ throughout the iterative computation process. It follows the updating strategy:

\begin{enumerate}

\item Initially, $Set\_{act,i}$ only contains the query source vertex $S\_i$.

\item Process the active vertices in $Set\_{act,i}$ according to the flow of the point-to-point query algorithm, removing the processed vertices from the active set.

\item If a vertex's state changes in this round and it is not pruned, add the vertex to $Set\_{act,i}$ for processing in the next round.

\end{enumerate}

With the above updating strategy, we can easily track the active vertex sets for each task in each iteration. Subsequently, leveraging the \texttt{block\_table}, we can first query the ID of active vertices and deduce the graph block to which they belong. Furthermore, we can then tally and utilize a specially designed array to store which partitions each graph block is associated with for each task. Since point-to-point queries adopt a pruning-based traversal strategy, the number of active vertices in each execution round is not high, allowing for the establishment of the association between query tasks and their respective blocks with relatively low overhead.

Determining the Priority of Partition Scheduling. After establishing the association between query tasks and their corresponding blocks, we can tally the number of tasks associated with each graph block. The higher the task count, the more tasks share the block, indicating greater benefits from processing this block. Consequently, blocks with a higher task count are prioritized for placement into the Last-Level Cache (LLC). Since we obtained the mapping relationship between shared blocks and query tasks in the previous step, by traversing the \texttt{block\_table}, we can quickly obtain the priority of each graph block.

Triggering Concurrent Execution of Associated Tasks. After determining the priority of graph blocks, we preferentially load high-priority shared blocks into the LLC. Subsequently, having obtained the shared graph data blocks, based on the association between shared blocks and query tasks, we can infer the active query tasks. These tasks share the graph structure data in the LLC, and we execute these query tasks using a batch computing approach. As shown in Algorithm X, active tasks generate new active vertices after one round of execution. If these new active vertices remain associated with the current shared block, the query tasks continue execution. Shared blocks always remain in the LLC until all query tasks associated with them are processed, at which point they are evicted.

三、相似任务批量执行

同一时刻并发任务池中有大量随机查询任务，它们的查询路径大不相同。一些任务的查询路径重叠比例很高，对他们进行数据共享的效率很高。一些任务的重叠比例很低，阻碍了数据共享的效率。我们发现查询任务的相似程度越高，路径的重叠率越高，数据的访问效率越高，冗余的同步迭代更少。注意，我们计算不同任务起点（目的顶点）之间的距离值来衡量任务之间的相似性。对此我们提出了一个相似任务感知的批量执行策略，每次从任务池中筛选相似任务批量执行，以进一步地利用数据相似性和计算相似性。具体地，GraphCPP首先从任务池中随机选择一个查询任务，获取任务的起始顶点和目标顶点。然后执行BFS算法获取起始顶点的邻居顶点集SetS，以及目标顶点的邻居顶点集SetD。注意，考虑到部分中心节点存在大量邻居节点，我们设置邻居节点的上限为500。随后遍历任务池，筛选出所有起始点位于SetS，目的点位于SetD的查询任务，它们被作为相似任务并发处理。需要注意的是，如果某个查询的起始顶点或目的顶点属于高度顶点，可以直接使用索引来加速查询过程，无需使用常规的查询步骤。排除掉高度顶点后K跳SSSP本身的开销很小，且执行过程可以和正常查询并发执行，执行开销可以忽略不计。

计算共享机制

GraphCPP通过全局索引机制和核心子图索引机制实现了两个层次的计算共享。全局索引的固有开销很大，且开销与全局索引数目成正比，因此实践中通常将全局顶点的数目设置的很小（通常为16）。然而由于图遵循幂律分布的特点，少量的全局顶点充当了大量查询路径上的枢纽节点。这意味着对于大部分点对点查询qi，都可以找到一条从si出发，途径至少一个全局顶点到达di的路径。这条路径虽然不一定是查询qi的最佳路径，但是为查询提供了有价值的剪枝界限。GraphCPP借助全局索引机制快速确定途径路径，实现了第一层次的计算共享；进一步的，核心子图机制在无需预处理的前提下，挖掘已有查询结果的最佳路径，实现对不同查询重叠热路径的计算的共享。和全局索引相比，核心子图更加轻量级，因此可以通过增加热顶点数目做到更高的覆盖范围，进而可以提供更精确的剪枝界限值，从而加速剪枝查询的收敛速度。算法3展示了计算共享机制的伪代码。

Batch Execution of Similar Tasks

At any given moment, a diverse set of random query tasks exists in the task pool, each with distinct query paths. Tasks with high path overlap demonstrate efficient data sharing, while low overlap hinders this efficiency. Notably, we observe that higher task similarity correlates with increased path overlap, resulting in enhanced data access efficiency and reduced redundant synchronous iterations. Task similarity is quantified by calculating distance values between different task starting points (destination vertices). In GrapCPP, we propose a batch execution strategy that is aware of similar tasks, selecting batches of similar tasks from the task pool for execution. This approach further leverages data and computation similarity. Specifically, GraphCPP randomly selects a query task from the task pool, retrieves the starting and destination vertices of the task, and performs BFS algorithm to obtain the neighbor vertex sets SetS for the starting vertex and SetD for the destination vertex. Note that, considering that some central nodes may have a large number of neighbor nodes, we set an upper limit of 500 for neighbor nodes. Subsequently, it traverses the task pool, filtering out all queries with starting points in SetS and destination points in SetD, treating them as similar tasks to be processed concurrently. It's important to note that if the starting or destination vertex of a query belongs to a high-degree vertex, indexing can be directly used to accelerate the query process without employing regular query steps. Excluding high-degree vertices, the overhead of the k-hop SSSP itself is minimal, and the execution process can be concurrent with regular queries, making the execution cost negligible.

**Computation Sharing Mechanism**

GraphCPP achieves computation sharing through two mechanisms: the global index and the core subgraph index. The inherent overhead of the global index is substantial and directly proportional to the number of global indices. In practice, the number of global vertices is typically kept low (e.g., 16) due to this overhead. However, because of the power-law distribution, these few hot vertices act as hub nodes for various queries. As a result, for most point-to-point queries (qi), a path can be traced from the source vertex (si) through at least one global vertex to the destination vertex (di). While this path may not always be the optimal route for qi, it serves as a valuable pruning boundary. GraphCPP utilizes the global index to rapidly identify these intermediary paths, constituting the first level of computation sharing. Additionally, the core subgraph mechanism, without preprocessing, reveals optimal paths based on existing query results, facilitating computation sharing for distinct yet overlapping hot paths. Compared to the global index, the core subgraph is lighter, allowing for a broader coverage range by increasing the number of hot vertices. Consequently, more precise pruning bounds are provided, accelerating the convergence speed of pruning queries. Algorithm 3 outlines the pseudocode for the computation sharing mechanism.

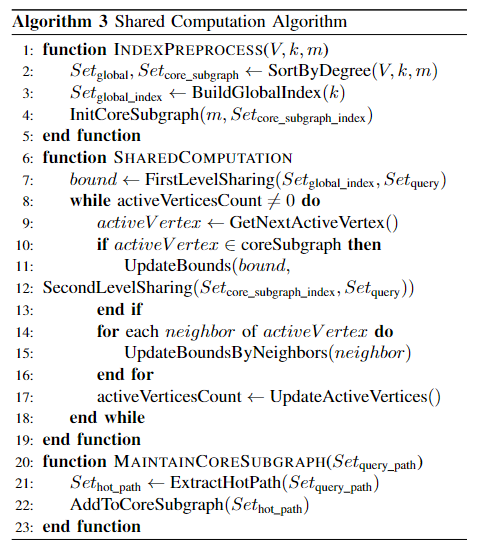


实现计算共享的执行步骤如下：1，索引预处理（第2行），系统在对顶点的度数进行排序之后，选择度数最高的k+m个热顶点，将前k个顶点作为全局索引顶点（k值由用户确定），剩下的顶点作为核心子图顶点。全局索引的计算在预处理阶段完成，GraphCPP会执行SSSP算法计算k个高度顶点与图上的所有顶点的最佳路径（包含索引值和路径父节点），将结果存入以高度顶点id为索引的数组保存。核心子图省去了预计算过程，直接复用每次查询的计算结果，因此在预处理阶段只需要进行初始化。2，计算共享（第6-19行）：全局索引顶点充当了查询路径的枢纽节点，大部分查询都存在至少一条经过全局索引顶点的路径，虽然这条路径不一定是最佳路径，但是却为查询剪枝提供了一个可靠参考。因此每次执行点对点查询前，首先借助全局索引确定粗略的界限值，这是第一层次的计算共享。接下来，执行迭代查询算法，不断处理新的活跃顶点，直至所有顶点都收敛。对于每一个活跃顶点，我们首先判断它是否属于核心子图以决定能否使用共享。由于初始时核心子图为空，所以不会参与共享，随着查询任务的执行，核心子图中逐渐新增了更多热路径。当活跃顶点属于核心子图成员时，就可以借助核心子图直接获取到对应起始顶点的热路径值，从而避免了对热路径的重复计算。此外核心子图可以让查询边界通过热路径直接从一个热顶点跳到另一个热顶点，加速了点对点查询的速度3，维护核心子图（第20-23行）：为了保证核心子图的轻量级，我们不对热路径进行预计算，而是通过从已有的最佳路径中发掘热路径的子集，来复用之前的计算结果。显然一条最佳路径上任意两个顶点之间的路径都是最佳路径，因此我们只需要以很小的开销，识别已有结果中的热顶点，并通过前缀和方法求得热顶点之间的结果即可。为了实现这一目的，我们需要在查询过程中保留遍历路径以及从源顶点出发到达每一个中间点的路径值，由于点对点查询本来需要计算这些信息，因此并不会造成额外的计算开销。通过上述步骤，我们用轻量级的核心子图索引，实现了高效地数据共享。The steps for implementing computation sharing are as follows:

1. \*\*Index Preprocessing (Lines 2):\*\* After sorting the degrees of vertices, the system selects the top k+m hot vertices with the highest degrees. The first k vertices serve as global index vertices (where k is user-defined), and the remaining vertices become core subgraph vertices. The computation of the global index is completed during preprocessing phrase. GraphCPP executes the SSSP algorithm to calculate the optimal paths (including index values and parent nodes) for k high-degree vertices to all vertices in the graph. The results are stored in an array indexed by the high-degree vertices' IDs. The core subgraph omits the precomputation process, directly reusing the computation results of each query, requiring only initialization during preprocessing.

2. \*\*Computation Sharing (Lines 6-19):\*\* Global index vertices act as pivotal nodes for query paths. Most queries have at least one path passing through global index vertices. Although this path may not be the optimal path, it provides a reliable reference for query pruning. Therefore, before executing point-to-point queries, an approximate boundary is determined using the global index, representing the first level of computation sharing. Subsequently, an iterative query algorithm is executed, continuously processing new active vertices until all vertices converge. For each active vertex, it is determined whether it belongs to the core subgraph. Initially, the core subgraph is empty and does not participate in sharing. As query tasks execute, the core subgraph gradually accumulates more hot paths. When an active vertex belongs to the core subgraph, the hot path value for the corresponding starting vertex can be directly obtained through the core subgraph, avoiding redundant computation. Additionally, the core subgraph allows the query boundary to jump directly from one hot vertex to another through the hot path, accelerating the speed of point-to-point queries.

3. \*\*Maintain the Core Subgraph (Lines 20-23):\*\* To ensure the lightweight nature of the core subgraph, hot paths are not precomputed. Instead, a subset of hot paths is explored from existing optimal paths, reusing previous computation results. Clearly, any path between any two vertices on an optimal path is also an optimal path. Therefore, with minimal overhead, identifying hot vertices from existing results and calculating results between hot vertices using a prefix sum method is sufficient. To achieve this, traversal paths and path values from the source vertex to each intermediate point need to be retained during the query process. Since point-to-point queries inherently require calculating this information, the overhead is minimal. Through these steps, we achieve efficient data sharing using a lightweight core subgraph index.



增量更新机制

实际应用中，供查询任务遍历的底层图常常是动态变化（发生边增加eadd和边删除edelete）的，而变化的图结构数据可能会导致原有的全局索引和核心子图索引不再正确。因此，当动态图发生图更新时，我们除了需要更新图结构信息，还需要动态更新索引。图结构信息更新：GraphCPP通过邻接列表来存储每个顶点的出边邻居，因此我们只需要根据边增加（边删除）时的源顶点信息，修改对应的邻接表项即可；索引更新：我们采用一种增量更新的方式，依次更新全局索引和核心子图索引，尽可能减少了索引更新的冗余计算开销。

全局索引顶点数目k一般较小（通常设为16），但是记录的索引值非常多（索引值为k\*|V|）。这些索引值如果用一个专门的数组存放会显得太臃肿了，但是如果把索引信息分散存放在各个顶点上就正合适。每个顶点维护两个表格，table1记录了该顶点到k个全局顶点的最佳路径上的父节点，table2记录了该顶点到k个全局顶点的最佳路径的索引值。我们根据边更新的类型，来对这两个表格进行增量更新。具体地，当发生边增加更新eadd时，我们首先获得更新边的源顶点src，目的顶点dst，以及两点之间的权重。接着我们依次检查每个全局索引顶点，如果Indexsrc+weight>indexdst，则更新table1中的parentdst为src，table2中的indexdst为Indexsrc+weight,否则无需更新该全局顶点索引；当发生边删除更新时，我们依次检查每一个全局索引顶点，判断parentdst是否等于src。如果是，表示我们删除了原本到达dst的最佳路径，此时需要重新计算indexdst。同时和其它的增量计算方法一样，对dst的更新会逐渐向外传递，所有经过dst的最佳路径的下游顶点都需要被更新。如果parentdst不等于src，则无需更新该全局索引顶点。

In practical applications, the underlying graph traversed by query tasks often undergoes dynamic changes, involving edge additions ($e\_{\text{add}}$) and edge deletions ($e\_{\text{delete}}$). Changes in the graph structure data can lead to errors in index values. Therefore, when dynamic updates occur in the dynamic graph, we not only need to update the graph structure information but also dynamically update the indexes. Graph structure information update: GraphCPP stores the out-neighbor of each vertex using an adjacency list. Therefore, we only need to modify the adjacency list of the corresponding out-neighbors based on the source vertex information when an edge is added (or deleted). Index update: We adopt an incremental updating approach, sequentially updating the global index and core subgraph index, minimizing redundant computation costs during index updates.

The number of global index vertices is relatively small ($k$ global index vertices), but it records a substantial number of index values ($k \times |V|$ global index values). Storing these index values in a dedicated array might result in excessive bulkiness, but dispersing the index information across individual vertices is a more suitable approach. Each vertex maintains two tables: $table1$ records the parent nodes on the optimal paths to $k$ global vertices, and $table2$ records the index values of the optimal paths from this vertex to $k$ global vertices. Incremental updates are performed on these two tables based on the type of edge update. Specifically, when an edge addition update ($e\_{\text{add}}$) occurs, we first obtain the source vertex $src$, destination vertex $dst$, and the weight between the two points. We then sequentially check each global index vertex. If $Index\_{\text{src}} + \text{weight} > Index\_{\text{dst}}$, we update $parent\_{\text{dst}}$ in $table1$ to $src$ and $Index\_{\text{dst}}$ in $table2$ to $Index\_{\text{src}} + \text{weight}$. Otherwise, there is no need to update the index for that global vertex. In the case of an edge deletion update, we check each global index vertex and determine if $parent\_{\text{dst}}$ equals $src$. If true, it indicates that we have deleted the original optimal path to $dst$, and we need to recalculate $Index\_{\text{dst}}$. Similar to other incremental computation methods, updates to $dst$ will gradually propagate outward, requiring updates for all downstream vertices on the optimal paths that pass through $dst$. If $parent\_{\text{dst}}$ is not equal to $src$, there is no need to update that global index vertex.

The core subgraph index records indexes between a small number of high-degree vertices, requiring the maintenance of at most $m \times m$ index values (where $m$ is orders of magnitude smaller than the graph's data scale). To store this information, we use an independent two-dimensional array for the core subgraph. Specifically, edge additions can introduce new shortcuts, leading to the degradation of original optimal paths into non-optimal ones. In the context of our pruning queries, although non-optimal path indexes can cause early overestimation of boundary values, the iterative process ensures that point-to-point queries still converge towards more optimal paths, ultimately reaching the correct optimal paths. Extracting the latest hot path values from these converged paths completes the update to hot paths. For edge deletion updates, GraphCPP checks if both vertices of the deleted edge appear on some hot path. If yes, the original hot paths are interrupted, rendering all affected hot paths invalid. If only one vertex or no vertices appear on some hot path, the deleted edge does not affect hot paths, and there is no need for an update. Since the core subgraph index reuses the optimal path results from each query, no separate calculation is needed, resulting in overall low overhead.

The above mechanism implements incremental maintenance of graph structure data, global indexes, and core subgraph indexes. Considering that subtle graph updates do not significantly impact the overall computation results, we temporarily store subtle graph updates $\Delta G$ until its size exceeds a preset threshold or a certain time interval is reached. Only then do we execute batch graph update operations, further reducing update costs.

核心子图索引只记录 数量很少的 热顶点 之间的索引，最多只需维护m\*m个索引值（m的数量级远小于图数据规模），所以我们采用独立的二维数组来存储核心子图。具体地，边增加更新可能产生新的捷径，导致原有的最佳路径退化为非最佳路径。对于我们的剪枝查询来说，非最佳路径的索引虽然会导致早期的界限值偏大，但是随着迭代的进行，点对点查询会依然会遍历到更优路径，最终会收敛到正确的最佳路径。此时从收敛路径中提取最新的热路径值，即可完成对热路径的更新；对于边删除更新，GraphCPP会判断删除边的两个顶点是否同时出现在某个热路径上。如果是，原有的热路径被中断，所有受影响的热路径都失效。如果只有一个顶点或者没有顶点出现在某个热路径上，则删除的边不会影响对热路径产生影响，此时无需更新。由核心子图索引复用了每次查询的最佳路径结果，无需专门计算，因此整体开销较小。

上述机制实现了对图结构数据、全局索引、核心子图索引的增量式维护。考虑到细微的图更新不会对整体计算结果产生大的影响，我们暂存细微的图更新∆G直到它的大小超出预设的阈值或者达到一定的时间间隔，才会批量执行图更新操作，从而进一步降低了更新开销。

实验评估

Experimental Setup

**硬件配置**。The experiments were conducted on an 8-node cluster, each machine equipped with 2 Intel Xeon E5-2680 v4 CPUs boasting 14 physical cores, 256 GB memory, and a 35MB LLC. All nodes were interconnected through an Infiniband network with a bandwidth of 300Gbps. The programs were compiled using gcc version 7.5.0, openMPI version 4.1.2, and with openMP enabled.(辛苦罗康来校正)

**图算法。**为了与之前的工作保持一致[xx]，我们选择了六种不同算法，它们被作为基准广泛应用于图聚类、图分类和图预测等领域。这些算法分为图算法和无向图算法。1）加权图算法：点对点最短路径（PPSP）、点对点最宽路径（PPWP）和点对点最窄路径（PPNP）分别用于找到两个顶点之间的之间的最短、最宽或最窄的路径。被广泛应用于于社交/金融网络、交通规划、监控洗钱行为和网络质量分析等领域；2）无权图图算法：广度优先搜索（BFS）、连接性和可达性和是未加权图上三个最常见的成对查询，分别用于确定两个顶点之间的最短路径、在无向图上，两个顶点是否连通、在有向图上两个顶点是否连通。它们被广泛应用于bi-connectivity、higher-order connectivity和graph clustering等高级算法。

**图数据集**。上述算法使用的图数据集如表x所示。其中LiveJournal和Twitter-2010属于社交网络图表。UK-2007-05和Gsh-2015-host为网页crawl图。它们都属于小直径和偏斜度分布的幂律图，贴合真实世界中的图分布情况。我们的实验基于动态图，利用快照机制，在未关闭的快照上执行图更新，在关闭的快照上执行图查询。系统定时将未关闭快照转换为关闭快照，取代原有快照。

EXPERIMENTAL EVALUATION

**Hardware Configuration**: The experiments were conducted on an 8-node cluster, with each machine equipped with 2 Intel Xeon E5-2680 v4 CPUs featuring 14 physical cores, 256 GB of memory, and a 35MB Last-Level Cache (LLC). All nodes were interconnected through an Infiniband network with a bandwidth of 300Gbps. The programs were compiled using gcc version 7.5.0, openMPI version 4.1.2, and with openMP enabled.

**Graph Algorithms:** To align with prior work [xx], we've selected six benchmark algorithms widely applied in graph clustering, classification, and prediction. These algorithms fall into two categories: graph and undirected graph algorithms. 1) Weighted graph algorithms: Point-to-point shortest path (PPSP), point-to-point widest path (PPWP), and point-to-point narrowest path (PPNP) are utilized to identify the shortest, widest, or narrowest paths between two vertices. They find extensive applications in social/financial networks, traffic planning, monitoring money laundering activities, and network quality analysis. 2) Unweighted graph algorithms: Breadth-first search (BFS), connectivity, and reachability are the three most common pairwise queries on unweighted graphs. They are employed to determine the shortest path between two vertices, whether two vertices are connected in an undirected graph, and whether two vertices are connected in a directed graph. These algorithms find widespread use in bi-connectivity, higher-order connectivity, and advanced algorithms for graph clustering.

**Graph Datasets**: The graph datasets used for the aforementioned algorithms are presented in Table x. LiveJournal and Twitter-2010 belong to social network graphs, while UK-2007-05 and Gsh-2015-host represent web-crawl graphs. These datasets exhibit power-law graphs with small diameters and skewed distributions, capturing real-world graph distribution scenarios. Our experiments are based on dynamic graphs, utilizing a snapshot mechanism where graph updates are performed on an unclosed snapshot, and graph queries are executed on a closed snapshot. Unclosed snapshots are periodically transformed into closed snapshots, replacing the original snapshot.

**系统比较**。我们对比了GraphCPP与现有的点对点查询方案，包括PnP、Tripoline和SGraph。在Section x中，由于SGraph是当前最先进的点对点查询系统，PnP-S、PnP-C、Tripoline-S、Tripoline-C的性能始终不如SGraph。因此，在后续的对比环节中，我们没有展示PnP和Tripoline的性能表现。由于它们都不是开源的，我们基于Gemini分布式图处理框架重新实现了它们的机制。鉴于PnP、Tripoline和SGraph这三个系统都不直接支持并发操作，我们进行了一些修改，以使它们能够同时处理多个作业。其中，带有“-S”后缀的系统采用按顺序处理任务的执行方式，而带有“-C”后缀的系统会并发地处理查询任务。此外，为了使实验对比更加科学，我们还与当前最优秀的通用并发图计算解决方案Glign进行了对比。

在测试并发查询的整体性能时，我们采用了混合提交的方法，生成了同等数量的PPsP、PPWP、PPNP、BFS、Connectivity和Reachability等算法的查询任务。值得注意的是，全局索引机制需要针对不同的图算法维护一套索引。为了公平起见，我们取6个算法全局索引开销的平均值作为混合算法的全局索引开销。同时，我们为每个查询任务设置了随机参数，采用同样的基准：将全局索引的数目k设为16，将GraphCPP中的核心子图顶点设为128。所有基准测试都执行了10次，实验结果报告取平均值。**System Comparison**: We conducted a comparative analysis between GraphCPP and existing point-to-point query solutions, including PnP, Tripoline, and SGraph. In Section x, as SGraph represents the state-of-the-art in point-to-point query systems, the performance of PnP-S, PnP-C, Tripoline-S, and Tripoline-C consistently falls behind SGraph. Therefore, in the subsequent comparative analysis, we did not present the performance results of PnP and Tripoline. Since these systems are not open source, we re-implemented their mechanisms based on the Gemini distributed graph processing framework. Given that PnP, Tripoline, and SGraph do not directly support concurrent operations, we made modifications to enable them to handle multiple jobs simultaneously. Systems with the "-S" suffix execute tasks sequentially, while those with the "-C" suffix handle queries concurrently, managed by the operating system.

Additionally, for a more scientifically rigorous experimental comparison, we benchmarked against the state-of-the-art general concurrent graph computing solution, Glign. When evaluating the overall performance of concurrent queries, we employed a mixed submission approach, generating an equal number of queries for algorithms such as PPsP, PPWP, PPNP, BFS, Connectivity, and Reachability. It is noteworthy that a global indexing mechanism needs to maintain a set of indices for different graph algorithms. To ensure fairness, we calculated the average global indexing cost for the six algorithms. Furthermore, random parameters were set for each query task, maintaining consistency with the baseline: the number of global indices (k) was set to 16, and the core subgraph vertices in GraphCPP were set to 128. All benchmarks were executed 10 times, and the reported experimental results represent the average values.

整体性能对比

Figure 9 shows the total execution time of xx concurrent jobs with different schemes. 为了简洁起见，只显示最佳结果由于不同测试用例的执行时间差异较大，我们将归一化的执行时间表示为PnP的性能。It can be observed that for all graphs, GraphCPP achieves shorter execution times (thus higher throughput) than the other schemes. Compared to SGraph-S, SGraph-C, PnP-S, PnP-C, Tripoline-S, and Tripoline-C, GraphCPP achieves an average throughput improvement of approximately xx, xx, xx, xx, xx, and xx times, respectively. The improvement of throughput is achieved by reducing the data access cost 和核心子图带来的高效剪枝in GraphCPP.

为了进一步地剖析性能，我们进一步地将总时间分成了数据访问时间和图处理时间。如图10所示，相比于其他系统，GraphCPP图数据访问占用的时间更少，并且随着图规模的增加该部分占用比例进一步减少。例如，对于Gsh-2015-host，GraphCPP的数据访问时间相比于其他系统分别减少了xx倍-xx倍。GraphCPP性能提升的原因有两个：1）不同并发作业所需图数据的相同部分在缓存中只需要加载和维护一个副本，减少了资源争用；2）图数据块根据关联任务数量的多少划分优先级，并定期地加载到LLC中被作业重用。优先处理优先级更高（关联任务数更多）能有效降低LLC miss率，减少不必要的内存数据传输。此外得益于两级计算共享机制，GraphCPP的计算时间也小于其他系统。Overall Performance Comparison

Figure 9 depicts the total execution time of xx concurrent jobs using different schemes. For conciseness, only the optimal results are displayed, and due to significant variations in the execution times of different test cases, we normalize the execution time relative to PnP's performance. It is evident that, for all graphs, GraphCPP achieves shorter execution times (and higher throughput) compared to the other schemes. In comparison to SGraph-S, SGraph-C, PnP-S, PnP-C, Tripoline-S, and Tripoline-C, GraphCPP demonstrates an average throughput improvement of approximately xx, xx, xx, xx, xx, and xx times, respectively. This enhancement in throughput is accomplished by reducing data access costs and efficiently pruning the core subgraph in GraphCPP.

To provide a more in-depth analysis of performance, we further divide the total time into data access time and graph processing time. As shown in Figure 10, GraphCPP requires less time for graph data access compared to other systems, and this proportion decreases further as the graph size increases. For example, in the case of Gsh-2015-host, GraphCPP's data access time is reduced by xx times to xx times compared to other systems. Two key factors contribute to GraphCPP's efficiency: 1) identical portions of graph data required by different concurrent jobs only need to load and maintain a single copy in memory, reducing memory consumption; 2) graph data blocks are prioritized and periodically loaded into the LLC based on the number of associated tasks, promoting job reuse and effectively lowering LLC miss rates, minimizing unnecessary memory data transfers. Additionally, thanks to the two-level computing sharing mechanism, GraphCPP's computation time is also lower than that of other systems.

数据共享机制的效率

GraphCPP通过数据共享机制，减少了冗余的数据访问，为了定性地说明数据共享机制的效率，我们评估不同系统的LLC利用率，并将结果显示在图11中。从图中可以看出，GraphCPP的LLC miss率低于另外6个系统。在UK-2007-05中，GraphCPP的LLC miss率仅为xx，相比之下，SGraph-S, SGraph-C, PnP-S, PnP-C, Tripoline-S, and Tripoline-C的LLC miss率分别为xx，xx，xx，xx，xx，and xx。这主要是因为在GraphCPP中，多个作业共享LLC中的一个图数据副本，能够更加充分地利用LLC，提高作业的数据局部性。

进一步地，我们还跟踪了并发任务交换到LLC中的数据总量。一般来讲，并发执行模式（-C）会比顺序执行模式（-S）交换更多的数据到LLC中，这是因为并发作业之间没有数据共享，不同作业之间强烈的缓存干扰会导致图数据在LLC中频繁的换入换出，产生更多的冗余内存数据传输。如图12所示，GraphCPP的数据交换量比SGraph-S，PnP-S，和Tripoline-S少得多（在UK-2007-05中分别是三者的xx，xx，and xx）。这是因为GraphCPP充分利用了并发任务之间的数据访问相似性。

计算共享机制效率

图x展示了系统图处理时间随时间变化的关系。为了比较不同系统的图处理时间，我们使用SGraph-S图处理时间进行了归一化表示。SGraph-C引入了并行执行策略，导致同步开销，使得单个任务的图处理时间略长于串行版本。相比之下，由于Glign缺乏针对点对点查询的专门优化，需要进行大量冗余计算，因此其处理时间最长。GraphCPP采用了双层计算共享机制。在初始阶段，核心子图无法参与共享，因此它在图处理时间上略高于SGraph-C，表现为普通的全局索引。随着查询的进行，新的热路径值不断加入核心子图，使得GraphCPP的计算共享效果逐渐提升，从而图处理时间逐渐减少。**Efficiency of Data Sharing Mechanism:**

GraphCPP employs a data sharing mechanism to reduce redundant data access. To qualitatively illustrate the efficiency of this mechanism, we evaluate the LLC utilization of different systems, and the results are presented in Figure 11. Notably, GraphCPP demonstrates lower LLC miss rates compared to the other six systems. In the case of UK-2007-05, GraphCPP's LLC miss rate is only xx, while SGraph-S, SGraph-C, PnP-S, PnP-C, Tripoline-S, and Tripoline-C exhibit LLC miss rates of xx, xx, xx, xx, xx, and xx, respectively. This is primarily attributed to GraphCPP allowing multiple jobs to share a single graph data copy in the LLC, enabling more efficient utilization of the LLC and enhancing data locality for jobs.

Additionally, we track the total amount of data swapped into the LLC by these 16 jobs. Generally, the concurrent execution mode (-C) tends to swap more data into the LLC compared to the sequential execution mode (-S). This is because concurrent jobs lack data sharing, leading to frequent swapping of graph data in and out of the LLC and resulting in more redundant memory data transfers. As illustrated in Figure 12, GraphCPP swaps significantly less data compared to SGraph-S, PnP-S, and Tripoline-S (xx, xx, and xx, respectively, in UK-2007-05). This reduction is attributed to GraphCPP maximizing the similarity in data access among concurrent tasks.

Efficiency of the Computation Sharing Mechanism

Figure x evaluates the relationship between the processing time of each system graph and its variation over time. Due to significant differences in the graph processing time of each system, we represent the normalized time as the PnP graph processing time. PnP relies purely on pruning without utilizing an index, reducing preprocessing time but resulting in the longest query computation time. Tripoline, leveraging upper-bound pruning and a global index, reduces graph processing time. SGraph, employing upper-bound and lower-bound pruning strategies, achieves the best pruning effect, requiring the fewest calculated vertices and minimizing graph processing time. While the graph processing time of these three systems may fluctuate slightly based on different query characteristics, overall, the graph processing time remains stable. In contrast, GraphCPP's graph processing time initially aligns with SGraph, as it adopts a global index mechanism similar to SGraph. However, due to the continuous improvement of GraphCPP's core subgraph index mechanism during queries, it can leverage optimizations at the second level to continuously accelerate graph processing time, resulting in a reduction over time; GraphCPP shortens its processing time.

**全局索引开销**。随着全局全局索引数目的增加，维护索引所需要的时间也不断。在我们的实验中，除了PnP由于没有采用全局索引而不会产生维护索引开销，Tripoline、SGraph、GraphCPP均采用了类似的全局索引机制。如图x所示，由于采用了相同的全局索引数目，GraphCPP构建索引的开销和其他系统持平。不过由于GraphCPP的吞吐量更高，相同时间可以处理更多查询任务，从而分摊了全局索引开销。

**核心子图索引开销**。我们也评估了核心子图索引对GraphCPP性能的影响。在全局索引数设置为16的情况下，GraphCPP-128，GraphCPP-256，和GraphCPP-without分别是核心子图索引选择128，256个顶点和不使用核心子图索引的版本。在表x中，我们展示了这三个版本核心子图占用内存空间的大小。可以看到GraphCPP-128和Graph-CPP-256相比于GraphCPP-without只增加了极少的内存空间占用（三者都维护16个全局索引）。这是因为相对于全局索引保存到所有顶点的距离，核心子图顶点只保存与其他核心子图顶点的距离，而这只需很少的额外空间。此外，表x显示了GraphCPP-128，GraphCPP-256，和GraphCPP-without在16个作业上的总执行时间。我们可以观察到GraphCPP-256和GraphCPP-128总是优于GraphCPP-without，并且GraphCPP-256也比GraphCPP-128更快。在Friendster上，GraphCPP-256和GraphCPP-128的处理时间分别只有GraphCPP-without的xx和xx。这是因为增加的这些核心子图顶点能够有效地提高计算共享比例，减少冗余计算量。

**更新维护开销**。

Tripoline、SGraph和GraphCPP这三个系统在全局索引机制上有共同之处，因为它们都将全局索引数设置为16，所以它们的全局索引更新开销相同。与此同时，GraphCPP通过核心子图机制实现了第二层次的共享，因此需要额外的更新开销。正如xxx节所述，当发生边增加更新时，无需专门更新相应的核心子图热路径。而在发生边删除更新时，只需删除受影响的热路径。由于我们没有专门计算核心子图，而是从已有的计算结果中提取热路径，因此图的更新只会影响核心子图机制的准确性，而不会引起昂贵的更新维护开销。此外，为了降低更新开销，GraphCPP只在初始阶段进行频繁的维护，当子图建立达到80%时就会减少维护的频率。在没有发生图突变的情况下，已记录的热路径值不会重复更新核心子图。

**Global Index Overhead:** As the number of global indices increases, the time required for maintaining the indices also grows. In our experiments, PnP did not incur maintenance overhead for global indices as it did not utilize them. However, Tripoline, SGraph, and GraphCPP employed similar global index mechanisms. As shown in Figure x, GraphCPP's index construction overhead is comparable to other systems due to the adoption of the same number of global indices. Nevertheless, GraphCPP achieves higher throughput, allowing it to handle more queries in the same time frame, thereby distributing the global index overhead.

**Core Subgraph Index Overhead**:

We also evaluated the impact of core subgraph indexing on GraphCPP performance. With the global index set to 16, GraphCPP-128, GraphCPP-256, and GraphCPP-without represent versions with core subgraph indices selecting 128, 256 vertices, and no core subgraph indexing, respectively. In Table x, we present the memory footprint of these versions, revealing that GraphCPP-128 and GraphCPP-256 exhibit minimal increases in memory usage compared to GraphCPP-without (all maintaining 16 global indices). This is due to the fact that core subgraph vertices store distances only to other core subgraph vertices, requiring minimal additional space compared to global indices stored for all vertices. Additionally, Table x displays the total execution times of GraphCPP-128, GraphCPP-256, and GraphCPP-without across 16 tasks. It is observed that both GraphCPP-256 and GraphCPP-128 consistently outperform GraphCPP-without, with GraphCPP-256 demonstrating superior performance to GraphCPP-128. On Friendster, the processing times for GraphCPP-256 and GraphCPP-128 are significantly lower than those for GraphCPP-without, showcasing the enhanced computational efficiency resulting from the additional core subgraph vertices, which effectively improves the computation sharing ratio and reduces redundant computational overhead.

**Update Maintenance Overhead**: Tripoline, SGraph, and GraphCPP share a common global index mechanism, with an equal global index number set to 16. GraphCPP, additionally implementing a second level of sharing through the core subgraph mechanism, incurs additional maintenance overhead. As described in Section xxx, during edge addition updates, there is no need to specifically update the corresponding core subgraph hot paths. In the case of edge deletion updates, only the affected hot paths need to be deleted. Since we do not perform a dedicated computation for the core subgraph but rather extract hot paths from existing results, graph updates only affect the accuracy of the core subgraph mechanism without incurring expensive update maintenance overhead. Furthermore, to minimize update overhead, GraphCPP conducts frequent maintenance only during the initial phase. Maintenance frequency decreases once the establishment of the subgraph reaches 80%. In the absence of graph mutations, previously recorded hot path values remain unchanged, eliminating redundant updates to the core subgraph.

可扩展性

图x（复用之前的图）显示了不同PPsP作业并发数目下GraphCPP和另外6个系统的性能比较。当并发作业数目增加时，GraphCPP可以得到更好的性能提升。当并发任务数分别为2、4、8和16时，GraphCPP相对于SGraph-S的加速分别为xx，xx，xx和xx。这是因为随着作业数目的增加，GraphCPP通过摊销节省了更多的数据访问和存储开销。请注意，当只有一个并发作业时，GraphCPP的细粒度调度操作不会发生，因此此时和其他方案相比执行时间没有太大差异。根据我们的测试，GraphCPP上块调度成本只占总执行时间的xx-xx%。此外，由于对LLC等资源的争夺，并发版本（-C）的性能要比GraphCPP甚至顺序版本（-S）差得多。因此，简单地修改现有的图处理系统来支持并发任务可能是一个糟糕的选择。

然后我们评估了GraphCPP的横向扩展性。为了实现这一目标，我们评估了1、2、4、8节点上不同方案的性能。如图18所示，GraphCPP在8个节点上的性能是单机的xx-xx倍，具有良好的扩展性。此外，GraphCPP的扩展性也要好于SGraph，PnP和Tripoline，这是因为数据共享和核心子图索引使得通信成本更低。因此我们相信GraphCPP可以高效地支持实际中的点对点查询应用。

Scalability

Figure 16 illustrates the performance comparison between GraphCPP and six other systems under varying numbers of concurrent PPsP jobs. GraphCPP exhibits superior performance improvement as the number of concurrent jobs increases. For 2, 4, 8, and 16 concurrent jobs, GraphCPP achieves acceleration ratios of xx, xx, xx, and xx, respectively, in comparison to SGraph-S. This improvement stems from GraphCPP's amortization, which saves more data access and storage costs with an increasing number of jobs. It's important to note that with only one concurrent job, GraphCPP's fine-grained scheduling operations do not occur, resulting in minimal differences in execution time compared to other schemes. According to our tests, the block scheduling cost of GraphCPP constitutes only xx-xx% of the total execution time. Furthermore, due to resource contention, the performance of the concurrent version (-C) is considerably worse than both GraphCPP and the sequential version (-S). Therefore, a simple modification of existing graph processing systems to support concurrent tasks might not be an optimal choice.

Next, we assess the horizontal scalability of GraphCPP. To achieve this goal, we evaluate the performance of different schemes on 1, 2, 4, and 8 nodes. As shown in Figure 18, GraphCPP's performance on 8 nodes is xx-xx times that of a single machine, indicating robust scalability. Moreover, GraphCPP's scalability surpasses that of SGraph, PnP, and Tripoline due to lower communication costs facilitated by data sharing and core subgraph indexing. Consequently, we believe that GraphCPP can efficiently support practical point-to-point query applications.

相关工作

**图计算系统**。随着图计算逐渐成为研究热点，有越来越多不同类型的图计算系统被提出。1）单机内存图计算系统：Ligra[x]通过push和pull计算模式的切换，加快图计算特别是图遍历算法的收敛。KickStarter[x]和GraphBolt[x]实现了对流式图的增量处理。DiGraph[x]提出一种GPU上的高效的迭代有向图处理系统。LCCG[x]、DepGraph[x]和TDGraph[x]利用拓扑感知执行方法，减少了图计算的冗余计算和数据访问成本。2）单机核外图计算系统：GraphChi[x]和X-Stream[x]通过顺序访问存储实现高效的核外图形处理。FlashGraph[x]采用半外部内存图形引擎，实现高IOPS和并行性。GridGraph[x]采用Streaming-Apply方式提高了局域性并减少了I/O操作。 DGraph[x]通过更快的状态传播加速图处理。GraphM[x]采用数据共享的思想，优化并发系统的吞吐量。3）分布式图计算系统。Pregel[x]提出BSP计算模型，在性能，可扩展性和容错方面满足了具有billions规模的边的图的处理。PowerGraph[x]提出了基于“顶点切割”（vertex-cut）的图划分思想，有效地减少了通信量以及由度数较高顶点导致的负载不均衡。PowerLyra[x]混合计算模型，针对高度顶点和低度顶点采用不同计算策略。Gemini[x]提出了一个双模式计算引擎，在确保性能的前提下实现了可扩展性。CGraph[x]使用以数据为中心的LTP（load-trigger-pushing）模型，利用并发任务之间的时间/空间相似性，降低了分布式系统的开销。上述工作都针对通用图算法而设计，然而由于点对点查询算法只关注特定顶点对之间的图关系，它和通用图算法有着显著不同。最直观地一点，点对点查询算法可以通过剪枝策略极大地提高执行效率，然而通用的图计算系统却并不支持。RELATED WORK

**Graph Processing Systems**: With the increasing prominence of graph computing as a research focus, an increasing number of diverse types of graph computing systems are being proposed. 1)Single-node in-memory graph computing systems: Ligra [x] accelerates graph computation, especially graph traversal algorithms, by switching between push and pull computation modes. KickStarter [x] and GraphBolt [x] implement incremental processing for streaming graphs. DiGraph [x] efficiently facilitates iterative directed graph processing on the GPU. LCCG [x], DepGraph [x], and TDGraph [x] utilize topology-aware execution methods, reducing redundant computation and data access costs; 2) Single-node out-of-core graph computing systems: GraphChi [x] and X-Stream [x] achieve efficient out-of-core graph processing through sequential storage access. FlashGraph [x] employs a semi-external memory graph engine, achieving high IOPS and parallelism. GridGraph [x] adopts the Streaming-Apply approach to enhance locality and reduce I/O operations. DGraph [x] accelerates graph processing through faster state propagation. GraphM [x] adopts a data-sharing approach, optimizing throughput for concurrent systems; 3) Distributed graph computing systems: Pregel [x] introduces the Bulk Synchronous Parallel (BSP) computation model, addressing the processing needs of graphs with billions of edges in terms of performance, scalability, and fault tolerance. PowerGraph [x] proposes a "vertex-cut" graph partitioning approach, effectively reducing communication volume and addressing load imbalance caused by high-degree vertices. PowerLyra [x] employs a hybrid computing model, using different computation strategies for high-degree and low-degree vertices. Gemini [x] introduces a dual-mode computation engine, ensuring scalability while maintaining performance. CGraph [x] uses a data-centric Load-Trigger-Pushing (LTP) model, leveraging temporal and spatial similarities between concurrent tasks to reduce distributed system overhead; The mentioned works are intended for general graph algorithms. However, point-to-point query algorithms, which concentrate on the specific relationships between vertex pairs in a graph, show notable distinctions. These query algorithms can significantly improve execution efficiency through pruning strategies. Nevertheless, general graph computing systems do not inherently accommodate such algorithms.

**点对点查询**。现有工作对点对点查询做出了许多研究，硬件方面，𝐻𝑢𝑏2 [x]提出了一种以高度顶点为中心的专用加速器，通过限制高度顶点的搜索范围以及对搜索过程剪枝来加速PPSP过程。软件方面，Quegel[x]走索引路线，通过在图加载时构建分布式图的静态索引，来提高查询的相应速度。PnP[x]走剪枝路线，通过一个通用的剪枝策略，减少点对点查询的过程中的冗余访问和冗余计算。Tripoline[x]同时结合索引和剪枝，利用三角不等式原理实现了无需先验知识的查询的增量评估。SGraph[x]进一步优化剪枝策略，利用基于上界和下界的剪枝策略，实现了在大型图上以亚秒级的延迟查询不断变化的数据。上述工作专注于通过剪枝和索引等机制优化单次点对点查询的速度，忽略了大规模并发查询的严重负载。

**并发图计算**。许多图计算系统都对并发图计算进行了研究。例如对于单机内存图处理系统。Congra[x]通过离线分析查询任务的内存带宽消耗和原子操作特征，在不因资源争用而阻塞查询的前提下动态调度任务，以获得更好的系统吞吐量和资源效率。Krill[x]提出了一种SAP模型，将图结构、算法和属性解耦。利用属性缓冲区轻松地写入和管理属性数据，利用图核融合技术将所有作业作为一个整体，来减少内存访问。ForkGraph[x]提出了一个高效的缓冲区执行模型，来实现并发任务的的数据共享，并且采用基于让步的调度策略加速了整体执行速度。对于单机核外图计算系统。GraphM[x]提出利用并发任务的时间和空间局部性实现并发图计算的数据共享。对于分布式图计算系统。Seraph[x]提出将图结构数据与任务特定数据解耦，以允许并发任务共享公共图结构数据。MultiLyra[x]和BEAD[x]通过图共享和边界共享，分摊集群中计算节点之间的通信成本，从而支持高效的批处理查询评估。CGraph[x]是GraphM[x]的分布式版本。上述方案专注于对并发任务的数据访问进行共享优化，忽略了并发任务之间的计算优化，且没有针对点对点查询进行专门优化。

**Point-to-Point Queries**: Previous studies have delved into extensive research on point-to-point queries. Notably, 𝐻𝑢𝑏2 [x] introduced a specialized accelerator with a hub-centric approach, emphasizing the challenges posed by vertices with a high degree of connections, or hubs, in expanding the search space for shortest path calculations. To address this, it proposed the hub-Network concept, limiting the search scope of hub nodes and accelerating the PPSP process through online pruning. However, due to the specialized nature of 𝐻𝑢𝑏2's dedicated accelerator, its applicability is constrained. PnP observed the traversal process of point-to-point queries and introduced an upper-bound-based pruning strategy, reducing unnecessary vertex traversals and providing a fresh perspective for point-to-point query research. Tripoline integrated both indexing and pruning, employing the triangle inequality principle to achieve incremental evaluation of point-to-point queries without prior knowledge. SGraph optimized pruning strategies further, using upper and lower bounds based on the triangle inequality principle, achieving sub-second query response times on large graphs. Despite these advancements, these systems predominantly concentrate on enhancing the speed of individual point-to-point queries, overlooking the substantial load posed by large-scale concurrent queries.

**Concurrent Graph Computing**: Numerous graph computing systems have explored concurrent graph computation, especially in the realm of single-machine memory graph processing systems. For instance, Congra[x] dynamically schedules tasks based on an offline analysis of query tasks' memory bandwidth consumption and atomic operation characteristics. This dynamic scheduling aims to enhance system throughput and resource efficiency without blocking queries due to resource contention. Krill[x] introduces an SAP model that decouples graph structure, algorithms, and attributes. It simplifies attribute data management using attribute buffers and employs graph kernel fusion to reduce memory access by treating all tasks as a cohesive unit. ForkGraph[x] proposes an efficient buffer execution model for concurrent tasks, facilitating data sharing and accelerating overall execution speed through a yield-based scheduling strategy. In the context of single-machine out-of-core graph computing systems, GraphM[x] leverages the temporal and spatial locality of concurrent tasks for data sharing in concurrent graph computation. For distributed graph computing systems, Seraph[x] suggests decoupling graph structure data from task-specific data to enable concurrent tasks to share common graph structure data. MultiLyra[x] and BEAD[x] distribute communication costs among cluster computing nodes through graph and boundary sharing, supporting efficient batch query evaluations. CGraph[x] serves as the distributed version of GraphM[x]. These approaches primarily focus on optimizing data access sharing for concurrent tasks, yet they overlook computation optimization between concurrent tasks and lack specialized optimization for point-to-point queries.

结论

现有的点对点查询系统聚焦于优化单次查询的速度，忽略了对并发查询吞吐量的优化。本文发现并发点对点查询任务存很强的数据访问相似性和计算相似性，并提出了一个数据驱动的并发点对点查询系统GraphCPP。它通过数据驱动的缓存执行机制，实现并发查询之间的重叠数据的访问共享。同时通过一个双层级计算共享机制，更好地实现了多任务之间的计算共享。实验表明GraphCPP的性能优于目前最先进的图查询系统SGraph[x]、Tripoline[x]、Pnp[x] XXX倍。

致谢

CONCLUSION

The existing point-to-point query systems primarily focus on optimizing the speed of individual queries, neglecting the optimization of throughput for concurrent queries. This paper identifies strong data access similarity and computation similarity among concurrent point-to-point query tasks. It proposes a data-driven concurrent point-to-point query system, GraphCPP. By employing a data-driven caching execution mechanism, GraphCPP achieves overlapping data access sharing among concurrent queries. Simultaneously, through a two-level computation sharing mechanism, it better realizes computation sharing among multiple tasks. Experimental results indicate that GraphCPP's performance surpasses that of the state-of-the-art graph query systems, including SGraph[x], Tripoline[x], and Pnp[x], by a factor of XXX.

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废弃材料

废弃摘要内容：

在面对高并发的点对点查询需求时，由于冗余的数据访问，处理效率很低。我们观察到并发查询任务之间存在着数据访问相似性，这启发我们提出了一种以数据为中心的并发点对点查询方法。具体地，我们将图查询过程中的数据分为“图结构数据”和“任务特定数据”，前者记录了图的拓扑信息，后者记录了查询任务所要访问的图结构数据分块，不同查询独立访问任务所需的数据分块，这些分块可能重叠，但在传统的查询方案中。因此，我们采用了一种数据驱动的调度方法：在执行并发点对点查询任务时，内存/LLC中只保留一份图结构数据。多任务之间以细粒度的图数据分块为单位共享数据。一次访问，多个任务处理，以此分摊数据访问的开销，提高并发图查询的吞吐量。为了展示GraphCPP的效率，

核心子图查询机制

如PnP使用基于下界的剪枝方法来减少查询过程中的冗余访问；Tripoline通过维护中心顶点到其它顶点的日常索引，实现无需先验知识的快速查询；SGraph利用三角不等式原理，提出了基于“上界+下界”的剪枝方法，进一步减少点对点查询过程中的冗余访问；

素材库：

CGP 作业固有的不规则访问导致由于局部性较差而导致底层内存子系统利用率不足。最终导致整个系统的吞吐量较低。首先，CGP作业由于其不同的遍历特性，对相同图结构数据表现出不规则的图遍历，并且这些作业同时访问同一图的不同部分。来自多个作业的这种不规则且不协调的内存访问会导致严重的缓存抖动。其次，CGP 作业对内存子系统造成激烈的资源争用。当在现有的多核处理器上运行多个作业时，这些作业会将与同一顶点关联的状态提取到不同的缓存行中。由于图的稀疏性，每个缓存行中只需要几个数据元素（甚至一个），因为图处理因展示对小数据元素（例如，每个顶点状态 4 或 8 字节）的固有随机访问而臭名昭著。整个图 [14,25,39]。

这会导致激烈的资源争用以及缓存和内存带宽的利用不足。

单作业加速器对于解决 CGP 作业之间不协调的图形数据访问效率低下

LCCG通过新的硬件机制增强了众核处理器：图遍历正则化和预取。前一个组件规范了 CGP 作业的图遍历，从根本上解决这些作业的不规则数据访问的挑战。与遍历正则化相结合，预取组件进一步隐藏了 CGP 作业的内存延迟，并有效地支持这些作业的合并访问。具体来说，顶点状态沿着图拓扑中固有的依赖关系传播。仅当其状态由其活动邻居更新时，非活动顶点才需要由作业处理。基于这一见解，提出了一种有效的拓扑感知执行方法，并得到 LCCG 的有效支持。它根据图拓扑动态探索所有 CGP 作业的以活动顶点为根的公共遍历路径，然后预取这些探索路径上的图数据，以驱动相应的作业一起同步处理这些数据。

CGP 作业会发出更多的冗余数据访问，并且由于不同作业在不同时间将更多冗余数据存储到缓存中，也会导致更严重的缓存干扰。它最终会导致系统吞吐量低下，因为数据访问成本通常占迭代图算法总执行时间 的主要部分。

中心网络可以被认为是由中心锚定的高速公路结构，用于在大型社交网络中路由最佳路径。由于枢纽的重要性，非枢纽顶点对之间的大多数最佳路径可能需要经过这样的网络，即起始顶点到达一个枢纽（作为高速公路入口），然后前往另一个枢纽（作为高速公路入口）出口），最后离开高速公路到达目的地。换句话说，集线器网络可用于限制（或优先考虑）集线器的邻居；集线器只能在集线器网络内扩展。

**数据集**

|  |  |  |  |
| --- | --- | --- | --- |
| Datasets | Vertices | Edges | Data sizes |
| LiveJournal[1] | 4.8M | 69M | 526MB |
| Twitter-2010[2] | 41.7M | 1.5B | 10.9GB |
| Gsh-2015-host[3] | 68.7M | 1.8B | 13.4GB |
| UK-2007-05[4] | 106M | 3.74B | 27.9GB |

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算法

为了与之前的工作保持一致[xx]，我们选择了六种不同算法，它们被广泛应用于图聚类、图分类和图预测等领域。这些算法分为图算法和无向图算法。

* 加权图算法：
  + 点对点最短路径（PPSP）、点对点最宽路径（PPWP）和点对点最窄路径（PPNP）分别用于找到两个顶点之间的之间的最短、最宽或最窄的路径。被广泛应用于于社交/金融网络、交通规划、监控洗钱行为和网络质量分析等领域
* 无权图图算法
  + 广度优先搜索（BFS）、连接性和可达性和是未加权图上三个最常见的成对查询，分别用于确定两个顶点之间的最短路径、在无向图上，两个顶点是否连通、在有向图上两个顶点是否连通。它们被广泛应用于bi-connectivity、higher-order connectivity和graph clustering等高级算法。
* 点对点最短路径（PPSP）是单源最短路径（SSSP）的“成对查询”版本。它用于发掘任意两对顶点之间的最短路径，被广泛应用于社交/金融网络等领域。
* 点对点最宽路径（PPWP）和点对点最窄路径（PPNP）用于找到两个顶点之间的之间的最宽或最窄的路径，被广泛应用于交通规划，监控洗钱行为和网络质量分析等领域
* 例如，单源最短路径（SSSP）是典型的单源查询应用程序，它计算从源到所有其他目标顶点的最短路径。相比之下，SSSP 的动态“成对查询”版本称为点对点最短路径（PPSP），其中用户只对一对两个任意顶点之间的最短路径感兴趣。 PPSP 不仅是动态道路图上的导航系统 [57] 中最重要的问题，而且也是社交/金融网络中许多高级图分析应用的基本构建块。
* 例如，推荐系统需要频繁检查从购物日志中提取的大型网络中两个任意用户之间的最短路径，风险检测系统使用 PPSP 来测量新到达的交易与某些风险用户之间的距离[22， 28、35]。

我们评估了竞争系统在 BC、LL 和 NCP 三种应用程序上的性能。为了与之前的工作保持一致[1,18,47]，我们对三个应用程序进行如下配置。

七种不同应用的多功能集，即最短路径 (PPSP)、广度优先搜索 (BFS)、可达性、连通性、最宽路径 (PPWP)、最窄路径 (PPNP) ）和维特比算法（Viterbi）。所有这些应用程序都是重要的成对图查询，1）不仅它们本身被广泛使用； 2）而且这些基本内核的组合可以形成许多重要的高级图分析应用，例如聚类、分类和预测。

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**Connectivity**

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