Practical and Theoretical Aspects of a Parallel Twig Join Algorithm for XML Processing using a GPGPU

Lila Shnaiderman
Computer Science Department, Technion
Haifa 32000, Israel
lilas@cs.technion.ac.il

Oded Shmueli
Computer Science Department, Technion
Haifa 32000, Israel
oshmu@cs.technion.ac.il

ABSTRACT
With an increasing amount of data and demand for fast query processing, the efficiency of database operations continues to be a challenging task. A common approach is to leverage parallel hardware platforms. With the introduction of general-purpose GPU (Graphics Processing Unit) computing, massively parallel hardware has become available within commodity hardware.

XML is based on a tree-structured data model. Naturally, the most popular XML querying language (XPath) uses patterns of selection predicates on multiple elements, related by a tree structure. These are often abstracted by twig patterns. Finding all occurrences of such a (XML query) twig pattern in an XML document is a core operation for XML query processing.

We present a new algorithm, GPU-Twig, for matching twig patterns in large XML documents, using a GPU. Our algorithm uses the data and task parallelism of the GPU to perform memory-intensive tasks whereas the CPU is used to perform I/O and resource management. We therefore efficiently exploit both the high-bandwidth GPU memory interface and the lower-bandwidth CPU main memory.

1. INTRODUCTION
XPath, the XML Path Language [11], is a query language for selecting nodes from an XML [44] document. The XPath language is based on a tree representation of the XML document, and provides the ability to navigate within the tree, selecting nodes by a variety of patterns. For example, consider the following XPath expression: 

"movie[name = 'Harry Potter']//actor[first='Daniel' AND last = 'Radcliffe']".

This expression matches 'actor' elements that (i) have a child element named 'first' with content 'Daniel', (ii) have a child element 'last' with content 'Radcliffe', and (iii) are descendants of 'movie' elements that have a child 'name' element with content 'Harry Potter'. This expression can be represented as a node-labeled tree called a twig pattern. The result of the matching between the given twig pattern and the XML database is the set of all the elements in the XML database with an 'actor' label which satisfy the matching described above, blurring the distinction between a document and a database. Finding all occurrences of a twig pattern, or specific data nodes corresponding to a specific twig node, in an XML database are fundamental operations in XML query processing.

As XPath is a critical component in many XML-based applications, it is essential to maximize its performance. There are many works dealing with optimizing performance of a single query [15], and a few studies deal with parallelizing the execution of a single XPath query. Most state-of-the-art XPath processors, such as Apache's Xalan, support parallel XPath queries, i.e., numerous XPath queries which are processed concurrently by different threads against the same query processor instance. Still, each XPath query is executed serially. By processing XPath queries concurrently, the overall latency is improved, but to enhance the overall performance we need to increase the speed of processing a single XPath query via parallelization. This is particularly important for large databases. Parallelization of XPath queries is also essential for parallelizing various host languages, such as XSL [46] or XQuery [45].

Recently, there have been attempts to use GPUs to boost the performance of various database algorithms. GPUs, also known as video cards, are regularly used to render graphical information. GPUs near universal use in desktop computers means that it is a cheap and ubiquitous source of processing power. There is a growing interest in applying this power to more general non-graphical problems through frameworks such as NVIDIA's CUDA, an application programming framework providing programmers a simple and standard way for executing general purpose programs on NVIDIA GPUs. Modern GPUs, with massively parallel execution architecture, have become powerful co-processors for many applications, including scientific computing [18] and databases [10, 47, 21].

Streams provide an important way for representing an XML document [7]. There is a dedicated stream for each element label in the document. Each stream contains the positional representations of the XML nodes whose label matches the particular element label of the stream.

The problem we address is how to use GPUs to speed up twig query processing. In this paper we present the GPU-Twig algorithm. The main idea underlying this algorithm is to copy the relevant parts of the database according to the input query to the GPU, to process the input query on the GPU, and to copy back to the CPU the query results. The key to parallelizing the query answering process, while using a stream representation scheme, is in the ability to expose some of the structural characteristics of the document tree within the streams. This is achieved by broadening the

\*L. Shnaiderman was funded in part by ISF grant 1104/05.
\*O. Shmueli was funded in part by ISF grant 1104/05.
Previous work dealt with possible strategies for parallelizing XPath queries [6]. To the best of our knowledge, we present the first parallel algorithm (GPU-Twig) that uses GPUs to accelerate the processing of a single query, when a stream representation of documents is used.

The results of an extensive experimentation are presented in a separate publication.

Organization
The rest of the paper is organized as follows. Section 2 provides background and briefly reviews the GPU architecture. Section 3 presents the GPU-Twig algorithm and proved its correctness. Section 4 presents related work. Section 5 presents conclusions and future work directions.

2. BACKGROUND

In this section, we briefly introduce GPUs and CUDA (the underlying platform upon which our algorithm is implemented), the XML stream scheme we use, and twig pattern matching.

2.1 Graphics Processors (GPUs)

GPUs, originally designed for graphics rendering tasks, have evolved into massively multi-threaded many-core co-processors for CPUs, and are widely available as commodity components in modern machines [1, 34]. GPU programming languages include graphics APIs such as OpenGL [33] and DirectX [4], and GPGPU framework such as NVIDIA’s CUDA [32]. Using these APIs, programmers consist of two kinds of code, the kernel code and the host code. The host code runs on the CPU. The host part is in charge of transferring data between the GPU and main memory, and starting kernels on the GPU. The kernel code is executed on the GPU. Programmers write their algorithms so that one part of the algorithm’s task runs on the CPU and the other part, which can be massively parallelized, runs on the GPU. In general, a computation task on the GPU is divided into three separate steps. First, the host code allocates GPU memory for input and output data, and copies input data from the main memory to the GPU memory. Second, the host code starts the kernels on the GPU. The kernels perform the required task on the GPU. Third, when the kernels finish their work, the host code copies results from the GPU memory to main memory.

The GPU architecture is illustrated in Figure 1. This architecture is common for both AMD [22] and NVIDIA GPUs [32]. The GPU consists of many SIMD (Single Instruction, Multiple Data) multi-processors (MPs), all sharing global memory (with size up to 4GB), which has both a high bandwidth and a high access latency. For example, the GTX480 GPU has access latency of 400-800 (according to [32]) cycles and a memory bandwidth of 177 GB/second. The latest GPUs, e.g., the GTX480, also have an L2 cache. CUDA, a general-purpose programming framework for NVIDIA GPUs, exposes a hierarchy of GPU threads. GPU threads execute the same code of a kernel, concurrently, on different data. The GPU supports thousands of concurrent threads. In some cases, during some operations, for example an if else statement, some of the threads in a multiprocessor are idle (during the if block or the else block), as according to the if else statement, they do not have to process the body of the if block or the else block of the statement. Warps, each of which consists of the same number of threads, are scheduled across MPs (each warp belongs to one MP). Within each MP, warps are further grouped into thread blocks. Threads in the same thread block share resources on one MP, e.g., registers and local memory (also called shared memory in NVIDIA’s term). The size of this shared memory is small and its access latency is low. GPU threads have both low context-switch and low creation time as compared to CPU threads.

The GPU has a hardware feature that is called coalesced access 1. Coalesced access means that when many threads in a warp access consecutive global memory addresses, these memory accesses are grouped into one access. By that, the number of global memory accesses is significantly reduced, and memory bandwidth utilization is improved.

2.2 XML (Extended) Stream Scheme

An XML database is a forest of rooted, ordered, labeled trees, each node corresponding to an element or a value, and the edges representing (direct) element-sub element or element-value relationships. The ordering of sibling nodes implicitly defines a total order on the nodes in a tree, obtained by a preorder traversal of the tree nodes.

In the classic stream scheme, the position of a string or element occurrence in the XML database is represented as a 3-tuple (DocId, LeftPos:RightPos, LevelNum), where (i) DocId is the identifier of the document; (ii) LevelNum is the nesting depth of the element (or string value) in the document; and (iii) LeftPos and RightPos are the open and close indexes of the element in the data tree, which are assigned according to an order given by a DFS variation, as follows. Document DocId tree is scanned in DFS order. We use a variable called counter initialized to zero. When visiting some element n, we increment counter, then assign its value to the LeftPos of n, then scan the subtree of n (in DFS order). After finishing the scan of the subtree of n, we increment counter, and assign its value to RightPos.

Let lbd denote a label in a database. Associated with each distinct lbd there is a stream Sbd. The stream contains the positional representations of the database nodes with the lbd label. The nodes in the stream are sorted by their (DocId, LeftPos) values.

For use in the algorithm, we extended the stream scheme, with additional structural information. The first additional field is added to each node is the ancStreamsL list. Let n be a node in the data tree, its ancStreamsL list holds information about all the streams that contain at least one node that belongs to the path between n and the root of the data tree (i.e., ancestors of n). The information that is held for each such stream is as follows: the name of the stream, and the index in the stream of a node that belongs to the path between n and the root which is closest to the root. The second additional field that is added to each node is a Boolean array, qArray. Its size is equal to the number of nodes in the twig pattern (see definition bellow).

1This feature is not used in our particular application.
Each node in the document tree appears in a single stream (the stream of the node’s label). In this scheme, each distinct leaf label also has a separate stream. This is very wasteful, as it causes a significant memory overhead. There are standard ways to overcome this problem. One is to assign a single stream for all labels of leaves; another one is to store all the leaves in a B-tree (according to the string order as the primary key and to the LeftPos order as the secondary key).

A stream is held in the memory as array of structs, while each struct contains the data as described above. This way is convenient while working with the GPU, as it is a compact way to store information, and the access to each node is easy and fast especially if the index of the node in the stream is known.

### 2.3 Twig Pattern Matching

The **twig pattern** is a rooted, ordered, labeled tree whose nodes’ labels are either element tags, attribute-value comparisons or string values, and edges are either parent-child edges (depicted using a single line) or ancestor-descendant edges (depicted using a double line). For example, the XPath expression: `movie[name='Harry Potter'][/actor[last='Radcliffe']` which matches movie elements that (i) have a child element named ’name’ with content ’Harry Potter’, (ii) have a descendant element ’actor’ with a child element named ’last’ with content ’Radcliffe’ can be represented as the twig pattern in Figure 2.

![Example of twig pattern](image)

We add two additional fields to each node in the twig pattern. The first field is the number (named `SibNum`) of left siblings having the same label. The second field is a Boolean field named `isAnswer`.

For simplicity we assume that a twig pattern contains only ancestor-descendant edges. When two nodes are connected with an ancestor-descendant edge, we call the node that is closer to the root the parent node, and the node that is farther from the root the child node.

Given a twig pattern \( Q \) with nodes \( (q_1,..., q_n) \) and an XML database \( D \), a match of \( Q \) in \( D \) is a mapping from nodes in \( Q \) to distinct nodes \( (d_1,..., d_n) \) in \( D \) such that: (i) \( d_i \) is matched with \( q_i \), \( 1 \leq i \leq n \), (ii) \( d_i \) and \( q_i \) have the same label, and (iii) the structural (parent-child and ancestor-descendant) relationships between query nodes are satisfied by the corresponding database nodes.

In query \( Q \), a single node is marked as the **target node** (technically, field `isAnswer` is set to `true`). A database node \( d \) that is the image of the target node of \( Q \) in a match is called an **answer node**.

We solve the problem is that of computing all answer nodes for query \( Q \) on database \( D \). A related problem, called the **Twig Pattern Matching** problem, not addressed here, is that of computing all matches of \( Q \) in \( D \), where each match is represented as a vector \( (d_1,..., d_n) \) corresponding to \( Q \)’s nodes \( q_i \), \( 1 \leq i \leq n \).

### 3. THE GPU-Twig ALGORITHM

The main special characteristic of the GPU-Twig algorithm is the ability to divide the work to hundreds or even thousands of threads that run in parallel. The GPU-Twig algorithm does not make use of most of the GPU features (like shared memory or coalesced memory access). The main GPU-specific features that we use are as follows. The first is the potential massive parallelization. The second is the fact that if there is massive work against the memory (such that at each moment there is data that has to be brought from the global memory), the overall time of bringing piece of data from the global memory by the GPU is smaller than bringing data from the RAM by the CPU due to the high bandwidth.

GPU-Twig processes only the document parts that are relevant to the input query. In other words, it processes only streams whose labels appear in the input twig pattern. In the first phase of the algorithm, it goes over all the relevant streams and derives additional structural information according to the input query. In the second phase of the algorithm, this structural information is used to produce the answer set.

To gain intuition about the algorithm, we start with some definitions. Next, we present the algorithm itself, and finally we present a correctness proof for the algorithm.

#### 3.1 Definitions

![Example for a qTree and a dTree](image)

First, we define when a node \( n \) of data tree \( dTree \) is **qualifying w.r.t. a node** \( q \) of twig pattern \( qTree \). The intuition behind this definition is that if \( n \) is **qualifying w.r.t.** \( q \), then the subtree rooted at node \( n \) satisfies the query requirements of the subtree rooted at node \( q \). So, it means that \( n \) is part of at least one match to the query represented by the subtree rooted at \( q \) in \( qTree \).

**Definition 1:** Let \( q \) be a node in \( qTree \) labeled \( qLabel \), let \( n \) be a node labeled \( qLabel \) in \( dTree \). We define, inductively on the height \( h \) of \( qTree \), when \( n \) is **qualifying w.r.t.** \( q \) as follows.

- \( h = 0 \): \( q \) is a leaf node in \( qTree \). Node \( n \) is **qualifying w.r.t.** node \( q \) if they both have the same label, namely \( qLabel \).  
- \( h > 0 \): \( q \) is a non-leaf node in \( qTree \). Node \( n \) is **qualifying w.r.t.** node \( q \) if: (1) \( n \) and \( q \) have the same label, namely \( qLabel \), (2) there is a bijection between all children of node \( q \) in \( qTree \), and a subset of the descendants of node \( n \) in \( dTree \) such that each descendant in the above subset is **qualifying w.r.t.** the corr. child of \( q \). The order between the children does not have to be preserved by their bijection images.

**Example 1.** For the twig pattern \( qTree \) and the \( dTree \) in Figure 3, nodes \((10:13,4), (9:6,3), (22:27,4) \) and \((9:20,3) \) in \( dTree \) are **qualifying w.r.t.** the node with index 2 in \( qTree \). Another example is node...
(8:31,2) in dTree. Node (8:31,2) is qualifying w.r.t. the node with index 1 in qTree. This is because it has child labeled c (29:30,3) that is qualifying w.r.t. the node labeled e with index 5, a descendant labeled b (22:27,4) or (9:20,3)) that is qualifying w.r.t. the node labeled b with index 3, and an additional descendant labeled b (9:20,3) or (10:13,4)) that is qualifying w.r.t. node b with index 2. Node (32:49,2) has descendants that are qualifying w.r.t. nodes with index 3 and 5, but it has no additional distinct descendant labeled b, i.e., node (32:49,2) does not have 3 distinct descendants, that are qualifying w.r.t. nodes with index 2, 3 and 5. Therefore, node (32:49,2) is not qualifying w.r.t. the node with index 1. □

Now, we define when a node n in dTree has k relatives labeled qLabel w.r.t. node p labeled pqLabel in qTree.

Definition 2: For twig pattern nodes q labeled qLabel and node pq labeled pqLabel in qTree (where pq is the parent of q), and for node n labeled qLabel and node p labeled pqLabel in dTree, n has k relatives w.r.t. p if n is a descendant of p and there are at least k distinct nodes, different than n, labeled qLabel in the subtree rooted at p. These nodes are called relatives of n. ■

Consider a query that is represented by the subtree rooted at pq labeled pqLabel, where pq is parent of q, and some node n labeled qLabel in dTree that has an ancestor node p labeled pqLabel. In order for node n to be part of at least one match to the query represented by the subtree rooted at pq, three conditions must be satisfied. The first is that node n has to be qualifying w.r.t. q. The second is that there has to be a bijection from a subset of the relatives of node n w.r.t. q and p to the set of left siblings of q with the same label as q. And, the last condition is that p must have an additional subset of distinct descendants (that are different from the descendants used in the second condition) that are qualifying w.r.t. all the other siblings of q (which are not left siblings with the same label as q). The next definition formally defines the second condition.

Definition 3: For twig pattern nodes q labeled qLabel and pq labeled pqLabel in qTree (where pq is the parent of q) and for node p labeled pqLabel in dTree, node n, a descendant of p in dTree (labeled qLabel) is left qualifying w.r.t. nodes q and p, if q has exactly lSibNum distinct left siblings labeled qLabel, and if node n has at least lSibNum distinct relatives labeled qLabel w.r.t. p, and there is a bijection between the left siblings of q and a subset of said relatives of n such that each relative of n is qualifying w.r.t. the corr. left sibling of q. The order between the left siblings does not have to be preserved by their images. ■

Observe that node n is not necessarily qualifying w.r.t. q.

Example 2. For the twig pattern qTree and the dTree in Figure 3, nodes (9:20,3) and (22:27,4) in dTree are qualifying w.r.t. the node with index 3, and left qualifying w.r.t. the node with index 3 (matches the q node in the definition) and node (8:31,2) (matches the p node in the definition). The node with index 3 (in qTree) has one left sibling (the node with index 2). Each one of nodes (9:20,3) and (22:27,4) has more than one distinct relatives that are qualifying w.r.t. the node with index 2. For example, the relatives of (22:27,4) are (9:20,3), (10:13,4), Node (10:13,4) does not satisfy the requirements of being qualifying w.r.t. the node with index 3 and left qualifying w.r.t. the node with index 3 and node (8:31,2), as it is not qualifying w.r.t. the node with index 3 even though it is left qualifying w.r.t. the node with index 3 and node (8:31,2). □

As we saw in Section 2, each node in a stream has a field named qArray which is a Boolean array. The qArray is used to encode the additional structural information that is derived in the first phase of the algorithm. In the following definition we define when bit i in the qArray of node n is set correctly w.r.t. some node q in qTree, where 0 ≤ i < the number of nodes in qTree. Intuitively, if bit i in the qArray of node n labeled qLabel is set correctly w.r.t. node q labeled qLabel, then n has some descendant node m whose subtree satisfies the query requirement w.r.t. the subtree rooted at node qChild with index i that is a child of node q.

Definition 4: Let n be an arbitrary node in dTree labeled qLabel. Let q be a node labeled qLabel in qTree. Let qChild be a child of q indexed i and labeled decLabel. Bit i in the qArray of node n is set correctly w.r.t. node q if the following holds. The value of bit i is true iff: (1) node n has a descendant node m labeled decLabel, (2) node m is qualifying w.r.t. qChild, and (3) node m is left qualifying w.r.t. qChild and n. ■

To indicate if the subtree rooted at node n (in dTree) satisfies the query requirements w.r.t. the subtree rooted at node q (in qTree) using the qArray, we define the subtree-correctness.

Definition 5: The qArray structure of node n labeled qLabel is subtree-correct w.r.t. node q, labeled qLabel in qTree, if for every child of q, say with index i, bit i of the qArray of node n is set correctly. Bit 2 is set correctly to true because node (8:25,2) has descendants that are qualifying w.r.t. the node with index 2 and left qualifying w.r.t. the node with index 2 in qTree and node (8:25,2) (nodes (10:11,4), (9:6,3) and (18:21,4)). Bit 3 is set correctly to true because node (8:25,2) has descendants that are qualifying w.r.t. the node with index 3 and left qualifying w.r.t. the node with index 3 and node (8:25,2) (nodes (9:16,3) and (18:21,4)). Bit 5 is set correctly to true because it has a child that is qualifying w.r.t. the node with index 5 and left qualifying w.r.t. the node with index 5 and node (8:25,2) (node (23:24,3)). □

3.2 The Algorithm

The algorithm has two phases. The goal of the first phase is to derive the additional structural information for all the nodes in the streams that correspond to the twig pattern nodes. The first phase of the algorithm works in a bottom up manner over the qTree twig pattern. It chooses some node q such that all its children and left siblings are already processed. I.e., the first nodes to be processed are the leaves that have no left siblings. For every node q in qTree, the algorithm processes all the nodes in the stream that corresponds to q. Suppose that the label of q is qLabel, the index of q in qTree is qIdx, and the parent of q is pq labeled pqLabel. For every node
in the qLabel stream, the first phase of the algorithm updates all the relevant qArray structures of nodes in the pqLabel stream, such that after processing all the nodes in the stream, for each node n in the pqLabel stream that has a descendant in the qLabel stream that is qualifying w.r.t. q, bit qIdx in the qArray of node n is set correctly w.r.t. pq. Note that we can not process qTree nodes in parallel, as the result of processing node q relies on the fact that all its children and left siblings are already processed. Another important issue is to understand the bottleneck of our algorithm. Our algorithm makes a very small amount of computations per data unit, while most of the work is to go over the algorithm’s data which means that it is memory intensive. So the bottleneck of our algorithm is the global memory bus bandwidth.

Before starting the first phase, all the relevant information for the query is copied using cudaMemcpy calls. The relevant information includes the streams of each query node and the query nodes data itself.

Figure 5 depicts the first phase of the GPU-Twig algorithm. The input to the first phase are the data tree dTree, and the twig pattern qTree. Line 4 contains the invocation of the CUDA kernel function gpuTwigFirstPhase which is processed on the GPU. I.e., the derivation of the additional structural information of dTree is executed on the GPU, while the task of the CPU is to run the outer loop over qTree nodes, and to prepare the information for the GPU.

The gpuTwigFirstPhase kernel call sets correctly bit qIdx in the qArray of all nodes pn in the pqLabel stream w.r.t. node pq. The code of gpuTwigFirstPhase is run for every node in qStream, which is the “Multiple Data”, while the “Single Instruction” is the code of the gpuTwigFirstPhase function itself. This provides the potential for an enormous number of parallel threads, as the number of nodes in such a stream can be in the tens and even hundreds of thousands. In GTX 480, the maximum number of resident threads per MP (multiprocessor) is 1536 (i.e., 1536*15 for all the MPs), while the maximum number of threads that can actually run in parallel at any point of time is 480 (32 on each of the 15 MPs). As the number of nodes in a stream is usually much larger than the number of compute units in the GPU, the utilization of the GPU is very high, i.e., the throughput of processing the work is high in comparison to multi-threaded CPU systems. The number of nodes in different streams can vary. This fact does not present any special problem, as usually the number of nodes in a stream of a large document is much larger than the number of GPU compute units.

Note that, for speeding up job processing, our algorithm uses mainly the feature of the GPU, namely that of potentially high parallelism. It does not use the shared memory, as each piece of data has to be read only once. The coalesced access data feature is also not used as this feature requires data accesses to be ordered, which does not happen, as the algorithm works with data that represents a tree, which is unordered data. The loop in line 4 is run only for nodes labeled pqLabel that are ancestors of node n. If the query pattern is allowed to contain the child axis, then line 4 of the algorithm has to be changed as follows. In case that the edge between node q and its parent is parent-child (and not ancestor-descendant), then instead of the FOREACH loop in line 4, we need to run lines 5-8 only for a single node, which is the parent node of n labeled pqLabel (if such a node exists). Parent nodes can be identified easily, by checking that the level of a potential parent node is one less than the level of node n. Line 7 checks if node n fulfills the conditions needed to set bit qIdx in the qArray of node pn according to Definition 4. I.e., whether node n is qualifying w.r.t. q (checked by the subtreeCorrect function) and is left qualifying w.r.t. q and

```
Input: 1) Data tree dTree. 2) Twig pattern qTree.
Goal: Build the additional structural information for all nodes in the streams that correspond to qTree nodes.
Method:
1. WHILE there are unprocessed nodes in qTree:
   2. Choose node q from qTree such that all its child nodes and all its left siblings were already processed
   3. SET qStream to q’s stream, qIdx to q’s index, pqStream to q’s parent stream
   4. Invoke CUDA kernel call for function: gpuTwigFirstPhase(qStream, pqStream, qIdx)
   5. Mark q as processed
   6. End WHILE
```

Figure 5: The first phase of the GPU-Twig Algorithm

pm (checked by the leftSiblingMatch function). In case it is, we set bit qIdx of the qArray of node pn to true (line 8).

The subtreeCorrect(q, n) function checks if node n is subtree-correct w.r.t. q according to Definition 5. The invariant maintained
by this function is that the value of all the bits in the qArray of q that correspond to the children of q are already set correctly w.r.t. q. In Section 3.3, we prove that when we call the subtreeCorrect function for some q and n, the above invariant holds. So, to check if node n is subtree-correct w.r.t. q, according to Definition 5, it suffices to check if for every child of q, say with index i, bit i of the qArray of n is true. This is exactly what is done in the subtreeCorrect function in lines (2-7). When we find that some bit i in the qArray of n that corresponds to some child of q is false (line 4), it means that n is not subtree-correct w.r.t. q.

The leftSiblingMatch(set1, set2) function checks if there is a bijection from some subset ss2 of set2 to set1 such that for each pair of nodes \( x \in ss_2 \) and \( y \in set_1 \) in the bijection the following holds: for each child of y indexed i, the value of bit i in the qArray structure of \( x \) is true. This is in fact the problem of finding a perfect matching in a bipartite graph. The best known complexity of the problem for graph \( G \) with V nodes and E edges, is \( O(\sqrt{VE}) \).

According to the first phase of the algorithm, set1 contains all the distinct left siblings of q labeled qLabel while set2 contains all the descendants of pn labeled qLabel except for \( n \). So, as proved in Section 3.3, the leftSiblingMatch function checks if node \( n \) is left qualifying w.r.t. nodes q and pn according to Definition 3. set1 is always very small (a few nodes), set2 is usually small (a few tens of nodes), so according to the above complexity, the run time of this function is usually small. In very rare cases in which set2 is large, the run time of the function begins to be significant.

The goal of the second phase of the algorithm is to find the answer nodes of a qTree twig pattern in dTree using the qArray structures of nodes in dTree that were derived in the first phase of the algorithm.

The second phase of the algorithm processes all nodes in stream \( s \) corresponding to the label of the qAns target node whose isAnswer field (see Section 2) is set to true. This is because each node currSN in the \( s \) stream is potentially an answer. We define a sub-query qPath as the path between the answer node qAnsN and the twig pattern root node. In order for a node currSN to be an answer, we need to check that there is at least one match of qPath in dTree such that the qAnsN node maps to currSN and the qArray of each node in the match (according to match definition) is subtree-correct w.r.t. the matched node in qPath. The algorithm works bottom up. It starts from node currSN and checks if currQN that is initialized to qAnsN’s parent (pCurrQN) maps to some ancestor of node currSN, called ancN, such that the qArray of ancN is subtree-correct w.r.t. pCurrQN. In case that such ancN is found, we update currSN to be ancN and currQN to be pCurrQN, otherwise we stop. This is because not finding such an ancN means that the match we are looking for does not exist. We continue this process until we find the desired match, or until we fail to find it (as explained above).

Figure 6 presents the second phase of the GPU-Twig algorithm. The input to the second phase are the source document tree dTree, and the twig pattern qTree. The output of the second phase is a set ansSet with all the answer nodes for qTree in dTree. Line 3 contains the invocation of the CUDA kernel function called gpuTwigSecondPhase that is processed on the GPU. In line 4, we prepare the ansSet set, by scanning the ansLabel stream for nodes whose isAnswer bit is set to true.

The gpuTwigSecondPhase kernel call sets the isAnswer bit of all the answer nodes for qTree in dTree (this bit is initialized to false). The code of gpuTwigSecondPhase is run for every node in qStream. As before, this provides a potential for an enormous number of parallel threads. Lines (5-20) check that there is at least one match of qPath (defined above) in dTree such that the qAnsN node maps to n (line 5) and the qArray of each node in the match is subtree-correct w.r.t. the matching node in qPath (line 13). Line 21 checks if such a match was found, and in case of a positive answer, line 22 sets the n.isAnswer bit to true. If the query pattern is allowed to contain the child axis, then the edge between pCurrQN and currQN is parent-child (and not ancestor-descendant), then instead of lined 9-12, we need to check if currSN has a parent node in pCurrQN. In case of a positive answer, we need to run lines 13,14 and to continue at line 17, otherwise, to go to line 17 (without running lines 13,14).

Example 4. Consider the twig pattern qTree and the dTree presented in Figure 4. After processing the first phase of the algorithm for all the leaves of qTree, the qArray of nodes (2:7,2), (8:25,2), (9:16,3), (18:21,4), and (26:37,2) in dTree are changed as shown in Figure 7. During the first phase of the algorithm for node with index 3, bit 3 in qArray of node (8:25,2) is set to true, because the qArray of node (18:21,4) is subtree-correct w.r.t. node with index 3, and because node (18:21,4) is left qualifying w.r.t. the node with index 3 and node (8:25,2). Node (9:16,3), for example, is the node that makes the node (18:21,4) left qualifying w.r.t. the node with index 3 and node (8:25,2). By this, the first phase of the algorithm
is finished.

The value of the isAnswer field in the node labeled c (with index 5) is true. So, according to the definition of answer nodes, the potential answer nodes are placed in the c stream. The c stream contains two nodes: (23:24,3) and (27:32,3).

First we describe the run of the second phase for node (23:24,3). The parent of the node labeled c in qTree is the node labeled a. The only ancestor node of (23:24,3) that is labeled a is (8:25,2). Node (8:25,2) has the highest LeftPos value in a’s stream such that it is an ancestor of node (23:24,3) and is subtree-correct w.r.t. the node with index 1 labeled a. We know it because the qArray structure of node (8:25,2) is subtree-correct w.r.t. the node labeled a (in qTree). The left qualifying definition is not relevant for node (8:25,2) because it is the root node. So, we update currSN to be (8:25,2). As the node labeled a is the root of qTree, the while loop finishes and currSN is labeled a, we add node (23:24,3) to ansSet (set of all answer nodes).

Lastly, we describe the run of the second phase for node (27:32,3). The parent node of the node labeled c in qTree is the node labeled a. The only ancestor node of (27:32,3) with label a is (26:37,2). Node (26:37,2) has the highest LeftPos value in a’s stream but, it is not qualifying w.r.t. currQ, because the qArray of node (26:37,2) is not subtree-correct w.r.t. the node labeled a (in qTree). This is because bits 2,3 in the qArray of (26:37,2), that correspond to nodes with index 2,3 in qTree, are false. As node a is the root of qTree, the while loop finishes. As we did not update currSN to be (26:37,2), we do not add node (27:32,3) to ansSet. □

3.3 Correctness Proof

Correctness proof of the first phase of the algorithm

Lemma 1: For node q labeled qLabel in qTree. If the qArray structure of dTree node n labeled qLabel is subtree-correct w.r.t. q then n is qualifying w.r.t. q, and n is part of at least one match of the qTree sub-query rooted at q in dTree.

Proof:

Let q be a node in qTree labeled qLabel, let n be a node labeled qLabel in dTree, and let h be the height h of qTree.

For h = 0 and q a leaf node in qTree: By Definition 1, any dTree leaf node n having the same label as q is qualifying w.r.t. q. So, as node q is a leaf node, it is qualifying w.r.t. q no matter how qArray is filled.

For h > 0 and q a non-leaf node in qTree: If the qArray structure of node n labeled qLabel is subtree-correct w.r.t. q then according to the definition of subtree-correct, for every child of q, say with index i, bit i of the qArray is set correctly and its value is true. According to the set correctly definition, the value of bit i in the qArray of node n is true if node n has a descendant node m labeled with the same label as child qC with index i such that m is qualifying w.r.t. qC and left qualifying w.r.t. qC and n. The left qualifying requirement assures that in case we have a few children with the same label, their images in dTree are distinct nodes. If the rightmost child node in the group of children with the same label is left qualifying w.r.t. qC and n, then all the images of the children with the same label are distinct nodes. So, in order to assure that all the images of the children with the same label are distinct nodes, we only need to look at the rightmost child node. Thus, as according to the definitions, for each child qC with index qIdx of node q, the bit qIdx in qArray of node n is true, it means that for each child qC of node q in qTree (including the rightmost in the group of children with the same label), node n has a distinct descendant node m in dTree such that node m is qualifying w.r.t. node qC.

I.e., there is a bijection from a subset of the descendants of n to all children of q such that each descendant in the above subset is qualifying w.r.t. the corr. child of q. So, according to Definition 2, n is qualifying w.r.t. q. □

Definition 6: For twig pattern qTree and for node q labeled qLabel in dTree, dTree is tree-correct w.r.t. q, if for each node n, labeled qLabel, in dTree that is qualifying (respectively, not qualifying) w.r.t. q, the qArray of node n is subtree-correct (respectively, not subtree-correct) w.r.t. q. □

Lemma 2: At the end of the run of the first phase of the algorithm, for all nodes q in qTree, dTree is tree-correct w.r.t. q.

Proof: By induction over the structure of qTree.

Base: For leaf node, dTree is tree-correct w.r.t. q, because according to the tree-correct definition, for each node n, labeled qLabel in dTree that is qualifying w.r.t. q, the qArray of node n is subtree-correct w.r.t. q. According to the qualifying definition, each leaf node ifN that is labeled qLabel is qualifying w.r.t. q. I.e., there are no special requirements for the qArray of ifN. So, no matter what is the value of the qArray of ifN, because ifN is labeled qLabel, it is also vacuously subtree-correct w.r.t. q.

Now, we prove that if dTree is tree-correct w.r.t. qC for each child qC of some node q in qTree, then dTree is tree-correct w.r.t. q.

Induction assumption: dTree is tree-correct w.r.t. all children qC of q.

We show that the algorithm marks dTree such that dTree is tree-correct w.r.t. q. Assume that the label of q is qLabel. Assume that pq is the parent of q with label pqLabel. Note that before starting the algorithm, all qArray structures, of all nodes, were initialized to false. Node n in dTree is part of a match, if n is the image of some node q in qTree in some match of qTree in dTree.

Claim 1: Assume qC, indexed qIdx, is a child of q. Assume n is a node labeled qLabel in dTree. We claim that bit qIdx in the qArray of n is set correctly during the processing of qC.

Proof: While child qC (with index cqIdx and label cqLabel) of q was considered, we processed each node nD in the cqLabel stream. By the algorithm, we set bit cqIdx to true in all nodes n in the qLabel stream that are ancestors of nD in case that the following conditions hold.

(1) For each child of qC indexed i, the value of bit i in the qArray structure of nD is true. According to Definition 5, if for each child of qC, say with index i, bit i of the qArray of nD is set correctly w.r.t. qC and its value is true, then the qArray structure of node nD is subtree-correct w.r.t. qC. By the assumption, dTree is tree-correct w.r.t. qC. So, based on Definition 5 and the assumption, if this requirement holds, it means that qArray of nD is subtree-correct w.r.t. qC.

(2) The leftSiblingMatch(set1, set2) function returned true.
where set1 contains all the distinct left siblings of node n that are labeled rhs, and set2 contains all the descendants of node n that are labeled rhs except for node n. According to Definition 3, nD is left qualifying w.r.t. rhs if nD has exactly lSibNum distinct left siblings labeled rhs and nD has at least lSibNum distinct relatives labeled rhs w.r.t. n and there is a bijection between the left siblings of n and a subset of said relatives of node n such that each relative of n is qualifying w.r.t. the corresponding left sibling. Function leftSiblingMatch checks exactly these requirements. It checks if there is a bijection from some subset sss2 of set2 to set1, such that for each pair of nodes x ∈ sss2 and y ∈ set1 in the bijection the following is true: for each child of y indexed i, the value of bit i in the qArray structure of x is true. By the assumption, dTree is tree-correct w.r.t. rhs for each child rhs of node n. So, based on Definition 3, the fact that leftSiblingMatch function returned true, and the assumption, the existence of such bijection means that nD is left qualifying w.r.t. rhs and n.

So, the fact that we set bit cIdx to true is correct according to Definition 4, as we found that nD is subtree-correct w.r.t. rhs and is left qualifying w.r.t. rhs and n, and according to Definition 4, in that case bit cIdx has to be true.

If after finishing processing all nodes in the rhs stream, bit cIdx in node n labeled qLabel was not set to true and its value at the end of the process remained false, it means that no node was found such that it satisfies the above requirements. The fact that no such node was found, means that node n labeled qLabel does not have any descendant that is labeled rhs such that it satisfies the above requirements. This is because, if such a node exists, it must be part of the rhs stream, but we checked all nodes in rhs stream, and did not find such a node. So, if bit cIdx in node n was not set to true during processing nodes in rhs stream, it must be because node n labeled qLabel does not have any descendant that is labeled rhs such that it satisfies the requirements of Definition 4.

So, the above process sets correctly the cIdx bit in qArray of all nodes n with label qLabel. Note that when some bit in qArray of any node is set to true, its value does not change during the continuation of the algorithm. □

Claim 2: Now we claim that before starting to process node n in qTree, dTree is tree-correct w.r.t. q.

Proof: By the algorithm, we start processing node q only after finishing to process all the children of q. Based on Claim 1, for each child node rhs of q, the bit that corresponds to rhs in the qArray structure of nodes labeled qLabel in dTree is set correctly during the processing of node rhs. So, after finishing processing all children of q, all bits that correspond to children of q in the qArray structure of nodes labeled qLabel in dTree are set correctly. So, according to Definition 6, dTree is tree-correct w.r.t. q. □

According to Claim 2 and to the fact that the algorithm continues until it processes all nodes in qTree, at the end of the execution of the algorithm, for all nodes q in qTree, dTree is tree-correct w.r.t. q.

Correctness proof of the second phase of the algorithm

Lemma 3: At the end of the run of the algorithm, all the answer nodes of twig pattern qTree in dTree are added to the output.

The Lemma is established using the following three Claims.

Claim 1: For the subtree rooted at node n in dTree, for node m in this subtree, and for the subtree rooted at q in qTree, if the qArray of node n is subtree-correct w.r.t. q, and m is part of a match mtch of the twig pattern defined by the subtree rooted at q in the subtree rooted at n, and there exists some ancestor ancN of node n whose qArray is subtree-correct w.r.t. the parent node pq labeled pqLabel of q, then mtch can be extended to a match mtchExt of the query defined by the subtree rooted at pq in the subtree rooted at ancN such that m is part of the match mtchExt matching the same qTree node as in match.

Proof: According to problem definition, the qArray of ancN is subtree-correct w.r.t. pq, so according to Lemma 2, ancN is part of at least one match of the twig pattern defined by the subtree rooted at pq in the subtree rooted at ancN. Assume that the index of node q is qIdx. Bit qIdx in the qArray of node ancN is true, as according to the problem definition the qArray of node ancN is subtree-correct w.r.t. pq. According to the claim definition, the qArray of node n is subtree-correct w.r.t. q, so according to Lemma 2, n is part of at least one match of the twig pattern defined by the subtree rooted at q in the subtree rooted at n. Based on the above, we can extend the match of q in the subtree rooted at n to the match of pq in the subtree of dTree rooted at ancN. The mapping of nodes of qTree subtree rooted at q to nodes of dTree subtree rooted at n remains the same, and we add to this mapping the pair (pq, ancN), i.e., pq maps to ancN. So, as we found a new (extended) match mtchExt, m is part of a match of the qTree subtree rooted at pq in the subtree of dTree rooted at ancN.

Claim 2: For a node n labeled qLabel and for a node q labeled pqLabel, if the qArray of node n is subtree-correct w.r.t. q, and n does not have any ancestor whose qArray is subtree-correct w.r.t. pq, where pq is the parent of q, then n does not participate in any match of sub-query pq in dTree.

Proof: Suppose, for the sake of deriving a contradiction, that the qArray of node n is subtree-correct w.r.t. q, and n does not have any ancestor whose qArray is subtree-correct w.r.t. pq where pq is the parent of q, and that n participates in match mtch of query pq in dTree. Match mtch looks as follows: (..., (q : n), (pq : pn)). According to the definition of a match, each qTree node maps to a distinct node in dTree, and the structural relationship between each parent child pair of nodes in qTree is satisfied by the corresponding dTree nodes. In match mtch, q maps to n and pq maps to pn. According to match definition, there has to be ancestor descendant relationship between nodes n and pn, as q and pq have a parent child relationship in qTree. According to the assumption, n does not have any ancestor whose qArray is subtree-correct w.r.t. pq which contradicts the fact that pn is an ancestor of n. Therefore, n does not participate in any match of sub-query pq in dTree. □

Claim 3: At the end of the run of the algorithm, all the answer nodes of twig pattern qTree in dTree are added to the output.

Proof: We consider every node that can potentially be an answer node as we consider all nodes that belong to the ansLabel stream. For each such node, say leaveN, we run a while loop. In each loop iteration, we take the current node (namely, currS) and look for an ancestor (namely, ancN) such that the qArray of node currS satisfies the following condition: for each child of node currQ (the parent of node currQ) indexed i, the value of bit i in the qArray structure of currS is true. Based on the correctness proof of phase one of the algorithm and on Definition 5, it means that the qArray structure of currS is subtree-correct w.r.t. node currQ. Each time we look for such an ancestor, we choose the ancestor with the highest lIdx value, which means the closest one to currS. This ensures that we never miss any potential matching data tree path. So, if such an ancestor does not exist, then based on Claim 2, currS is not part of any match, which means that leaveN is also not part of any match. If we found such an ancestor ancN, according to Claim 1, node leaveN is part of at least one match to the target node of the twig pattern defined by the subtree rooted at currQ in the subtree rooted at ancN. □

At the end of the algorithm (after ending the while loop) we check if currQ is equal to the root of qTree (rq) and that currS
is not NULL, which means (according to Claim 1) that $\text{leaf}_N$ is part of at least one match of of the twig pattern defined by the subtree rooted at $r_g$ in the subtree rooted at $\text{curr}_S$. I.e., $\text{leaf}_N$ is an answer node in $d\text{Tree}$. ■

4. RELATED WORK

Recently, there have been research efforts aiming to parallelize relational DBMS query processors [28, 38, 39, 9]. This is mainly due to the emergence of multi-core processors. One example is InfiniteDB, which is a PC-Cluster-based Parallel Massive Database Management System [25]. Another example is an extensive study of SQL query parallelization in the context of both distributed and centralized repositories [23, 24, 29].

Parallelization of SQL queries differs from that of XPath parallelization. (1) XPath processing is read-only, while SQL allows inplace updates. (2) SQL is associated with a relational data model which leads to natural partitioning along either rows or columns. XPath is associated with a tree data model that is less naturally partitioned. Hence, XML query parallelization is challenging.

As XPath is a critical component in many XML-based applications, it is important to maximize its performance. There has been extensive work on optimizing performance of a single XPath query by improving its traversal pattern [16, 27, 30]. Studies on parallelization of XML processing began to appear only recently; for example, studies regarding parallel XML parsing [31, 37, 35, 36], parallel data placement in XML databases [41], and parallel processors for XML databases [13, 42, 43]. Most existing XML processing engines are thread-safe and allow multiple threads to issue concurrent XPath queries against an XML database. Distributed XML processing is discussed in [8, 12]. Almost no published works deal with parallelization of a single query.

Parallelization of a single XPath query using the Xalan XPath engine on shared address space multi-core systems is presented in [6]. It evaluates opportunities for parallelizing a single XPath query, in a shared-address space environment, on commodity multi-core processors. It proposes three strategies for parallelizing individual XPath queries. Data Partitioning approach: executes the same (sub)query on different sections of the same XML document. Query Partitioning approach: executes different (sub)queries on the same XML dataset. The third is the Hybrid Partitioning approach that combines both the data and query partitioning schemes. Continuation work by the same authors is presented in [5]. It proposes a parallelization framework that determines the optimal way of parallelizing an XML query. They demonstrated that it is possible to accelerate XPath processing using commodity multi-core systems.

As GPUs emerged, they were mainly used to accelerate scientific, geometric, and imaging applications. State-of-the-art General Purpose GPU (GPGPU) techniques can be found in [34]. Lately, there are efforts to use GPUs to improve the performance of database operations. For example, in [40] the rendering and search capabilities of GPUs are used for spatial selection and join operations. In [3] GPU-based spatial operations are implemented as external procedures in a commercial DBMS. Govindaraju et al. [20, 19, 17] are novel GPU-based algorithms for relational operators. Most recently, in [26], a similarity join was implemented on CUDA.

5. CONCLUSIONS AND FUTURE WORK

The GPU-Twig algorithm is a novel efficient algorithm for matching XML twig patterns, using a stream representation scheme, in a parallel multi-threaded computing platform, while using a GPU as a CPU co-processor. GPU-Twig employs techniques that allow it to run hundreds of threads in parallel.

As part of future work we intend to extend our algorithms to work more efficiently with larger terabyte sized files. We also intend to examine certain features, and their associated trade-offs, of the algorithm and determine whether we can further optimize it. An example of such a tradeoff is the checking of the left qualifying property for each child rather than just for the rightmost child for each particular label. We also plan to check potential parallelism in other aspects of XML and semi-structured databases in general (for example, parallelization of DataGuides [14], Path Summaries [2] and more).

6. REFERENCES


