Proceedings of the

# 2007 ACM SIGPLAN Symposium on Principles and Practice of Parallel Programming

# PPoPP'07

March 14-17, 2007 • San Jose, California, USA

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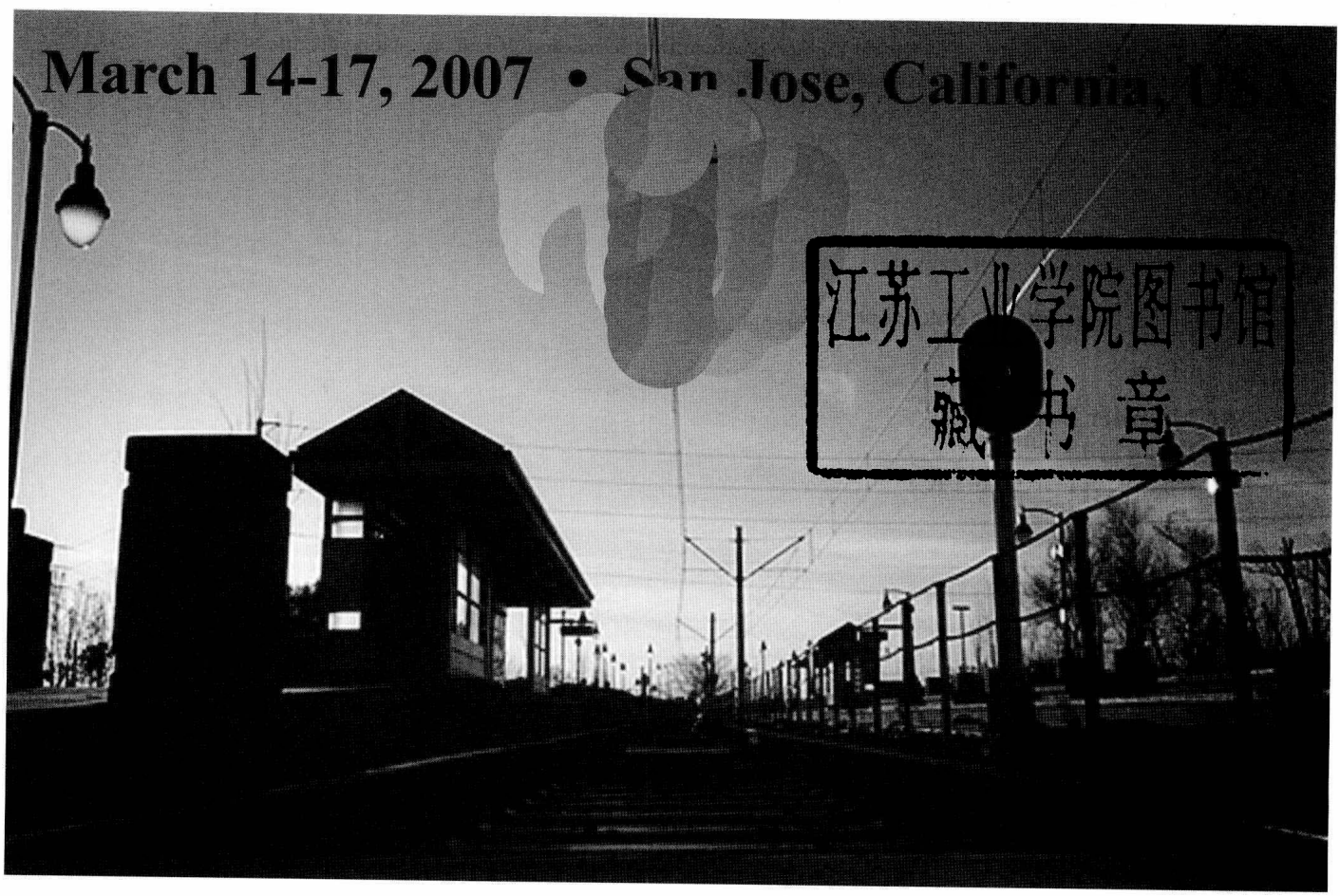


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# Foreword

It is our pleasure to welcome you to the 12th *ACM Symposium on Principles and Practice of Parallel Programming (PPoPP'07)*. This past year has been an exciting one for the field. The abrupt switch to multi-core designs for commodity microprocessors has transformed parallel computing from a fringe technology to one on the critical path for the success of products ranging from game consoles to supercomputers. The road ahead is full of challenges with increasing interest in heterogeneous architectures and the impending arrival of many-core microprocessors. The mission of this symposium is to serve as a forum for presenting new ideas ranging from the theoretical foundations of parallel programming, to programming models, algorithms, and software for parallel systems. *PPoPP* provides researchers and practitioners an opportunity to share their diverse perspectives.

The call for papers attracted 65 submissions from Asia, Europe, North America, and South America. The program committee accepted 22 papers on topics ranging from theory to practice. This year, *PPoPP* includes a poster session whose aim is to broaden participation and increase the exchange of ideas without sacrificing the symposium's single-track format. The program also includes keynote speeches by Jesse Fang and Andrew Chien, along with a panel on transactions moderated by Maurice Herlihy. For the first time, *PPoPP'07* includes companion workshops that provide an opportunity to learn about topics in greater depth. We hope that you find the program thought provoking and that you value the symposium as an opportunity to exchange ideas with colleagues from institutions around the world.

Putting together *PPoPP'07* was a team effort. Most importantly, we thank the paper and poster authors, keynote speakers, panelists, and workshop presenters for contributing the intellectual content of the program. We are grateful for the dedication of the program committee and external reviewers, who carefully read submissions and provided suggestions for improving them. We thank Costin Iancu, our Workshops Chair and Local Arrangements Co-chair, Yeen Mankin, our other Local Arrangements Co-chair, Parry Husbands, our Finance and Registration Chair, and John Hules, our Publicity and Web Chair; their efforts have been vital to making the symposium a success. We thank Google, IBM, Lawrence Berkeley National Laboratory, and Microsoft Research for their support of the symposium. Finally, we thank our sponsor, ACM SIGPLAN, for their continued support.

**Katherine Yelick**
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**John Mellor-Crummey**
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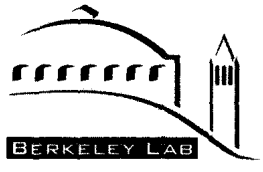




# Table of Contents

## Session 4: Accelerators

Session Chair: A. Cohen *(INRIA Futurs)*



## Session 5: Adaptive Parallelism

Session Chair: S. Kumar *(Intel Corporation)*



## Poster Session

## Keynote Talk

Session Chair: J. Mellor-Crummey *(Rice University)*



## Session 6: Memory Models and Concurrency Analysis

Session Chair: K. Yelick *(University of California at Berkeley/LBNL)*



## Session 7: Thread-level Speculation

Session Chair: V. Sarkar *(IBM T. J. Watson Research Center)*



## Session 8: Compilation, Performance, and Energy

Session Chair: D. Lowenthal *(University of Georgia)*

## Workshops

## Keynote Talk

# Parallel Programming Environment: A Key to Translating Tera-scale Platforms into a Big Success

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Intel Corporation
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### Abstract

Moore's Law will continue to increase the number of transistors on die for a couple of decades, as silicon technology moves from 65nm today to 45nm, 32 nm and 22nm in the future. Since power and thermal constraints increase with frequency, multi-core or many-core microprocessors will be the way of the future. In the near future, hardware platforms will have sixteen or more cores on die to achieve more than one Tera Instructions Per second (TIPs) computation power. These cores will communicate each other through an on-die interconnect fabric with more than one TB/s on-die bandwidth and less than 30 cycles latency. Off-die D-cache will employ 3D stacked memory technology to tremendously increase off-die cache/memory bandwidth and reduce the latency. Fast copper flex cables will link CPU-DRAM on socket and optical silicon photonics will provide up to one Tb/s I/O bandwidth between boxes. The hardware system with TIPs of compute power operating on terabytes of data make this a "tera-scale" platform. What are the software implications with the hardware changes from uniprocessor to tera-scale platform with many cores as "the way of the future?" It will be a great challenge for programming environments to help programmers develop concurrent code for most client software. A good concurrent programming environment should extend existing programming languages that typical programmers are familiar with, and bring benefits for concurrent programming. There are many research topics. Examples topics include flexible parallel programming models based on needs from applications, better synchronization mechanisms such as Transactional Memory to replace simple "Thread + Lock" structure, nested data parallel language primitives with new protocols, fine-grained synchronization mechanisms with hardware support, maybe fine-grained message passing, advanced compiler optimizations for the threaded code, and software tools in the concurrent programming environment. A more interesting problem is how to use such a many-core system to improve single-threaded performance.

***Categories & Subject Descriptors*** C.1 Computer Systems Organization.Processor Architectures D.1 Software. Programming Techniques, D.2 Software.Programming Languages, and D.3 Software.Software Engineering,

***General Terms*** Design, Performance, Languages.

### Bio

Jesse Fang is Director and Chief Scientist of Programming System Lab at Intel/CTG (Corp. Technology Group). Jesse created the lab about 11 years ago, and has been leading the lab to develop programming environment technologies to enable Intel hardware microarchitecture research and microprocessor design, and to transfer SW technologies to Intel's Software Solution Group. Before joining Intel in 1995, Jesse was manager of Hewlett-Packet Research Lab compiler team that initiated the Itanium Architecture in 1991. Jesse ran a small start-up between working at HP and Intel. Before HP Labs, Jesse was working as manager or technical leader on parallel/vector compilers at Convex and Concurrent Computer Corporation, Respectively, in 1989 and 1986. Jesse Fang got his Ph.D. in Computer Science at University of Nebraska-Lincoln before he did a post-Doctorate at University of Illinois Urbana-Champaign. He was Assistant Professor at Wichita State University at Kansas before moving to industry. Jesse got his B.S. in Math at Fudan University in Shanghai.


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# Toward Terabyte Pattern Mining

## An Architecture-conscious Solution

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## Abstract

We present a strategy for mining frequent itemsets from terabyte-scale data sets on cluster systems. The algorithm embraces the holistic notion of architecture-conscious data mining, taking into account the capabilities of the processor, the memory hierarchy and the available network interconnects. Optimizations have been designed for lowering communication costs using compressed data structures and a succinct encoding. Optimizations for improving cache, memory and I/O utilization using pruning and tiling techniques, and smart data placement strategies are also employed. We leverage the extended memory space and computational resources of a distributed message-passing cluster to design a scalable solution, where each node can extend its meta structures beyond main memory by leveraging 64-bit architecture support. Our solution strategy is presented in the context of FPGrowth, a well-studied and rather efficient frequent pattern mining algorithm. Results demonstrate that the proposed strategy result in near-linear scaleup on up to 48 nodes.

***Categories and Subject Descriptors*** H.2.8 [*Database Management*]: Database Applications - Data Mining

***General Terms*** Algorithms, Performance

***Keywords*** itemset mining, data mining, parallel, out of core


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## 1. Introduction

"Data mining, also popularly referred to as knowledge discovery from data (KDD), is the automated or convenient extraction of patterns representing knowledge implicitly stored or catchable in *large* data sets, data warehouses, the Web, (and) other *massive information repositories or data streams*" [14]. This statement, from a popular textbook, and its variants resound in numerous articles published over the last decade in the field of data mining and knowledge discovery. As a field, one of the emphasis points has been on the development of mining techniques that can scale to truly large data sets (ranging from hundreds of gigabytes to terabytes in size). Applications requiring such techniques abound, ranging from analyzing large transactional data to mining genomic and proteomic data, from analyzing the astronomical data produced by the Sloan Sky Survey to analyzing the data produced from massive simulation runs.

However, mining truly large data is extremely challenging. As implicit evidence, consider the fact that while a large percent of the papers describing data mining techniques often include a statement similar to the one quoted above, a small fraction actually mine large data sets. In many cases, the data set fits in main memory. There are several reasons why mining large data is particularly daunting. First, many data mining algorithms are computationally complex and often scale non-linearly with the size of the data set (even if the data can fit in memory). Second, when the data sets are large, the algorithms become I/O bound. Third, the data sets and the meta data structures employed may exceed disk capacity of a single machine.

A natural cost-effective solution to this problem that several researchers have taken [2, 9, 13, 19, 20, 27] is to parallelize such algorithms on commodity clusters to take advantage of distributed computing power, aggregate memory and disk space, and parallel I/O capabilities. However, to date none of these approaches have been shown to scale

to terabyte-sized data sets. Moreover, as has been recently shown, many of these algorithms are greatly under-utilizing modern hardware[11]. Finally, many of these algorithms rely on multiple database scans and oftentimes transfer subsets of the data around repeatedly.

In this work, we focus on the relatively mature problem domain of frequent itemset mining[1]. Frequent itemset mining is the process of enumerating all subsets of items in a transactional database which occur in at least a minimum number of transactions. It is the precursor phase to association rule mining, first defined by Agrawal and Srikant[3]. Frequent itemset mining also plays an important role in mining correlations [5], causality [24], sequential patterns [4], episodes [17], and emerging patterns [10].

Our solution embraces one of the fastest known sequential algorithms (FPGrowth), and extends it to work in a parallel setting, utilizing all available resources efficiently. In particular, our solution relies on an algorithmic design strategy that is cache-, memory-, disk- and network- conscious, embodying the comprehensive notion of *architecture-conscious data mining*[6, 11]. Our solution is placed in the context of a cache- and I/O-conscious frequent pattern mining algorithm recently developed, which has been shown to be be efficient on large data sets.

A highlight of our parallel solution is that we only scan the data set twice, whereas all existing parallel implementations based on the well-known *Apriori* algorithm [4] require a number of data set scans proportional to the cardinality of the largest frequent itemset. The sequential algorithm targeted in this work makes use of tree structures to efficiently search and prune the space of itemsets. Trees are generally not readily efficient, when local trees have to be exchanged among processors, because of the pointer-based nature of tree structure implementations. We devise a mechanism for efficient serialization and merging of local trees called *strip-marshaling and merging*, to allow each node to make global decisions as to which itemsets are frequent. Our approach minimizes synchronization between nodes, while also reducing the data set size required at each node. Finally, our strategy is able to address situations where the meta data does not fit in core, a key limitation of existing parallel algorithms based on the pattern growth paradigm[9].

Through empirical evaluation, we illustrate the effectiveness of the proposed optimizations. Strip marshaling of the local trees into succinct encoding affords a significant reduction in communication costs, when compared to passing the data set. In addition, local tree pruning reduces the data structure at each node by a factor of up to 14-fold on 48 nodes. Finally, our overall execution times are an order of magnitude faster than existing solutions, such as *CD, DD, IDD* and *HD*.

## 2. Challenges

In this section, we first present challenges associated with itemset mining of large data sets in a parallel setting. The frequent pattern mining problem was first formulated by Agrawal *et al.* [1] for association rule mining. Briefly, the problem description is as follows: Let $I = \{i_1, i_2, \cdots, i_n\}$ be a set of $n$ items, and let $D = \{T_1, T_2, \cdots, T_m\}$ be a set of $m$ transactions, where each transaction $T_i$ is a subset of $I$. An itemset $i \subseteq I$ of size $k$ is known as a $k$-itemset. The *support* of $i$ is $\sum_{j=1}^{m}(1 : i \subseteq T_j)$, or informally speaking, the number of transactions in $D$ that have $i$ as a subset. The frequent pattern mining problem is to find all $i \in D$ with *support* greater than a minimum value, $minsupp$.

In most parallel algorithms, the data set $D$=$D_1 \cup D_2 \cup ... \cup D_n$, $D_i \cap D_j$=$\emptyset$, $i \neq j$, is distributed or partitioned over $n$ machines. Each partition $D_i$ is a set of transactions. An itemset that is globally frequent *must be* locally frequent in at least one $D_i$. Also, an itemset not frequent in any $D_i$ cannot be globally frequent, and an itemset locally frequent in all $D_i$ must be globally frequent. The goal *of the parallel itemset mining problem* is to mine for set of all frequent itemsets in a data set that is distributed over different machines. Several fundamental challenges must be addressed when mining itemsets on such platforms.

### 2.1 Computational Complexity

The complexity of itemset mining primarily arises from the exponential (over the set of items) size of the itemset lattice. In a parallel setting, each machine operates on a small local partition to reduce the time spent in computation. However, since the data set is distributed, global decision making (e.g., computing the support of an itemset) becomes a difficult task. Each machine must spend time communicating the partially mined information with other machines. One needs to devise algorithms that will achieve load balance among machines while minimizing inter-machine communication overheads.

### 2.2 Communication Costs

The time spent in communication can vary significantly depending on the type of information communicated; data, counts, itemsets, or meta-structures. Also, the degree of synchronization required can vary greatly. For example, one of the optimizations to speed up frequent itemset mining algorithms is to eliminate candidates which are infrequent.The method by which candidates are eliminated is called *search space pruning*. Breadth-first algorithms prune infrequent itemsets at each level. Depth-first algorithms eliminate candidates when the data structure is projected. Each projection has an associated context, which is the parent itemset.

When the data is distributed across several machines, candidate elimination and support counting operations require inter-machine communication since a global decision must be reached to determine result sets. There are two fundamen-

tal approaches for reaching a global decision. First, one can *communicate all the needed data, and then compute asynchronously*; An alternate strategy is to *communicate knowledge after every step of computation*. In the former strategy, each machine sends its local portion of the input data set to all the other machines. While this approach minimizes the number of inter-machine communications, it can suffer from high communication overhead when the number of machines and the size of the input data set are large. The communication cost increases with the number of machines due to the broadcast of the large data set. In addition to communication overhead, this approach scales poorly in terms of disk storage space. Each machine requires sufficient disk space to store the aggregated input data set. For extremely large data sets, full data redundancy may not be feasible. Even when it is feasible, the execution cost of exchanging the entire data set may be too high to make it a practical approach.

In the latter strategy, each machine computes local data and a merge operation is performed to obtain global support counts. Such communication is carried out after every level of the mining process. The advantage of this approach is that it scales well with increasing processors, since the global merge operation can be carried out in $O(N)$, where $N$ is the size of the global count array. However, it has the potential to incur a high communication overhead because of the number of communication operations and large message sizes. As the candidate set size increases, this approach might become prohibitively expensive.

Clearly there are trade-offs between these two different approaches. Algorithm designers must compromise between approaches that copy local data globally, and approaches which retrieve information from remote machines as needed. Hybrid approaches may be developed in order to exploit the benefits from both strategies.

### 2.3 I/O Costs

When mining very large data sets, care should also be taken to reduce I/O overheads. Many data structures used in itemset mining algorithms have sizes proportional to the size of the data set. With very large data sets, these structures can potentially exceed the available main memory, resulting in page faults. As a result, the performance of the algorithm may degrade significantly. When large, out-of-core data structures need to be maintained, the degree of this degradation is in part a function of the temporal and spatial locality of the algorithm. The size of meta-structures can be reduced by maintaining less information. Therefore, algorithms should be redesigned to keep the meta-structures from exceeding the main memory by reorganizing the computation or by redesigning the data structures [11].

### 2.4 Load Imbalance

Another issue in parallel data mining is to achieve good computational load balance among the machines in the system. Even if the input data set is evenly distributed among machines or replicated on each machine, the computational load of generating candidates may not be evenly distributed. As the data mining process progresses, the number of candidates handled by a machine may be (significantly) different from that of other machines. One approach to achieve load balanced distribution of computation is to look at the distribution of frequent itemsets in a sub-sampled version of the input data set. A disadvantage of this approach is that it introduces overhead because of the sub-sampling of the input data set and mining of the sub-sampled data set. Another approach is to dynamically redistribute computations for candidate generation and support counting among machines when computation load imbalance exceeds a threshold. This method is likely to achieve better load balance, but it introduces overhead associated with redistributing the required data.

| No. | Transaction | Sorted Transaction with Frequent Items |
|---|---|---|
| 1 | $f, a, c, d, g, i, m, p$ | $a, c, f, m, p$ |
| 2 | $a, b, c, f, l, m, o$ | $a, c, f, b, m$ |
| 3 | $b, f, h, j, o$ | $f, b$ |
| 4 | $b, c, k, s, p$ | $c, b, p$ |
| 5 | $a, f, c, e, l, p, m, n$ | $a, c, f, m, p$ |
| 6 | $a, k$ | $a$ |

**Table 1.** A transaction data set with $minsup = 3$

Parallel itemset mining offers trade-offs among computation, communication, synchronization, memory usage, and also the use of domain-specific information. In the next section, we describe our parallelization approach and its associated optimizations.

## 3. FPGrowth in Serial

*FPGrowth* proposed by Han *et al* [15] is a state-of-the-art algorithm frequent itemset miner. It draws inspiration from Eclat [26] in various aspects. Both algorithms build meta-structures in two database scans. They both traverse of the search space in depth-first manner, and employ a pattern-growth approach. We briefly describe *FPGrowth*, since it is the algorithm upon which we base our parallelization.

The algorithm summarizes the data set in the form of a prefix tree, called an *FPTree*. Each node of the tree stores an item label and a count, where the count represents the number of transactions which contain all the items in the path from the root node to the current node. By ordering items in a transaction based on their frequency in the data set, a high degree of overlap is established, reducing the size of the tree. *FPGrowth* can prune the search space very efficiently and can handle the problem of skewness by projecting the data set during the mining process.

A prefix tree is constructed as follows. The algorithm first scans the data set to produce a list of frequent 1-items. These items are then sorted in frequency descending order. Following this step, the transactions are sorted based on the order from the second step. Then, infrequent 1-items are pruned away. Finally, for each transaction, the algorithm

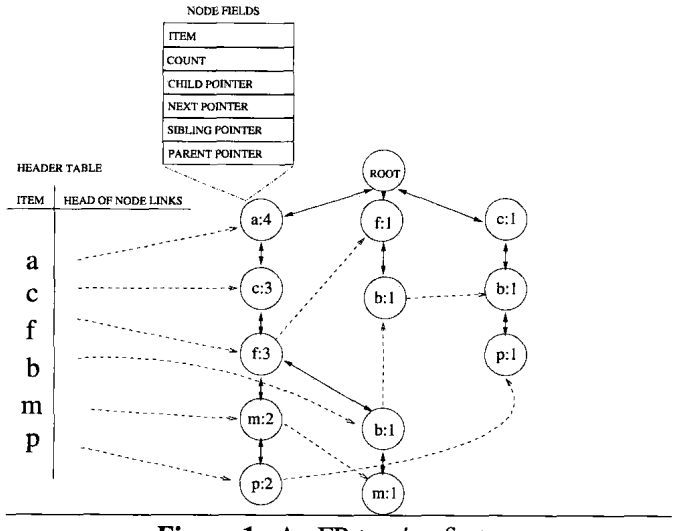


**Figure 1.** An FP-tree/prefix tree

inserts each of its items into a tree, in sequential order, generating new nodes when a node with the appropriate label is not found, and incrementing the count of existing nodes otherwise.

Table 1 shows a sample data set, and Figure 1 shows the corresponding tree. Each node in the tree consists of an *item*, a *count*, a *nodelink ptr* (which points to the next item in the tree with the same item-id), and *child ptrs* (a list of pointers to all its children). Pointers to the first occurrence of each item in the tree are stored in a header table.

The frequency count for an itemset, say $ca$, is computed as follows. First, each occurrence of item $c$ in the tree is determined using the node link pointers. Next, for each occurrence of $c$, the tree is traversed in a bottom up fashion in search of an occurrence of $a$. The count for itemset $ca$ is then the sum of counts for each node $c$ in the tree that has $a$ as an ancestor.

## 4. Parallel Optimizations

In this work, we target a distributed-memory parallel architecture, where each node has one or more local disks and data exchange among the nodes is done through message passing. The input data set is evenly partitioned across the nodes in the system. We first present our optimizations, and then in Section 4.5 we discuss how these optimizations are combined in the parallel implementation.

### 4.1 Minimizing Communication Costs

One of the fundamental challenges in parallel frequent itemset mining is that global knowledge is required to prove an itemset is not frequent. It can be shown that if an itemset is locally frequent or infrequent in every partition, then it is globally frequent or infrequent, respectively. However, in practice, most itemsets lie in between; they are locally frequent in a nonempty proper subset of the partitions and infrequent in the remaining partitions. These itemsets must have their exact support counts from each partition summed for a decision to be made. In Apriori-style algorithms, this is not an additional constraint, because this information is present. Apriori maintains exact counts for each potentially frequent candidate at each level. However, *FPGrowth* discards infrequent itemsets when projecting the data set.

It is too expensive for a node to maintain the count information so that it can be retrieved by another node. This would equate to mining the data set at a support of one. Alternatively, synchronizing at every pass of every projection of each equivalence class is also excessive. Our solution is for each machine to communicate its local *FPTree* to all other machines using a ring broadcast protocol. That is, each node receives an *FPTree* from its left neighbor in a ring organization, merges the received tree with its local *FPTree*, and passes the tree received from its left neighbor to its right neighbor.

Exchanging the *FPTree* structure reduces communication overhead because the tree is typically much smaller than the frequent data set (due to transaction overlap). To further reduce the volume of communication, instead of communicating the original tree, each processor transfers a concise encoding, a process we term *strip marshaling*. The tree is represented as a array of integers. To compute the array (or encoding), the tree is traversed in depth first order, and the label of each tree node is appended to the array in the order it is visited. Then, for each step back up the tree, the negative of the support of that node is also added. We use the negative of the support so that when decoding the array, it can be determined which integers are tree node labels and which integers are support values. Naturally, we again negate the support value upon decoding, so that the original support value is used.

This encoding has two desired effects. First, the encoded tree is significantly smaller than the entire tree, since each tree node can be represented by two integers only. Typically, *FPTree* nodes are 48 bytes, but the encoding requires only 8 bytes, resulting in a 6-fold reduction in size. Second and more importantly, because the encoded representation of the tree is in depth-first order, each node can traverse its local tree and add necessary nodes online. Thus, merging the encoded tree into the existing local tree is efficient, as it only requires one traversal of the each tree. When the tree node exists in the encoding but not in the local tree, we add it to the local tree (with the associated count); otherwise we add the received count (or support) to the existing tree node in the local tree. Because the processing of the encoded tree is efficient, we can effectively overlap communication with processing. Also, transferring these succinct structures dispatches our synchronization requirements. The global knowledge afforded allows each machine to subsequently process all its assigned tasks independently.

For example, Figure 2 illustrates the tree encoding for the tree from our example in Section 2. Note that the labels of

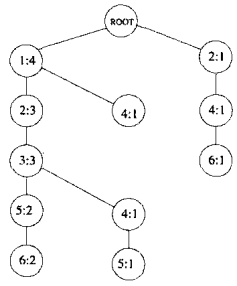


**Figure 2.** *Strip Marshaling* the *FPTree* provides a succinct representation for communication.

the tree nodes are recoded as integers after the first scan of the input data set.

### 4.2 Pruning Redundant Data

Although the prefix tree representation (*FPTree*) for the projected data set is typically quite concise, there is not a guaranteed compression ratio with this data structure. In rare cases, the size of the tree can meet or exceed the size of the input data set. A large data set may not fit on the disk of a single machine. To alleviate this concern, we prune the local prefix tree of unnecessary data. Specifically, each node maintains the portion of the *FPTree* required to mine the itemsets assigned to that node.

Recall that to mine an item $i$ in the *FPTree*, the algorithm traverses every path from any occurrence of $i$ in the tree up to the root of the tree. These upward traversals form the projected data set for that item, which is used to construct a new *FPTree*. Thus, to correctly mine $i$ only the nodes from occurrences of $i$ to the root are required.

Let the items assigned to machine $M$ be $I$. Consider any $i \in I$, and let $n_i$ be a node in the *FPTree* with its label. Suppose a particular path $P$ in the tree of length $k$ is

$$P = (n_1, n_2, ..., n_i, n_i + 1, ..., n_k). \quad (1)$$

To correctly mine item $i$, only the portion of $P$ from $n_1$ to $n_i$ is required for correctness. Therefore, for every path $P$ in the *FPTree*, $M$ may delete all nodes $n_j$ occurring after $n_i$. This is because the deleted items will never be used in any projection made by $M$. In practice, $M$ can start at every leaf in the tree, and delete all nodes from $n_k$ to the first occurrence of any item $i \in I$ assigned to $M$. $M$ simply evaluates this condition on the *strip marshaled* tree as it arrives, removing unnecessary nodes.

As an example, we return to the *FPTree* described in Section 2. Assume we adopt a round-robin assignment function, so machine $M$ is assigned all items $i$ such that

$$i \ \% \ |Cluster| = rank(M). \quad (2)$$

We illustrate the local tree for each of the four machines in Figure 3. A nice property of this scheme is that as we increase the number of machines in the cluster, we increase the amount of pruning available.

### 4.3 Partitioning the Mining Process

We determine the mapping of tasks to machines before any mining occurs. Researchers[9] have shown that intelligent allocation can in this fashion can lead to efficient load balancing with low process idle times, in particular with *FP-Growth*. We leverage such sampling techniques to assign *frequent-one* items to machines after the first parallel scan of the data set.

### 4.4 Memory Hierarchy-conscious Mining

Local tree pruning lowers the required main memory requirements. However, it may still be the case that the size of the tree exceeds main memory. In such cases, mining the tree can incur page faults. To remedy this issue, we incorporate several optimizations to improve the performance. Through detailed studies, we discovered that locality improvements in both the tree building process, and the subsequent mining process lead to improved execution times for large data sets [6].

Designers of OS paging mechanisms work under the assumption that programs will exhibit good locality, and store recently accessed data in main memory accordingly. Therefore, it is imperative that we find any existing temporal locality and restructure computation to exploit it. Further details of the following procedures are available elsewhere [6, 11].

#### 4.4.1 Improving the Tree Building Process

The initial step in *FPGrowth* is to construct a prefix tree. For out-of-core data sets, construction of the first tree results in severe performance degradation. If the first tree does not fit in main memory, the algorithm can spend up to 90% of the execution time building it. The reason is that transactions are in the database in random order, which results in random access to the tree nodes during construction, and excessive page faulting. To solve this problem, we incorporate domain knowledge and the frequency information collected in the first scan to intelligently place the frequent transactions into a partition of blocks. Each block is implemented as a separate file on disk. The hashing algorithm guarantees that each transaction in $\text{block}_i$ sorts before all transactions in $\text{block}_{i+1}$, and the maximum size of a block is no larger than a preset threshold. By blocking the frequent data set, we can build the tree on disk in fixed chunks. A block as well as the portion of the tree being updated by the block will fit in main memory during tree construction, reducing page faults considerably. In short, transactions with the most frequent items are allocated a larger portion of the partition. Further details are available in a prior publication[6].

#### 4.4.2 Improving the Mining Process

Mining the large tree results in significant page faulting because for any two connected nodes, it is unlikely that they

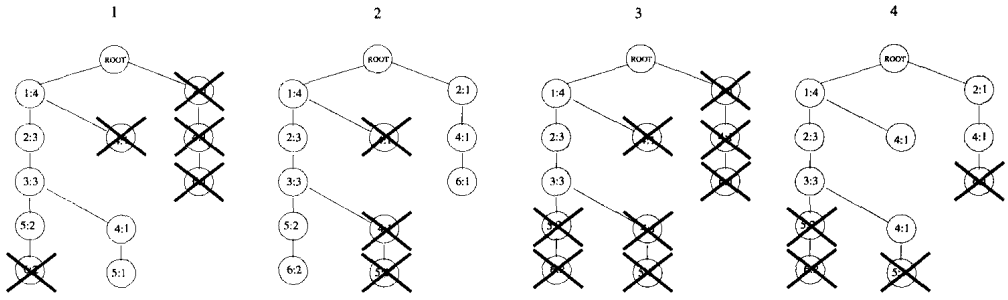


**Figure 3.** Each node stores a partially overlapping subtree of the global tree.

are near each other in memory. We improve spatial locality by reallocating the tree in virtual memory, such that the new tree allocation is in depth-first order. We *malloc*() fixed sized blocks of memory, whose sum is equal to the total size of the tree. Next, we traverse the tree in depth-first order, and (in one pass) copy each node to the next location (in sequential order) in the newly allocated blocks of virtual memory. This simple reallocation strategy provides significant improvements, because *FPGrowth* accesses the prefix tree many times in a bottom up fashion, which is primarily a depth-first order of the tree.

Finally, to improve temporal locality while accessing the tree, we tile paths of the tree. Our approach relies on *page blocking*, and is analogous to our tiling techniques for improving temporal locality in in-core pattern mining algorithms. Since each tree is traversed once for each frequent item at that projection, we can walk a small percentage of the tree paths for each item, before continuing to the next set of paths. This improves the probability that the paths will be in cache.

### 4.5 Putting It All Together: Architecture-conscious Data Mining

We now use the optimizations above to construct our solution. The approach is shown in Algorithm 1, and we label it DFP (Distributed FPGrowth).

The machines are logically structured in a ring. In phase one (lines 1 - 5), each machine scans its local data set to retrieve the counts for each item. Each machine then sends its count array to its right-neighbor in the ring, and receives the counts from its left neighbor. This communication continues *n-1* times until each count array has been witnessed by each machine. The machines then perform a voting procedure to statically assign frequent-one items to particular nodes. The mechanism for voting is designed to minimize load imbalance.

In phase two (lines 6 - 12), each machine builds a prefix tree of its local data set using the global counts derived from phase 1. Then, each machine encodes the tree as an array of integers. These arrays are circulated in a ring manner, as was performed with the count array. Since each machine requires only a subset of the total data to mine its assigned elements, upon receiving the array the local machine incorporates only the contextually pertinent parts of the array into its local tree before passing it to its right-neighbor.

In phase three (lines 13 - 14), each machine independently mines its assigned items. No synchronization between machines is required during the mining process. The results are then aggregated.

**Algorithm 1** DFP

**Input:** Data set $D$=$D_1 \cup ... \cup D_n$, *Global* Support $\sigma$
**Output:** $F$ = Set of frequent itemsets

1: **for** each node $i$=1 to $n$ **do**
2: Scan $D_i$ for item frequencies, $LF_i$
3: **end for**
4: Aggregate $LF_i$, $i$=1..$n$ (using a ring)
5: Assign itemsets to nodes
6: **for** each node $i$=1 to $n$ **do**
7: Scan the $D_i$ to build a *local* Prefix Tree, $T_i$
8: Encode $T_i$ as an array, $S_i$
9: Prune $T_i$ of unneeded data
10: **end for**
11: Distribute $S_i$, $i$=1..$n$ (using a ring)
12: and build a pruned global tree at each node
13: Locally mine the pruned global tree
14: Aggregate the final results (using a ring)

## 5. Experiments

We implement our optimizations in C++ and MPI. The test cluster has 64 machines connected via Infiniband, 48 of which are available to us. Each compute machine has two 64-bit AMD Opteron 250 single core processors, 2 RAID-0 250GB SATA hard drives, 8GB of RAM, and runs the Linux Operating System. We are afforded 100GB (per machine) of the available disk space. For this work, we only use one of the two available processors. All synthetic data sets were created with the IBM Quest generator, with 100,000 distinct items, an average pattern length of 8, and 100,000 patterns. Other settings were defaults. The number of transactions varies depending on the experiment, and will be expressed herein. Our main data set is 1.1 terabytes, distributed over 48 machines (24GB each), called 1TB. The real data sets we