

# ANALYTICAL AND EXPERIMENTAL EVALUATION OF STREAM-BASED JOIN

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Abstract: Continuous queries over data streams have gained popularity as the breadth of possible applications, ranging from network monitoring to online pattern discovery, have increased. Joining of streams is a fundamental issue that must be resolved to enable complex queries over multiple streams. However, as streams can represent potentially infinite data, it is infeasible to have full join evaluations as is the case with traditional databases. Joins in a stream environment are thus evaluated not over entire streams, but on specific windows defined on the streams. In this paper, we present windowed implementations of the traditional nested loops and hash join algorithms. In our work we analytically and experimentally evaluate the performance of these algorithms for different parameters. We find that, in general, a hash join provides better performance. We also investigate invalidation strategies to remove stale data from the window buffers, and propose an optimal strategy that balances processing time versus buffer size.

## 1 INTRODUCTION

The proliferation of the Internet, the Web, and sensor networks have fueled the development of applications that treat data as a continuous stream, rather than as a fixed set. Telephone call records, stock and sports tickers, streaming data from medical instruments, and data feeds from sensors are examples of streaming data. As opposed to the traditional database view where data is fixed (passive) and the queries considered to be active, in these applications data is considered to be the active component, and the queries are long-standing or continuous. Recently, a number of systems have been proposed (Babu and Widom, 2001; Motwani et al., 2003; Babcock et al., 2002; Carney et al., 2002; Chen et al., 2000) to address this paradigm shift from traditional database systems to now meet the needs of query processing over streaming data.

Many of the proposed data stream management systems (DSMSs) (Babu and Widom, 2001; Motwani et al., 2003; Babcock et al., 2002; Chen et al., 2000) are based on relational databases, with suitable modifications to handle streaming data. Typically in a DSMS, the streaming data is given by tuples that follow a fixed schema. Given this perspective, a stream

is similar to an infinitely extended relational table in the sense that the table is never closed and can always be extended in the future. Queries against such streams are composed of stream operators that attempt to preserve as much as possible the semantics of the familiar relational operators. However, the potentially infinite nature of data streams poses difficulties in both the definition of the semantics of such stream operators as well as their implementation. One of the key challenges is therefore to provide stream operators with well-defined semantics that nevertheless do not require infinite storage and resources to compute their results.

There are two basic approaches for providing semantics for stream operators. The first approach is to compute summary information. A data stream is queried to produce a statistical summary of the data seen so far. New data increments the statistical summary and can then be thrown away. The second approach is to compute exact results while at the same time limiting the memory resources required for the computation. This approach adds a time window to the definition of query operators so that only data falling within the time window produces results. When data falls outside the window it can be discarded since by definition it cannot produce any new

results. However, to efficiently answer a query and to provide scalability of user queries a query optimizer must be able to analyze and compare the cost of the different implementations of these *windowed* stream operators. Towards that end, in this paper we provide an analytical and experimental comparison of two implementations of a windowed join operator.

The windowed join operator computes the join between two streams  $\mathcal{A}$  and  $\mathcal{B}$ , with windows  $\text{window}_A$  and  $\text{window}_B$  respectively, using timestamps to limit the possible matches. A tuple from stream  $\mathcal{A}$ ,  $t_A$ , with timestamp  $\text{time}(t_A)$ , may join with an earlier tuple from stream  $\mathcal{B}$ ,  $t_B$ , with timestamp  $\text{time}(t_B)$ , only if  $\text{time}(t_A) - \text{time}(t_B) < \text{window}_B$ . The symmetric statement holds with  $t_A$  and  $t_B$  interchanged. Based on this definition, the window join is well-defined provided the tuples are processed in order of their timestamps. If a tuple's timestamp is given by time-of-arrival at the join input then the total order requirement is fulfilled.

In this paper we examine the performance characteristics of two implementations, namely the windowed nested-loops and the windowed hash, of a windowed join operator. We use an evaluation metric based on a *rate-based* cost model that can be used by the query optimizer to determine the best plan for evaluating a query over streaming data (Viglas and Naughton, 2002). The cost model incorporates the costs for the three fundamental steps that compose each algorithm, namely scan, invalidation and insertion. For a tuple  $t_A$  arriving on stream  $\mathcal{A}$ , scan is the cost of scanning the stream  $\mathcal{B}$  buffer for a match. Insertion is the cost of inserting the tuple  $t_A$  into stream  $\mathcal{A}$ 's window buffer, and invalidation is the cost of removing the expired tuples from the window buffers. A tuple is considered to be expired if its time-stamp falls outside the defined window for its stream. For each step we posit an average time per tuple cost and combine this cost with the rates of the inputs to derive a formula for the total processing cost. In this paper, we derive the cost formulas for each of the algorithms and compare them to the experimental measurements.

However, the cost model considers only the time cost of the join algorithms, and not the memory resources utilized by each of the algorithms. For scalability of stream operators, where resource contention can be a primary issue, such an analysis is essential. In our work we consider four invalidation strategies, namely invalidation of tuples at scan time, invalidation of all buffers at once, and the invalidation of only the buffers that are actually probed. For each of these invalidation strategies we present an analytical model to evaluate both their processing cost as well their effect on memory utilization. We show experimentally that the best choice is likely to be to invalidate a bucket only when it is probed or scanned. The invalidation requirement of the join operators as discussed

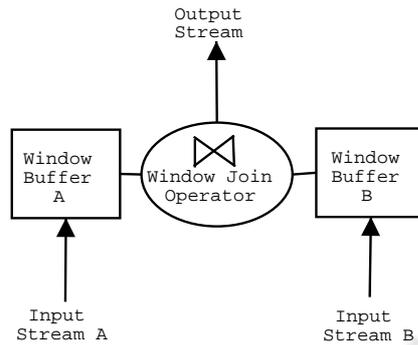


Figure 1: The Window Join Operator.

here can be easily extended to other windowed stream operators.

**Roadmap.** The rest of the paper is organized as follows. Section 2 presents an overview of the two windowed join algorithms. In Sections 3 and 4 we present our analysis and experimental results. We conclude in Section 6.

## 2 WINDOWED JOIN ALGORITHMS

In this section, we present windowed versions of two widely used join algorithms, namely the nested loops and the hash join algorithms (Ullman and Widom, 1997). In the windowed version, timestamps are assigned to tuples as they arrive for processing on either of the windowed join's two inputs. Both windowed algorithms, WNL (windowed nested loops) and WHJ (windowed hash join), share a common structure as shown in Figure 1. Here, there are two input streams. Each input stream has a buffer that holds (at least) one window's worth of tuples. We term the stream on which a tuple arrives the arrival stream, and we call the other stream the opposite stream. Whenever a tuple arrives on one stream, the opposite stream's window buffer is probed to check for matching join attributes. The tuple is then placed in the arrival stream's window buffer. Invalidation of stale tuples in a window buffer can be performed at probe time, when a tuple arrives on the opposite stream, or at insertion time, when a tuple arrives on the arrival stream.

**Windowed Nested Loops Join.** In the WNL algorithm, the window buffer of each stream is given by a circular buffer structure ordered by arrival time stamp. When a tuple  $t_A$  arrives on one of the streams, say stream  $\mathcal{A}$ , the tuples in the opposite stream's (stream  $\mathcal{B}$ 's) window buffer ( $\mathcal{B}$ ) are first checked for expired

tuples. The remaining tuples in the window buffer  $B$  are then scanned to match, based on the join attribute, with the arriving tuple. The newly arrived tuple  $t_A$  is inserted at the head of arrival stream's (stream  $A$ ) window buffer ( $A$ ). Lastly, the expired tuples at the tail of the window buffer  $A$  are removed. This last step is optional from the point of view of the semantics of the window join. That is, failure to remove these expired tuples will not produce erroneous results since they will also be expired when a new tuple arrives to be processed on the opposite stream (stream  $B$ ). Note that this property is solely due to the assumed correct arrival ordering property of tuple timestamps. However, failure to expire these tuples will cost in memory resources, which could be significant depending on the relative arrival rates of the two streams. Figure 2 outlines the windowed nested loops join algorithm.

```

WNL (Stream A, Stream B) {
  event: (tuple arrives on stream A) do {
    while (bottom tuple in buffer B expired) do
      remove bottom tuple from buffer B;
    for each (tuple in buffer B) do
      if match then form join tuple and output;
    insert (tuple) on head of buffer A;
    //next step is optional
    while (tail tuple in buffer A expired)
      remove tail tuple from buffer A;
  }
}

```

Figure 2: Windowed Nested Join Algorithm.

**Windowed Hash Join.** For the Windowed Hash join, the window buffer of each stream is divided into hash buckets based on the join attributes. When a tuple  $t_A$  arrives on stream  $A$ , it is hashed to the corresponding bucket of the opposite stream's (stream  $B$ ) window buffer. Expired tuples in this bucket are removed, and the bucket is then scanned for matches. The arriving tuple  $t_A$  is hashed into the correct hash bucket of the arrival stream's window buffer  $A$  and (again optionally) the bucket is scanned for expired tuples. The hash buckets are individually arranged as circular buffers in order of time stamp to facilitate checking for expired tuples. Figure 3 outlines the windowed hash join algorithm.

**Invalidation Strategies.** Both join algorithms discussed in this paper must **remove** expired tuples from the buffer about to be scanned *before* the scan phase to ensure that the presence of stale tuples does not produce erroneous results. This is the first **remove** step in the algorithms given in Figures 2 and 3. In

```

WHJ (Stream A, Stream B) {
event: (tuple arrives on stream A) do {
  compute hash(tuple.joinAttributes)
  retrieve handle to corres. hashbucket B;
  //next steps use the circular buffer structure of
  // each hash bucket
  while (tail tuple in hash bucket B expired) do
    remove tail tuple from hash bucket B;
  for each (tuple in hashbucket B) do
    if match then form join tuple and output;
  retrieve handle to corres. hashbucket A
  insert (tuple) into hashbucket A
  //next step is optional
  while (tail tuple in hashbucket A expired)
    remove tail tuple from hashbucket A;
}
}

```

Figure 3: Windowed Hash Join Algorithm.

addition to this required remove step, additional remove steps may be employed to delete expired tuples as soon as possible in order to decrease buffer sizes. For example, in the case of the windowed hash join (nested loops can be considered a windowed hash join with only one hash bucket), we can check and remove expired tuples in the insertion buffer prior to the insertion phase. This is indicated by the second **remove** step in the algorithms given in Figure 2 and 3. Additionally, each **remove** step in the windowed hash join algorithm may also scan *all* other buckets to remove stale data before it can accumulate. Based on our implementation using circular buffers, stale tuples can only exist at the bottom of the circular buffer. Thus, the cost of invalidation of a hash bucket is the product of the tuple invalidation cost and the number of stale tuples in the buffer. The added cost of scanning all the buckets is the cost of scanning at least the bottom tuple in each bucket.

### 3 ANALYTIC COST MODEL

In this section we present a cost model, based on the average cost metric introduced by Viglas et al. (Viglas and Naughton, 2002), to evaluate the total processing costs of the two join algorithms described in Section 2. While Viglas et al. (Viglas and Naughton, 2002) focus on the output rate of a stream operator, an important quantity for a query optimizer to calculate in order to guarantee a certain result rate, we focus on the scalability of the operators. Towards that end we analyze the average cost per unit time of the join op-

erator. We also look at the effect of the invalidation strategies on the use of memory resources.

### 3.1 Total Processing Cost

In general, the average cost per unit time of the join operator is given by the average cost of processing one tuple on one input multiplied by the input rate. For each operator the *half-cost*, that is, the theoretical cost to process one of the input streams, is computed first. Then the total cost, the cost to process both input streams, given by the sum of the two half-costs is calculated. We assume that the operators are symmetric in their inputs to simplify the cost formulas. For the windowed nested loops join this total cost  $\text{Cost}(\text{WNL})_{total}$ , is given as:

$$\mathcal{C}(\text{WNL})_{total} = 2 * \text{Cost}(\text{WNL})_{half}$$

where  $\text{Cost}(\text{WNL})_{half} = \lambda_A(\mathcal{C}_t)$ . Here,  $\lambda_A$  is the rate of arrival of the tuples on stream  $\mathcal{A}$ ; and  $\mathcal{C}_t$  is the cost to handle one tuple and is given as:

$$\mathcal{C}_t = \frac{\lambda_B}{\lambda_A} \mathcal{C}_{invalidate} + T_B \lambda_B \mathcal{C}_{scan} + \mathcal{C}_{insert}$$

Here  $\lambda_B$  is the rate of arrival of tuples on stream  $\mathcal{B}$ ,  $\mathcal{C}_{invalidate}$  is the cost of invalidating tuples in the window buffer  $B$  of the stream  $\mathcal{B}$ . Recall that invalidation is the garbage collection of the expired tuples from the buffers of the input streams. A tuple is considered to be expired if it's time-stamp falls outside the defined window for its stream. The term  $T_B$  is the size in seconds of the window on the stream  $\mathcal{B}$  input,  $\mathcal{C}_{scan}$  the cost of scanning the tuples in the window buffer  $B$  for a match, and  $\mathcal{C}_{insert}$  is the cost of inserting a tuple into the window buffer  $A$  of the stream  $\mathcal{A}$ . The factor  $\frac{\lambda_B}{\lambda_A}$  gives the average number of buffer tuples that need to be invalidated upon arrival of a tuple on stream  $\mathcal{A}$ . Thus, under the symmetry assumption (in particular that the insertion, invalidation, and scan costs are the same on both inputs), the total cost of computing a join for tuples arriving on the two streams  $\mathcal{A}$  and  $\mathcal{B}$  is as given in Equation 1.

$$\mathcal{C}(\text{WNL})_{total} = (\lambda_A + \lambda_B)(\mathcal{C}_{invalidate} + \mathcal{C}_{insert}) + \lambda_A \lambda_B (T_A + T_B) \mathcal{C}_{scan} \quad (1)$$

Similarly, the total cost of evaluating the join of two streams  $\mathcal{A}$  and  $\mathcal{B}$  using a windowed hash join algorithm is given as the sum of its two half-costs. For a windowed hash join, the half cost,  $\mathcal{C}(\text{WHJ})_{half}$  is given as:

$$\mathcal{C}(\text{WHJ})_{half} = \lambda_A \left( \frac{\lambda_B}{\lambda_A} \mathcal{C}_{invalidate} + \frac{T_B \lambda_B}{N_B} \mathcal{C}_{scan} + \mathcal{C}_{insert} \right)$$

where  $N_B$  is the number of hash buckets on stream  $\mathcal{B}$ 's side. The total cost for a windowed hash join is given as:

$$\mathcal{C}(\text{WHJ})_{total} = (\lambda_A + \lambda_B)(\mathcal{C}_{invalidate} + \mathcal{C}_{insert}) + \frac{\lambda_A \lambda_B}{N_B} (T_A + T_B) \mathcal{C}_{scan} \quad (2)$$

Equation 1 and 2 show that both the algorithms, windowed nested loops (WNL) and the windowed hash join (WHJ), have the same overall functional dependence on the input rates. In particular, holding one of the input rates fixed, the average cost per unit time depends linearly on the input rate of the second stream. This similarity is not unexpected when we consider that the hash join algorithm with only one bucket is nearly the same as the nested loops algorithm. The most significant difference between the two algorithms is that the hash join algorithm needs to scan only a fraction of the buffered tuples residing in one bucket, and therefore, should have superior performance when the number of buckets is large, whereas the nested loops algorithm needs to scan the entire buffer.

### 3.2 Invalidation Costs

A key aspect of the windowed join operator, and for that matter any windowed operator, is the invalidation of the tuples that fall outside the window. Eventually, the stale data that falls outside the window must be removed in order to preserve system resources and to ensure correct results. In the steady state, the rate of tuples falling outside the window should *on average* be equal to the rate of new tuples entering the system. Therefore, the invalidation strategies for windowed algorithms differ only in *when* they invalidate and not in the *rate* at which they invalidate. Approaches for invalidating stale tuples range from greedy to lazy strategies. Greedy strategies attempt to remove stale tuples as soon as possible, whereas lazy strategies delay removal until an appropriate time.

In the case of the windowed hash join algorithm invalidation occurs at the arrival time of a tuple on an input. The greedy approach is to invalidate every bucket at this time, while the lazy approach is to invalidate only the bucket about to be probed. The greedy approach ensures optimal memory usage since no stale tuples are allowed to accumulate between arrivals. The lazy approach allows stale tuples to build up in a bucket until that bucket is probed. In general, the average number of tuples that build up in a bucket is the product of the time interval between invalidations and the rate that tuples enter that bucket. If invalidation occurs only at probe time, then the number of stale tuples that build up in buffer  $B$  is  $\lambda_B / \lambda_A$  as the time between probes is the time between the

arrivals on stream  $\mathcal{A}$ ,  $N_B/\lambda_A$ , and the rate that tuples enter the bucket  $\lambda_B/N_B$ . Here  $N_B$  is the number of hash buckets for stream  $\mathcal{B}$ . Thus, significant accumulation of stale tuples occurs only if the rate of the probe stream is small compared to the rate of the arrival stream. An intermediate strategy is to invalidate a bucket at both probe time and at insertion time. Since the rate of either insertion or probe is the sum of the individual rates, the average number of stale tuples that accumulate between invalidations is  $\lambda_B/(\lambda_A + \lambda_B)$ , implying that large buildups of stale tuples should not occur even if the rates of the streams differ considerably.

The time cost of invalidation itself depends on the algorithm. For our implementation of the windowed hash join, the circular buffer structure of the hash bucket results in efficient invalidation as stale tuples can accumulate only at the bottom of the buffer. Thus, the total number of comparisons needed is  $1 + N_{stale}$  as at least one comparison is needed with the first non-stale tuple. The term  $N_{stale}$  denotes the number of stale tuples. The higher time cost of the optimal greedy invalidation strategy is the cost of performing at least one comparison with a tuple in every bucket. The trade-off between greedy and lazy invalidation is thus one of space versus time.

## 4 EXPERIMENTAL EVALUATION

In this section, we present our experimental evaluation of the two join algorithms, windowed nested loops (WNL) join and the windowed hash (WHJ) join.

### 4.1 Experimental Setup and Methodology

The windowed nested loops join and hash join algorithms were implemented in C++ and evaluated on Dell 2.0 GHz Pentium 4 workstation with 512MB of memory. A batch of tuples was prepared and processed *en mass* and the total processing time measured. The size of a batch is determined directly to simulate the desired input rate. All tests were performed for a batch of 60 seconds worth of tuples and a time window of 30 seconds for both inputs. Only the last 30 seconds worth of tuples were timed in order to allow the buffers to reach steady-state conditions. For the comparison measurements, the selectivity of the join was set to 0.01 and the number of hash buckets set to a corresponding value of 100. In addition to the total processing cost, the effect of tuning the hash bucket algorithm to match the selectivity to the number of hash buckets was measured. Finally, the

effectiveness of invalidation strategies with respect to memory and processing time were also measured.

## 4.2 Performance Measurements

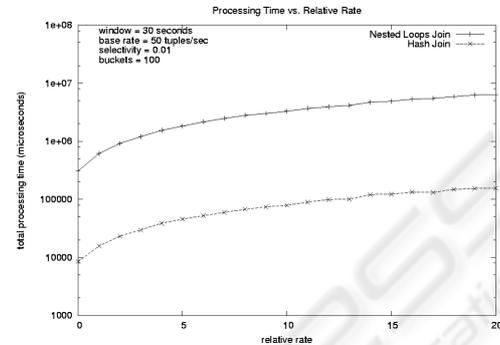


Figure 4: Performance of the Windowed Nested Loop and Windowed Hash Join with Respect to the Relative Rate of the Input Streams.

Figure 4 shows the performance difference between WNL and WHJ for 100 buckets. The two order of magnitude difference indicates that the cost to scan buffers for matches is the dominating cost. The cost formulas (Equations 1 and 2) show that this cost is inversely proportional to the number of buckets (100 in this case), and the measurements bear this out. Figure 5 shows that the total processing time is inversely proportional to number of buckets (everything else held constant). Note that when the number of buckets is greater than the number of distinct values of the join attributes, there is no longer any advantage to increasing the number of buckets. The graph shows the flattening occurs at 100 for selectivity 0.01 (implying 100 distinct join values) as expected. Note that this flattening out effect is not captured by the cost formula given in Equation 2.

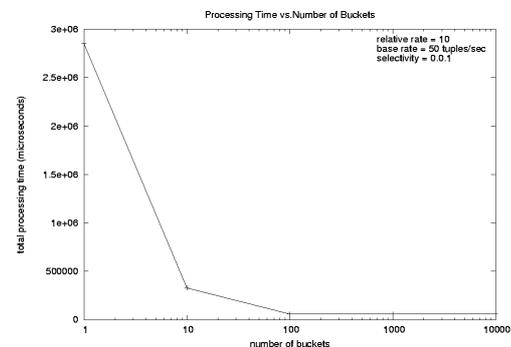


Figure 5: Performance of the Windowed Hash Join with Respect to the Number of Hash Buckets.

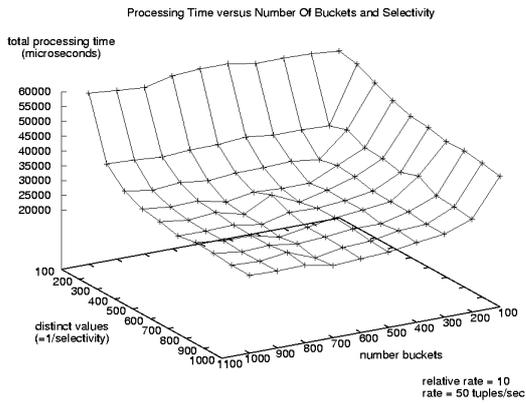


Figure 6: Performance of the Windowed Hash Join with Respect to the Join Selectivity and the Number of Hash Buckets.

Figure 6 depicts total processing time of the windowed hash join for different values of selectivity and number of hash buckets, and also shows that flattening occurs approximately when the number of buckets equals the number of distinct hash values.

The effect of using extra invalidation in the hash join algorithm was also measured. We measured the processing cost and the memory utilization of four invalidation strategies. The four strategies are described as follows. *Probe time invalidation* is the minimal invalidation required for the algorithm's correctness, and consists of removing stale tuples from the probed hash bucket only whenever a tuple arrives on any input. *Probe and insert time invalidation* removes stale tuples from the probed and the insertion hash buckets, in addition to the minimal invalidation of the probe time invalidation strategy. The next two invalidation strategies, called *probe all buckets* and *optimal*, remove tuples from all hash buckets on the probe side only and all hash buckets on both the probe and insertion sides respectively. Figure 7 shows the total processing time of the four strategies. We see that the probe and insert invalidation strategy does as well as minimal invalidation strategy, i.e., the probe time invalidation strategy. Both these strategies substantially outperform the two greedy strategies that invalidate all buckets.

Finally, Figure 8 shows the memory costs of the four invalidation strategies. In these experiments, the stream on the probed side had a relative rate 100 times the rate of the opposite arrival side stream, and the average occupancy of the entire set of all the hash buckets on the probed side was measured every 2 seconds for 60 seconds. We note that the steady state conditions were reached after 30 seconds, which is expected given a window size of 30 seconds. Ad-

ditionally, we note that, with the exception of *probe time invalidation*, all the other strategies had approximately the same average memory usage. In particular, the *probe and insert time invalidation* performed as well as *optimal invalidation* strategy. Given the superior processing time performance in Figure 7 and its memory consumption, we conclude that the *probe and insert time invalidation* provides the best choice both for performance and memory consumption under steady state conditions.

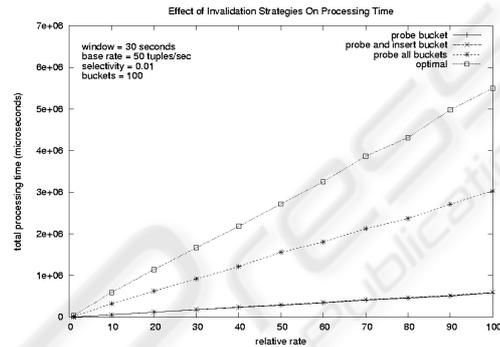


Figure 7: Processing Costs Of Four Invalidation Strategies.

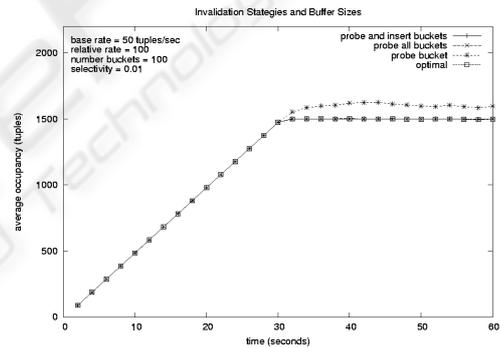


Figure 8: Average Memory Occupancy of Hash Table Buffers For Four Invalidation Strategies.

## 5 RELATED WORK

Recent years have seen a flurry of activity in streams and continuous queries. We briefly describe three *pure* stream databases that are being implemented, the Aurora system(Carney et al., 2002), the STREAM system(Arasu et al., 2002) and the Gigascope system(Cranor et al., 2002). The Aurora project(Carney et al., 2002) proposes an architecture for a stream database system based on a data flow architecture. The user of the Aurora system designs a query by manipulating a diagram of the query in a GUI. The query is built from boxes that represent individual

operations on a stream. The boxes are analogous to the relational operators in a relational system and the diagram of boxes analogous to a relational query plan. However, there is no higher level declarative query language analogous to SQL to compose these queries. The operators themselves perform filtering operations (which require no buffering) and windowing operations (which require buffering). The notion of a window is extended to include slides, latches, and tumbles. Slide moves a window continuously downstream, tumble moves a window discontinuously so that consecutive windows share no tuples, and latch moves a window like a tumble but also keeps state information between positions of the window. The analysis presented in this paper can be easily extended to slide, tumble and latch windows.

STREAM is a design for a stream database system currently being constructed at Stanford University (Arasu et al., 2002). The STREAM system is designed to be a conservative extension of relational database concepts. They provide an SQL-like query language, CQL, with extensions for windowing and other stream primitive operators, a semantics based on mapping CQL to relational tables, and an implementation architecture based on a dataflow paradigm. A CQL query is parsed into a query plan consisting of a tree of stream operators. Synopses are general data structures associated with an operator that maintain any state needed by an operator to compute correct results. The query plan can then be optimized both statically at compile time and dynamically at run time. Most of the reported optimization strategies attempt to minimize total memory requirements. Our analysis goes along the lines of the STREAM (Arasu et al., 2002) work and analyzes the memory requirements for the different invalidation strategies a key factor when dealing with windowed operators.

Gigascope is a network performance monitoring tool that incorporates stream database ideas in its implementation (Cranor et al., 2002). The kinds of complex queries that users typically wish to make against network data streams are difficult or impossible to express in SQL. Ordering tuples from a data stream by time stamp is not sufficient since, for example, session information may present a different order than the time of arrival. Therefore, the notion of order in a stream needs to be extended. The implications of this extension for stream database operators are numerous. The most important is that buffering requirements are increased since the determination of when to discard stale data is no longer directly tied to time. For example, in a windowed join operator, if one stream stalls the other may need to have unbounded buffers while waiting for new data to arrive on the stalled stream. Extending the definition of order may help optimization, since there is more room to play with in the implementation of an operator: dif-

ferent operator implementations may produce different ordering properties in the output. Gigascope implements some of these new ordering definitions into its operators. The Minimum Memory join algorithm presented in (Cranor et al., 2002) is similar to our windowed nested loops join (WNL) algorithm presented in Section 2, and as such our analysis of the invalidation strategies can be applied.

Viglas et al. (Viglas and Naughton, 2002) in their work have presented brief discussions on non-blocking, windowed versions of nested loops join and symmetric hash join algorithms for the implementation of the windowed join operator. Although our approach is based on the cost model proposed by Viglas et al. (Viglas and Naughton, 2002), our work differs in three ways. First, our version of the windowed nested loops join differs from the one presented in (Viglas and Naughton, 2002) in its invalidation process. In particular, the Viglas nested loops join (Viglas and Naughton, 2002) does not invalidate the opposite window on arrival of a tuple and therefore can output join tuples that are not strictly within the window. Second, while Viglas et al. (Viglas and Naughton, 2002) provide some discussion of a hash join, the algorithm itself is not presented. We explicitly present a windowed hash join in this paper. Third, we directly compare our results to those reported in (Viglas and Naughton, 2002). A significant difference between the two results is the quadratic dependence on the input rate as discussed in (Viglas and Naughton, 2002) for the windowed hash join. We did not observe the same quadratic dependence. Rather, our implementation provides a linear dependence to the input rate (in the half-cost analysis) for our implementation of windowed hash join. We further provide an analysis of both the performance and the memory requirements of the different invalidation strategies.

## 6 CONCLUSIONS AND FUTURE WORK

In this paper we have presented analytical and experimental evaluation of two implementations of a windowed join operator. The results clearly show that the windowed hash join is superior to windowed nested loops join based on an average cost per unit time. Both analysis and measurement yield this result. We also compared our results to those reported in (Viglas and Naughton, 2002). A significant difference between the two results was the quadratic dependence on the input rate as discussed in (Viglas and Naughton, 2002) for the windowed hash join. We did not observe the same quadratic dependence. Rather our implementation uses circular buffer based hash-buckets to provide linear performance. It should be

noted however that the circular buffer approach is applicable only when the tuples are ordered by arrival time stamp. We also examined the cost of lazy and greedy invalidation strategies for both windowed join algorithms and examined both the processing cost as well as the memory requirements for both invalidation schemes. It should be noted that the analysis of the invalidation strategies can be easily extended to apply for any windowed operator.

In terms of continuing work, while in this paper we have presented implementations of the windowed join operator, we have found that this join operator is not associative and it relies on strict order of arrival time alone. In general we have found that precisely-defined stream operator algebra that can be used to express well-defined stream queries – much in the same way that the relational algebra defines relational queries – is not found in the stream database literature. Each system implements their own set of operators but does not provide a way to describe the composition of operators. The general problem of the composition of stream operators is difficult. One would like to have operators that would take stream inputs with well-defined properties and produce stream outputs with well-defined properties in such a manner that the resulting composition algebra is simple. That these goals may conflict can be seen from a consideration of the window join operator. If the output of the window join operator is ordered by the time stamp of one of its composite tuples, then neither choice will lead to an associative window join operator. Perhaps the closest well-defined stream semantics and query language are those proposed by the Stanford STREAM project (Arasu et al., 2002). These semantics depend upon mapping stream queries onto the standard relational semantics. However, no stream operator definitions are given that may implement the proposed stream semantics (Arasu et al., 2002). We are now working on defining a pure stream algebra that addresses these problems and provides well-defined stream semantics.

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