Fault Tolerance Approach For Storing OLAP Records on Standard Disks

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Fault tolerance approach for OLAP

Abstract

OLAP is a widely used approach that allows quick answers to analytical queries that may lie in differents dimension than the traditional data view. Since OLAP systems deal with large sets of data, many of them are set up either in parallel or in a distributed manner (such as a grid of computers). Parallel and distributed machines tend to use standard disks to store their data and some may often fail. This paper will aim to address data fault tolerance in such systems, with a model integration with one of the discussed fault tolerance schemes.

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Introduction

OLAP today is being used by many business enterprises, in order for them to be able to make decisions based on the data analysis. Data in OLAP contains many dimensions as each field in a relation represents such a dimension. These dimensions from large data structures that are used by the OLAP system in their analytical queries, and today are being computed, partitioned and stored on parallel machines. Many parallel machines, such as shared-nothing clusters, tend to have personal computing architectures with personal computing hardware integrated in their units. The use of such machines allows, with a larger probability, for hardware failures. Therefore focus in the field of fault tolerance should be taken when designing such systems.

There has been many discussions in this area, with many different designs and techniques on making parallel systems fault tolerant [1]. These methods can be directly applied in a parallel OLAP model, to gain the desired fault tolerance. This paper aims to discuss fault tolerance issues of the data stored by OLAP systems, in a quest to develop a parallel model to efficiently survive multiple failures in various parallel machines.

Notations

The notations used here are similar to the ones found in [2]. In our further discussion we will be analyzing a *p+1-node* (where we have p-query nodes and a management node (described in the design bellow)) shared nothing cluster, that will allow for a maximum of *k* node failures (being k-fault tolerant). When looking at a failed system, $p' < p$ will be used to refer to the remaining nodes and *f* will be used to refer to the failed nodes.

Failures in a Parallel System

There are different models associated with certain failures of parallel systems, and help determine the behavior of the system after the fault. Fault tolerance techniques would assume a certain model in order to explain the types of faults it can handle [1]. The general faults are to be described in this section with an emphasis on fail-stop faults, the type to be tolerated by our proposed system.

Byzantine fault model represents the most complicated type of fault to handle. In this model failed nodes are still alive in the system, interacting with the rest of it, as if not faulty. These nodes tend to give incorrect output (thus the fault) and requires complicated techniques in order to determine which nodes has actually failed. This model can represent random system failures, more importantly malicious hacker attacks and random memory corruption [1]. It is known that no guarantees can be made when m or more failures are experienced in a system with 3m+1 nodes [3].

The main model that we will aim to tolerate using our approach would be **Fail-stop** faults. As the name implies, this model states that when a failure is experienced by a node, it ceases to produce output and stops interacting with the rest of the system [1]. Furthermore, the other nodes should be able to identify the failed node(s). This model mainly represents failures suchas a node crash.

A third model can also be used in classifying faults, and is known as **Fail-stutter** faults. This model is not as general as the Byzantine model; However, is an extension to the Fail-stop model. It includes all the provisions of the fail-stop model, but also allows for weak performance faults. Such a fault is one where a component unexpectedly provides low performance within the parallel system, however continues to function properly with correct output. This model may be important in parallel systems especially since the speed of the system is related to the speed of the slowest component. This model allows for faults such as poor latency performance of a network switch, or high traffic loads in a sub section of the network. This model is still not commonly used in the community despite its advantages [1].

In general, using any fault model, there are certain requirements that need to be fulfilled in order to fulfill fault tolerance. They are that failures can be detected, information needed to continue the processing is available and the processing procedure can be restarted [4].

Fault tolerance

Many parallel computing machines depend on centralized components to function properly [1]. Management nodes tend to handle job scheduling and node monitoring, storage nodes provide access to disk storage and compute nodes tend to perform the computations. Clusters also have head nodes which allow users to interact with the parallel machine without slowing down the other nodes. In a parallel machine designed for OLAP many of these components are not essential. The diagram in Figure 1 shows a design for a parallel shared nothing cluster that may be used to implement OLAP. The management node is responsible for receiving the queries that are to be processed. This node then sends the query to all query nodes. The query nodes answer the query based on the data stored at that node. The results are then sent to the management node to return to the sender of the query. This design needs to be complemented with a strategy of dividing the data amongst the nodes. The data should be partitioned such that queries may be answered as fast as possible on the parallel machine, meaning that each node should have the same response time on average for a given query. A method of doing so is partitioning the data the records in the different OLAP views using Hilbert curves. This method is proven to perform well in certain implementations. For our discussion of fault tolerance, it is sufficient to show a fault tolerant strategy for an arbitrary view of an OLAP table, with its records partitioned across the parallel machine. Also the design shown in the figure above would be used as the basic system design, to be used to discuss the different fault tolerant strategies.

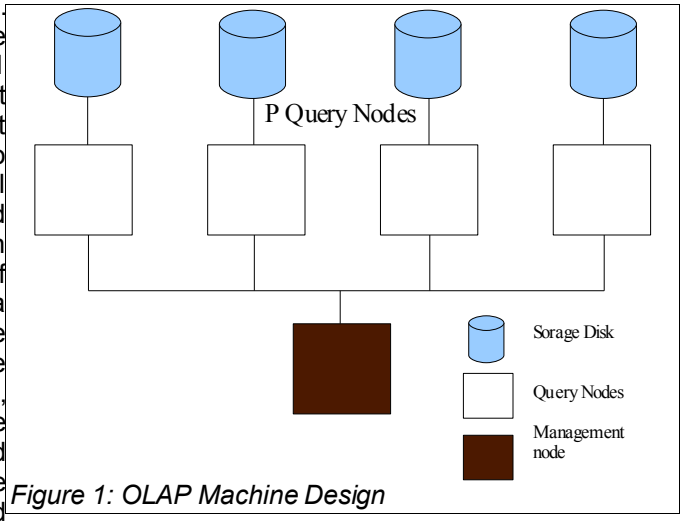


Figure 1: OLAP Machine Design

Replication

Fault tolerance in a parallel machine may be done by means of replicating fault prone components. In the field of fault tolerance such replication can take one of two forms [1].

The first being active replication [1], where nodes are cloned to form backup nodes. The backup nodes are running along side the standard nodes, receiving all input sent to them, thus always being up to date. When an unexpected behavior by the standard nodes is observed, the backup nodes promote themselves to becoming the standard nodes and take over the responsibilities. This change would require negligible time since the nodes are in an identical state. An extension to this approach that is able to handle byzantine faults, requires multiple backup nodes, running in parallel, with a consensus approach. All nodes would compute the output for a given input and a byzantine algorithm would be used to vote on which is the correct output. Nodes failing multiple times would be deemed faulty. The standard approach does not only handle a single fault in each of the nodes, it also would be quite expensive for many systems. The systems would have to have twice as many nodes, as they would have originally and not be able to use these machines independently. The extended approach leads to even more redundant machines. In certain environments where errors cannot be tolerated the extended approach aims to solve the byzantine generals problem.

Along side active replication, is another approach known as passive replication [1]. In such an approach “cold spares” are used to employ all the software installed on the primary nodes. The “cold spares” should be kept up to date via checkpoints in the system in order to not incur any interruption of service. Using a monitoring approach, a faulty node can be detected and replaced with its cold spare. In a finer approach fault prone node components can be replicated within a node, and switched to when that part is considered faulty. In both cases, the systems administrator would be notified about the fault, to either debug the original system, or replace it. Both these replication approaches would not be adequate for OLAP, since they do not tolerate many faults (especially subsequent ones in the same component) and may result in loss of data with an unknown probability.

Redundancy & Erasure Codes

Coded redundancy can be used to design a more OLAP oriented fault tolerant scheme. In coded redundancy the

data is encoded to form the backups. To be able to recover data after k out of p nodes have failed, then the amount of information available in the remaining k-p nodes must be equal to the original data [2]. One can see that this requires storing multiple (redundant) copies of the data, this increases the amount of data needed to be stored on each node. In general, using coded redundancy a moderate net storage cost of 2.5 times will allow for a failure rate of 33% [2].

Using erasure codes, an optimal solution appears for our OLAP problem. Reed-Solomon codes are an example of erasure codes that allow for a data fault tolerant machine. Many applications such as compact disc players use such codes to be able to correct data that has been disturbed due to noise in the channel. This coding scheme, published in 1960 [5], uses finite field geometry to code and decode data. Using such codes, data can be divided into an arbitrary number of pieces m, and can be set to withstand k faults. Meaning that only m-k units of the backups are needed in order to restore the data. To apply this to our OLAP design, each query node would use RS codes, to backup its partition of the OLAP records. The backups would consist of p-1 units, to be distributed across the p processor machine, and would be computed to tolerate k faults. In such a scheme, when any k nodes fail, the data can be decoded from the remaining p' (p' = p-k) nodes, since the computed backups would allow such a recovery.

The way these codes work, is that if we require p-1 chunks of data to tolerate k faults, then the original data would be divided into (p-1) – k units (referred to as n in [6]), and k checksums (referred to as m in [6]). Thus having n+m chunks in total (equal to p-1) to be distributed for backup purposes. These checksums allow for the fault tolerant properties of these codes, as they can be used to recompute the original data, when enough surrounding data is present. This condition is satisfied when and n or more chunks (≥p-1-k) are available.

Computation of RS codes requires the implementation of certain mathematical functions. Many of the functions used in these computations are arithmetic functions in the Galois Field. A mathematically optimized implementation of Galois Field arithmetic (with RS examples), is available under the GNU Lesser General Public License on the web [6]. Also included is an excellent tutorial on the coding theory needed to compute Reed Solomon codes [7]. The GF library, found in [6] allows for GF arithmetic to the fields $GF(2^8)$ and $GF(2^{16})$. Where 8 and 16 represent the length of the blocks (words) to be coded. This library computes tables (described bellow) to aid in optimizing the coding. The data structures created in the $GF(2^8)$ field, are smaller than the ones formed for the larger field. However, in the smaller field only 255 chunks are allowed including the checksum chunks (i.e. The number of partitions x + the number of checksums y = p-1 in our OLAP system ≤ 255). The $GF(2^{16})$ field allows up to 65536 chunks. In a large scale distributed OLAP environment the need for the larger field may be explainable; However, in most scenarios where less than 255 copies are needed, i.e. a machine with at most 256 query nodes (in the design proposed above) would fit in the smaller, more optimized field. This parameter is passed to ***gflib*** [6] as a compiler directive.

1. Choose a value of w such that $2^w > n + m$. It is easiest to choose $w = 8$ or $w = 16$, as words then fall directly on byte boundaries. Note that with $w = 16$, $n + m$ can be as large as $65,535$.
2. Set up the tables `gflog` and `gfilog` as described in Appendix A and implemented in Figure 4.
3. Set up the matrix F to be the $m \times n$ Vandermonde matrix: $f_{i,j} = j^{i-1}$ (for $1 \leq i \leq m, 1 \leq j \leq n$) where multiplication is performed over $GF(2^w)$.
4. Use the matrix F to calculate and maintain each word of the checksum devices from the words of the data devices. Again, all addition and multiplication is performed over $GF(2^w)$.
5. If any number of devices up to m fail, then they can be restored in the following manner. Choose any n of the remaining devices, and construct the matrix A' and vector E' as defined previously. Then solve for D in $A'D = E'$. This enables the data devices to be restored. Once the data devices are restored, the failed checksum devices may be recalculated using the matrix F.

Figure 2: Algorithm to create n+m chunks from the data, that can be recovered after m chunks being lost

The algorithm seen in Figure 2, is the general algorithm for computing the coding of the data into chunks of n+m = p-1. The *gflog* and *gfilog* (described in step two (Fig 2)), are lookup tables, the first being the logarithms of the table indicies in the respective Galois Field, while the second is the inverse logarithm in the field. Thus maintaining the following relation: "`gflog[gfilog[i]]=i` , and `int gfilog[gflog[i]] = i`" [7].

A design similar to the one discussed above, is analyzed in [7] as a raid like configuration. They have analyzed the time needed to perform the encoding of n+m blocks of size S_{block} (Fig 4) in such a system. The formula for the time complexity can be seen in Figure 4. In the Figure R_{XOR} represents the rate of an XOR operation and R_{GFmult} is the rate of performing a multiplication in the GF. The reason for having one less GF multiply operation, is due to the fact that the first checksum is computed without multiplication, since the first row of the matrix used for the multiplication is all ones. The formula shows that for each word around m XOR and GF multiplication operations occur to calculate its m checksums.

Another operation that is useful is overwriting words in a file. This can be done with a certain degree of efficiency with RS codes. The cost of overwriting a word in one of the files is captured in the formula presented in Figure 5. To overwrite a word, the word has to be written to the backup containing the original word + the corresponding word in each of the checksums has to be recomputed (hence the number m+1 in the formula). The variable j represents the partition in which the original data is located. If the data is located in the first partition, the computation would be faster than if the word to be changed was in any of the other segments.

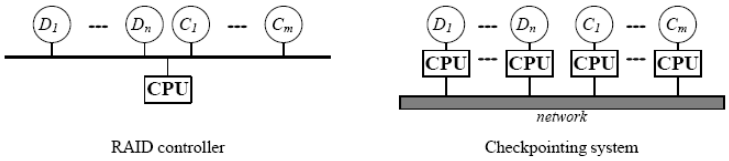


Figure 3: Raid like configurations [7]

$$S_{Block}(n-1)\left(\frac{m}{R_{\text{XOR}}}+\frac{(m-1)}{R_{GFmult}}\right)$$

Figure 5: Time to compute n+m blocks [7]

$$\text{The cost of writing one word to } m+1 \text{ disks} + \begin{cases} \left(\frac{m+1}{R_{\text{XOR}}}\right) & \text{if } j=1 \\ \left(\frac{m+1}{R_{\text{XOR}}}\right)+\left(\frac{m-1}{R_{GFmult}}\right) & \text{otherwise.} \end{cases}$$

Figure 4: Time to overwrite one word in segment j [7]

The calculation required for recovery has two parts, a Gaussian Elimination (taking $O(size(f)^2 n)$) and recalculation [7]. Since the number of failed nodes is relatively small the first step is compared to linear speed. The time to recover a block of data is upper bounded by the formula seen in figure 6. In Figure 6 the size(f) (number of failed nodes) is referred to as y. According to [7] the cost of both updating and writing is dominated by the time taken to write to the disks.

$$\left(\begin{array}{c}\text{The cost of reading one}\\ \text{block from each of } n \text{ disks}\end{array}\right)+\left(\frac{(y)S_{Block}(n-1)}{R_{\text{XOR}}}\right)+\left(\frac{(y)S_{Block}(n)}{R_{GFmult}}\right)+\left(\begin{array}{c}\text{The costs of writing one}\\ \text{block to each of } y \text{ disks}\end{array}\right)$$

Figure 6: Time to recover one block [7]

These are the redundancy costs of a raid like system. Other systems are proposed in [7] and are labeled check pointing systems. Broadcast and Fan-out algorithms are analyzed for such systems and are analyzed for time complexity within [7]. The paper also discusses Hamming codes as an optimal alternative to Reed Solomon Codes when $k \in \{1,2\}$.

MPI Applications

A common misunderstanding amongst MPI programmers is that “MPI is not fault tolerant” [4]. This misconception is derived from another misconception that if any process dies, then the rest of the processes must die. This occurs when the communicator MPI_COMM_WORLD is used since the default error handler on that communicator is MPI_ERRORS_ARE_FATAL. Using this error handler, if a process exits before sending an MPI_Finalize, then the rest of the processes should detect this condition and exit under MPI specifications [4]. The MPI specification defines this as the default; However, this default behavior can be changed.

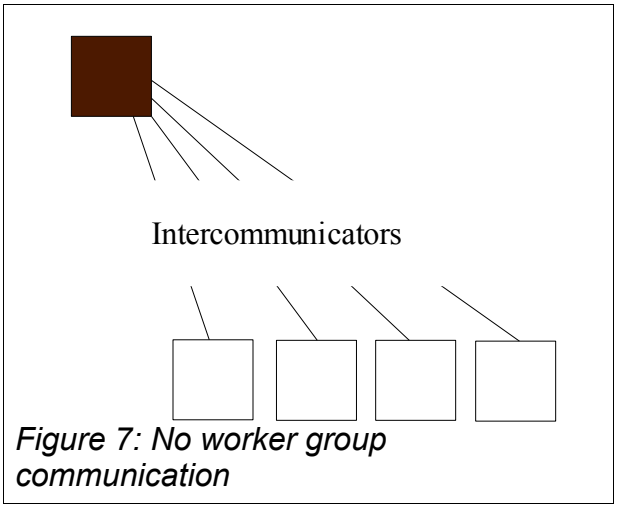


Figure 7: No worker group communication

The MPI specification mandates that all

communicators inherit their error handlers from their parent communicator, and thus any communicator created from MPI_COMM_WORLD would have the ERRORS_ARE_FATAL error handler. One can change the error handler on the communicator to be MPI_ERRORS_RETURN [4], thus allowing MPI programs to return with an error code instead of exiting. Also communicators used to communicate with nodes that have failed should be abandoned. These procedures are explained in detail in [4] with samples from MPI-1 in C and Fortran. In an OLAP setting these characteristics can be appended to the model earlier proposed in this paper. The Management node would handle the communication with each of the Query nodes, and detect a failure at a specific node when communication with that node fails (i.e. An error code is returned by an MPI function).

Some MPI libraries such as MPI-FT aimed to create a fault tolerant framework for MPI applications. Under such implementations of MPI, checkpoints and message logging are used to restart aborted processes. However, many believe that fault tolerance cannot be a property of an MPI implementation since no specific implementation can ensure that a system is immune from all faults. The claim is that fault tolerance is a property of an MPI program, and should be designed according to the users needs [4]. [4] also has a proposition to encapsulate code that would allow programmers to set up MPI applications in such a way as the one illustrated in Fig 7. Under the setup discussed above (Figure 7) along with RS coding, certain responsibilities have to be carried out by the management node while others by the query node. In the table bellow are the different responsibilities that can be carried out by the different types of nodes. It must be noted that in such a scheme in MPI the management node cannot tolerate faults, since it is responsible for co-ordinating the Query nodes. The query nodes will be designed to tolerate *k* disk failures.

Management Node's Responsibilities	Query Nodes' Responsibilities
● Receive RS Backups OR Receive Data & Compute Backups ● Distribute backups amongst nodes (p-1 parts to each node) ● Detect dead nodes and abandon communicator ● Recover Dead nodes Data and distribute ● Send Query and Receive results from all nodes	● Send Computed Backups OR Send Data ● Receive (p-1) backup segments ● Receive extra records from management node to be appended to nodes records (for query processing purposes) ● Process Queries from and send results to manager node.

OLAP FT Algorithm

Using the different aspects discussed above, a general view of the procedures in the fault tolerant OLAP design can be generalized into the algorithm seen bellow. Note that when recovering the data from the remaining *p'* nodes, after having already recovered from a failure previously, would result in tracking which records were recovered. The algorithm below, first determines that there are enough pieces to recover the data, then deletes all the records received at any recovery stage from live Query nodes. Following that, the entire set of records (that used to be owned by dead nodes) are recomputed from the backups and distributed.

General Algorithm

Precondition: Data distributed among the Query Nodes
Initialization:
    For all nodes compute backups and send to manager
    Manger: distribute backups amongst query nodes
Processing:
    Answer queries from management Node
After any Failure:
    if size(*f*) < *k* :
        for each *p'* drop all records not in initial partition
        for all failed nodes recover their data from the backups at *p'*
        # this ensures all records are recovered
        Distribute recovered backups to the *p'* nodes
    else:
        Exit("No more than *k* failures can be tolerated")

C/MPI FT Prototype

A small prototype has been written in to use the algorithm stated above in order to test the ability to attain fault tolerance and comparatively test the speed of such a system.

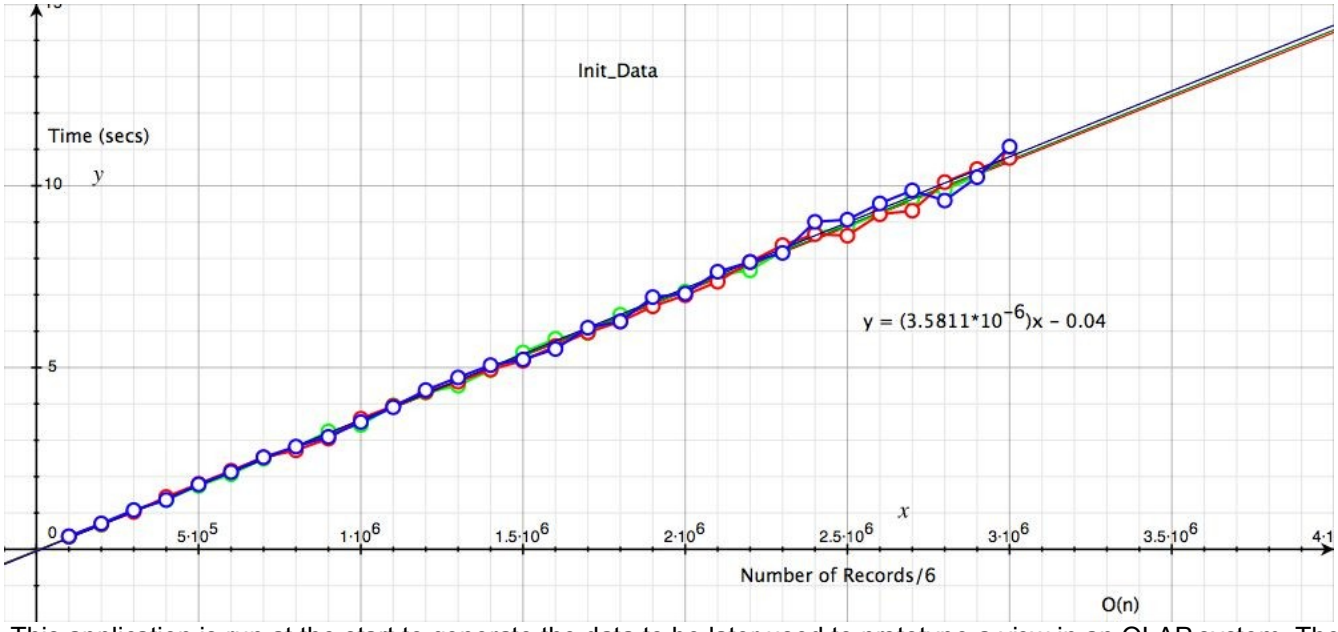
System Description

The system was setup to use records that have two fields, a key and data fields. An “init_data” application was written to generate a random set of records on each of the *p* nodes. Following that each query node runs the “rs_parallel_encode” application to encode the initialized data and compute the backups. The backups are then distributed via the “rs_dist_codes” application, which places the computed codes in the right locations on the other query nodes. At this stage the backups have been computed and distributed, allowing the system to withstand *k*-failures. A “query_processor” application was written to answer simple queries on the query nodes returning the results to the management node, similar to an OLAP system. When a node is sensed to be dead, the “rs_gather_codes” application is run to gather the dead nodes RS codes (from the *f* live nodes) on the management node, which runs the “rs_parallel_decode” application in order to attain the original data set. Following that the “dist_records” application is run, which sends each of the recovered records to one of the live query nodes. The “query_processor” application then uses these recovered records in order to answer following queries.

Testing & Results

The values *p* & *k* are parameters given to the application and were set to *p*=6 (where the system runs on *p+1* nodes (7 nodes)) and k was set to three, allowing for a maximum of three out of the 6 nodes to be marked dead (50% system failure). Data on which node has dies is passed to the respective applications in order to determine where to get the backups and who to send it to. Bellow are the results of the testing procedure, and a comparison between the amount of time spent in different applications in this system, along with the data sizes used.

Data Initialization:

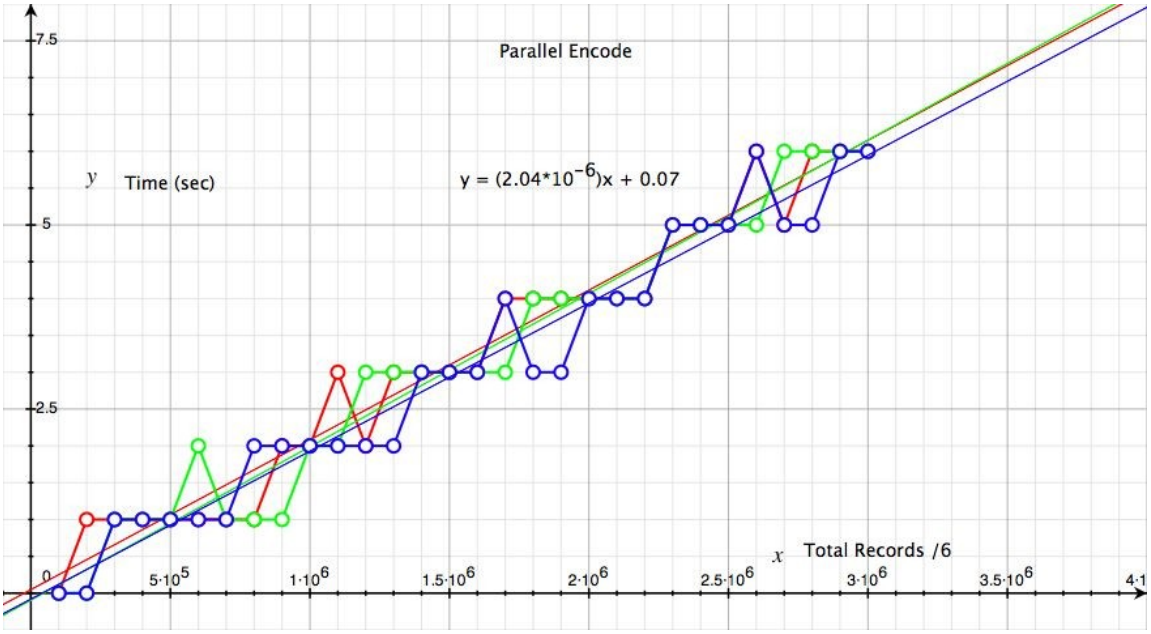


This application is run at the start to generate the data to be later used to prototype a view in an OLAP system. The

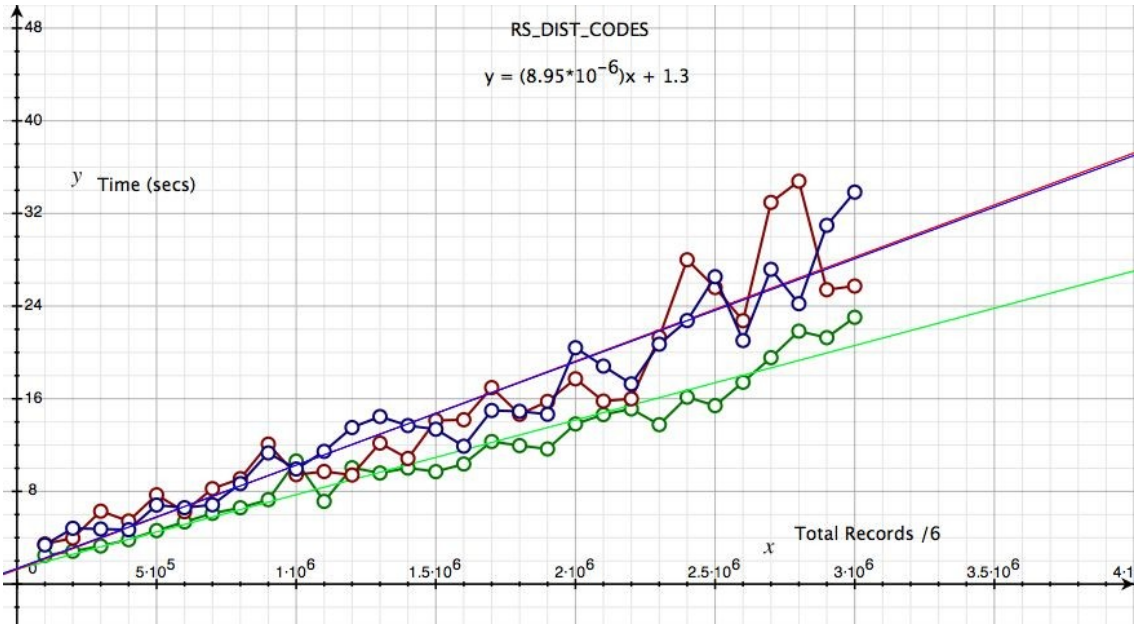
data generated here have two fields. An integer key field, and a floating point data field. This application takes as a parameter the number of records to generate on each node, thus the units of the x-axis in the above graph is *Total Records / 6* (since there are 6 query nodes in this testing run).

Reed Solomon Initialization

RS Parallel Encode



RS Distribute Codes



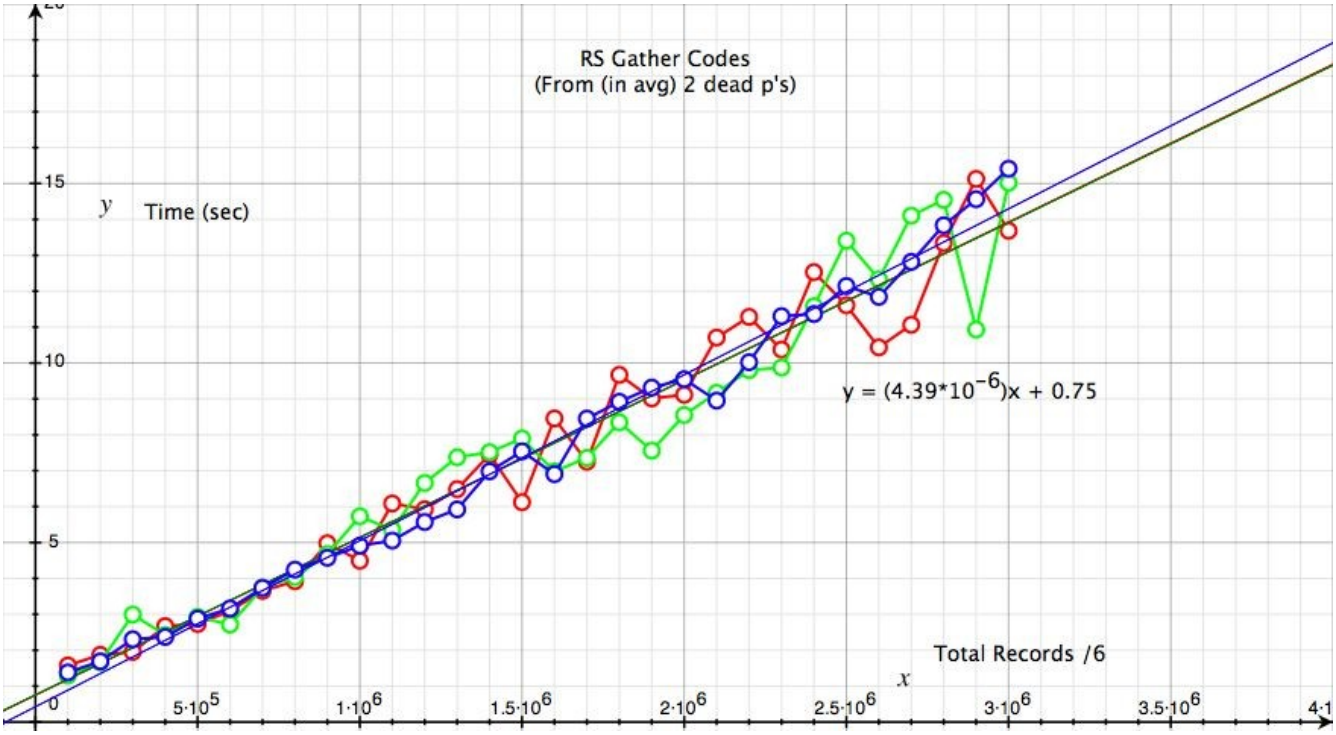
These two applications complete the initialization of the RS codes such that when a node dies, its backups can be

found on the other live nodes (given number of dead nodes < K-ft (=3)). The first application is the one responsible for computing the RS Codes. It can be seen from the graph, that the computation happens in blocks, once the number of records reaches a certain point a new block is to be created and processed which requires more time. The block sizes are determinable from the graph, and they seem to be around 500,000 records / block.

The second application is responsible for distributing the codes computed by each of the nodes to all the other nodes, giving a piece of the backups to each. Surely, each node distributes all the pieces related to its data, not keeping any pieces to itself, since they are only needed when the node dies. A decision has been made to use *ssh* to distribute the records since this is the method of transfer available on the LAM enabled cluster used for testing. The distribute application determines the name of each node then calls *scp*, supplying the required to and from variables allowing the distribution of the records across the parallel machine.

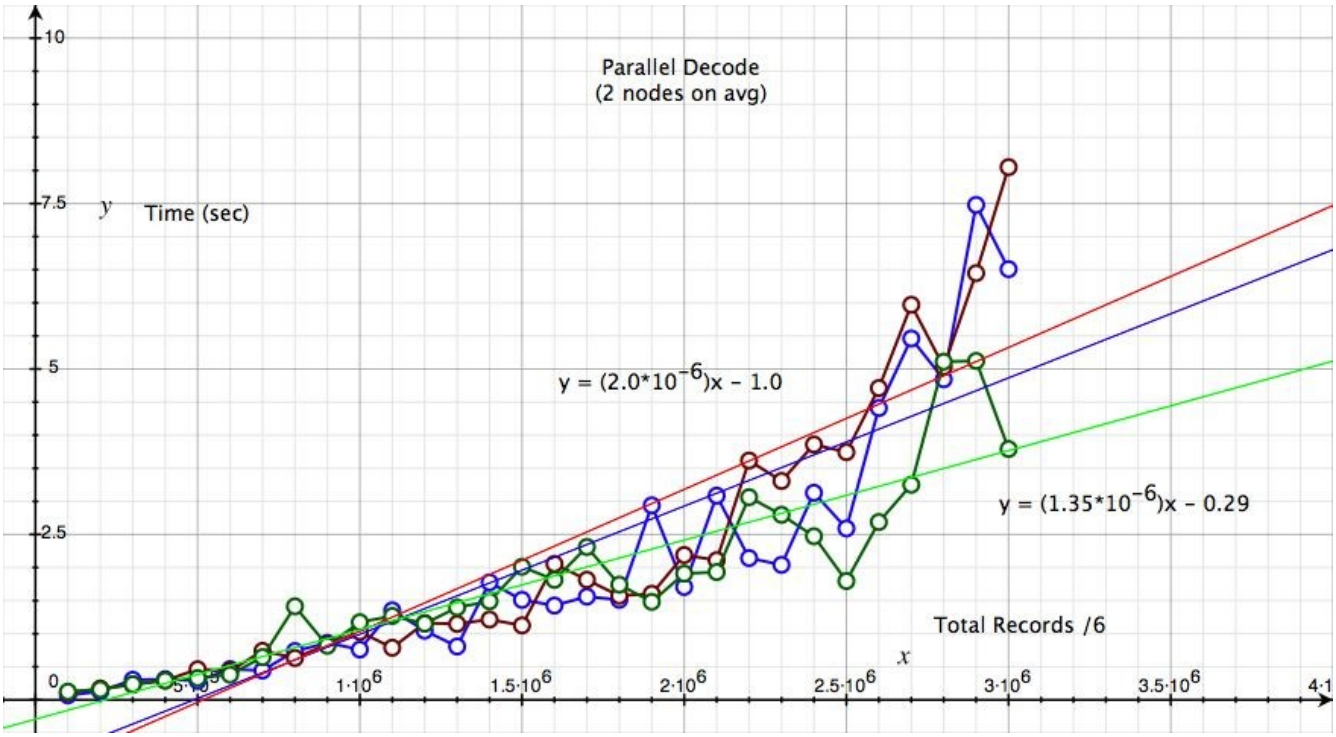
Reed Solomon (In Action)

Gather Codes



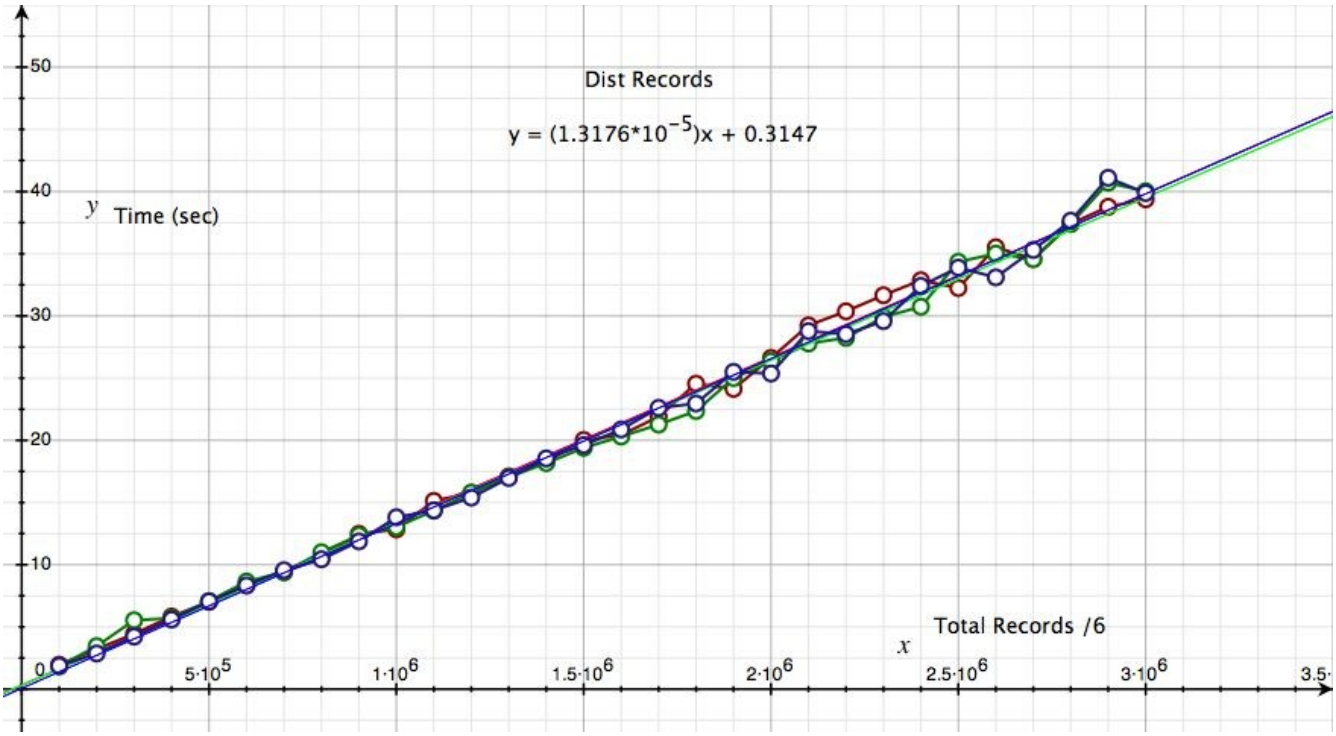
Similar to the distribute application, this application uses *scp* to gather any dead nodes' data to the main ("management") node. In this prototype, the decoding of each of the dead nodes' data is done sequentially (done by the *decode* application graphed bellow) on Node 0. The gather and distribute applications seem to take the longest time. Initially the assumption that the *scp* application has a high overhead came to mind. However, after analysis of the results of the *Distribute Records* application (which does not use *scp*), it became clear that it is the mere file sizes that causes the delay.

RS Decode



This application runs on the management node after the gathering of the decode pieces from the live query nodes. In turn checks to see the next dead node, then decodes its data into a file labeled according to the deceased node's id.

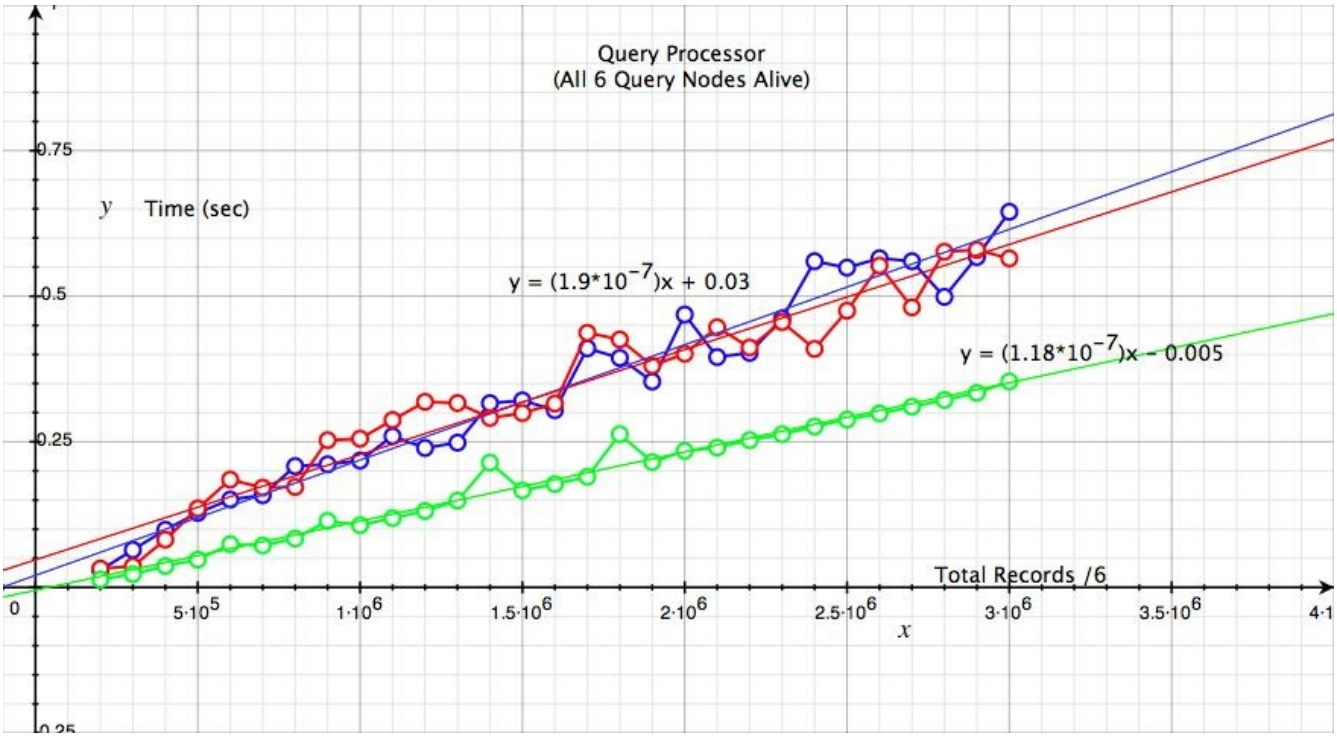
Distribute Records



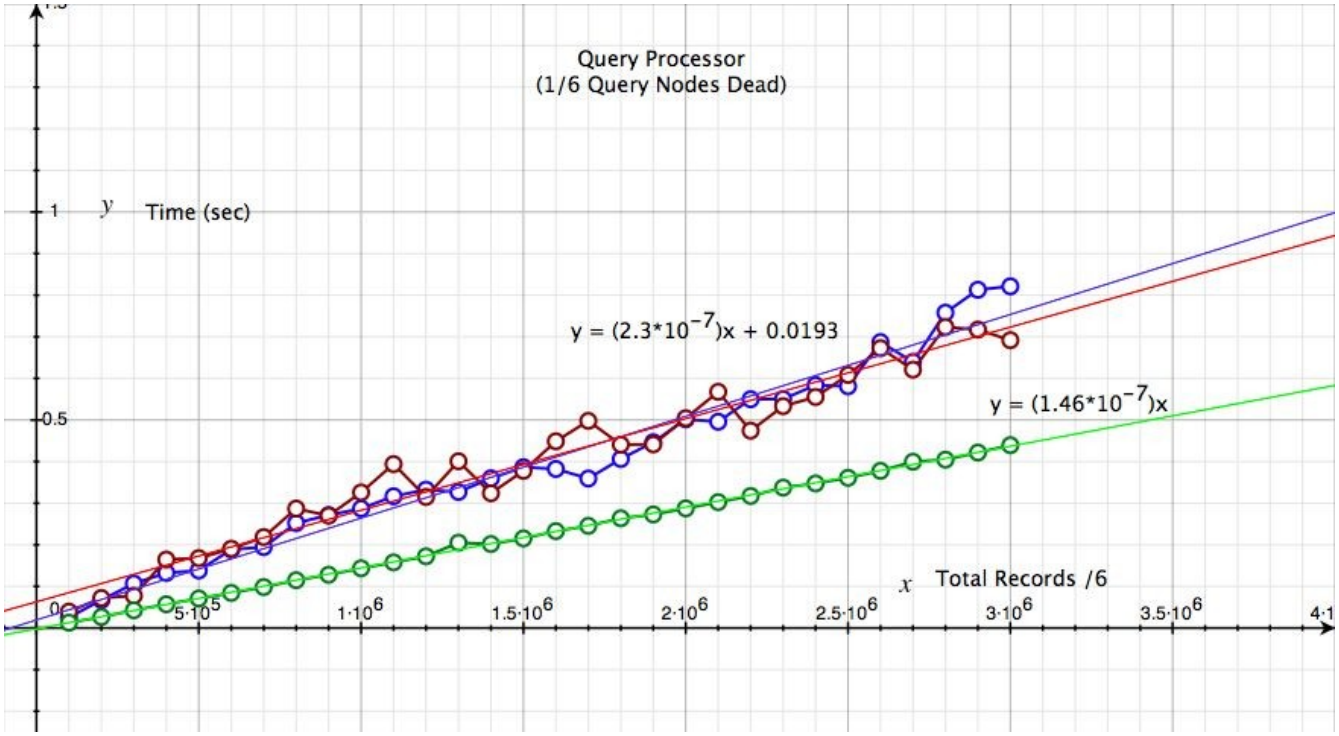
This application uses MPI to read each dead nodes data and send to all live nodes the records in a round robin fashion, to maintain record distribution across the live query nodes of the machine. At 3,000,000 records per dead ode this application takes on average 40 seconds where number of dead nodes, $p - f \leq 3$.

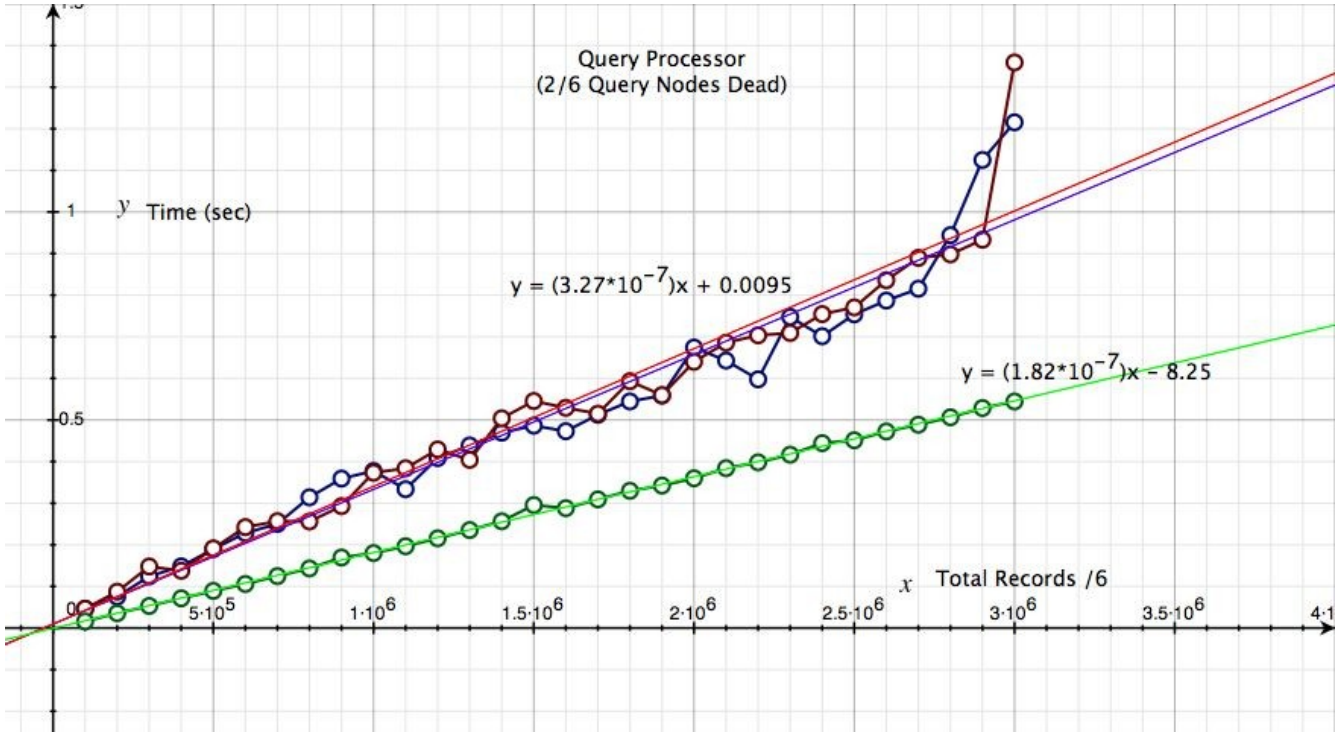
Query Processing

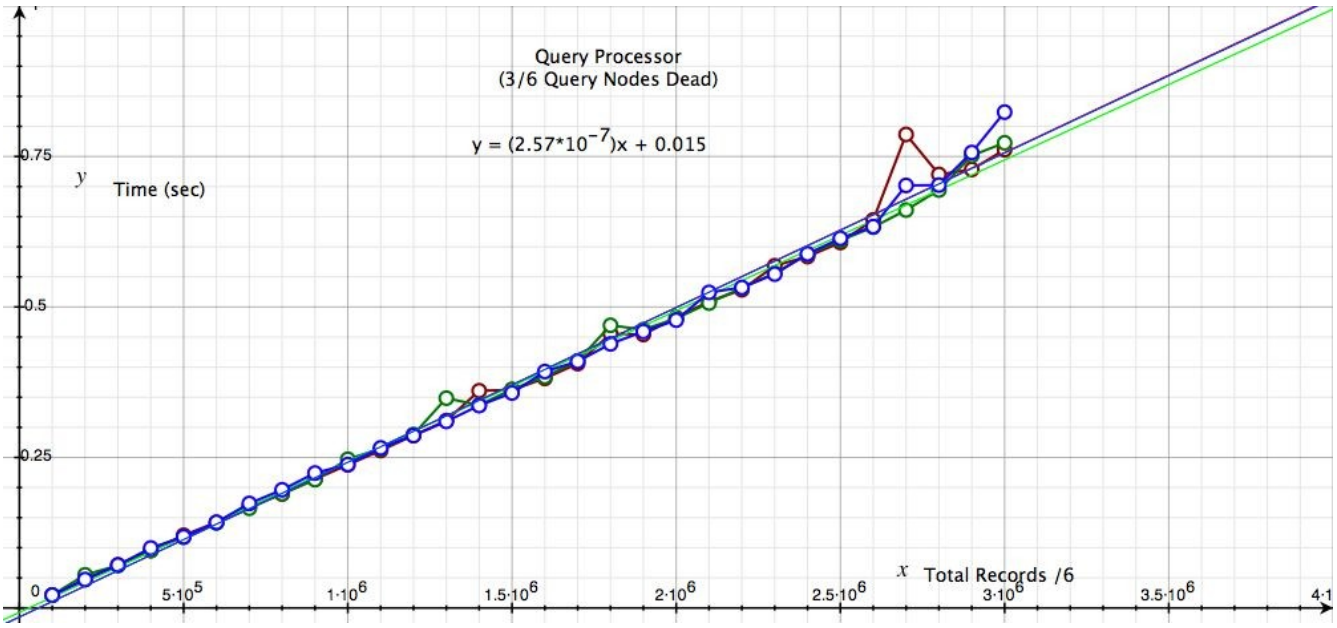
The query processor was run multiple time in each situation, each time running a set of 24 standard queries. The average time per query was recorded. The situations graphed were 0, 1, 2, 3 dead with the plot indicating the average of all experiments for this specific situation and data size. Since the queries run were all the same, queries run on the same instance of the application, i.e. ones began with the same *init_data* call, i.e. all the plots with the same data size, all return the same number of records. Also the query processor does not finish the transfer of all the nodes to the main node, the query is considered complete once all the nodes duplicate the query satisfying data locally and send the counts to the management node. Bellow are the graphs for the time taken per query *Y* versus *X* the total number of records divided by 6.



For the first three situations the third experiment (green) ran faster than the other two experiments. It is assumed that this was due to other processes slowing down this target process, and these factors were reduced in the third occasion. The equation of this third experiment was left out separately, while the first two were averaged out to get the equation seen above. This is also true for the other graphs with two equations.


Query Processor
(1/6 Query Nodes Dead)
y
Time (sec)
1
0.5
y = (2.3*10^-7)x + 0.0193
y = (1.46*10^-7)x
x
Total Records /6
0
5·10^5
1·10^6
1.5·10^6
2·10^6
2.5·10^6
3·10^6
3.5·10^6

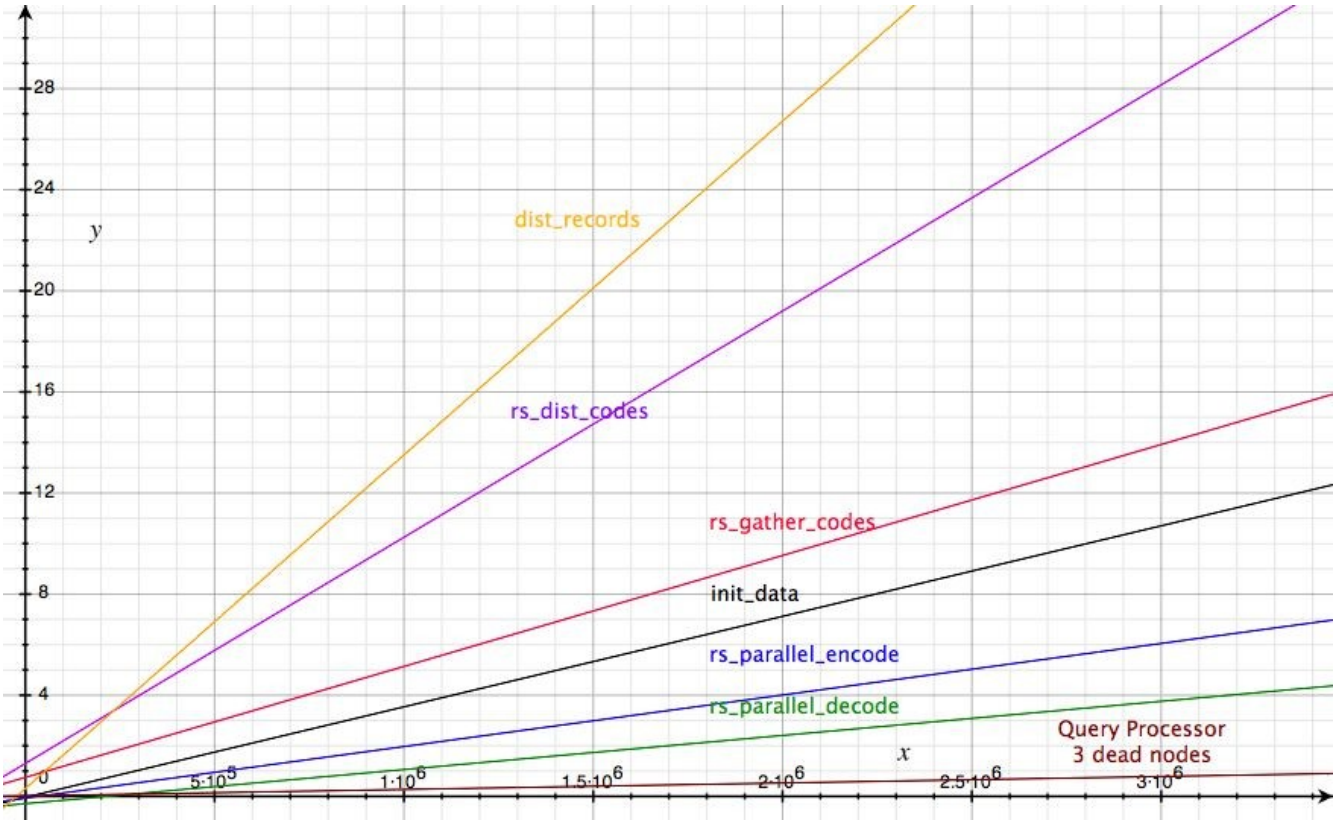

Query Processor
(2/6 Query Nodes Dead)
y
Time (sec)
1
0.5
y = (3.27*10^-7)x + 0.0095
y = (1.82*10^-7)x - 8.25
x
Total Records /6
0
5·10^5
1·10^6
1.5·10^6
2·10^6
2.5·10^6
3·10^6
3.5·10^6

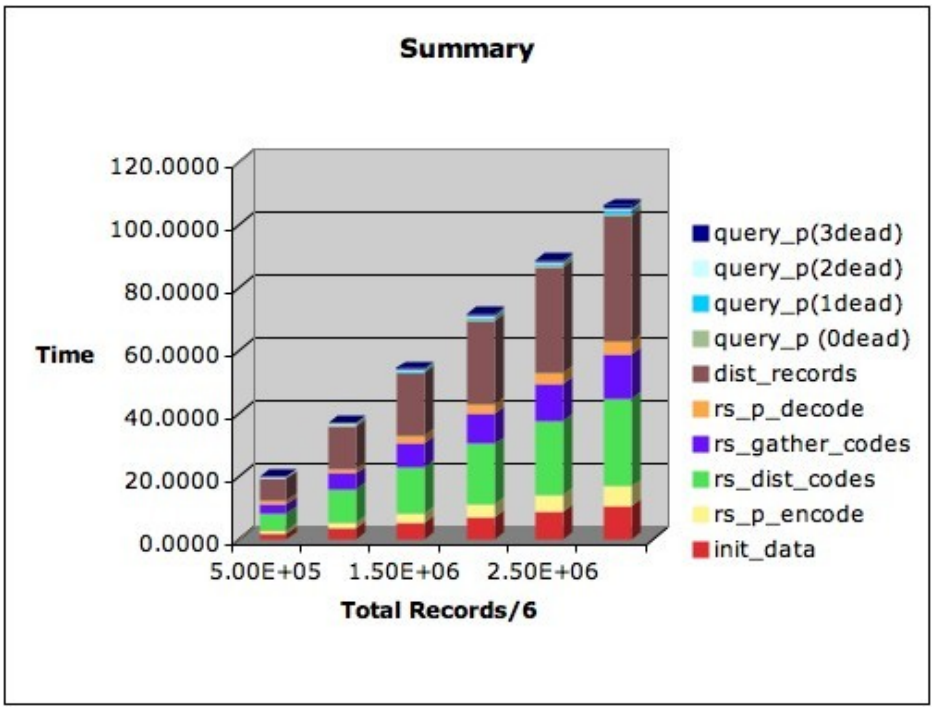


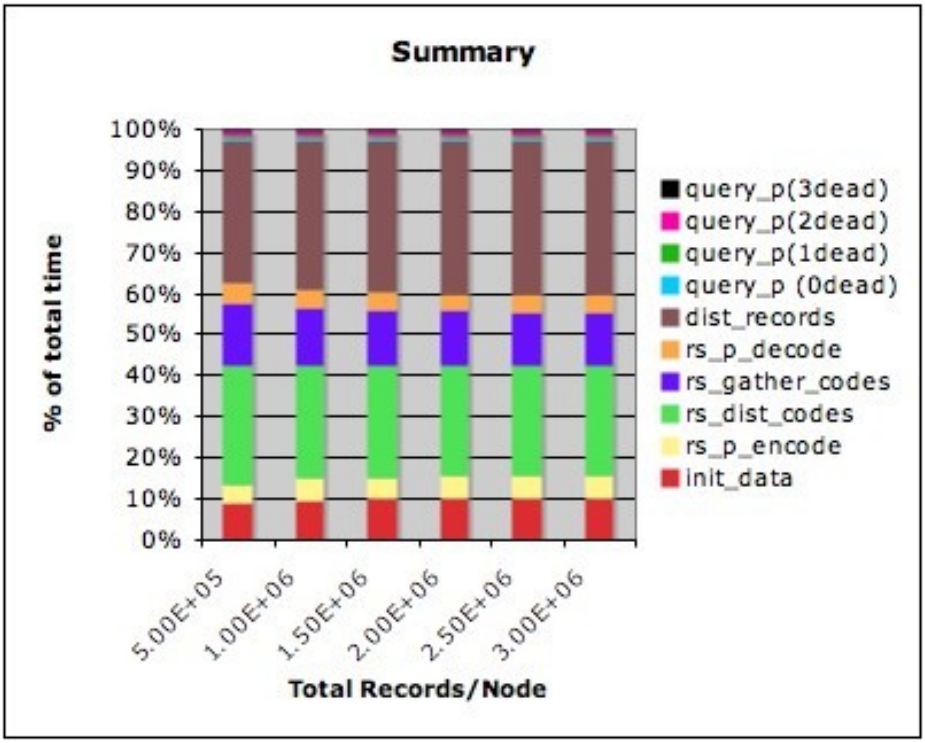
In general a queries took less than a second , even when analyzing around three million records per query node. With all nodes alive, queries took less than .75 of a second with the same massive data set.

Comparison

Bellow are graphs showing all the system components with their relative speed (faster components have a smaller slope). From the bar chart bellow, it can be seen that not much time is spent on decoding and encoding in comparison with the other functions. It can be seen the encoding and decoding time is comparable to query execution time.







Even though encoding and decoding time is much smaller than the other functions, records distribution, code gathering and distribution are also vital functions needed to complete the backup system and therefore have to be included in the backup cost.

Future Work

This paper has not discussed issues with updating to the OLAP structure. Many issues exist, specially in a situation like this when backups have to be computed. A strategy could rely on having a changes vector, where records are either deleted or appended, queries would be checked (by each query node) against the changes vector in order to add or remove records from the result set. When the changes vector reaches a stage of inefficiency, a new re computation of the backups may be of order. Such a scheme needs to be analyzed in a running OLAP system in order to determine the size capacity of such a changes vector, and to determine when would be a good time to recompute backups. Also periods of inactivity at the query nodes can be considered as good opportunities to recompute backups, as to not disrupt the service.

Conclusion

This paper has proposed a design for an OLAP machine that may handle k-failures. This has been shown through the means of coded redundancy, using Reed Solomon Codes, along with an MPI guideline on fault tolerant implementation issues. This paper discussed the proposed an approach (prototyped and timed) to handle a single view in OLAP; However, doing so can be replicated for all views, using the same approach In conclusion, using the concepts outlined in this paper, an efficient fault tolerant approach can be applied to OLAP.

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Appendix

Pseudo Code for OLAP Algorithm in MPI

```
main(int argc, char * argv [ ] )
{
      int i, my_rank, p, k;
      MPI_Comm *my_comm;

      MPI_Init( &argc, &argv );
      MPI_Comm_rank( MPI_COMM_WORLD, &my_rank );
      MPI_Comm_size( MPI_COMM_WORLD, &p );
      k = p;

      /* create intercommunicators and set error handlers */
      if(my_rank == 0) //manager process
      {
          my_comm = (MPI_Comm*)malloc(p*sizeof(MPI_Comm));
          for ( i = 1; i < currsize; i++ )
          {
             MPI_Intercomm_create( MPI_COMM_SELF, 0, MPI_COMM_WORLD, i,
                                   IC_CREATE_TAG, &my_comm[i-1]);
             MPI_Comm_set_errhandler( my_comm[i-1], MPI_ERRORS_RETURN );
          }
      }
      else //other processes
      {
          my_comm = (MPI_Comm*)malloc(sizeof(MPI_Comm));
          MPI_Intercomm_create(MPI_COMM_SELF, 0, MPI_COMM_WORLD, 0, IC_CREATE_TAG,
                               my_comm);
          MPI_Comm_set_errhandler(*my_comm, MPI_ERRORS_RETURN );
      }

      /*    now each p has a communicator with the manager process     */

      if(not manager)
      {
          Data = Get_My_OLAP_Record_Partition();
          //this can be elaborated into send/recv pairs to allow the manager to
distribute
          Backup_Array = RS_encode_data(&Data, n = p-1-m , m);
          MPI_send_to_manager();
          MPI_recv_other_backups();
          //Write_backups_to_local_file();
      }
      else
      {
          Gather_Backup_data();
          Distribute_Backup_data();
      }

      if(manager)
      {
          get_olap_query();
          //in the send query phase, dead nodes will be detected.
          send_query_to_nodes(dead_node_marker [ ] );
          if(all_alive)
```

```
         {
            send_go_signal();
            gather_answer();
         }
         else
         {
            for(dead_nodes)
                  recover_data[i] = gather_dead_nodes_data();
            //recover_data now contains the subset of the original records
            //distribute records on processes + regather backups (to be modulated)
         }
      }
      else
      {
         receive_query();
         receive_message();
         if(message==go) answer_query();
         else
         {
            parse_message();
            get_RS_backup_of_dead_nodes();
            for(dead_nodes) send_backups_to_manager();
            //receive new record set + append to my set + recompute backups
         }
         send_answer_to_manager();
      }

      /*                        program complete             */

      if(my_rank==0) for ( i = 1; i < currsize; i++ ) MPI_Comm_free( &my_comm[i-
1] );
      else MPI_Comm_free(my_comm);

      MPI_Finalize( );
      return 0;
}
```