

Map Reduce on a Chord Distributed Hash Table

Andrew Rosen Brendan Benshoof Matt Erwin Robert Harrison Anu Bourgeois
Department of Computer Science, Georgia State University
34 Peachtree St NW
Atlanta, Georgia 30303
rosen@cs.gsu.edu

Abstract—Large problems in Computer Science are often able to be split into many smaller, functionally identical tasks, the results of which can be reduced into the desired solution. MapReduce is a framework for performing distributed computations of these types of problems, but most of these frameworks are strongly dependent on a heirarchical structure. Chord is a distributed hash table that provides $\log_2 n$ connectivity among processors. Our experiments show that a Chord ring has number of desirable advantages for implementing MapReduce, such as a lack of a single point of failure, fault-tolerance, an even distribution of work, scalability, and minimal overhead.

TODO GO THROUGH AND UNIFY TERMINOLOGY:
MAPREDUCE TASK/JOB

RELATED WORK MIGHT BE BETTER PLACED NEAR
CONCLUSION

CAPITALIZE ALL MAPS AND REDUCES

ADD WHAT CHRONUS STANDS FOR

CHECK FORMATTING MATCHES WHAT THEY WANT
FOR SUBMISSION

GO OVER NETWORKING TERMS WITH DR. ANU TO
MAKE SURE WE ARE USING THE RIGHT ONES

I. INTRODUCTION

Ever since Google published a paper on the subject [4], MapReduce has rapidly become an integral part in the world of data processing. Using MapReduce, a user can take a large problem, split it into small, equivalent parts and send those parts off to be worked on by other processors. These results of these computations are then sent back to the user and combined until one large answer results. Numerous programming tasks - word counts, reverse indexing, sorting, Monte-Carlo approximations - can be efficiently distributed using MapReduce [4].

The most popular platform for MapReduce is Hadoop [2]. Hadoop is an open-source Java implementation deveolped by Apache and Yahoo! [9]. Hadoop has two components, the Hadoop Distributed File System (HDFS) and the Hadoop MapReduce Framework [5]. Under HFDS, nodes are arranged in a heirarchical tree, with a master node, called the NameNode, at the top. The NameNode is responsible for keeping track of whcih DataNodes posess which files, as well as coordinat-ing the work done under a MapReduce job ^{double check the latter}.

However, what if we desire a less heirarchical structure among our nodes? A single node in charge is a single point of failure. We need a system that can scale, is fault tolerant, has a minimal amount of latency, and distributes files evenly.

Chord [14] is a distributed hash table (DHT) that possesses these qualities. Chord guarantees a worst-case $\log n$ lookup time for a particular node or file in the network. It is highly fault-tolerant to node failures and churn. It scales extremely well and there is little maintenance required by the network as a whole to handle individual nodes. Files in the network are distributed evenly among its members.

However, rather than viewing Chord solely as a means for sharing files, we see it as a means for distributing work. We have developed a system, called CHRONUS, that builds off the concepts that make Chord a powerful means of evenly distributing files and applies it toward distributing work among member nodes¹. We built a framework on CHRONUS for performing Map and Reduce tasks on Chord ring. CHRONUS leverages the underlying protocol to distribute map and reduce tasks to nodes evenly, provide greater data redundancy, and guarantee a greater amount of fault tolerance. The network has no single point of failure.

At the same time we avoid the architectural and file system constraints of systems like Hadoop. Nodes in CHRONUS can be setup in a cluster for high performance or they can be deployed the Internet, for volunteer computing tasks. Our experiments demonstrate that our framework is highly scalable, solving problems significantly faster when distributed. The larger the problem is, the greater the speedup gained by incorporating more nodes into the problem. Our framework also provides a high level of robustness during execution; we can lose many nodes from churn and still process jobs successfully. If we find a job requires more computational power, we can add more nodes to the job during runtime.

Section X covers the specifics of the Chord Protocol and the design choices we made for implementation. We describe MapReduce and Hadoop in more detail in Section QA4162. Related Work is discussed in Section 42. Details of CHRONUS's implementation and code is described in Section Q, while our experiments and their results are covered in Section Z. Lastly, Section L discusses fruitful avenues of future research.

II. CHORD

The Chord protocol [14] takes in some key and returns the identity (ID) of the node responsible for that key. These keys are generated by hashing a value of the node, such as the IP

¹repetitive

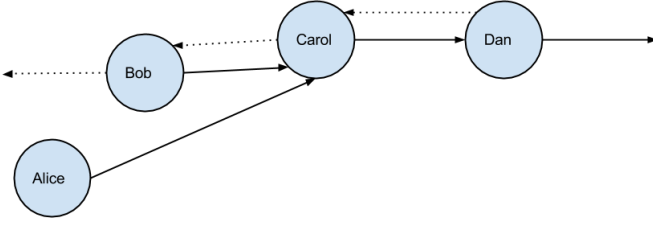


Fig. 1: Alice has incorrectly determined that Carol is her appropriate successor. When Alice stabilizes, Carol will let her know about Bob.

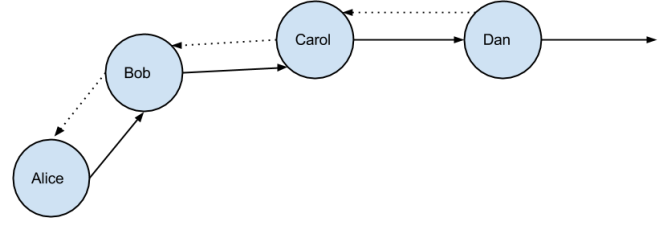


Fig. 2: After completing stabilize, Alice makes Bob her successor and notifies him. Bob then made Alice as his predecessor.

address and port, or by hashing the filename of a file. The hashing process creates a m -bit hash identifier.

The nodes are then arranged in a ring from the lowest hash-value to highest. Chord then takes the hashed files and places each in the node that has the same hashed identifier as it. If no such node exists, the node with the first identifier that follows this value. This node responsible for the key κ is called the *successor* of κ , or $successor(\kappa)$. Since the overlay is a circle, this assignment is computed in module 2^m space. For example, if there were some portion of the network with nodes 20, 25, and 27, node 25 could be responsible for the files with the keys (21,22,23,24,25). If node 25 were to decide to leave the network, its absence would inform node 27, who would then be responsible for all the keys node 25 was covering. An example Chord network is drawn in in Figure INSERT FIG HERE.

With this scheme, we can reliably find the node responsible for some key by asking the next node in the circle for the information, who would then pass the request through the circle until the successor was found. We can then proceed to directly connect with the successor to retrieve the file. This naive approach is largely inefficient, and is a simplification of the lookup process, but it is the basis of how Chord theoretically works.

To speed up the lookup time, each node builds and maintains a *finger table*. The *finger table* contains the locations of up to m other nodes in the ring. The i th entry of node n 's *finger table* corresponds to the node that is the $successor(n + 2^{i-1}) \bmod 2^m$. Because hash values won't be perfectly distributed, it is perfectly acceptable to have duplicate entries in the *finger table*.

When a node n is told to find some key, n looks to see if the key is between n and $successor(n)$ and return $successor(n)$'s information to the requester. If not, it looks for the entry in the finger table for the closest preceding node n' it knows and asks n' to find the successor. This allows each step in the to skip up to half the nodes in the network, giving a $\log_2(n)$ lookup time. Because nodes can constantly join and leave the network, each entry in the table is periodically checked and updated.

To join the network, node n first asks n' to find $successor(n)$ for it. Node n uses the information to set his

successor, but the other nodes in the ring will not acknowledge n 's presence yet. Node n relies on the stabilize routine to fully integrate into the ring.

The stabilize routine helps the network integrate new nodes and route around nodes who have left the networks. Each node periodically checks to see who their successor's predecessor is. In the case of a static network, this would be the checking node. However, if the checking node gets back a different node, it looks at that returned node's hash value and changes their successor if needed. Regardless of whether the checking node changes its successor, that node then notifies the (possibly) new successor, essentially telling the successor "based on the information I have, I'm your predecessor. Check to see if you need to update your predecessor information," to which the successor obliges. A more concrete example:

Suppose Alice, Bob, Carol, and Dan are members of the ring and everyone happens to be ordered alphabetically (Figure 1). Alice is quite sure that Carol is her successor. Alice asks Carol who her predecessor is and Carol says Bob is. Since Bob is closer than Carol, Alice changes her successor to Bob and notifies him.

When Bob sees that notification, he can see Alice is closer than whoever his previous predecessor is and sets Alice to be his predecessor. During the next stabilization cycle, Alice will see that she is still Bob's predecessor and notify him that she's still there (Figure 2).

One of the major design choices for Chord implementation is not figuring which node is responsible for a given key, but figuring out who decides which node is responsible for a given key. In our implementation, a node n is responsible for the keys $(predecessor(n), n]$. In other words, when n gets a message, it considers itself the intended destination for the message if the message's destination hash is between $predecessor(n)$ and n . A node that does not have a predecessor assigns itself as its own predecessor and considers itself responsible for all messages it receives.

When a node n changes his successor, n asks if the successor is holding any data n should be responsible for. The successor looks at all the data n is responsible for and sends it to n . The successor does not have to delete this data. In fact, keeping this data as a backup is beneficial to the network as a whole, as n could decide to leave the network at any point.

Due to the potentially volatile nature of a peer-to-peer network, Chord has to be able to handle (or at the very least, tolerate) an arbitrary amount of churn. We already detailed how Chord gradually guides nodes into their correct locations after they join the network. The same is true for when a node leaves the network; the stabilize procedure will guide nodes to their correct successors and predecessors. However, we can exert more control over how to handle nodes leaving the network.

Chord specifies two ways a node can leave the ring. A node can either suddenly drop out of existence, or a node can tell the network he is about to leave, letting his successor and predecessor immediately perform the needed changes.

When a node politely quits, he informs both his successor and predecessor and gives them all the information they need to fill the gap that would be left over. He also sends all of the data he is responsible for to his successor, who would become responsible for that data when that node left. Fingers that pointed to that node would be corrected during the finger maintenance period. This allows for the network to adjust to the change with a minimum of fuss.

Unfortunately, it is impossible that every time a node leave the network it will do so politely. If a node suddenly quits, the data it had stored goes with it. To prevent data from becoming irretrievable, a node can periodically send backups to its successor. So as not to overwhelm the ring with a cascade of backups of backups, the node only passes along what it considers itself responsible for, which changes as nodes enter and leave the network. If the backup leaves, he send his stuff to his successor, since the backup's successor would be the one responsible for the info now.

Our prototype framework does not implement a polite disconnect; when a node quits, it does so quickly and abruptly. This design forced us to ensure that system would be able to handle churn under the worst of cases. Polite quit could be implemented quite easily, but it would provide minimal benefit for our use cases.

A. Extensions of Chord

The Cooperative File System (CFS) is an anonymous, distributed file sharing system built on top of Chord [3]. In CFS, rather than storing an entire file at a single node, the file is split up into multiple chunks around 10 kilbytes in size. These chunks are each assigned a hash and stored in nodes corresponding to their hash in the same way that whole files are. The node that would normally store the whole file instead stores a *key block*, which holds the hash address of the chunks of the file.

The chunking allows for numerous advantages. First, it promotes load balancing. Each piece of the overall file would (ideally) be stored in a different node, each with a different backup or backups. This would prevent any single node from becoming overwhelmed from fulfilling multiple requests for a large file. It would also prevent retrieval from being bottlenecked by a node with a relatively low bandwidth. Finally, when Chord uses some sort of caching scheme like

that described in CFS [3], caching chunks as opposed to the entire file resulted in about 1000 times less storage overhead.

Chunking also opens up the options for implementing additional redundancy such as erasure codes[10]. With erasure codes, redundant chunks are created but any combination of a particular number of chunks is sufficient to recreate the file. For example, a file that would normally be split into 10 chunks might be split into 15 encoded chunks. The retrieval of any 10 of those 15 chunks is enough to recreate the file. Implementing erasure codes would presumably make the network more fault tolerant, but that is an exercise left for future work.

III. MAPREDUCE AND HADOOP

At its core, MapReduce [4] is a system for division of labor, providing a layer of operation between the programmer and the nastier parts of parallel processing. The programmer sends a large task to a master node, who then divides that task among slave nodes (which may further divide the task). This task has two distinct parts: Map and Reduce. Map performs some operation on a set of data and then produces a result for each map operation. This intermediate data can then be reduced, combining these sets of intermediate data into a set, which is further combined with other sets. This process continues until one set of data remains.

The classic example given for MapReduce is counting the occurrence of each word in a collection of documents. The master node splits up the documents into multiple chunks and sends them off to workers. Each worker then goes through each chunk and creates a small word frequency list. These lists are then used by other workers, who combine them into larger and larger lists, until the master node is left with a word frequency list of all the words in the documents.

One very popular open-source implementation of MapReduce is Apache's Hadoop [2]. Hadoop serves as both a distributed file system and framework for MapReduce[12]. Like any implementation, Hadoop has certain quirks to distinguish it from the platonic ideal. Hadoop's MapReduce framework is very strongly tied to the Hadoop Distributed File System (HDFS) and the heirarchy of servers that implies. Hadoop is centralized around the NameNode. The NameNode's job is to organize and distribute information to the slave nodes, called DataNodes. This makes the NameNode a single point of failure [12] in the network, as well as a potential bottleneck for the system [13].

To do work on Hadoop, the user stores thier data on the network. This is handled by the NameNode, which equally apportions the data among the DataNodes. When a user wants to run some analysis on the data or some subset the data, then that function is sent by the NameNode to each of the DataNodes that is responsible for the indicated data. After the DataNode finishes processing, the result is sent back to the NameNode to be reduced.

Key differences between Hadoop and CHRONUS are discussed in Section V.

IV. RELATED WORK

We have identified two extant papers that have done work on combining P2P concepts with MapReduce. Both papers are similar to our research, but differ in crucial ways.

A. P2P-MapReduce

Marozzo et al. [8] looked at the issue of fault tolerance in centralized MapReduce architectures such as Hadoop. They focused on creating a new, P2P based MapReduce architecture called P2P-MapReduce. P2P-MapReduce is designed to be more robust, able to better handle node and job failures during execution.

Rather than use a single master node, P2P-MapReduce would have multiple master nodes, each responsible for some job. If one of those master nodes fails, another will be ready as a backup to take its place and manage the slave nodes assigned to that job. This avoids the single point of failure that Hadoop is vulnerable to. Failures of the slave nodes are handled by the master node responsible for it.

Experimental results were gathered via simulation. Their results showed that while P2P-MapReduce could generate an order of magnitude more messages than a centralized approach, the difference rapidly began to shrink at higher rates of churn. However, when looking at actual amounts of *data* being passed around the network, rather than the number of messages, the bandwidth² required by the centralized approach greatly increases as a function of churn, while the distributed approach again remains relatively static in terms of increased bandwidth usage and messages sent.

They concluded that P2P-MapReduce would, in general, use more network resources than a centralized approach. However, this was an acceptable cost as the P2P-MapReduce would lose less time from node and job failures³ [8].

Our work differs from Marozzo et al.'s in that P2P-MapReduce doesn't examine leverage using the underlying strengths of a particular P2P protocol or group of protocols, which would have made the architecture simpler. P2P-MapReduce is decentralized, but still relies on a very definite master/slave hierarchy. All nodes in CHRONUS are workers and masters. We also implemented our MapReduce system rather than simulating the work⁴.

B. MapReduce using Symphony

Lee et al.'s work more strongly resembles our own in that their system uses a P2P protocol to perform Map Reduce[6]. Their work, like ours, draws attention to the fact that a P2P network can be much more than a way to distribute files and demonstrates how to accomplish different tasks using map and reduce functions.

²ANU, is this the correct term?

³"In summary, the experimental results show that even if the P2P-MapReduce system consumes in most cases more network resources than a centralized implementation of MapReduce, it is far more efficient in job management since it minimizes the lost computing time due to jobs failures." [8]

⁴Rewrite, any way to make this more polite?

Rather than using Chord, Lee et al. used very similar DHT protocol with a ring topology, Symphony [7]⁵. To run a MapReduce job over the Symphony ring, a node is selected by the user to effectively act as the master. This ad-hoc master then performs a bounded broadcast over a subsection the ring. Each node repeats this broadcasts over a subsection of that subsection, resulting in a tree with the first node at the top. Map tasks are disseminated evenly throughout the tree and their intermediate results are reduced on the way back up to the ad-hoc master node. This allows the ring to disseminate Map and Reduce tasks without the need for a coordinator responsible for distributing these tasks and keeping track of them, unlike Hadoop.

Their deployed experimental results showed that the latency experienced by a centralized configuration is similar to the latency experienced in a completely distributed framework⁶.

One of the major improvements that can be made to Lee et al.'s method is improving the fault tolerance of the system. While in most cases the network is able to cope with churn via the underlying Symphony protocol, no arrangements are made to handle the loss of nodes during the execution of a MapReduce task [6]. This means the MapReduce operation on Symphony has the same single point of failure Hadoop has.

CHRONUS exploits the backup feature used for files to protect MapReduce tasks from failure. Our network doesn't care if the node our reduced data is being sent to goes down, as the data is being sent to a address on the ring, rather than a particular node.

C. Differences in our work

To summarize, Marozzo et al. [8] shows that adding additional fault-tolerance features to a MapReduce architecture is worth the added cost of maintenance, as the time lost due to node failures is greatly reduced. However, Marozzo et al. do not explore the benefits of leveraging the properties of a P2P protocol to reduce the complexity of the architecture and completely distribute the responsibility of the task across the network. As a result, P2P-MapReduce still relies on specific nodes to coordinate the network's actions.

Lee et al.'s [6] explores the benefits of building a MapReduce module to run on top of an existing P2P protocol, specifically Symphony. This allows the MapReduce tasks to be executed without the need of a central source of coordination, unlike Hadoop. The MapReduce architecture is constructed at runtime, via bounded broadcast. Despite these benefits, the Symphony based MapReduce architecture would be greatly improved by the addition of components to handle the failure of nodes during execution. As it stands now, if a node crashes the job will fail due to the loss data

⁵I can expand here on Symphony if we need space, but I think that is better suited for the journal paper

⁶I feel these results are useless; it's just measuring the latency of the connections over the same protocol. Seriously their results seem so...obvious and uninformative.

Both these papers have promising results and confirm the viability of our own framework. CHRONUS uses Chord to act as a completely distributed topology for MapReduce, negating the need to assign any explicit roles to nodes or have a scheduler or coordinator. CHRONUS does not need to assign specific nodes the task of backing up work; nodes backup their tasks using the same process that would be used for any other data being sent around the ring. Finally intermediate data works its way back to a specified hash address, rather than a specific hash node, eliminating any single point of failure in the network. The result is a simple, distribute, and highly robust architecture for MapReduce.

V. CHRONUS

CHRONUS, at its core, is a fully functional Chord implementation in Python⁷. Our installation was designed to be as simple as possible. It consists of downloading our code[11] and running chord.py. You can specify the port you plan on using and the IP and port of a node in the ring you want to join. Once that is done, the node will automatically integrate into the ring.

Other than a hashing library, we wrote the protocol and networking code from scratch. Once we could create a stable ring, we created various services to run on top the network, such as a file system. Our file system is capable of storing whole files or splitting the file up among the ring. Our MapReduce module is a service that runs on top of our Chord implementation, just like our file service. We avoided any complicated additions to the Chord architecture; instead we used the protocol's properties to create the features we desired in our MapReduce framework.

In our implementation of MapReduce, each node takes on responsibilities of both a worker and master, much in the same way that a node in a P2P file-sharing service will act as both a client and a server. To start a job, the user contacts a node at a specified hash address. The node he contacts to be the stager may be his own computer, and this is preferable when the job involves dividing up a large pile of data.

The job of this stager is to take the work and divide it into *data atoms*, which are the smallest individual units that work can be done on. This might a line of text in a document, the result of a summation for a particular intermediate value, or a subset of items to be sorted. The specifics of how to divide the work are defined by the user in a *stage* function. These data atoms are then given a random hash⁸ and sent to that hash address, guaranteeing an even distribution of the data atoms throughout the network. The data atoms also contain the map function and reduce function, as defined by the user. A job id is also included, so that data atoms from different jobs don't get mixed up.

ASSUMPTION OF NUMBER OF TASKS BEING SPLIT UP

Nodes which receive data atoms apply the map function to the data to create intermediate data atoms, which are then sent

back to the stager's hash address (or some other user defined address). Traveling using Chord's fingers, this will take $\log n$ hops. At each hop, the node waits .1 seconds to accumulate additional intermediate data⁹.

Nodes that receive at least two intermediate data merge them into one data atom using the Reduce function. The atoms are continually merged until only one remains at the hash address of the stager.

Once the reductions are finished, the user gets his results from the node at the stager's address. This may not be the stager himself, as once the stager has sent all the data atoms, his job is done. The stager does not need to collect the results work, since the work is sent to the stager's hash address, rather than the stager itself. Thus, the stager could quit the network after staging, and both the user and the network would be unaffected by the change.

Similar precautions are taken for nodes working on map and reduce tasks. Those tasks get backed up by a node's successor, who will run the task if the node quits the network before the doing the job (eg the successor loses his predecessor). The only addition to the architecture we've made here is that a node n will send a message to his successor when n 's map or reduce task is done. This message tells n 's successor that the backup is no longer needed. This is done to prevent a job being submitted twice if n goes down after finishing his task and sending it out.

An advantage of our system is the ease of development and deployment. The developer does not need to worry about distributing work evenly, nor does he have to worry about any node in the network going down. The underlying Chord ring handles that automatically. If a node joins the ring as the MapReduce process is running, that node can be assigned work automatically. The stager does not need to keep track of the status of the network. In a node goes down while performing an operation, his successor takes over for him.

ADD ADDING NODES DURING RUNTIME

All a developer needs to do to write three functions: the staging function, map, and reduce. These define how to split up the work into manageable portions, the work to be performed on each portion to get some results, and how to combine these results into a single result.

While MapReduce is most efficient when each node is physically close in a cluster, minimizing the impact of latency, this does not exclude the option of tasks being distributed throughout the world. This setup maybe more applicable to a volunteer computing framework, such as Folding@home [1].

Many local configurations assume identical or near identical hardware, running an equal amount of nodes, performing an equal amount of work. This is not always a safe assumption to make. If the hardware used for computations is not equal, then some processors can be left idling when they could be doing more work, while others may be overwhelmed, holding back the rest of the network.

⁷The original implementation is in C++

⁸address for optimization in future work section

⁹Actual footnote: The amount of time spent waiting can be manipulated to tradeoff between time spent reducing and network usage

This is relatively easy to fix on the user's end. If some hardware can take more work than others, then that system can boot up more instances of nodes locally. Running two nodes locally would mean that approximately twice as much work would be assigned to that computer. Automatically balancing this load is an avenue for future research.

A. This section may need to be merged with the rest of the CHRONUS section

The centralized structure of Hadoop requires that the NameNode be solely responsible for keeping track of where all the data is in the network[2]. CHRONUS has two options for the handling of the data used for performing MapReduce. Data may be distributed by the stager along with the dissemination of the Map and Reduce functions. The data may also be stored in the ring[3]. In either case, no single node is responsible for knowing the location of all of the data.

Because in CHRONUS nodes do not know stuff is, we need an intelligent procedure to send and store large volumes of data. Attempting to distribute each data atom via its own individual message quickly overwhelmed the networking library. Thus, when the stager distributes data atoms, it sends at most one message to each of its fingers. This message contains the subset of data atoms for which that subsection of the network is responsible for. This data is further divided by those servers such that the data atoms are distributed via an emergent minimum spanning tree, similar to the bounded broadcast¹⁰ used in [6]. The intermediate data being sent back using the Chord routing protocol produces a similar emergent tree.

The execution of the Reduce stage in this manner prevents the node responsible for the final result from being overwhelmed with traffic [13]. This configuration ensures that the average amount of data transferred between any two nodes is less than or equal to $\frac{\text{size of all intermediate data}}{\text{number of nodes}}$. This assumes that the Reduce step results in a data atom whose contents are equal to or less than the size of the combined intermediate data. This is guaranteed to be equal to or less than the average amount of data distributed from each DataNode to the NameNode in Hadoop¹¹.

- DataNodes register with the NameNode, so that the DataNode's identity and responsibilities persist even if the node is restarted under a different address or port.
- no need for heartbeats. HFDS has nodes send a heartbeat to the NameNode every 3 seconds [12].

VI. EXPERIMENTS

To stress test our framework, we ran a Monte-Carlo approximation of π . This process is largely analogous to having a square with the top-right quarter of a circle going through it (fig. Dartboard), and then throwing darts at it. We then check to see where these darts land. Counting the ratio of darts that

land inside the circle¹² to the total number of throws give us an approximation¹³ of $\frac{\pi}{4}$.

This makes the job extremely easy to distribute. Each map job defines the number of throws the node needs to make and yields an intermediate result containing the number of throws that node made and the number of those throws that landed inside the circular section. Reducing intermediate results is then a matter of adding the respective fields of the intermediate results together.

A. Setup

We ran this experiment under these scenarios with these systems.

Once started, nodes pull the latest version of the code and run it, automatically joining the network. We can choose any arbitrary node as the stager and tell it to run the MapReduce process. We found that the network was robust enough that we could take a node we wanted to be the stager out of the network, modify its MapReduce test code, have it rejoin the network, and then run the code new code without any problems. Since only the stager has to know how to create the map tasks, the other nodes don't have to be updated and are happy to perform the tasks they are given.

B. Results

Look at our data! See how nice and pretty it is? Look at those graphs! Aren't they lovely and informative?

VII. CONCLUSION AND FUTURE WORK

Our stuff [11] is awesome. CHRONUS can be adapted to handle mutable data, unlike other MapReduce schemes. Tackle security and distributed authentication. We can have multiple non-interacting secure file systems. Really security, We're aware that as our prototype code currently stands, and an adversary could make his map and reduce tasks do anything he wants (I direct your attention to the word *prototype*)

1) *File system via hash prefixing*: First k bits of hash used to describe files

REFERENCES

- [1] Adam L. Beberg, Daniel L. Ensign, Guha Jayachandran, Siraj Khaliq, and Vijay S. Pande. Folding@home: Lessons from eight years of volunteer distributed computing. In *Parallel & Distributed Processing, 2009. IPDPS 2009. IEEE International Symposium on*, pages 1–8. IEEE, 2009.
- [2] Dhruba Borthakur. The hadoop distributed file system: Architecture and design, 2007.
- [3] Frank Dabek, M. Frans Kaashoek, David Karger, Robert Morris, and Ion Stoica. Wide-area cooperative storage with cfs. *ACM SIGOPS Operating Systems Review*, 35(5):202–215, 2001.
- [4] Jeffrey Dean and Sanjay Ghemawat. Mapreduce: simplified data processing on large clusters. *Communications of the ACM*, 51(1):107–113, 2008.
- [5] Kyong-Ha Lee, Yoon-Joon Lee, Hyunsik Choi, Yon Dohn Chung, and Bongki Moon. Parallel data processing with mapreduce: a survey. *ACM SIGMOD Record*, 40(4):11–20, 2012.

¹²caption for the figure: The "dartboard." The computer throws a dart by choosing a random x and y . If $x^2 + y^2 < 1^2$, the dart landed inside the circle.

¹³This is not intended to be a particularly good approximate of π .

¹⁰check the above about bounded broadcast

¹¹PROOF WOULD BE NICE

- [6] Kyungyong Lee, Tae Woong Choi, A. Ganguly, D.I. Wolinsky, P.O. Boykin, and R. Figueiredo. Parallel processing framework on a p2p system using map and reduce primitives. In *Parallel and Distributed Processing Workshops and Phd Forum (IPDPSW), 2011 IEEE International Symposium on*, pages 1602–1609, 2011.
- [7] Gurmeet Singh Manku, Mayank Bawa, Prabhakar Raghavan, et al. Symphony: Distributed hashing in a small world. In *USENIX Symposium on Internet Technologies and Systems*, page 10, 2003.
- [8] Fabrizio Marozzo, Domenico Talia, and Paolo Trunfio. P2p-mapreduce: Parallel data processing in dynamic cloud environments. *Journal of Computer and System Sciences*, 78(5):1382–1402, 2012.
- [9] Andrew Pavlo, Erik Paulson, Alexander Rasin, Daniel J Abadi, David J DeWitt, Samuel Madden, and Michael Stonebraker. A comparison of approaches to large-scale data analysis. In *Proceedings of the 2009 ACM SIGMOD International Conference on Management of data*, pages 165–178. ACM, 2009.
- [10] Luigi Rizzo. Effective erasure codes for reliable computer communication protocols. *ACM SIGCOMM Computer Communication Review*, 27(2):24–36, 1997.
- [11] Andrew Rosen, Brendan Benshoof, and Matt Erwin. Chronus. <https://github.com/BrendanBenshoof/CHRONUS>.
- [12] Konstantin Shvachko, Hairong Kuang, Sanjay Radia, and Robert Chansler. The hadoop distributed file system. In *Mass Storage Systems and Technologies (MSST), 2010 IEEE 26th Symposium on*, pages 1–10. IEEE, 2010.
- [13] Konstantin V. Shvachko. Scalability of the hadoop distributed file system. <http://developer.yahoo.com/blogs/hadoop/scalability-hadoop-distributed-file-system-452.html>.
- [14] Ion Stoica, Robert Morris, David Karger, M. Frans Kaashoek, and Hari Balakrishnan. Chord: A scalable peer-to-peer lookup service for internet applications. *SIGCOMM Comput. Commun. Rev.*, 31:149–160, August 2001.