

Week # 15

Monday's Lecture

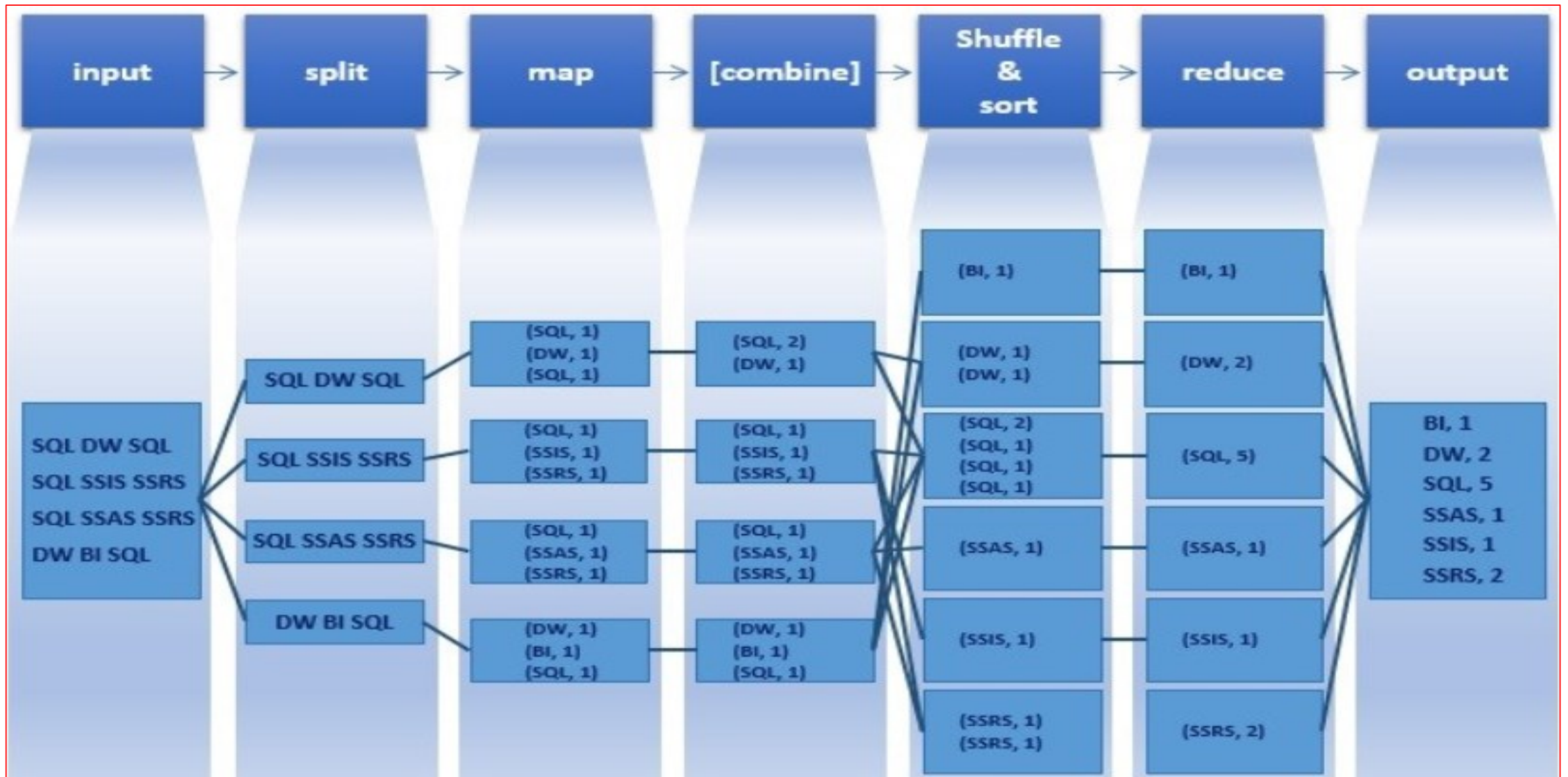
Map Function code template

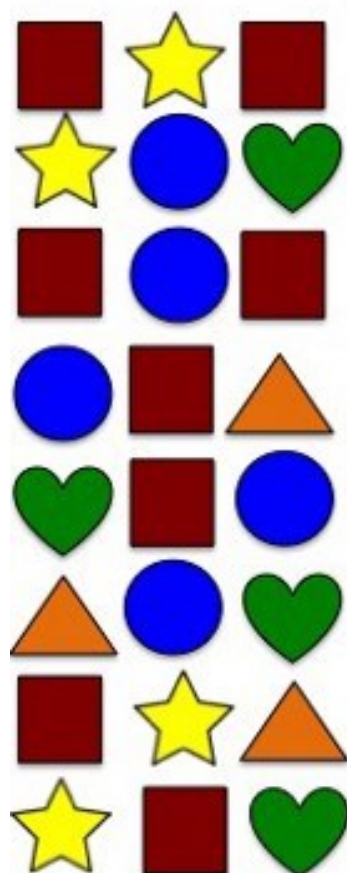
```
virtual void Map(const MapInput& input) {
    const string& text = input.value();
    const int n = text.size();
    for (int i = 0; i < n; ) {
        // Skip past leading whitespace
        while ((i < n) && isspace(text[i]))
            i++;

        // Find word end
        int start = i;
        while ((i < n) && !isspace(text[i]))
            i++;
        if (start < i)
            Emit(text.substr(start, i-start), "1");
    }
}
```

Reduce Function code template

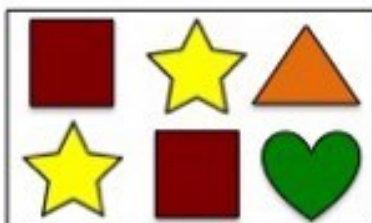
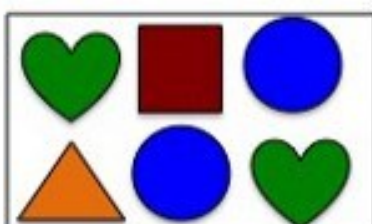
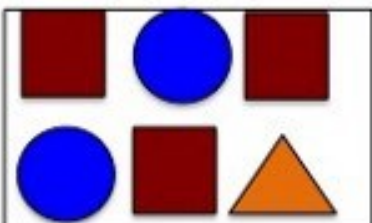
```
virtual void Reduce(ReduceInput* input) {  
    // Iterate over all entries with the  
    // same key and add the values  
    int64 value = 0;  
    while (!input->done()) {  
        value += StringToInt(input->value());  
        input->NextValue();  
    }  
  
    // Emit sum for input->key()  
    Emit(IntToString(value));  
}
```



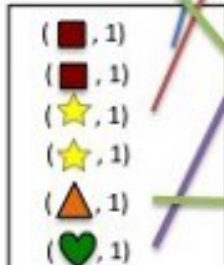
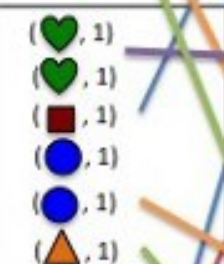
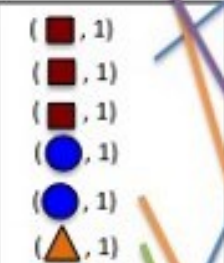
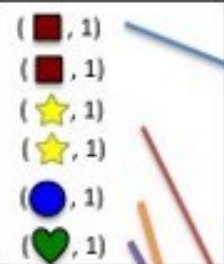


STEP 0 – STORE TO HDFS

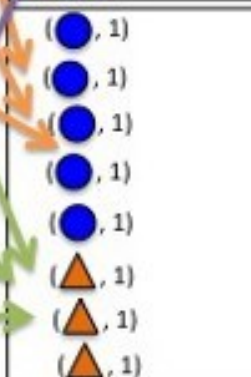
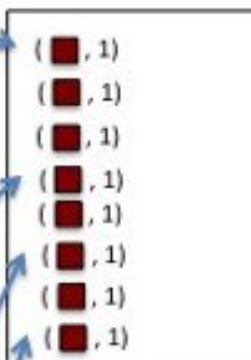
Assume 4 data
partitions.



1 - MAP



2 – SHUFFLE and SORT



3 - REDUCE

(Red square , 8)

(Yellow star , 4)

(Blue circle , 5)

(Green heart , 4)

(Orange triangle , 3)

Write Map and Reduce C code

- Suppose a large web log is already stored on a HDFS in the form of a CSV file. This file has the following fields per line:
 - hostname,
 - host IP address,
 - timestamp,
 - browser name (e.g. Chrome, Firefox, Edge),
 - URL requested,
 - amount of data sent.
- Write Map and Reduce function C code for the following:

Write Map and Reduce C code (2)

- How much data is requested per unique URL?
 - The output file contains URL and total data requested.
- Which host provided the URL to the user?
 - The output file contains hostname and a list of URLs.
- Count the number of hosts in the cluster. The output file contains the sentence "This cluster consists of 250 hosts".


```
//  
//Q8(a):How much data is requested per unique URL? The output file contains URL and total data requested.  
//  
Map(const MapInput& input) {  
    const string& str = input.value();  
    const int n = text.size();  
  
    string& p_key = get_key (str,"REQ_URL"); // string operation per line  
    string& p_value = get_value (str,"DATA_SENT"); // strings operations per line  
    Emit(p_key,p_value);  
}  
Reduce(ReduceInput* input) {  
    // Iterate over all entries with the same key and concatenate the values  
    int64 value = 0;  
  
    while (!input->done()) {  
        value += StringToInt(input->value());  
        input->NextValue();  
    }  
    Emit(value); // Emit sum for input->key()  
}
```

```

//
// Q8(b) Which host provided the URL to the user? The output file contains hostname and a list of URLs.
//
Map(const MapInput& input) {
    const string& str = input.value();
    const int n = text.size();

    string& p_key = get_key (str,"HOST"); // string operation per line
    string& p_value = get_value (str,"REQ_URL"); // strings operations per line
    Emit(p_key,p_value);
}

Reduce(ReduceInput* input) {
    // Iterate over all entries with the same key and concatenate the values. Also count
    string& p_value_list;
    int64 count = 0;
    while (!input->done()) {
        count++;
        p_value_list = p_value_list + "," + input->value();
        input->NextValue();
        p_value_list = IntToString(count) + " URLs. List: " + p_value_list;
    }
    Emit(p_value_list); // Emit sum for input->key()
}

```

```
//
//c) Count the number of hosts in the cluster. The output file contains the sentence
// "This cluster consists of 250 hosts", where 250 is the computed value.
//
Map(const MapInput& input) {
    const string& str = input.value();
    const int n = text.size();

    string& p_key = get_key (str,"HOST"); // string operation per line
    if check_valid_host(p_key) // check validity of host
    |   Emit("HOST",1); // for counting we ignore host name and use only "HOST" string
}
Reduce(ReduceInput* input) { // As there is only one key HOST this is the only reducer in the system
    // Iterate over all entries with the same key and concatenate the values
    int64 value = 0;
    string& p_value_list;

    while (!input->done()) {
        value += StringToInt(input->value());
        input->NextValue();
    }
    p_value_list = "This cluster consist of " + IntToString(value) + "hosts";
    Emit(p_value_list); // Emit sum for input->key()
}
```

More Examples

Distributed Grep: The map function emits a line if it matches a supplied pattern. The reduce function is an identity function that just copies the supplied intermediate data to the output.

Count of URL Access Frequency: The map function processes logs of web page requests and outputs $\langle \text{URL}, 1 \rangle$. The reduce function adds together all values for the same URL and emits a $\langle \text{URL}, \text{total count} \rangle$ pair.

Reverse Web-Link Graph: The map function outputs $\langle \text{target}, \text{source} \rangle$ pairs for each link to a target URL found in a page named `source`. The reduce function concatenates the list of all source URLs associated with a given target URL and emits the pair: $\langle \text{target}, \text{list}(\text{source}) \rangle$

Term-Vector per Host: A term vector summarizes the most important words that occur in a document or a set of documents as a list of $\langle \text{word}, \text{frequency} \rangle$ pairs. The map function emits a $\langle \text{hostname}, \text{term vector} \rangle$ pair for each input document (where the hostname is extracted from the URL of the document). The reduce function is passed all per-document term vectors for a given host. It adds these term vectors together, throwing away infrequent terms, and then emits a final $\langle \text{hostname}, \text{term vector} \rangle$ pair.

Inverted Index: The map function parses each document, and emits a sequence of $\langle \text{word}, \text{document ID} \rangle$ pairs. The reduce function accepts all pairs for a given word, sorts the corresponding document IDs and emits a $\langle \text{word}, \text{list}(\text{document ID}) \rangle$ pair. The set of all output pairs forms a simple inverted index. It is easy to augment this computation to keep track of word positions.

3.1 Execution Overview

The *Map* invocations are distributed across multiple machines by automatically partitioning the input data into a set of M *splits*. The input splits can be processed in parallel by different machines. *Reduce* invocations are distributed by partitioning the intermediate key space into R pieces using a partitioning function (e.g., $\text{hash}(\text{key}) \bmod R$). The number of partitions (R) and the partitioning function are specified by the user.

Figure 1 shows the overall flow of a MapReduce operation in our implementation. When the user program calls the `MapReduce` function, the following sequence of actions occurs (the numbered labels in Figure 1 correspond to the numbers in the list below):

1. The MapReduce library in the user program first splits the input files into M pieces of typically 16 megabytes to 64 megabytes (MB) per piece (controllable by the user via an optional parameter). It then starts up many copies of the program on a cluster of machines.
2. One of the copies of the program is special – the master. The rest are workers that are assigned work by the master. There are M map tasks and R reduce tasks to assign. The master picks idle workers and assigns each one a map task or a reduce task.

3. A worker who is assigned a map task reads the contents of the corresponding input split. It parses key/value pairs out of the input data and passes each pair to the user-defined *Map* function. The intermediate key/value pairs produced by the *Map* function are buffered in memory.
4. Periodically, the buffered pairs are written to local disk, partitioned into R regions by the partitioning function. The locations of these buffered pairs on the local disk are passed back to the master, who is responsible for forwarding these locations to the reduce workers.
5. When a reduce worker is notified by the master about these locations, it uses remote procedure calls to read the buffered data from the local disks of the map workers. When a reduce worker has read all intermediate data, it sorts it by the intermediate keys so that all occurrences of the same key are grouped together. The sorting is needed because typically many different keys map to the same reduce task. If the amount of intermediate data is too large to fit in memory, an external sort is used.
6. The reduce worker iterates over the sorted intermediate data and for each unique intermediate key encountered, it passes the key and the corresponding set of intermediate values to the user's *Reduce* function. The output of the *Reduce* function is appended to a final output file for this reduce partition.

7. When all map tasks and reduce tasks have been completed, the master wakes up the user program. At this point, the `MapReduce` call in the user program returns back to the user code.

After successful completion, the output of the mapreduce execution is available in the R output files (one per reduce task, with file names as specified by the user). Typically, users do not need to combine these R output files into one file – they often pass these files as input to another MapReduce call, or use them from another distributed application that is able to deal with input that is partitioned into multiple files.

Worker Failure

The master pings every worker periodically. If no response is received from a worker in a certain amount of time, the master marks the worker as failed. Any map tasks completed by the worker are reset back to their initial *idle* state, and therefore become eligible for scheduling on other workers. Similarly, any map task or reduce task in progress on a failed worker is also reset to *idle* and becomes eligible for rescheduling.

Completed map tasks are re-executed on a failure because their output is stored on the local disk(s) of the failed machine and is therefore inaccessible. Completed reduce tasks do not need to be re-executed since their output is stored in a global file system.

When a map task is executed first by worker *A* and then later executed by worker *B* (because *A* failed), all workers executing reduce tasks are notified of the re-execution. Any reduce task that has not already read the data from worker *A* will read the data from worker *B*.

MapReduce is resilient to large-scale worker failures. For example, during one MapReduce operation, network maintenance on a running cluster was causing groups of 80 machines at a time to become unreachable for several minutes. The MapReduce master simply re-executed the work done by the unreachable worker machines, and continued to make forward progress, eventually completing the MapReduce operation.

Master Failure

It is easy to make the master write periodic checkpoints of the master data structures described above. If the master task dies, a new copy can be started from the last checkpointed state. However, given that there is only a single master, its failure is unlikely; therefore our current implementation aborts the MapReduce computation if the master fails. Clients can check for this condition and retry the MapReduce operation if they desire.

3.4 Locality

Network bandwidth is a relatively scarce resource in our computing environment. We conserve network bandwidth by taking advantage of the fact that the input data (managed by GFS [8]) is stored on the local disks of the machines that make up our cluster. GFS divides each file into 64 MB blocks, and stores several copies of each block (typically 3 copies) on different machines. The MapReduce master takes the location information of the input files into account and attempts to schedule a map task on a machine that contains a replica of the corresponding input data. Failing that, it attempts to schedule a map task near a replica of that task's input data (e.g., on a worker machine that is on the same network switch as the machine containing the data). When running large MapReduce operations on a significant fraction of the workers in a cluster, most input data is read locally and consumes no network bandwidth.

3.5 Task Granularity

We subdivide the map phase into M pieces and the reduce phase into R pieces, as described above. Ideally, M and R should be much larger than the number of worker machines. Having each worker perform many different tasks improves dynamic load balancing, and also speeds up recovery when a worker fails: the many map tasks it has completed can be spread out across all the other worker machines.

Furthermore, R is often constrained by users because the output of each reduce task ends up in a separate output file. In practice, we tend to choose M so that each individual task is roughly 16 MB to 64 MB of input data (so that the locality optimization described above is most effective), and we make R a small multiple of the number of worker machines we expect to use. We often perform MapReduce computations with $M = 200,000$ and $R = 5,000$, using 2,000 worker machines.

4.3 Combiner Function

In some cases, there is significant repetition in the intermediate keys produced by each map task, and the user-specified *Reduce* function is commutative and associative. A good example of this is the word counting example in Section 2.1. Since word frequencies tend to follow a Zipf distribution, each map task will produce hundreds or thousands of records of the form `<the, 1>`. All of these counts will be sent over the network to a single reduce task and then added together by the *Reduce* function to produce one number. We allow the user to specify an optional *Combiner* function that does partial merging of this data before it is sent over the network.

The *Combiner* function is executed on each machine that performs a map task. Typically the same code is used to implement both the combiner and the reduce functions. The only difference between a reduce function and a combiner function is how the MapReduce library handles the output of the function. The output of a reduce function is written to the final output file. The output of a combiner function is written to an intermediate file that will be sent to a reduce task.

Partial combining significantly speeds up certain classes of MapReduce operations. Appendix A contains an example that uses a combiner.

4.4 Input and Output Types

The MapReduce library provides support for reading input data in several different formats. For example, “text” mode input treats each line as a key/value pair: the key is the offset in the file and the value is the contents of the line. Another common supported format stores a sequence of key/value pairs sorted by key. Each input type implementation knows how to split itself into meaningful ranges for processing as separate map tasks (e.g. text mode’s range splitting ensures that range splits occur only at line boundaries). Users can add support for a new input type by providing an implementation of a simple *reader* interface, though most users just use one of a small number of predefined input types.

A *reader* does not necessarily need to provide data read from a file. For example, it is easy to define a *reader* that reads records from a database, or from data structures mapped in memory.

In a similar fashion, we support a set of output types for producing data in different formats and it is easy for user code to add support for new output types.

5.1 Cluster Configuration

All of the programs were executed on a cluster that consisted of approximately 1800 machines. Each machine had two 2GHz Intel Xeon processors with Hyper-Threading enabled, 4GB of memory, two 160GB IDE disks, and a gigabit Ethernet link. The machines were arranged in a two-level tree-shaped switched network with approximately 100-200 Gbps of aggregate bandwidth available at the root. All of the machines were in the same hosting facility and therefore the round-trip time between any pair of machines was less than a millisecond.

Out of the 4GB of memory, approximately 1-1.5GB was reserved by other tasks running on the cluster. The programs were executed on a weekend afternoon, when the CPUs, disks, and network were mostly idle.

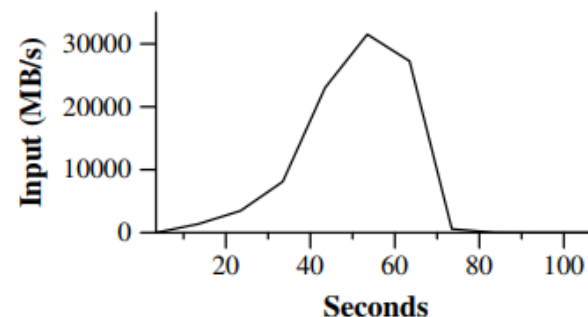


Figure 2: Data transfer rate over time