

CPS352 Lecture - Map/Reduce Paradigm; NoSQL DBMS's

Last revised April 6, 2023

Objectives:

1. To review speedup and scaleup issues
2. To introduce the Map/Reduce Paradigm
3. To elucidate reasons for a desire to move to models other than the relational model for some applications
4. To introduce key-value, document, column store, and graph data models.
5. To discuss issues involved in choosing an approach for a particular problem

Materials:

1. Projectable of map and reduce examples
2. Projectable of excerpt from a web server log file
3. Projectables of Sadalage/Fowler figures 2.1, 2.3, 2.3 with corresponding JSON, 2.4 with corresponding JSON, 2.5
4. Prprojectable of Sadalage/Fowler Figures 11.1, 11.2

I. Introduction

A. The chapter assigned for today in the textbook talks about "Big Data". This is something of a buzz word that captures the idea that applications are arising that depend on being able to deal with huge amounts of data - sizes much greater than the kinds of problems for which DBMS's were first developed.

1. Analytics dealing with data produced by web sites or other processors of large volumes of data such as Netflix.
2. All sorts of Data Mining
3. etc.

B. We saw last time that with growing problem sizes and reliance on interactive access through pweb ages, several needs have arisen.

1. The need for SCALEUP - to make it possible to handle a greater volume of work in the same amount of time. This, in turn has two sub-categories:
 - a. BATCH SCALEUP may be needed to deal with the SIZE of individual transactions, as would occur if transactions become more complex and/or if the size of a database grows, so that operations such as select and join require scanning more tuples.
 - b. TRANSACTION SCALEUP may be needed to deal with increasing the VOLUME of transactions, as would occur if the number of users accessing the database were to grow.
2. The need for transaction SPEEDUP - to make the processing of individual transactions (of the same size) faster - to satisfy the expectations of interactive users.

C. To meet such needs, new database models have arisen that can cope with size. These deal with issues like:

1. Support for computations using massive parallelism - e.g. scores, hundreds, or thousands of processors working together on a single problem. We talked about this idea last time. Today we will look at a particular software approach that is widely used on parallel systems, known as the map/reduce paradigm.
2. Support for handling a rate and/or size of transaction arrival that requires moving away from the requirement of normalized data and the support for ACID transactions that have characterized the relational model. There are a number of such models that are collectively known (actually somewhat inaccurately) as NoSQL models.

D. Before we look at NoSQL models, we will consider a programming paradigm that is useful when dealing with large volumes of data, regardless of how stored.

II. Map/Reduce

A. Map/reduce is a programming paradigm that supports a very high degree of parallelism.

1. Though not directly tied to NoSQL databases, it is often used in conjunction with them, but can also be used with relational databases.
2. For example: Google makes considerable use of the map-reduce paradigm, often using data stored in one of the non-relational database model they have developed such as what you'll read about in preparation for Dr. Tuck's guest lecture next class..

B. This paradigm makes use of two functions - a mapper and a reducer.

1. The mapper processes aggregates to produce key-value pairs. Since the processing of each aggregate is independent of the others, this can be done using massive parallelism.

PROJECT MAP EXAMPLE

2. All the key-value pairs having the same key - presumably from multiple processors are collected and submitted to a reducer, which reduces them to a single value. Reducing for different keys can also be done using massive parallelism.

PROJECT REDUCE EXAMPLE

3. The most widely used example of Map/Reduce - and one included in your book - is Word Count - count the frequency of occurrence of words is a collection of documents.
4. I will look at a different one - which I found by googling for an example of map/reduce other than Word Count. (Unfortunately, I couldn't seem to find the page again while writing this lecture!)

C. An example of Map/Reduce.

1. As you probably know, web servers maintain a log of operations they perform - e.g. GETs, PUTs, etc.
 - a. Each log entry includes a timestamp indicating when the request arrived.
 - b. Large web sites may produce thousands of log entries per hour.

Here's a few lines from the log file for the web server on our departmental site (cut off to fit the available space!)

```
172.17.1.2 - - [28/Feb/2021:07:00:23 -0500] "GET /courses/J2SEDocs/api/index.html?java/awt/CheckboxGr  
172.17.1.2 - - [28/Feb/2021:07:00:27 -0500] "GET / HTTP/1.1" 200 2530 "-" "NodePing"  
172.17.1.2 - - [28/Feb/2021:07:00:35 -0500] "GET / HTTP/1.1" 200 2511 "https://gigienadez.ru/" "Mozill  
172.17.1.2 - - [28/Feb/2021:07:00:35 -0500] "GET / HTTP/1.1" 200 2511 "https://gigienadez.ru/" "Mozill
```

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2. Now suppose that an operation such as installation of new software on a web-server requires that the server be shut down for an hour. To minimize the inconvenience to the users, it is desired to schedule the maintenance at a time when the least number of requests is anticipated. (Some users will be inconvenienced - the goal is to inconvenience as few as possible.)
3. One way to choose a time would be to analyze the log files to see what hour during the day typically has the least traffic.
 - a. In order to get reliable results, it is desired to do this with a month's worth of log files.
 - b. The size of the log files is such that use of parallel processing is needed to get results quickly enough.
4. The task is broken down into two parts - a map part and a reduce part - with a shuffle in between.

- a. In the map part 30 (or 31) processors are assigned to each analyze the log file for one day during the month. The task is to count the number of operations done during each of the 24 hours of that day.
 - i. This task is made easier by the fact that the log entries are kept in order of time.
 - ii. Nonetheless, this involves reading each line in the log and extracting the hour at which it was done, so a significant amount of computation is involved.
 - iii. The output of the map part is 24 pairs of numbers, each consisting of one of the numbers 0 to 23 (assume military time is used) and the number of operations logged during that hour.
 - b. In the reduce part, each of 24 processors is assigned to one of the hours of the day. It receives the pairs from the mappers specifying the assigned hour - 30 pairs in all. Its task is to reduce the pairs to the sum of the counts.
 - c. The final output is 24 pairs - each consisting of an hour number and the count of operations occurring during the month in that hour. From this information, it is easy to choose the hour with the least activity for the maintenance.
- D. As an aside - does this remind you of anything you've done in a previous course?

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map() and reduce() in Python - which draw on this idea though not done in parallel in CPS121, of course!

III. Issues Arising From the Relational Model When Dealing with a High Rate of Transactions - Motivating Alternate Models

A. As we have noted throughout the course, the relational model has become the dominant database model and remains the best choice for many applications. However, there are good reasons why an alternate model might be desirable in certain cases. The reasons why the relational model has prevailed include:

1. Support for integrating data from multiple applications, and allowing multiple applications to share a common database.
2. An interactive query facility which allows accessing data without custom programming through the use of a common language: SQL.
3. Strong support for ACID transactions that are central to maintaining database consistency in the face of concurrent operations and threats of data lost due to things like hardware failure.

B. However, significant issues arise with the use of the relational model for some very large applications or those serving a large number of users simultaneously - e.g. large-scale analytics and web ecommerce, among others.

C. One of the key reasons for interest in non-relational models arises from the ramifications of support for ACID transactions in the context of cluster or distributed systems.

1. Traditionally, databases have been stored on single computer systems.

If more performance was needed, the solution was to use a faster computer and disk subsystem.

But there are fundamental speed and capacity limits on this, of course.

2. Typically, when high performance is needed, the solution of choice has been to use clusters of scores, hundreds, or even thousands of inexpensive processors - perhaps housed in a single location or multiple locations.

3. Often distributed systems are used to prevent temporarily losing the ability to access the database at all in the event of the failure of a single site due to power or network issues.
4. For a variety of reasons, when parallel and/or distributed systems are used, it is generally impractical to store a complete copy of the database on each of the systems managing it - which would entail maintaining hundreds or thousands of complete copies of the database.
 - a. Instead, this is typically addressed by "sharding" the data so that different portions are stored on different systems - which could mean that for many transactions only a single system needs to be accessed.

The sharding scheme may be set up intentionally, or the DBMS itself may handle the sharding and the mapping of accesses to the correct shard.
 - b. In addition, each shard is generally stored in more than one place to avoid losing access to its data if the system on which it is stored goes down - which implies that an update transaction will need to update multiple copies.
 - c. Support for ACID transactions then entails communication between the various processors and/or physical locations when a transaction involves accessing data stored at more than one location or updating replicated data.
5. We have seen that the CAP theorem says that, in a distributed context, you can have any two of Consistency, Availability, and Partition Tolerance - but you cannot have all three. .
 - a. Since the kinds of physical failures that result in partitioning a network are not avoidable, sacrificing Partition Tolerance is generally not an option, since this would mean shutting down the entire system should a partition occur.

- b. In practice, then, this boils down to saying that there is a tradeoff between Consistency and Availability - where there is no one "right" answer for all systems.
 - c. This is a motivation for moving away from a database model that entails support for ACID transactions.
 - d. We have noted that one alternative to strict ACID consistency in such systems is sometimes called BASE - Basically Available, Soft State, Eventually Consistent.
6. The relational model exacerbates the problem because normalization typically requires partitioning entities across multiple tables - increasing the number of tables that must be updated atomically.

This becomes a motivation for moving away from the traditional relational model.

D. The Normalization requirement for Relational Databases leads to needing to use joins - sometimes several of them - for many queries. But joins are computationally expensive, which becomes a significant issue when handling a large volume of queries.

E. Another Issue Relates to Structured and Unstructured Data

- 1. The relational model expects that every row in a given table has the same set of columns, each of which holds the same type of data (whether atomic or non-atomic in a relational extension). The structure of the individual tables - and their relationships to one another - is represented by an explicit schema.
- 2. While this works well for many applications, there are some applications that require the ability to handle data that is inherently nonstructured - eg processing involving the content of social media posts.

F. The impedance mismatch between the relational data model and the requirements of OO we talked about earlier, together with the performance implications of supporting ACID transactions in the relational model on high performance systems, the dependence on joins for many queries, and the need to deal with unstructured data in some cases has led to an interest in exploring other data models that differ significantly from the relational model.

1. These models are known collectively as "NoSQL models". In much of this lecture, I will draw heavily on a book called *NoSQL Distilled* by Prasad Sadalage and Martin Fowler. (In our library, and a good place to go if you want to study this further.)

2. Actually, that's basically a term of convenience and something of a misnomer.

The term was originally used as the name for a relational database that didn't support SQL.

3. The term has come to be used collectively a variety of different data models - most of which share some common characteristics.

a) They are not relational, and don't use standard SQL - though some support a variant of SQL. Access to information is generally done through a programming language interface.

b) They have no strict schema - the structure of individual records is dynamic and can vary from record to record.

c) They are generally - but not always - open-source.

d) They are generally - but not all - cluster-oriented.

e) The first two of these (not relational, no schema) are characteristic of all NoSQL models. The last two (open-source, cluster-oriented) are not true of all.

4. Sadalage and Fowler distinguish four broad categories of NoSQL models: key-value, document, column-family, and graph. These are all quite different from each other!

IV.A quick overview of NoSQL models

A. Before we look at these models in detail, though, it is worth noting that there are things that are lost by going this way - hence the need for considering tradeoffs.

1. Sadalage and Fowler draw a distinction between what it calls "integration databases" and "application databases".
 - a) An integration database supports integrating multiple applications using a common database. This is a strength of the relational model.
 - b) An application database is "owned" by a single application (like in the old file-processing days) - though this can be ameliorated by making data available through web services.
 - c) Relational databases do well as integration databases; while NoSQL databases can serve well as application databases but do not support integration of multiple applications with diverse requirements well.

One writer (C.J. Date) puts it this way: "Although the programming language and database management disciplines certainly have a lot in common, they do also differ in certain important aspects (of course). To be specific: An application program is intended - by definition - to solve some specific problem. By contrast, a database is intended - again by definition - to solve a variety of different problems, some of which might not even be known at the time the database is established." (*An Introduction to Database Systems* - 7th ed (Addison Wesley, 2000) p. 813)

2. Support for ad-hoc queries. It would be hard to imagine an ordinary user formulating queries interactively in a programming language such as C++,

Java, or C# - though some of the NoSQL models do provide some support for interactive queries, even including some SQL-like facilities, as we shall see.

3. Support for “set at a time” processing - to perform some operation on all the members of a top-level collection, one must code a loop using something akin to an iterator.
4. Support for referential integrity through notion of keys, etc.
5. For this reason, Sadalage and Martin argue for the notion of "polyglot persistence" - choosing the appropriate model to fit a particular set of needs. This may be a relational database or one of the NoSQL models.

B. Database Models Based on Aggregates

1. Three of the four kinds of NoSQL model store data in aggregates, rather than in tables. Something of the difference between the two approaches can be seen from examples in the Sadalage and Fowler book:

- a) The reality to be modeled.

PROJECT Sadalage Figure 2.1

- b) A corresponding relational database structure

PROJECT Sadalage Figure 2.2

- c) An aggregate structure using two kinds of aggregates - customer and order. (Full information on products is represented elsewhere).

PROJECT Sadalage Figure 2.3 and JSON for aggregates

- d) Orders could also be embedded in the customer aggregate.

PROJECT Sadalage Figure 2.4 and JSON

2. Two things are gained by using aggregates.

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- a) Fewer disk accesses - in the second case everything needed to handle an order can be transferred by one disk read and one disk write.
- b) Simpler code.

3. Some things are also lost by using aggregates.

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- a) The ability to access parts of an aggregate without writing special code - e.g. the ability to look at all orders for a given product, rather than for a given customer (requires accessing all the customer aggregates.)
 - b) Sadalage and Fowler cite this as another example of the difference between integration and application databases.
4. Aggregates do facilitate sharding, since if a database using aggregates is sharded, data that is accessed together will often end up in the same aggregate and hence in the same shard.

[Omit if insufficient time]

5. Several of the NoSQL models are built on use of aggregates.

- a) Key-value databases store key-value pairs - the key is a unique identifier and the value is an aggregate, whose internal structure is opaque to the database. (Thus all the database can do is allow the program to access, store or delete aggregates by key, but getting at what is stored within is the responsibility of the application program.)

- (1) The value associated with a given key may be stored as JSON - as in the examples earlier of aggregate structures, or XML, or any sort of binary data.
- (2) Sadalage and Fowler suggest places where a key-value store might be used, including:
 - (a) Shopping carts - the key would be the user's identifier (like the user's username or email), and the value would be the entire contents of the shopping cart. Stored this way, the entire cart can be accessed by a single disk access.
 - (b) User preferences / profile information - again the key would be the user's identifier and the values would be the users' preferences / profile - all accessible via a single disk access.
- (3) They also cite places where a key-value database might not be desirable.
 - (a) Applications involving relationships between items that are not part of the same bucket.
 - (b) Transactions that involve operations on two or more different aggregates - since, while access to a single aggregate is atomic, there is may be no mechanism for accessing several aggregates as a single atomic operation.
 - (c) Queries based on data stored in an aggregate.
 - (d) Queries requiring access to multiple aggregates (set at a time processing.)
- (4) Amazon's DynamoDB - which is part of the Amazon Web Services (AWS) portfolio is a member of this family.

b) Document databases are similar to key-value databases, but have some knowledge of the internal structure of the aggregate - and so can allow some access to the content of the aggregate through the DBMS.

(1) This is done by requiring the document to be stored using a notation such as JSON or XML or similar.

(2) However, there is no schema requiring all documents to have the same structure.

(3) The DBMS is able to perform queries and based on the content of the document, not just on the key, and can do partial updates of the content of the document.

(4) The DBMS also supports indexes based on the content of aggregates.

(5) MongoDB - a widely-used open-source DBMS - is an example of a member of this family that stores documents represented using JSON.

c) Column-family databases can be thought of as two-level aggregates - i.e. each aggregate is itself a map of keys and values stored in that aggregate. The result ends up looking something like this:

PROJECT Sidalage/Fowler Figure 2.5

Google's BigTable (now superseded) was an example of a member of this family

C.Graph Databases [Omit if insufficient time]

1. As we pointed out earlier, the term "NoSQL" is a generic term that encompasses a wide variety of databases. We now consider a type of database that is included in the NoSQL category, though it is not an

aggregate-oriented model (though it does share the other characteristics of NoSQL databases): the Graph Database.

2. One of the weaknesses of aggregate-oriented models is that relationships are only represented within aggregates (e.g. by physical proximity). There is no support for relationships between entities in different aggregates. A graph database, on the other hand, models relationships explicitly by means of nodes that represent entities and links that represent relationships (that can have names and values).

PROJECT: Sadalage/Fowler Figure 11.1

3. Though both relational and graph databases provide for modeling relationships between entities, the way that they do it is very different.
 - a) In a relational database, the relationships are part of the schema - so every row in the same table participates (at least potentially) in a defined set of relationships.
 - b) In a graph database, there is no schema that defines things like:
 - i. What relationships a given node can participate in.
 - ii. What properties a node may have.
 - iii. What properties a relationship may have.

PROJECT Sadalage/Fowler Figure 11.2.

4. Graph databases support a variety of queries based on traversing the graph.
5. In contrast to the other NoSQL models, many graph databases are designed to run on a single system, rather than a cluster. If sharding becomes necessary for performance reasons, the shards need to be based on application-specific criteria, as in the following example: But note that

graph databases work typically work better with a single node.

PROJECT Sadalage/Fowler Figure 11.3

6. Graph databases support ACID transactions involving various nodes and relationships.

D. Other Issues - Resume Covering Here if no time for Model details

1. NoSQL databases are schema-less. (The technical term is they have emergent schemas - i.e. each aggregate has its own schema). This has advantages and disadvantages.

a. Advantages

- i. No need to predefine data structures.
- ii. Easy to change as needed.
- iii. Good support for non-uniform data.

b. Disadvantages

- i. Potential for inconsistent names for the same value in different aggregates - e.g. quantity, Quantity, QUANTITY, qty etc.
(A scheme in a relational database would prevent this)
- ii. Instead, there is an implicit schema which the application must now enforce. So you need to look at the code to see what the scheme is.
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- iii. What do you do if multiple applications need to access the same database?

2. In an aggregate-oriented database, relationships can pose problems.

- a. There may be no DBMS support for traversing relationships (equivalent to foreign keys in a relational database), though some provide mechanisms to make link-walking easier.
 - b. But since there is no support for updating more than one aggregate atomically, updating relationships consistently can present a challenge.
3. There is no support for set-at-processing. So something like querying all the orders for a given item (across multiple aggregates) is complex.

V. Choosing between the Relational Model and a NoSQL Approach

Recall the Distinction between Integration Databases we Mentioned Earlier

- A. An integration database supports integrating multiple applications using a common database. When a database is to be used in this way, a relational database is often the best choice.
- B. An application database is "owned" by a single application (like in the old file-processing days). In the case of a single application of a very large database where performance is paramount, one of the NoSQL models may be a better choice.