

**Efficient Parallel Data Processing
in the Cloud**

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Summary

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Acknowledgements

Most of all I'd like to thank my project supervisor ...

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Chapter 1

Introduction

1.1 Project Aim

Large scale data processing is an emerging trend in Computing, with benefits to both academia and industry. The aim of this project is to investigate the challenges of large scale parallel data processing, discuss the benefits of Cloud Computing and investigate how the efficiency of large scale data processing may be improved.

This project will aim to provide a reasoned and objective evaluation of the efficiency of data processing techniques, whilst comparing current state of the art tools and technologies with newer research in the field.

Specifically, the data processing tools Hadoop and Nephele will be compared, allowing comparison of the individual tools, and a wider discussion of the pros and cons of the MapReduce and PACT programming paradigms.

1.1.1 Research Questions

The project aims to answer the following questions:

- Does PACT overcome the inherent disadvantages of the MapReduce paradigm?
- How well does Nephele perform MapReduce tasks?
- How do Hadoop and Nephele perform in a highly elastic Cloud Computing environment?

1.2 Objectives

The objectives of the project are:

- Investigate Cloud Computing, Big Data and other relevant background trends
- Design a series of experiments to determine the efficiency of data processing technologies
- Implement the experiments for both Hadoop and Nephele
- Evaluate the experiment results to draw meaningful conclusions to the research questions

1.3 Methodology

The project will be broken into three main phases. The order to the phases provides a structured approach to the project, and completion of each phase ensures the project is completed in a methodical manner. The **Background Research** section will provide a comprehensive literature review to provide context to the project. This will be followed by a phase of **Experimentation**, which will aim to test the necessary factors of Hadoop and Nephele to answer the research questions. Finally, the **Evaluation** phase will evaluate the results of the experiments and the project as a whole.

The phases of the project will be performed according to Agile principles. Work will be carried out in weekly sprints, with clearly defined targets for each sprint. Supervisor meetings will be used as an opportunity to reflect on the achievements and shortcomings of the previous week, and to set targets for the upcoming sprint.

1.3.1 Background Research

The background research will aim to provide context for the project by surveying the current research landscape. It will summarise the fundamental concepts underlying the project and give a strong theoretical foundation for the rest of the project.

The first section of the background research will focus on Cloud Computing. It will explore the principles of the cloud, the service and deployment models and the technologies which make the cloud possible. It will also look at the unique advantages that the cloud provides in data processing scenarios.

The second segment of the background research will look in to Big Data and what challenges it introduces. An overview will be given of tools and techniques which have been developed to process Big Data, including Hadoop and Nephele.

1.3.2 Experimentation

Experiments will be designed to test the efficiency of data processing tools in relevant situations. This will require identifying relevant areas of interest, and deriving scenarios which will test the efficiency

of Hadoop and Nephele. The experiments should be designed to take into account the various different problems that data processing tools are required to solve and to provide findings for the research questions.

As part of the experiment design, a hypothesis will be produced.

The experiments will be implemented and executed, in order to provide results which can be used to answer the research questions.

1.3.3 Evaluation

The project can be evaluated on various factors.

A technical evaluation will be carried out to analyse the results of the experiments. It will compare the efficiency of Hadoop and Nephele, referring to data obtained in the experimentation phase. The results will be compared to existing research (obtained during the background research) and the hypothesis, and any discrepancies will be discussed.

An evaluation will also be carried out to determine whether the aims and objectives of the project have been met. This will involve determining whether the research questions have been answered in a satisfactory manner, and determining the relevance of the project in regards to existing literature and how it contributes to the research landscape. Any future scope for research will be identified.

The methodology and management of the project will also be evaluated to identify areas of improvement in project management.

1.4 Schedule

The project schedule will be created around a set of fixed milestones in the project process. Work will be allocated in weekly sprints to ensure that the relevant work is completed in time for each milestone. Work will be prioritised so that scope can be cut to meet a milestone if required.

1.4.1 Milestones

There are a series of milestones which must be met throughout the project. This provides a framework for the project plan, as necessary tasks must be completed before the milestones.

1. Submission of Aims & Objectives

The Aims & Objectives of the project must be decided, which is crucial in setting the scope and direction for the rest of the project.

2. Presentation to the Distributed Systems and Services Group

The presentation to the Distributed Systems and Services group provides an opportunity to get early feedback on the project, and present much of what will be present in the mid year report. In order to present the project, a sufficient amount of content must be prepared. By this point a

substantial amount of background research should have been carried out, and early ideas about experimental design should be formed.

3. Mid-Year Project Report

The Mid-Year Project Report is a chance to get feedback from the assessor about the direction and progress of the project. By this stage the background research should be completed, and should demonstrate that necessary steps have been taken to understand the problem. The Aims & Objectives should be clearly defined, with a set of deliverables, a methodology, and a schedule. At this point experimental design will not have been completed, but the Mid-Year Report should give indications about the type of experiments that will be executed and why they were chosen. Finally, evidence of basic implementation should be shown, to demonstrate knowledge of the tools required for experiment implementation.

4. Progress Meeting

The progress meeting occurs in the late stages of the project, so at this point most of the work should be completed. Experiments should have been implemented and performed, and code should be available for inspection.

5. Final Report Submission

The final report submission marks a point where all work on the project has to be complete.

1.5 Deliverables

The project will deliver 2 things.

1. An evaluation of the efficiency of Hadoop and Nephele in various data processing situations
2. Code for experiments, designed to test the efficiency of Hadoop and Nephele

Chapter 2

Background Research

This chapter is intended to give an overview of the current research landscape, and to summarise the core technologies and concepts which form a basis for this project. The chapter will discuss trends toward Cloud Computing, how it is relevant to Data Processing, and key technologies which have been developed in this area, giving a foundation for further investigation into the efficiency of Data Processing techniques and how they are impacted by the Cloud.

2.1 Cloud Computing

Cloud Computing is the latest major infrastructure paradigm which looks to deliver on the promise of Utility Computing. In practice, the term ‘Cloud Computing’ is ambiguous. Whilst no clear definition exists many experts agree that the cloud exhibits the core benefits of Utility Computing such as elasticity and scalability, whilst making heavy use of virtualisation and pay-per-usage business models [30].

Elasticity in clouds refers to the ability for a user to dynamically select the amount of computing resources they require, allowing them to scale their applications according to demand. The resources that can be acquired are essentially limitless from the user’s perspective [21].

Elasticity represents a dramatic shift from the ‘traditional’ method of building and deploying applications. Rather than purchasing and provisioning hardware and acquiring physical space (such as a data centre), a user can use a Cloud Service Provider. This allows for greater flexibility in business and application development, as users can cope with unpredictable or inconsistent levels of demand. An example of where this flexibility would benefit a company is in the case of an online store. A store may receive fluctuating traffic throughout a year, such as being particularly busy around the Christmas

period. It would be economically inefficient for the store to purchase extra servers to cope with demand over the festive period, as they would be redundant for the majority of the year, but they must improve hardware capability in order to take advantage of the extra business. The inherent flexibility from the elasticity of the cloud would allow the store to simply acquire new computing capacity from their Cloud Service Provider on a temporary basis, giving them the capability of accommodating with the peak traffic but not using (or paying for) the extra resources when they are not needed. Having this scalability is seen as a core benefit of Cloud Computing.

A Cloud Service Provider is an organisation that provides access to Cloud Computing resources. They manage the underlying hardware, and typically provide APIs and other methods for a user to manage their resources. Some of the largest Cloud Service Providers are Amazon through AWS (Amazon Web Services), Microsoft through Windows Azure and Google through Google Apps.

A Cloud Service Provider does not have to be an external organisation, but when they are they typically use pay-per-usage business models. Rather than pay a fixed monthly cost, or have a one-off license fee, customers will pay the Cloud Service Provider for the resources they use (usually on a per-hour basis). For example, a 'Medium' size Virtual Machine costs 0.077 an hour from Windows Azure [22]. This allows businesses to only pay for the resources that they need.

2.1.1 Related Ideas

2.1.1.1 Utility Computing

Utility Computing is the idea that households and businesses could outsource their demand to external companies, who provide the relevant amount of service on a pay-per-usage basis. Customers would access computing resources over a network, and would pay for the length of computing time that they use.

This is analogous to other utilities such as Gas or Electricity. In the case of Electricity, power is provided from the National Grid and the customer pays for how much they use. This allows a customer change the amount of power they require without having to pay a fixed cost (for example, using less electricity when they are on holiday).

Utility Computing is an established concept, with leading thinkers such as Leonard Klienrock (part of the original ARPANET project) referencing it as early as 1969 [19]. Various technologies have emerged which offer some attributes associated with utility computing, with Grids and Clouds appearing to be the most promising [11].

2.1.1.2 Virtualisation

Virtualisation is one of the key enabling technologies behind Cloud Computing. It abstracts away the details of the physical hardware and allows Cloud Service Operators to run several virtual machines on one physical machine [37], completely independently of one another. This allows for customers applications and the physical hardware to be consolidated, utilising resources more efficiently and

making it financially feasible to run a cloud [15].

The configurability afforded by virtualisation is another property essential to Cloud Computing. It allows Cloud Service Providers to support a diverse range of applications, which may have different requirements (high compute, high memory, etc). Virtualisation allows this to be achieved, as it would be prohibitively costly at hardware level [15].

The reliability of a cloud can also be improved through the use of virtualisation techniques. Virtual Machines can be backed up, migrated and replicated simply, allowing applications to recover from hardware failure.

2.2 Cloud Computing Service Models

Depending on the scenario, the Cloud offers several different service models. These models allow for clients to provision services in a different manner depending their requirements.

The different service models provide different levels of abstraction for the user. In Infrastructure as a Service, the user has full control over the machines that they acquire from the Cloud Service Provider, where in Software as a Service they are given less control, and need not worry about the underlying hardware whatsoever.

2.2.1 Infrastructure as a Service

Infrastructure as a Service (IaaS) provides an abstraction on top of a virtualisation platform, so that the client does not need to worry about what method of virtualisation is being used, and does not have to learn about the underlying technologies [5].

Clients can request Virtual Machines in varying configurations, and a Virtual Infrastructure Manager will provision an appropriate Virtual Machine on a physical machine which has capacity. In addition to allowing users to provision virtual machines, IaaS systems may allow a user to configure other infrastructure elements, such as virtual networks.

This provides a great deal of control to the user, as they are essentially renting a machine of a requested specification for a short period of time. They are free to install whatever Operating System and software on the machine as required, and can configure it in essentially any way.

An example of an Infrastructure as a Service provider would be Amazon EC2 [4]. Amazon provide a variety of different Virtual Machine types, including those specialising in High Performance Computing or applications requiring a large amount of memory. Virtual Machines can use a range of images provided by Amazon (including Windows and various distributions of Linux), or users can create and upload their own custom Virtual Machine images.

2.2.2 Platform as a Service

Platform as a Service (PaaS) is a higher level abstraction which allows applications to be built and deployed without worrying about the underlying Operating System or runtime environment [18]. The

user still specifies the resources required, but no longer has to manually manage the virtual machines. The Cloud Service Provider will maintain the machines, providing the necessary software (Operating Systems, Web Servers, etc) and updating them frequently.

The advantage of PaaS is that it allows users to deploy their own applications, without having to worry about maintaining the underlying infrastructure. Whilst this decreases the control the user has over the deployment environment, it reduces the complexity of managing the infrastructure themselves.

PaaS offerings may also provide supplementary services to users, such as health and availability monitoring, or auto-scaling.

Windows Azure is an example of a Platform as a Service provider [23]. Whilst they provide Infrastructure as a Service offerings, they also provide Platform as a Service capabilities through Windows Azure Web Sites. Windows Azure Web Sites allow users to upload applications written in a variety of web technologies (ASP.NET, Python, PHP, Node.js) and have them hosted in the Windows Azure runtime environment. This means the client does not manually have to manage web servers, frameworks and other necessary technologies.

2.2.3 Software as a Service

Software as a Service (SaaS) refers to providing access to applications over the internet on-demand [37]. Software is centrally hosted by the Cloud Service Provider, and clients can access the application through a web browser or other form of client. As the software is centrally hosted, Cloud Service Providers can handle updating the software for all users, ensuring all users benefit from bug fixes or additional features.

Software as a Service applications can reduce the cost of deploying and using software for an organisation as they don't have to purchase their own hardware, install and configure software, and can avoid having technical support staff. An example of a successful Software as a Service application is Salesforce [27]. Salesforce is a Customer Relationship Management tool which charges organisations per user, making it a viable choice for small businesses. Salesforce can be accessed through a web browser, enabling customers to use their software regardless of location or device.

2.3 Cloud Computing Deployment Models

Cloud Services can be deployed in several different ways. The National Institute of Science and Technology defines 4 Cloud Computing deployment models [21].

2.3.1 Public Cloud

A public cloud is designed to for use by the general public. A public cloud will typically be owned by a third-party Cloud Service Provider such as Microsoft or Amazon, and will serve lots of different individuals and organisations.

The benefit of a public cloud is that physical infrastructure is completely managed and maintained by the Cloud Service Provider, reducing the effort required to provision computing resources and therefore maximising the benefit of the cloud.

2.3.2 Private Cloud

A private cloud is designed for use by one organisation. This allows individual components of an organisation (such as departments, product groups or engineering teams) to utilise the benefits of Cloud Computing, whilst allowing the organisation to maintain control over the computing resources. A private cloud allows an organisation to completely tailor the cloud to their unique requirements, including specialised hardware, specific Platform/Software as a Service offerings and control over the permissions clients of the cloud environment have.

A private cloud can also be necessary in overcoming concerns about security and data governance. One of the major disadvantages of a public cloud is a lack of control over data (real or perceived). It may not be possible to ascertain where data is geographically located (and therefore what legislation applies to it), and companies may simply not trust confidential information with a third-party Cloud Service Provider.

Whilst a private cloud still requires an organisation to acquire, provision and manage hardware (rather than outsourcing to a third-party Cloud Service Provider), it can still provide a reduction in cost over time. A private cloud allows centralisation of an organisations computing resources, allowing components of the organisation to use resources elastically as required from the central private cloud, rather than duplicating necessary computing infrastructure.

2.3.3 Community Cloud

A community cloud is developed by several organisations that have shared requirements. It allows them to pool together computing resources to the benefit of all organisations involved, reducing the investment needed for a private cloud. Organisations may opt to develop a community cloud to reduce dependency on a public cloud provider, mitigating the privacy and security concerns often cited as being a problem for public clouds, and allowing the resulting cloud system to be tailored to take in to account legislative or administrative restrictions which might be part of some industries or other organisational groups.

Whilst creating a community cloud provides tangible security and customisability benefits over a public cloud, and cost benefits over developing a private cloud system, they also have their issues. Community clouds can make it more difficult to deal with standard distributing computing issues such as latency and resource management, and additional security requirements may be needed [10].

2.3.4 Hybrid Cloud

A hybrid cloud is a composition of 2 other cloud types (public, private and community). Typically, a hybrid cloud uses technology to enable data and applications to be transported between clouds. An example of a hybrid cloud solution would be a private cloud, which utilises a public cloud if it runs out of resources. This allows the private cloud to exhibit the same elasticity benefits of a public cloud, appearing to clients as though it has essentially limitless resources (whilst actually just making use of a public cloud for overflow capacity).

It may be difficult to create a hybrid cloud in some situations as the technologies used may be complete distinct and difficult to combine. There may also be concerns about data security and privacy. Business rules may have to be defined which specify (for example) what types of data can be stored on a public cloud, and what types of data are too sensitive and must remain private at all costs.

2.4 Big Data

The term ‘Big Data’ refers to large scale data sets which present new problems for the processing and analysis of data. These datasets are often too large to be comfortably worked with using standard tools for statistical analysis [28]. Sources of Big Data are diverse; datasets can be from science, industry, social networking sites or various other sources. Consider the following:

- In 2011, Facebook had 30 PetaBytes of data used for performing analytics [35].
- The Large Hadron Collider generates 25 PetaBytes of data annually [34].
- Phase one of the 1000 Genome Project has a dataset of 180 TeraBytes of human genetic information [17].
- In 2008, Google were capable of processing 20 PetaBytes of data a day [14].

2.4.1 Challenges

Big Data introduces several challenges which make the use of traditional analysis tools and techniques infeasible.

2.4.1.1 Scale

The defining characteristic of Big Data problems is their massive scale. Typical problems may require processing datasets in the magnitude of PetaBytes of information. This makes it unrealistic to process the data in serial, as it would take far too long. Data processing techniques designed for Big Data problems must process information in parallel.

The scale of the data also makes storing data on a single machine unrealistic. Whilst the capacity of hard drives has been increasing over time, the speed of I/O has not increased by the same factor

[33]. This makes it time consuming to read an entire dataset off of one physical disk, even if a disk exists with enough capacity.

Unfortunately, the alternative approach of distributing data across multiple machines also has issues. Using a higher number of nodes increases the likelihood that one of those nodes will fail, which could lead to irrecoverable data loss. In order to prevent this, systems for processing Big Data should be designed to be fault tolerant, usually by introducing redundancy.

2.4.1.2 Predictability

Not all Big Data is static. There has been increasing interest in performing sentiment analysis on social networks to predict the results of real-world events such as box office revenues [6], financial markets [8], or surveys on political opinion [24].

It can be difficult to predict the quantity of data which may need to be processed when analysing real-time data, such as that gathered by Twitter. In August 2013 Twitter experienced an unexpected increase in traffic, leading to a new record for the number of tweets in a second [20]. This highlights the potentially unpredictable nature of real-time data analytics.

The challenges of predicting resources required for real time data analytics show the advantage of using Cloud Computing for data processing. The elastic nature of clouds would allow resources to be dynamically acquired when an unpredictable increase in data occurs.

2.4.1.3 Data Heterogeneity

It is very rare for different data sources represent data in the same way. Where data is processed from multiple sources, the lack of standard methods of storing data can make it difficult to develop accurate processing techniques [12].

A lack of structure in data can also cause problems with analysis. Much of the data used in large scale processing is strongly unstructured (social network data, text from articles, etc) which can cause issues with processing techniques. For example a simple data processing task which counts the frequency of words in a text document may produce inaccurate results if there are spelling mistakes in the corpus.

2.5 MapReduce

MapReduce is a programming paradigm designed as a generalised solution to processing large scale datasets [13]. A programmer specifies both a *map* and *reduce* function, a set of input data, and a location for the output. A MapReduce runtime determines how to distribute the task, taking the data and dispersing it amongst its nodes, enabling the data to be processed in parallel.

The key advantage of MapReduce is that it provides an abstraction on top of concurrent programming. This allows a developer to specify what they want to do to the data (in terms of the *map* and *reduce* functions) without having the obscuring the code and having the cognitive overhead of

handling common concurrency issues, such as fault tolerance, data distribution, and safe parallelism without the risk of problems such as race conditions and deadlocks.

The MapReduce method of performing distributed parallel data processing is inspired by the *map* and *reduce* functions present in many functional programming languages [13].

2.5.1 Map

The first function that a developer provides is the *map* function.

$$map = (k, v) \rightarrow list(k', v')$$

The *map* function receives a key and a value as input (an *Input Pair*), and returns a list of (different) keys and values (a list of *Output Pairs*). The MapReduce runtime will take all output pairs with the same key, and combine them in to a list before passing the resulting values to the *reduce* function. The reduce function therefore receives an argument of type $(k, list(v))$.

2.5.2 Reduce

The *reduce* function is the second function provided by the developer.

$$reduce = (k, list(v)) \rightarrow list(v')$$

A *reduce* function merges values together to produce a smaller list of values. Typically, the reduce function is an aggregate function, returning either 1 or 0 results (such as sum, average, etc).

2.5.3 Word Counting Example

A common MapReduce operation is word counting. The following pseudo-code implementation of the *map* and *reduce* functions for counting words in a document obtained from [13].

Algorithm 1 Map function for word counting

Require: key: document name

Require: value: document contents

for all w in value **do**

 EmitIntermediate(w, 1)

end for

The *map* function takes a document, and returns a number of Key/Value pairs, where the key is a word appearing in the document, and the value is 1. The runtime environment will then cluster the values together where the keys match. Each word will therefore have a list of 1's, with the length of the list indicating how many times the word has occurred.

Algorithm 2 Reduce function for word counting

Require: key: a word

Require: value: a list of counts

result = 0

for all v in values **do**

result += v

end for

return result

The reduce function takes the list of values (all of which are 1) and sums them together. This gives a total number of times the word has occurred in the document.

2.5.4 Disadvantages

The primary criticism of MapReduce is that it provides a limited programming framework [36]. Whilst the MapReduce paradigm is a relatively general concept which applies to many types of application, not all problems can be formulated in a way which is compatible with MapReduce. The MapReduce process consists of a static *map* operation, performed across the data, and a static *reduce* operation performed subsequently. The *map* and *reduce* functions are both stateless.

This imposes limitations on the types of problem which can be solved by MapReduce. If it is not possible to formulate a *map* and *reduce* function for a problem, it cannot be solved by the MapReduce paradigm. Alternatively, whilst it may be possible to express a data processing task in terms of *map* and *reduce*, it does not always provide the most fluent or efficient method of solving the problem.

Prominent examples of this type of algorithm can be found in Machine Learning, where problems are often iterative in nature. Iterative tasks, such as K-Means Clustering can be implemented using the MapReduce paradigm [38], but often require multiple passes of the *map* and *reduce* functions, which causes a significant performance penalty as data must be loaded from the disk every iteration.

2.5.5 Hadoop

Hadoop is an Open Source implementation of the MapReduce programming paradigm [2]. It consists of several modules designed to overcome the problems associated with large scale data processing. In addition to the MapReduce programming model (Hadoop MapReduce), the Hadoop platform also has a distributed file system (HDFS) and a resource management and scheduling component (Hadoop YARN).

Hadoop is a particularly popular implementation of the MapReduce interface in the data processing community, emerging as the de-facto standard implementation of MapReduce [26].

2.6 PACTs

Parallelization Contracts (PACTs) is an alternative programming paradigm which is a generalization of the MapReduce concept [7]. The aim of PACT is to overcome the perceived weaknesses in the MapReduce paradigm, whilst still providing a generic enough framework to represent any data processing task. PACT sets out to improve MapReduce by observing that the *map* and *reduce* functions alone cannot represent all data processing tasks in a natural or efficient way, that MapReduce does not provide flexibility in the order of operations (strictly a *map* followed by a *reduce*) and that MapReduce makes no assumption about the user defined functions, limiting the scope of potential optimizations.

PACT aims to solve these issues in 2 ways. It introduces the concept of Parallelization Contracts, which define properties of a user defined functions input and output data, and it represents the data flow of a data processing job as a Directed Acyclic Graph (DAG), rather than strictly as a *map* and *reduce* task.

2.6.1 Processing Tasks

A data processing job can be described as a set of tasks, where each task performs a transformation on the data. A processing task has 3 core components.

A data processing task acts upon a list of records. Unlike the classic MapReduce paradigm, input is not restricted to Key/Value pairs. A record can consist of any number of fields, each which can be either a key or value. All fields must be capable of being serialized and deserialized, and fields defined as keys must be capable of being compared with other keys.

2.6.1.1 Input Contract

A task can be described as consisting of multiple Parallelization Units (PUs). A PU is a core block of computation which must be performed in serial. PUs are isolated from one another, and do not require communication, meaning that they can be distributed across different nodes and can be ran in parallel to one another. PACT specifies a set of Input Contracts which define how a problem is broken down into PUs. The Input Contract is therefore key in determining how the problem is parallelized and distributed between nodes.

The PACT Programming Model provides 5 Input Contracts [3].

- **Map** takes a list of records and creates a PU for each individual record. This allows every record to be processed in parallel. The Map Input Contract is typically used for transforming or filtering data.
- **Reduce** takes a list of records and groups them by record key. It then creates a PU for each group, allowing the resulting subsets to be processed in parallel. The Reduce Input Contract is often used for aggregating data, performing functions like sum or average.

- **Cross** is a multi-input contract, taking 2 lists of records. It takes the Cartesian product of the 2 lists, and creates a PU for each element in the resulting set. This allows every combination of input to be processed in parallel.
- **CoGroup** takes 2 lists of records and groups them by key. A PU is then generated for every resulting group. This is similar to the Reduce Input Contract, but it operates across 2 lists rather than 1.
- **Match/Join** takes 2 lists and matches records from the first with records from the second based on whether they have the same key. A PU is generated for every resulting pair of records. This is conceptually similar to an equi-join operation.

2.6.1.2 User Defined Function

The User Function is the programmer defined function which will be executed on the data. This may be counting the frequency of words, searching for a particular string, or various other things. The arguments that the User Function will receive are based on the input contract - if a Map Input Contract is used, the User Function will receive an individual record. If a Reduce Contract is used, the User Function will receive a group of records with similar keys.

2.6.1.3 Output Contracts

An Output Contract is an optional component of a data processing task. An Output Contract is used to provide guarantees about the type of data that the user function will return. This allows the PACT runtime to optimise the process to make a more efficient data flow. An Output Contract can indicate that data does not have to be repartitioned between nodes before going on to the next stage data processing task.

There are various Output Contracts.

- **Same-Key** ensures that each record generated by the user defined function has the same key as its input. This ensures that any partitioning between nodes can be kept for the next stage of processing.
- **Super-Key** provides a super-key of the records it was generated from. A function with the Super-Key output contract allows partitioning between nodes to be kept the same.
- **Unique-Key** gives each record a globally unique key across all nodes. This allows records to be stored in data sources which require globally unique keys (e.g. in a relational database table with a primary key).
- **Partitioned-By-Key** partitions records by their key. This has similar implications to the Super-Key contract, in that partitioning is kept, but there is no order within the partitions.

2.6.2 Directed Acyclic Graph

Data Processing jobs are represented as Directed Acyclic Graphs [31]. A vertex in the graph represents an individual task (a combination of an input contract, a user defined function, and optionally an output contract). Edges represent the communication between different tasks. Tasks can be connected to multiple other tasks.

The primary advantage of a DAG is that it allows for a more flexible representation of data processing tasks, allowing complex workflows of tasks, rather than being limited to a map task, followed by a reduce task. This allows for arbitrarily complex graphs to be defined, allowing more complex data processing jobs to be completed.

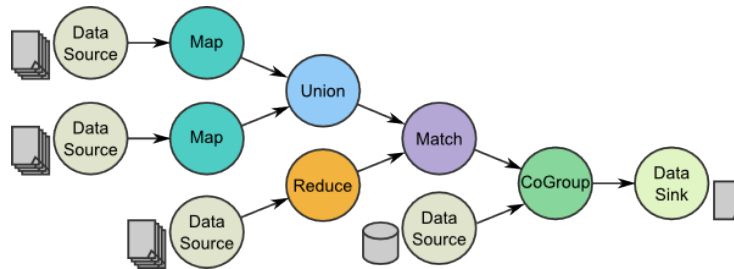


Figure 2.1: An example of a complex dataflow [1]

Directed Acyclic Graphs can also be composed together, by connecting the output of one graph to the input of the next.

The classic MapReduce paradigm could be emulated by having 2 tasks, one with the Map Input Contract and another with the Reduce Input Contract (neither would have Output Contracts). The result of the Map task would be piped directly in to the Reduce task.

2.6.3 Nephele

Nephele is the reference implementation of the PACT programming model. It is a runtime environment which takes a Directed Acyclic Graph specifying the desired data processing workflow (the Job Graph) and compiles it in to an Execution Graph - a more concrete description with information about how the tasks will be parallelized and what types of computing resources will be used [32].

A secondary focus of the Nephele runtime is to take advantage of the opportunities afforded by Cloud Computing. The core benefit of Cloud Computing is elasticity, allowing resources to be obtained on demand. By removing the assumption that resources must be static throughout the duration of a data processing job, Nephele is able to utilise the dynamic resource allocation made possible by the cloud. This changes the emphasis of task scheduling, allowing the scheduler to determine and acquire what resources a given task needs, rather than attempting to schedule tasks depending on the resources available at the time [32].

Chapter 3

Experiment Design

A series of experiments have been designed in order to objectively analyse the efficiency of Nephele and Hadoop. This section discusses the design of the experiments in regards to the aims of the project.

Experiments are designed in a modular fashion, enabling a subset of them to be completed whilst still providing relevant research results. This approach was taken to limit the risk that is introduced by the time constraints of the project.

3.1 Experiment Variables

There are a total of 30 experiments with 3 varying factors, in order to test the data processing tools in a range of relevant scenarios.

3.1.1 Data Processing Tools

The first factor that will be varied is the tool used to process the data. This relates to the first two research goals: providing a comparison of the MapReduce and PACT programming paradigms, and ascertaining how well Nephele can perform MapReduce tasks.

3.1.1.1 Hadoop

Hadoop is an open source implementation of the MapReduce paradigm, which has become the de-facto standard for big data processing [26]. This makes it an ideal choice for comparing MapReduce and PACT.

Experiments will be run in Hadoop to provide an indication of the efficiency for the current state of the art in data processing. This provides a reference point to which alternative data processing technologies can be compared.

3.1.1.2 Nephele (PACT)

Nephele is a tool which implements the PACT programming paradigm, which as a superset of MapReduce can also perform tasks in a MapReduce style. This means that experiments can be implemented using the same tool, but in different programming paradigms, allowing a fair test of PACT vs Nephele. This is designed to answer the first research question, namely whether or not PACT overcomes the inherent disadvantages of the MapReduce paradigm.

In a broader sense, it allows a complete comparison of Hadoop and Nephele. In real-world data processing scenarios, users of Nephele would be unlikely to restrict their programming options to just MapReduce, and would be likely to use other aspects of PACT as appropriate. Running experiments in the same way allows a fairer comparison of the 2 tools, where all of their functionality is available.

3.1.1.3 Nephele (MapReduce)

Experiments will also be run using just the Map and Reduce operations of Nephele. Whilst Nephele has a wider set of operations, solving data processing tasks using just Map and Reduce allows Nephele and Hadoop to be directly compared, aiming to answer the second research question. If Nephele can perform MapReduce tasks with comparable efficiency to Hadoop, it will indicate that Nephele is a more efficient tool for large-scale data processing in general, not just for those situations where a problem cannot be formulated in terms of MapReduce.

3.1.2 Data Processing Task

The second varying factor will be the data processing task that the tools have to complete. The tasks have been chosen to represent real-world issues as closely as possible, to give an indication of performance in scenarios where the tools are likely to be used, rather than having synthetic benchmarks such as word counting or Terasort.

3.1.2.1 Reverse Link Graph

The first problem the data processing tools will have to solve is generating a Reverse Link Graph [14]. In some situations, finding the transpose of a directed graph can be difficult. For example, when considering the Web Graph; it is relatively trivial to find the edges coming out of a vertex (as the hyperlinks on a page indicate its outgoing edges), but it is far more difficult to find incoming edges (pages which link to the current page).

The Reverse Link Graph problem has been solved as it is a ‘classic’ MapReduce problem. A ‘classic’ MapReduce problem is a problem which can easily be formulated in terms of MapReduce. Classic MapReduce problems tend to be stateless, and do not depend on other parts of the data. This makes it easier to compute the solution in parallel, but means that many problems are not well suited to MapReduce (such as naturally iterative problems). An example of a classic MapReduce problem would be Word Counting, as each document can be processed in parallel.

The Reverse Link Graph has been chosen in order to measure how effective both Hadoop and Nephelē are at processing data using the MapReduce paradigm. This specifically relates to the second research question (“How well does Nephelē perform MapReduce tasks?”).

Finding a reverse link graph of the web is a key component in many search engines [25] where backlinks are used to indicate how important a page is, and can also be used to analyse a network of academic articles by treating references as edges [16].

3.1.2.2 PageRank

The second problem for the data processing tools to tackle is the PageRank algorithm. PageRank is a method of objectively and mechanically rating the importance of a web page, trying to measure human interest and the attention paid to the page [25].

The PageRank algorithm is an example of the type of problem that MapReduce is traditionally cited as being poor at completing. It is an iterative algorithm which converges on a PageRank for each node. It requires information from adjacent nodes to compute a nodes PageRank at each step, which means that each step of the iteration must be performed sequentially, as part of a separate MapReduce pass.

By contrast, PageRank should use many of the additional features that the PACT programming model provides over MapReduce. The presence of iteration support and dedicated operations for Joins should test the additional operations that PACT provides in order to determine whether they yield tangible performance benefits.

Computing the PageRank of a graph of pages is a suitable test of how well the PACT programming model overcomes the issues of MapReduce, as it exercises many of the additional features. This will provide an answer to the first research question (“Does PACT overcome the inherent disadvantages of the MapReduce paradigm?”).

3.1.3 Cluster Size

The size of the cluster will be varied in order to give an indication of how well the data processing technologies perform at scale. This is a key factor in processing large scale data, as technologies which do not scale well as machines are added are unlikely to perform well in real-world scenarios, where the size of data may run into the Petabytes.

The elasticity of the Cloud will be required to scale the size of the cluster for different experiments. Specifically, experiments will be run using 2, 4, 6, 8 and 10 nodes. Scaling the size of the cluster will test both the scalability of the data processing tools, and the ability for the tools to harness the elasticity of the cloud, meeting the third research aim.

3.2 Measurements

Measurements will be taken from the experiments in order to give quantitative metrics which can be used for objective analysis.

3.2.1 Runtime

Runtime is the length of time that a program (or data processing task) takes to execute. Runtime is one of the primary mechanisms for determining the efficiency of the data processing solutions. The time it takes to perform a task is a key element in large scale data processing, as the sheer scale of data can cause operations to take a long period of time.

3.2.2 Scalability

The Scalability of data processing tools is also a key metric in determining how efficient they are. The scalability of a system refers to how well it accommodates additional resources [9], such as additional machines.

In the context of Data Processing tools such as Hadoop and Nephele, it is desirable for systems to be able to scale according to both the size of data, and the number of nodes in the cluster. A data processing tool should be able to handle any amount of data, providing that it has the correct amount of system resources. Indeed, this is what distinguishes tools like Hadoop from other data processing tools such as numpy - the ability to analyse petabytes of data. A Data Processing system should also be able to scale according to the number of nodes added. There should be no upper limit to the number of nodes in a cluster, as this provides an important mechanism of adding the necessary resources to handle larger processing tasks. Adding a large number of nodes with lesser resources may be more cost efficient than adding fewer nodes which have comparatively larger system resources. This may be a reason why many users that engage in large scale data processing build clusters from commodity components [29].

The specific type of scalability that will be considered in these experiments is Runtime Scalability. Intuitively, as nodes are added to the cluster the runtime for experiments should decrease as work can be partitioned out to a larger set of working nodes. In an ideal world, this would follow a linear progression; as the number of processors is doubled the runtime should be halved. This can be measured by taking the runtime of a task when the processor count doubles (so the processor count is 2^p where p is an integer representing the processor count) and taking the derivative.

3.2.3 Alternative Measurements

Various alternative mechanisms could be used to determine the efficiency of the data processing tools. The scope of the project will be limited to measuring the runtime and runtime scalability, but some other measurements which could be used are as follows.

3.2.3.1 Data Scalability

It is important for clusters to be able to deal with large amounts of data in a reasonably efficient manner. A further test of scalability would be to test the cluster with various different datasets of different sizes. As with runtime scalability, this would ideally be linear, so that when the size of the data is doubled, runtime would also approximately double. The data processing tools may be of less use if the runtime increase is larger (for example, an exponential increase in runtime) as this would make running tasks on petabytes of data unreasonable.

3.2.3.2 Resource Utilisation

The resources used on nodes can be measured to determine how efficient the data processing tool is. An efficient data processing tool could be defined as one which uses the resources of each node effectively, by utilising a high amount of memory and CPU capacity. This would indicate that the data processing tool is using each node to the highest capacity possible, rather than requiring extra nodes to be added for more resources to become available.

The utilisation of the network can also be used in determining efficiency, as a significant factor in how well a system scales is how much it communicates with other nodes. Larger amounts of communication overhead will increase the runtime of a system as it scales. Measuring the network overhead gives an indication of how much nodes communicate with each other, therefore giving an indication of communication overhead and scalability.

3.2.3.3 Cost

Another metric which can be used to compare data processing tools is cost efficiency. In situations where a cluster is being built using Cloud Computing services, running data processing jobs will cost on a per-usage basis. Depending on the runtime scalability, it may be more cost efficient to run a job on a larger number of nodes (so that it completes faster), versus running it on a smaller number of nodes (which will take longer, but cost less per hour).

It may also be more cost efficient to create a private cluster of machines to run data processing jobs, rather than using a pay-per-usage cloud model.

3.3 Hypothesis

The project as a whole focuses on answering 3 core research questions. Rather than hypothesising the result to each individual experiment, there will be a prediction for each research question. Each experiment is used as a way of gathering information to answer one of the three core questions, and as such the results to individual experiments can be inferred from the broader descriptions.

3.3.1 Does PACT overcome the inherent disadvantages of the MapReduce paradigm?

In order to determine whether PACT overcomes the inherent disadvantages of MapReduce, both tools will solve the PageRank problem; a data processing task which exhibits many of the features generally considered to be a poor fit for MapReduce.

It is likely that PACT will demonstrate a clear superiority over MapReduce in these situations by having a smaller runtime, regardless of the number of nodes that are used to process the data. The presence of dedicated PACT operators for both iteration and delta-iteration will be a significant benefit for PACT, as PageRank is a naturally iterative algorithm. Additionally, PACT provides operators for joins, which are used throughout the PageRank algorithm. This will allow the Stratosphere runtime to optimise these steps accordingly.

In contrast, MapReduce lacks a dedicated method of iteration, meaning that any iterative algorithm must be implemented using multiple Map and Reduce steps. Additionally, any joins required by the algorithm will have to be implemented using additional Map and Reduce operations, causing multiple steps per iteration.

This will cause the PACT runtime to outperform the MapReduce runtime when running the PageRank experiment, indicating that it overcomes the inherent flaws in the MapReduce paradigm.

3.3.2 How well does Nephele perform MapReduce tasks?

The Reverse Link Graph problem will be used to determine how well Nephele performs MapReduce tasks. As a classic MapReduce problem it allows comparison with Hadoop, the current status quo of data processing tools.

In these situations Hadoop should be the clear winner in terms of performance. It is a simpler tool, designed for running MapReduce processes without the overhead associated with having other operations available. This allows the MapReduce runtime to be highly optimised to performing those tasks. As a research project, it is far more likely that the limited development resources of Nephele would be focussed towards optimising other operations, designed to be the source of an advantage over MapReduce. This may lead to a less efficient MapReduce implementation.

Nephele is also a relatively immature project in comparison to Hadoop. It has existed for far less time, and therefore has less contributions. It is a less visible project than Hadoop, and has been used less in production. On this basis it can be reasoned that Nephele will have had less development attention towards optimising the Map and Reduce processes, and will therefore have inferior performance with these tasks.

3.3.3 How do Hadoop and Nephele perform in a highly elastic Cloud Computing environment?

An important factor in how suitable data processing tools are to large scale data sets is how well they scale. This is particularly important in Cloud Computing environments. In order to evaluate how well the tools scale, both the Reverse Link Graph experiment and the PageRank experiment will be

run using a varying number of nodes, with the difference in runtime evaluated to determine how well adding additional resources impacts the data processing tools.

Both Nephele and Hadoop (and in a broader sense, PACT and MapReduce) are based on stateless functions being distributed across nodes, evaluating data massively in parallel. Because of the nature of this model, communication overhead (the primary cause of parallel overhead) should be minimised during the primary processing time of the tools. It can therefore be expected that both Nephele and Hadoop will increase in a generally linear fashion.

It would be unrealistic to expect the tools to scale in a perfectly linear manner, as there is still communication required between the nodes. In particular, some operations can be made parallel more easily than others; map is a naturally parallel action, where the nature of reduce requires communication between at least 2 completed map operations. There will also be communication required at the start and end of each job, as input and output data must be read from, and written to, the file system. Finally, there will be overhead required to schedule tasks to nodes throughout the cluster. This process is centralised, with the master node determining which nodes will be responsible for processing different parts of the data at each stage. This computation is serial by necessity, and in contrast to most other processing tasks may increase in time as more nodes are added (as the scheduling problem will become progressively more complex).

One major cause of scalability issues in parallel computing can be the underlying file system. Communicating to disk is expensive, and will be even more so if a node has to communicate over the network to get access to the file system. The file system implementation may therefore play a key role in determining the scalability of the system. An inferior file system implementation may lead to more network communication, significantly negatively impacting the runtime of a processing task. As both Nephele and Hadoop use the Hadoop Distributed File System, this discrepancy will not be an issue when assessing the relative scalability of the two systems.

Based on this analysis, it can be expected that Nephele and Hadoop will not show any major differences in scalability, with both scaling in a near-linear fashion.

Chapter 4

Experiment Implementation

Chapter 5

Evaluation

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Appendix A

Personal Reflection

I think my project went well.

Appendix B

Record of External Materials Used

I developed all of the materials presented in this project myself.

Appendix C

Potential Ethical Issues

Ethical issues may occur depending on the data used for the experiments. A variety of different datasets are available which could be used for the ‘real-world’ experiment. Data may contain personally identifiable information, or have other ethical concerns.

It can be assumed that any dataset used will be publicly available, and will be suitably anonymised with suitable stakeholders having been consulted. For example, the 1000 Genomes project will contain the genome information of a large number of people. It can be assumed that those people have agreed to make their genome data available for research purposes.

There may be no ethical concerns, depending on the dataset selected.