



Dissertation Project

A Comparison of NoSQL and Indexing Solutions for Big Data

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Introduction

The era of Big Data is upon us, bringing with it a range of new challenges “Without big data, you are blind and deaf and in the middle of a freeway.”[3] . The significance of these challenges encouraged the formulation of new approaches for cleansing, processing and utilising enormous amounts of data. (Section 1.1)

Data is being collated and stored every second of every day and the value of doing so has never been greater. Billion dollar companies such as Google and Amazon dominate the market in data collection and pride themselves in knowing everything about everything. Former CEO of Google, Eric Schmidt famously said in 2010 “We know where you are. We know where you’ve been. We can more or less know what you’re thinking” [6]. Thus the power of data collection has led to the development of a range of technologies designed to meet the needs of big data.

The purpose of the following research, by way of investigation, is to deliver an insightful examination of a subset of new technologies which deliver high performance querying of large datasets. The ultimate aim of the project is to gain an understanding of these technologies and achieve a level of mastery which permits a thorough scrutiny of their application to big data.

There are a number of different indexing solutions available. In order to encapsulate a comprehensive examination a focus will be on leading NoSQL solutions, modern search and analytics engines and for comparative reasons a conventional relational database management system. The following technologies which will be used for the project:

- MongoDB (Section 4.3.1)
- Neo4j (Section 4.3.2)
- Apache Cassandra (Section 4.3.3)
- MySQL (Section 4.3.4)

o.1 Objectives

The three key objectives and main intended outcomes for the project are:

1. Investigate the strengths and weaknesses of the functionality each technology provides.
2. Compare and contrast the analytical capabilities of each technology by way of querying prototype models.
3. Conduct a comparative analysis to investigate the scalability of each technology.

o.2 Motivation

My interest in the field of data science stems from university modules I have undertaken as part of my BSc Computer Science degree. Modules such as ‘Database Management Systems’, ‘Data Mining and Machine Learning’ and a course I am currently studying ‘Big Data’. The material involved in these courses have given me an insight into the field of data science and provided me with the opportunity to get a hands on feel for the manipulation, cleansing and processing of a variety of real life data sets and database systems.

Whilst studying for my degree, I have successfully completed modules which have required a working knowledge of MySQL as a prerequisite therefore my comprehension of MySQL is proficient. One of the main attractions to undertaking this project was to be given the opportunity to learn about a number of next generation database management systems. It was important for me to undertake a project in which I will be able to apply my learning and findings to progress in a career path within the data science field.

Since the summer of 2015 I have been working as a Data Analyst for a software company in Edinburgh. In this role I have had the opportunity to use some of the indexing solutions and analytics engines discussed in this project such as MongoDB and Elastic Search. This background knowledge has contributed to my understanding of this project, as it has provided me with an already functioning knowledge of some of the concepts used.

o.3 Definitions

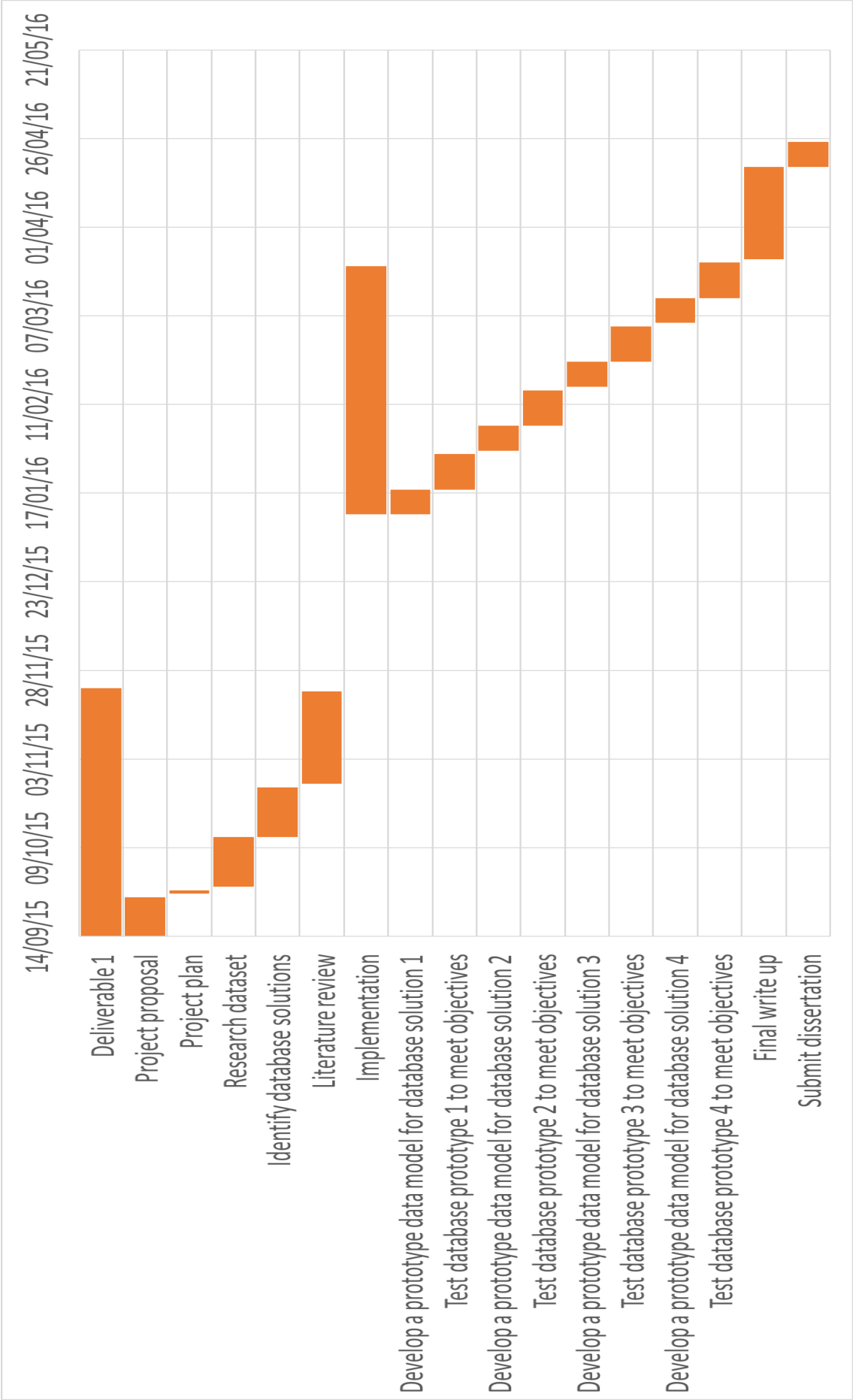
The data source being used in this document comes from the biological field and therefore relies on an understanding of basic concepts and terms. The below table of definitions

provides an overview into the main terms used throughout the report with the aim of providing the reader of the document with a sufficient level of understanding. The table also includes the definitions of generally obscure terms and phrases which will be discussed throughout this project.

Term	Definition
Edinburgh Mouse Atlas Project (EMAP)	The combined research projects of Dr Duncan Davidson and Prof Richard Baldock.
EMAP anatomy	A freely available, structured, stage specific list of 13,000+ terms that describe visible anatomical structures in the developing mouse embryo.
Edinburgh Mouse Atlas Project Abstract (EMAPA)	A refined and algorithmically developed non-stage specific anatomical ontology representation of the EMAP anatomy.
Edinburgh Mouse Atlas of Gene Expression (EMAGE)	A database of in situ gene expression data in the developing mouse embryo
Theiler Stage (TS)	Each stages defines the development of a mouse embryo by a set of organism structure criteria.
Assay	One or more <i>assay</i> comprises an experiment.
Not only SQL (NoSQL)	A non-relational database environment which is useful for very large sets of distributed data. Allows rapid, ad-hoc organisation and analysis of extremely high-volume, disparate data types.
Ontology	Refers to the science of describing the kinds of entities in the world and how they are related.
Web Ontology Language (OWL)	A language representation standard for designing and authoring Web ontologies produced from the World Wide Web Consortium W3C.
OBO	A flat file format ontology representation language

o.4 Project Plan

The below gantt chart illustrates the time scale in which deadlines and deliverables will be met throughout the project.



Chapter 1

Big Data Defined

Big Data is a broad, evolving term bound to a complex and powerful application of analytical insight which over recent years has had a variety of definitions. In simplistic terms Big Data can be described as extremely large datasets that may be studied computationally to reveal patterns, trends, and associations for ongoing discovery and analysis.

1.1 Big Data

The 2011 McKinsey Global Institute (MGI), a multinational management consultancy firm, compiled a report namely “Big data: The next frontier for innovation, competition, and productivity” outlines the potential effects big data will have on a number of industries. The report suggests that with the increasing “exponential” growth of data volume, simply recruiting a “few data-orientated managers” will be a temporary fix rather than a lasting solution. MGI suggest that if companies in a variety of sectors, such as the healthcare and retail industry, were to take advantage of the value which big data brings could see potentially huge returns. “...a retailer using big data to the full could increase its operating margin by more than 60 percent” [18]. The report also states that if “healthcare were to use big data creatively and effectively to drive efficiency and quality, the sector could create more than \$300 billion in value every year” [18]. Thus further cementing the view which accepts that big data plays a pivotal role in everyday modern life.

1.1.1 5vs Model

In 2001, Gartner analyst Doug Laney delivered the *3vs model* which defines the challenges and opportunities which have arisen from the increase in data volume. Laney categorises big data into three dimensions; Volume, Velocity and Variety, with the increase of each encapsulating the challenges currently faced today of big data management.

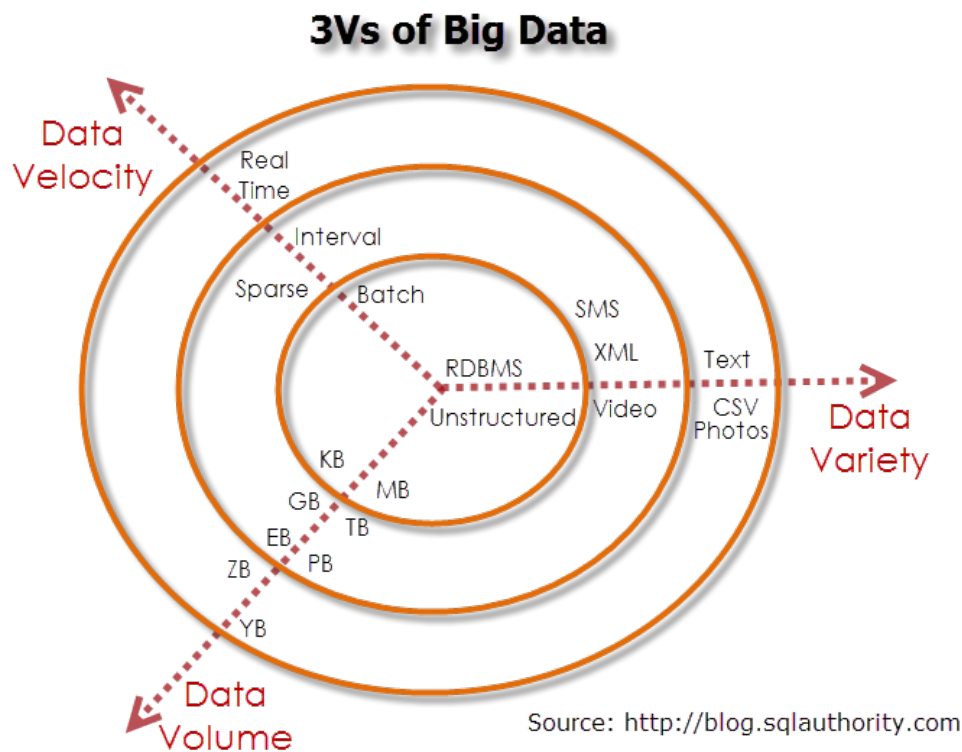


Figure 1.1: 3vs data model

The characteristics of each property illustrated in figure 1.1 are defined as: **Volume** - The vast amounts of data generated every second. With the creation and storage of large quantities of data, the scale of this data becomes progressively vast. **Velocity** - The speed at which new data is generated and the speed at which data moves around emphasising the “timeliness” of the big data. In order to fully profit from the commercial value of big data, data collection and data examination must be conducted promptly. **Variety** - This characteristic alludes to the various types of data we can now use; semi-structured and unstructured. Examples being “audio, video, webpage and text as well as traditional structured data” [19].

Big Data is a term becoming increasingly common in business and society. Overcoming obstacles and implementing effective, actionable Big Data strategies is key for successful big data management. In recent years a fourth category was introduced; **Veracity** - Data

inconsistencies and incompleteness result in data uncertainty and unreliability; which creates a new challenge, keeping data organised [19].

The final, and considered by many to be the most important *V* of big data, is **Value**. “All the volumes of fast-moving data of different variety and veracity have to be turned into value” [12]. One of the biggest challenges faced by organisations is having the ability to turn data into something useful. It can be an easy trap to fall into for a business aiming to embark on big data initiatives without a clear understanding of costs and benefits [19]. Thus the importance of establishing clear and achievable business objectives.

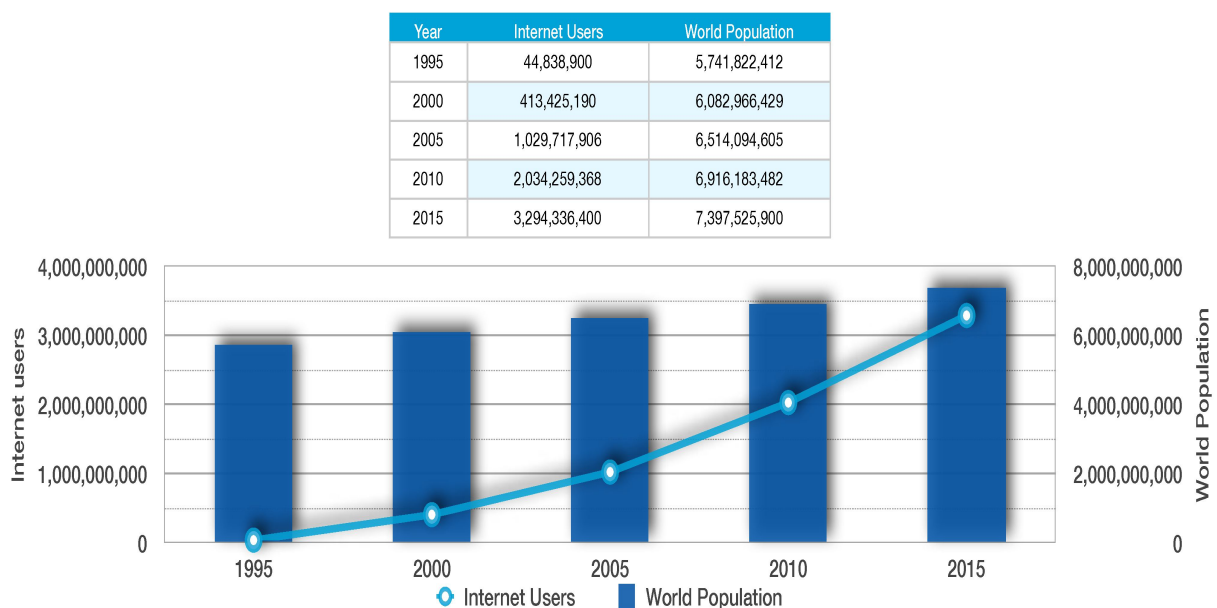


Figure 1.2: World population vs Internet users

The amount of data produced has dramatically increased from when Laney first introduced the 3vs model in 2001. This is in no small part due to the availability and accessibility of the internet. In 1995 the internet had on average 45 million users, 1% of the worlds population. This figure increased to over 1 billion people with internet access worldwide in 2005, and by 2010 nearly 2 billion which was 30% of the worlds population. The latest figures show that in 2015 the penetration of the internet reached 3 billion people, 40% of the entire population. Social media sites such as Facebook, Twitter, Snapchat, Instagram and Pinterest, are some of the main contributors in generating large volumes of user data. Facebook boast a staggering, 1 million links shared, 2 million friend requests and 3 million messages sent on average every twenty minutes [10]. The graph and data table in figure 1.2 illustrate the continual growth of internet accessibility as a whole.

Chapter 2

Extract Transform Load

This project will require the extraction, manipulation and processing of a data source from one data model to another. This process is commonly known as Extract Transform Load (ETL). Section 2.1 discusses each stage involved in the ETL procedure followed by section ?? which examines the ETL implementation methodology and its relevance to this project.

2.1 Process

A basic definition of the Extract Transform Load (ETL) process is pulling data from one database, refactoring the composition of the data and putting the data into another database. While the name ETL implies there are 3 main categorisation stages - extract, transform, load - the procedure in its entirety is a much broader and expansive process which encompass these stages. Despite this the procedure is split in to these three stages. Figure 2.1 illustrates the ETL process with data coming from a source; a file or database management system for example then being transformed in to the required format for a successful load.

2.1.1 Extract

Extract is the first step in the ETL procedure in which data is read from a source system, usually a database but not restricted to, and makes it available for processing. The main objective of the extract stage is to retrieve all the required data from a source system using as little resources as possible [5]. It is common for data to be extracted from source systems with different organisations and formats to that of the target system. The extract stage provides an opportunity to *cleanse* the data from the source system as often there will be redundant or

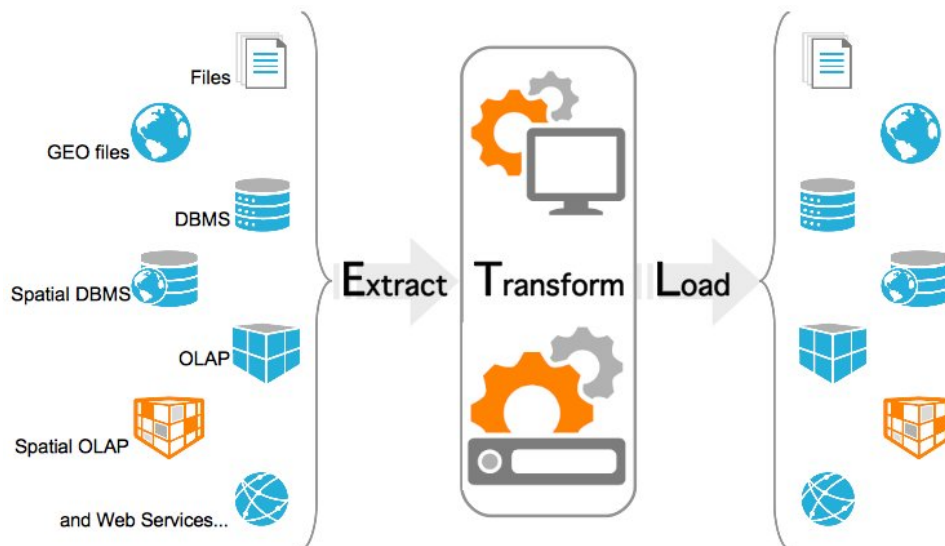


Figure 2.1: ETL process

irrelevant data which is not required.

2.1.2 Transform

Transform is where the extracted data is manipulated from its previous state and converted into a target system format. The step involves the application of a set of rules or functions to transform the data from the source to the target. As well as the applied rules and functions the transformation step is responsible for the validation of records ensuring unacceptable records are removed accordingly. “The most common processes used for transformation are conversion, clearing the duplicates, standardizing, filtering, sorting, translating and looking up or verifying if the data sources are inconsistent.” [4].

2.1.3 Load

Load completes the three step procedure and is where data is written into the target system. There are multiple ways in which data is loaded into a system using the ELT methodology. One of which and the most obvious is to physically insert the data. For example if the target repository is a SQL database insert the data as a new row using the relevant *Insert* statement. An alternative to loading the process manually is that some ETL tool implementations have the capability to “...link the extraction, transformation, and loading processes for each record from the source.” [4]. Depending on the technique applied the load step of the process can become the most time consuming.

2.2 Software Tools

This chapter discusses the tools which were used in the project as part of the ETL process. It focuses on the lesser known software packages such as Google Refine in section ?? and

Chapter 3

Knowledge Representation Languages

A Knowledge Representation (KR) language can be defined as: for any given interpretation of a sentence or string of text the KR must have the ability to effectively and unambiguously express knowledge in a both a human and computer manageable form.

There are a number of options and possibilities for communicating data and information which range from binary representation to meta markup languages such as Extensible Markup Language (XML) for example. Markup languages which are easily read by humans such as XML which as a result of its rigid set of rules lends its self to both humans and machines. Comparatively binary notation which uses 1's and 0's to represent data, while relatively cheap in terms of computing power the ability to comprehend this notation requires a unique and specific skill set.

3.0.1 Semantic Web

The Semantic Web is an extension of the Web through standards by the World Wide Web Consortium (W3C). “The standards promote common data formats and exchange protocols on the Web, most fundamentally the Resource Description Framework (RDF).” [1]

The Semantic Web has two main intended outcomes. The first is about the standardised formats of data pulled from variety of sources, whereas the original Web concentrated on the interchange of documents [1]. The second outcome of the Semantic Web is the language for recording the relation between data and objects in the real world. “That allows a person, or a machine, to start off in one database, and then move through an unending set of databases

which are connected not by wires but by being about the same thing.” [1].

3.0.2 Web Ontology Language OWL

The Web Ontology Language OWL is a language representation standard for designing and authoring Web ontologies produced from the World Wide Web Consortium W3C. [8]. The OWL file format is designed to be used by applications required to process the content of the information and to be humanly readable. “[OWL] is intended to provide a language that can be used to describe the classes and relations between them that are inherent in Web documents and applications.”[8]. The OWL languages are characterised by formal semantics and are built upon the W3C standard RDF format - discussed in section ??

3.0.3 OBO

The OBO flat file format is an ontology representation language. “The concepts it models represent a subset of the concepts in the OWL description logic language, with several extensions for meta-data modelling and the modelling of concepts that are not supported in DL languages.” [22]

[22] outlines the intended outcome of the file format aiming to achieve the following criteria :

- Human readability
- Ease of parsing
- Extensibility
- Minimal redundancy

Chapter 4

NoSQL

NoSQL is labeled as a next generation database known to most as “Not only SQL” [21]. This definition however insinuates its defiance against the industry standard SQL. It was originally developed in 1998 by Carlo Strozzi; a member of the Italian Linux society, with the intention of being a non-relational, widely distributable and highly scalable database. Strozzi named the database management system NoSQL to merely state it does not express queries in the traditional SQL format. Sadalage and Fowler believe the definition we commonly refer NoSQL as comes from a 2009 conference in San Francisco held by Johan Oskarsson, a software developer. Sadalage and Fowler recall Oskarssons desire to generate publicity surrounding the event and in an attempt to do so devised the twitter hashtag “NoSQL Meetup”. The main attendees at the conference debrief session were Cassandra, CouchDB, HBase and MongoDB and so the association stuck. [21]

NoSQL solutions are not bound by a definitive schema structure. This permits the ability to freely adapt database records or add custom fields for example without considering structural changes. This is extremely effective when dealing with varying data types and data sets, in comparison to the traditional relational database model which when tackling this issue often resulted in ambiguous field names. [21]

4.1 Brewer's CAP Theorem

4.2 Database Classification

One of the first decisions to be made when selecting a database is the characteristics of the data you are looking to leverage. [14] There are a multitude of options available with many different classifications. The following sections discuss a subset of these which are relevant to this project.

4.2.1 Distributed Database

A distributed database (DDB) comprises of two or more data files located at different sites and servers on a computer network. [23] The advantage of using a DD is that as the database is distributed, multiple users can access a portion of the database at different locations locally and remotely without obstructing one another's work. It is pivotal for the DD database management system to periodically synchronise the scattered databases to make sure that they all have consistent data. [23] For example if a user updates or deletes data in one location it is essential this change is mirrored on all databases. This ability to remotely access a database from all across the world lends itself to not only multinational companies for example but also startup businesses which recruit the expertise of others from various locations.

4.2.2 Document-Oriented Database

Document-orientated database (DODB) are designed for storing, retrieving and managing document files such as XML, JSON and BSON. The documents stored in a DODB model are data objects which describe the data in the document, as well as the data itself. Figure 8.2 illustrates an example document stored in a DODB specifically in MongoDB. The data is a recognisable JSON format and the joins of the document are between common variable values within each document.

4.2.3 Graph-Orientated Database

A graph-oriented database (GODB), is a form of NoSQL database solution that uses graph theory to store, map and query relationships. A graph is a collection of nodes connected by

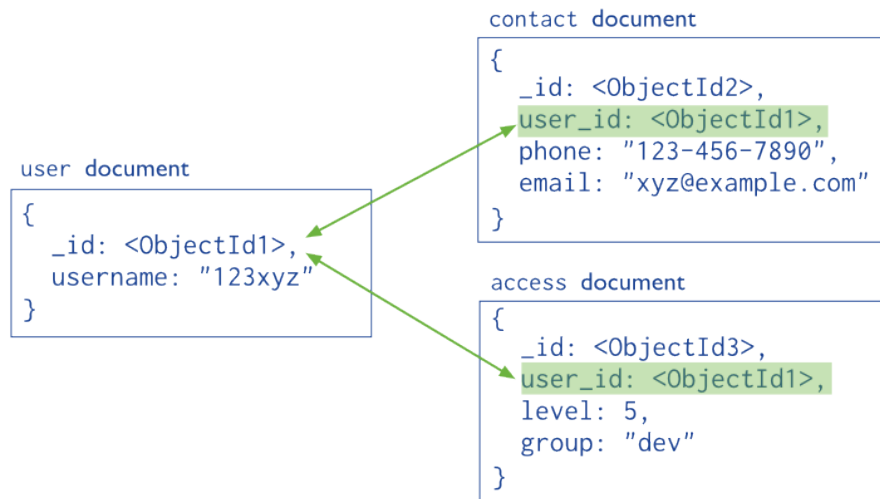


Figure 4.1: MongoDB document

relationships. “Graphs represent entities as nodes and the ways in which those entities relate to the world as relationships.” [20] The formation of the graph database structure is extremely useful and eloquent as it permits clear modelling of a vast and often eclectic array of data types. [20] An example of data represented in a graph structure is the Twitter relationship model. Figure 4.2 illustrates the nodes involved in a standard tweet and the relationship link

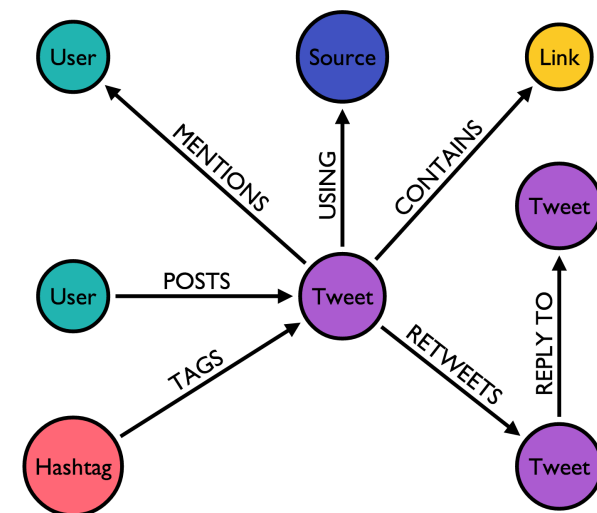


Figure 4.2: Example tweet data relationship

between them. The labeled nodes indicate the various operations which are involved in one the tweet. One interpretation of the figure 4.2 example is that a user posts a tweet, using the Twitter App which mentions another user and includes a hashtag and link.

4.2.4 Relational Database

A relational database (RDB) is a collection of data items organised as a set of tables, records and columns from which data can be accessed or reassembled in many different ways [15]. The connected tables are known as relations and contain one or more columns which comprise of data records called rows. Relations can also be instantiated between the data rows to form functional dependencies.

- One to One: One table record relates to another record in another table.
- One to Many: One table record relates to many records in another table.
- Many to One: More than one table record relates to another table record.
- Many to Many: More than one table record relates to more than one record in another table.

4.2.5 Column-Orientated Database

A column-orientated database (CODB) is a database management system that stores data tables as columns of data rather than as rows of data. The main objective of a CODB is to write and read data from the hard disk efficiently in an attempt to speed up querying time. A CODB has the ability to self index which uses less disk space than RDBMS which holds the same data. A CODB can also be highly compressed, resulting in aggregate functions such as MIN, MAX and SUM to be performed at a extremely high rate. [17].

Figure 4.3 illustrates the comparison of a RDB model against a CODB model. Within the row based model the data contains both multiple values per record and null values. However in the CODB model null values are not required as each record contains a minimum and maximum of one value.

4.3 Technology Evaluation

The technologies being evaluated in this project are outlined below.

4.3.1 MongoDB

MongoDB is an open source cross-platform DODB. The premise for using MongoDB is simplicity, speed and scalability [16]. Its ever growing popularity, specifically amongst

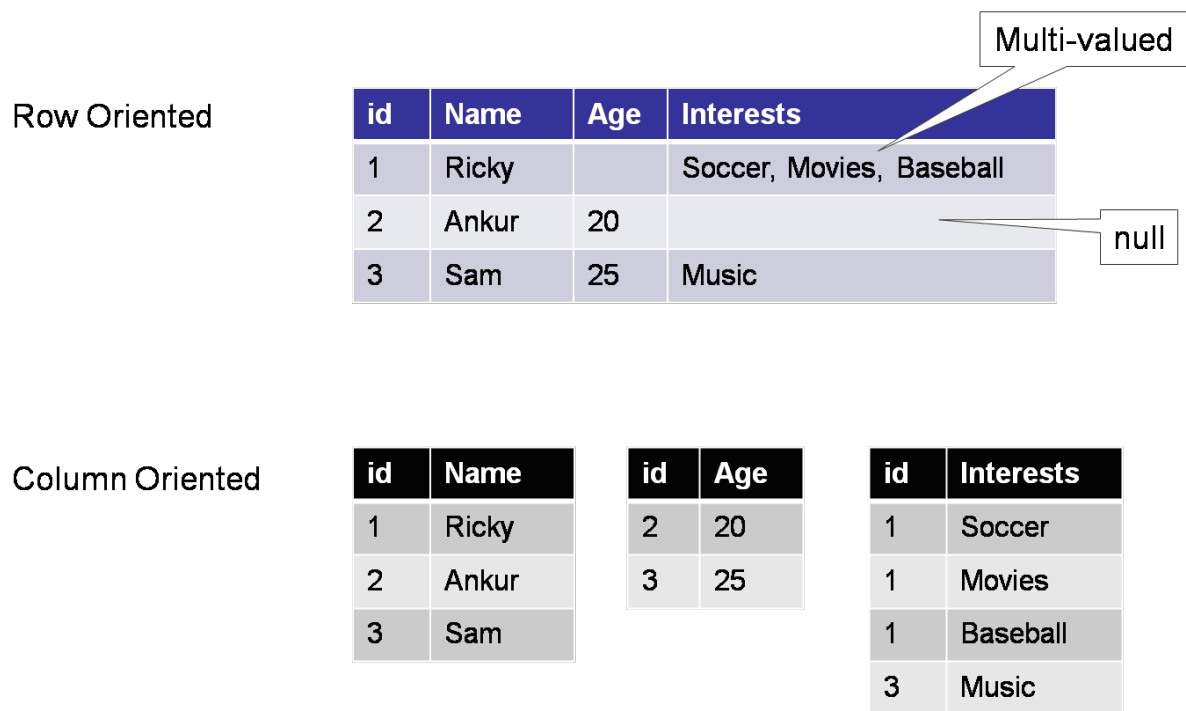


Figure 4.3: Column orientated database example

programmers, stems from the unrestrictive and flexible DODB data model which gives you the ability to query on all fields and boasts instinctive mapping of objects in modern programming languages. [16] The database design of MongoDB is based on the JSON file format named BSON.

A record in MongoDB is known as a document; a data structure composed of field and value pairs. The values of fields can include other documents, arrays and arrays of other documents. The key features of using MongoDB are its high performance data persistence, provide high availability and automatic scaling [16].

4.3.2 Neo4j

Neo4j is an open-source NoSQL GODB which imposes the Property Graph Model throughout its implementation. The team behind the development of Neo4j describe it as an “An intuitive approach to data problems” [7]. One of the reasons in which Neo4j is favoured predominantly amongst database administrators and developers is its efficiency and high scalability. This is in part due to its compact storage and memory caching for the graphs. “Neo4j scales up and out, supporting tens of billions of nodes and relationships, and hundreds of thousands of ACID transactions per second.” [7]

The key features of Neo4j which lends itself to users, developers and database administrators are its ability to establish relationships on creating, the equality of relationships permits the addition of new relationships being created after initial implementation at no performance cost and its use of memory caching for graphs which allows efficient scaling.

4.3.3 Apache Cassandra

Apache Cassandra is an open source column-orientated DDB that is designed for storing and managing vast amounts of data across multiple servers. “Apache Cassandra is a highly scalable, high-performance distributed database designed to handle large amounts of data across many commodity servers, providing high availability with no single point of failure.” [11]. Apache Cassandra define the key features of their database management system as “continuous availability, linear scale performance, operational simplicity and easy data distribution across multiple data centres and cloud availability zones.” [11]. Figure 4.4 illustrates an example record stored in a Cassandra database.

Users Table		
user_id	name	email
101	otto	o@t.to

Tweets Table			
tweet_id	author_id	name	body
9990	101	otto	Hello!

Follows Table		Followed Table	
user_id	follows_list	id	followed_list
104	[101,117]	101	[104,109]

Figure 4.4: Example Cassandra record

4.3.4 MySQL

MySQL is a freely available open source RDB that uses Structured Query Language (SQL). MySQL is commonly used for web applications with its speed and reliability being a key feature. The MySQL database stores data in tables - a collection of related data - which consists of columns and rows. MySQL runs as a server and allows multiple users to manage and create numerous databases.

SQL is a programming language used to communicate with databases through queries. SQL queries are used to perform tasks such as update or retrieve data in a database. The queries are in the form of command line language which include keyword statements such as select, insert and update.

Chapter 5

Data Source and Representation

The dataset used as a resource to populate the database solutions is called EMAP; a freely available anatomical ontology of the developmental stages of mouse embryos. The EMAP dataset was chosen for this project as my supervisor has much experience in the field and would be able to assist me with any queries I had regarding the data. The size and granularity of the EMAP dataset also meets the criteria which will be required to test the database solutions, explore the limitations of each database comparatively and pose insight into the overall performance of each database.

5.1 EMAP

The *Edinburgh Mouse Atlas Project* (EMAP) is an ongoing research project to develop a digital atlas of mouse development. The objective of the EMAP is to implement a digital model of mouse embryos for each time stage in development [13]. The collated model embryo data is then used to form a database from which further research can be conducted and experiments can be mapped.

Each time step in the digital model are named *Theiler Stages* inspired by the research conducted by Karl Theiler. A Theiler Stage defines the development of a mouse embryo by the form and structure of organisms and their specific anatomical structural features. There are 26 individual Theiler Stages which define the growth and evolution of the mouse embryo. The Theiler Stage scheme comprises of both the anatomical developmental stage definition and the estimated length of time since conception. Each Theiler Stage also provides a brief description of the anatomy and any significant changes between the current and previous stage.

Theiler proposed using this scheme as embryos at the same developmental age can have evolved at different rates and therefore exhibit different structural characteristics. EMAP has developed a collection of three dimensional computer models which illustrate and summarise each Theiler Stage.[13]

The anatomy generated at each Theiler Stage has an associated ontological representation. Each provides an alternative aspect of the evolution of a mouse embryo which corresponds with a respective Theiler Stage. The abbreviated term EMAP carries a certain amount of ambiguity as it refers to the name of the project, and one of the stages in the implemented anatomy. For the purpose of this project the main anatomy to be utilised is the aggregated non stage specific Edinburgh Mouse Atlas Project Abstract (EMAPA) anatomy.

5.1.1 EMAP anatomy

The EMAP anatomy ontology was originally developed to deliver a stage-specific anatomical structure for the developing laboratory mouse. As the EMAP research has progressed, the ontology has followed suit, and is continually under development.

The original EMAP anatomy ontology consists of a series of relational components organised in a hierarchical tree structure which utilise “part-of” relations and subdivisions which encompass each Theiler Stage [13]. The intention behind the implementation of the original ontology structure was to “...describe the whole embryo as a tree of anatomical structures successively divided into non-overlapping named parts” [13].

Each of the Theiler Stage components has an appropriately named term label, known as the *short name* which describes each respective component. Each Theiler Stage also has a *full name* which comes in the form of the components entire hierarchical path [13]. Neither the *full* nor *short* anatomical name of each component are required to be distinct and can appear in several Theiler Stages. Therefore to avoid ambiguity each component can be addressed by a unique identifier. The unique identifier is in the form of the relevant anatomy followed by a number (EMAP:number). For example “choroid plexus” is the short name of TS20/mouse/body region/head/brain/choroid plexus and has a unique identifier of EMAP:4218.

The EMAP hierarchical structure facilitates the need for basic “data annotation and integration” however a combination of the lack of hierarchical views, missing or poorly represented Theiler Stages and label name ambiguity exposed the limitations of the EMAP

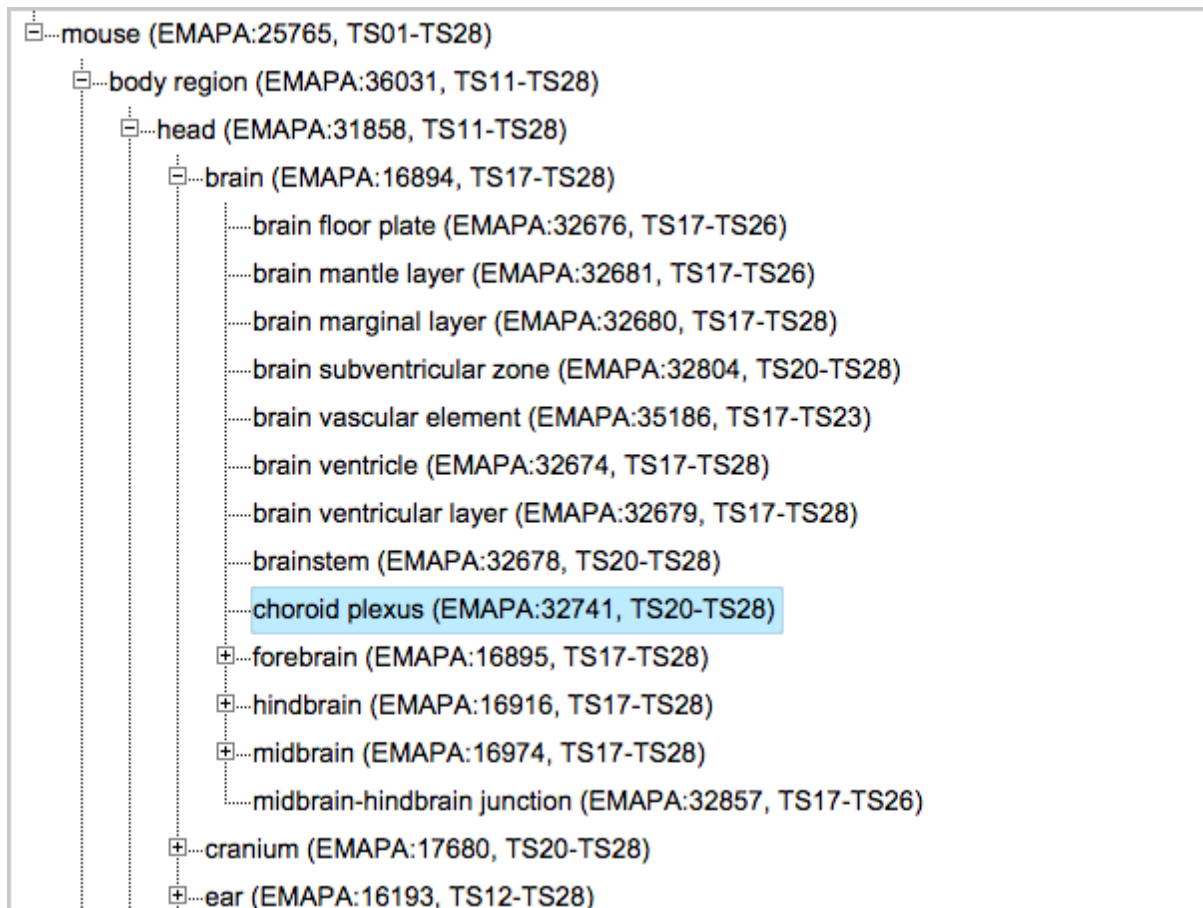


Figure 5.1: EMAPA data structure

structure. As a result the need for a hybrid “abstract” version of the anatomy was identified and subsequently developed; EMAPA. [13] Thus the EMAPA anatomy will be the main data source for this work.

The research surrounding the EMAP resource is continually being developed, thus the growth of the project as a whole is progressively increasing with the richness of data at the heart [13]. The EMAPA ontology discussed below in section 5.1.2 is now considered the primary data source thus the EMAP dataset is available in a combined EMAP and EMAPA standard ontological format developed by the Open Biological Ontologies (OBO) consortium (Section 3.0.3).

5.1.2 EMAPA anatomy

EMAPA is a refined and algorithmically developed non-stage specific anatomical ontology *abstract* representation of the EMAP anatomy. The EMAPA implementation replaces the EMAP hierarchical tree structure for a *directed acyclic graph* structure; a graph in which it is

impossible to start at some vertex v and follow a sequence of edges that eventually loops back to v again. Thus enabling the ability to represent multiple parental relationships and other forms of “is-a” relations where appropriate [13].

Each anatomical component in the EMAPA anatomy is identified as a single term, coupled with the appropriate start and end Theiler Stage at which the component is considered to be present in the developing embryo. [13] With the aim of enhancing user experience, the EMAPA anatomy implements an alternative naming convention from the EMAP anatomy replacing full path names for components to “*print names*”. Using the above example for comparison, “EMAP:4218” in the EMAP anatomy becomes “TS20 brain choroid plexus” in EMAPA. This naming convention supplements the requirement of uniqueness and is easily comprehensible.

The EMAPA ontology is available in a standard ontological format developed by the Open Biological Ontologies (OBO) consortium (Section 3.0.3) and is also available in a Web Ontology Language (OWL); a standard produced from W3C discussed in section 3.0.2. This enhanced version of the ontology EMAPA, is now considered to be the primary EMAP anatomy ontology thus will be the main source for the work on this project.

5.1.3 EMAGE anatomy

EMAGE is a database consisting primarily of image data of *in situ* gene expression data of the developing mouse embryo. The data is sourced from in the community and which is then taken by curators who monitor the EMAGE project and implement it in a standardised way that allows data query and exchange. The description includes a text-based component but the unique aspect of EMAGE is its spatial annotation focus. [13]

“Sites of gene/enhancer expression in EMAGE are described by denoting appropriate regions in the EMAP virtual embryos where expression is detected (and not detected) and also describing this information with an accompanying text-based description, which is achieved by referring to appropriate terms in the anatomy ontology” [13]

The EMAGE anatomy provides an alternative view of the EMAP anatomical ontology. The main data source for this project will be EMAPA however should the need for a data set which holds larger data then the EMAGE data set will be used.

Chapter 6

Evaluation Strategy

The purpose of this chapter is to discuss the methods used to carry out the primary research for this project. In order to achieve the objectives outlined in section 0.1 a formal set of requirements have been established to meet each intended target. Section 6.1 details how each objective will be evaluated and examples are provided of how each technology will be measured by way of competency questions.

The requirement section below is a high level view of what and how the data solutions will be analysed throughout the project. In order to get a detailed and finalised set of requirements an initial prototype model will be developed which will give an insight in to what will be expected to be achieved from the project. It is likely that the requirements below while they may form the basis of the project objectives will change drastically once the prototype model has been developed.

6.1 Requirements

The first objective of the project is to investigate the strengths and weaknesses of the functionality each technology provides. In order to evaluate the functional limitations of each technology, prototype data models will be developed for each solution. The solutions will then be loaded with the EMAPA dataset. Competency questions will be devised which will return a simple yes or no answer. Example competency questions can be found at section 6.1.1. These questions will be translated in to the relevant query language for each of the datasets. The competency questions will range from a beginner level where it will be expected that all database solutions will be able to return the intended value to an advanced level. The

difficulty of writing these queries will also be recorded and used to analyse the performance of the database solution. The time taken for the query to run will also be recorded and used for analysis

1. Is this query possible in database X?

For example the first query in the EMAPA competency question table asks : “For structure X, find all the ancestors.” If this query is possible in a given database, move on to the next query in the list and continue until failure. Once this step has been complete for all database solutions, by way of comparison evaluate the strength of each database.

Objective two of the project is to compare and contrast the analytical capabilities of each technology. This will follow on from the tasks undertaken in the first objective. This objective will also identify and analyse the difficulties which may or may not have arisen in the first objective on the ease of writing the query.

1. If the query is possible in a given database how rich a return of the dataset can it provide.
2. Does any database offer any querying capabilities/functionality which compared with another which aids the query in any way.

The final key objective to be evaluated in this project is to conduct a comparative analysis of the scalability of each technology. This will be achieved by loading the data sources in to each prototype data model. The specific requirements which will measure the performance of each database are :

1. Ease of ETL implementation - The focus of this requirement will be to evaluate any challenges which were faced during the ETL process.
2. Did the data model handle the volume of data and were there any issues as a result.

6.1.1 Data Source Competency Questions

EMAPA	EMAGE
For structure X, find all the ancestors.	Where is gene X expressed?
For structure X, find all the decedents.	What is expressed in structure X?
For structure X, find all structures in the same group (this only makes sense in limited situations, e.g., find all “hair”).	Which genes are expressed in both structures X and Y? (This is so-called co-expression).
Find all the structures in Theiler Stage X.	Which genes are most commonly co-expressed? (This is getting towards BI and is possibly out with the scope of your thesis, but it does no harm to discuss it.
Find all the structures in Theiler Stages X to Y (e.g., 17-19).	
What stages does structure X appear in?	
Given search term X return the “best match” structure (e.g., if Isearch on “heart” I would expect the output to be heart, heart atrium, heart septum heart mesentery)	
Given an EMAPA ID return the name of the structure.	
Given a name return the EMAPA ID.	

Chapter 7

Risk Assessment

The following table is a summation of the potential risks which may occur during the various stages of this project and the mitigation plans in place.

Risk	Mitigation Plan
Corrupt computer hard drive	Regular data back ups will occur on an external hard drive. Multiple file storage services such as Google Drive and Dropbox will be used for the document files.
Postural problems	The appropriate use of a chair and sitting position will be adopted at all times
Visual problems	Optical eye wear such as prescribed glasses will be worn when using the computer equipment
Fatigue and stress	A project plan has been developed which will allow a level control and organisation

Chapter 8

Database Modelling

In order for me to design a complete database model for each of the technologies, an initial investigation into the specific dataset values was required discussed in section 8.1. Once this was complete I followed the same database design process for each indexing solution which is discussed in section 8.2.

8.1 Cleansing the data

The EMAGE data which was supplied was made up of 4 tab separated files. Each file contained information pertaining a certain aspect of the dataset; Annotations, Publications, Submissions and Results.

- **Annotations** - Data such as the EMAPA structure ID, the EMAPA structure term, the Theiler Stage, the EMAGE structure ID and the strength in which the each gene was detected.
- **Publications** - Data regarding all authored publications for the EMAGE dataset. Data included the title, author(s), Theiler Stage and EMAGE ID for the genes.
- **Submissions** - Information on each EMAGE assay. Data such as EMAGE ID, Theiler Stage, probe ID, type of assay (in situ or part of), specimen type and specimen strain.

On initial review each of the files contained similar, repetitive, meta-data values. Thus creating a level of noise which would not be add anything to the project in terms of analysis and evaluation. Therefore I undertook an initial cleansing of the data before implementing the database design.

This cleansing process consisted of loading the data into Open Refine (OR) and manually manipulating the data using the filtering and editing tools the package provides. Using this tool allowed me to identify any erroneous rows of data which would affect the integrity of the dataset. In each file there was at most 5 rows of data which were either blank or inconsistent with the convention of the rest of the file. I decided to remove these rows as their inclusion in the file was unnecessary.

Another irregularity found in the *Publications* data file was the characters used in the title and author fields. There were over 600 rows of data which contained a non-ascii character. For example - ten Berge D, Brouwer A, el Bahi S, GuÃ©net JL, Robert B, Meijlink F. These rows would be rejected when importing into the databases as by default I decided to apply a UTF-8 character encoding to each indexing solution. Despite these values only contributing to around 5% of the file, the issue needed to be addressed. To do this I devised a regular expression which would identify and subsequently remove any of these characters.

Using a software tool such as OR enabled me to manipulate and cleanse the data in such a way that I would be able to load it successfully into the databases. Despite accomplishing the cleansing successfully, from the challenges I faced, I identified some problematic circumstances which, despite not being as prevalent using the EMAGE data, may affect other big data sets.

The maximum number of rows uploaded into OR was around 150,000. The EMAGE dataset is relatively small in comparison to large scale data collation, however the volume of data was a factor in my decision to use a software tool in an ETL workflow as opposed to rolling my own scripting solution. It is important when choosing a methodology or tool to enhance the veracity of a dataset that the volume of data is taken into consideration. OR is a Java application that utilises the Java Virtual Machine (JVM) and therefore it is integral to allocate enough memory to handle processing large files and thus avoid Java heap space errors. The OR developers suggest that a typical best practice is “start with no more than 50% of your available physical memory, since certain OS’s will utilize up to 1 Gig or more of physical RAM.” [?]. While using this software solution was sufficient for the data in this project, should the dataset be of a greater scale, a more robust and resilient system would need to be considered.

As discussed in section 1.1.1 a major challenge in data collection and manipulation is ensuring the veracity of your data. A leading contributor to this challenge is human error. It is

a fact of life that humans are error prone and can often make mistakes, therefore where possible the minimal amount of manual handling of a dataset is key. An example of an issue which can arise from this may be as simple as date formatting changing over time. The data may initially be input in a UK standard date format of DD-MM-YYYY by one person and then stored in a US standard data format of MM-DD-YYYY by another person. A simple example, however one which can have serious repercussions on the validity of a dataset. The cleansing of the EMAGE dataset relied on my knowledge of the data and any obvious flaws such as blank values where a value was required. While the data provided was reliable and generally healthy; a richer more granular dataset may require a more rigorous method of validation. One way to do this would be to implement a software script which takes a subset of the data, defines a format, and restructures the remaining data in the dataset accordingly.

8.2 Designing the data models

In order for me to develop multiple and reliable data models which accurately represent the dataset, I created a database diagram for each indexing solution. Each diagram effectively illustrates the relationship between the data entities. The order in which I decided to create the database model designs, was based upon two main reasons; which hinge upon aiding the readers comprehension of this thesis. The first reason was based upon my previous experience of using each of the database systems. My previous experience ranged from a competent level to the complete unknown. Secondly, as MySQL is a well known database management system, and is widely used for a number of applications, it is expected that the reader will have an already functioning knowledge of the system. As a result I decided the first data model I would develop would be for the relational database management system, MySQL. The next system I developed was MongoDB, followed by Neo4j and finally Apache Cassandra. Each implementation presented a different challenge all of which will be discussed below.

MySQL

As discussed in section 4.3.4 MySQL is a relational database management system which stores and represents structured data through entity tables and relationships. There are a number of variations in which the design of the MySQL database could be modelled for the EMAGE data. Figure 8.1 is an entity-relationship (ER) diagram which illustrates the implementation of my

MySQL normalised database design. Normalisation in database design is a process by which an existing schema is modified to bring its component tables into compliance through a series of progressive normal forms. It aids in better, faster, stronger searches as it entails fewer entities to scan in comparison with the earlier searches based on mixed entities. Data integrity is improved through database normalisation as it splits all the data into individual entities yet building strong linkages with the related data. A description of the tables is below the diagram.

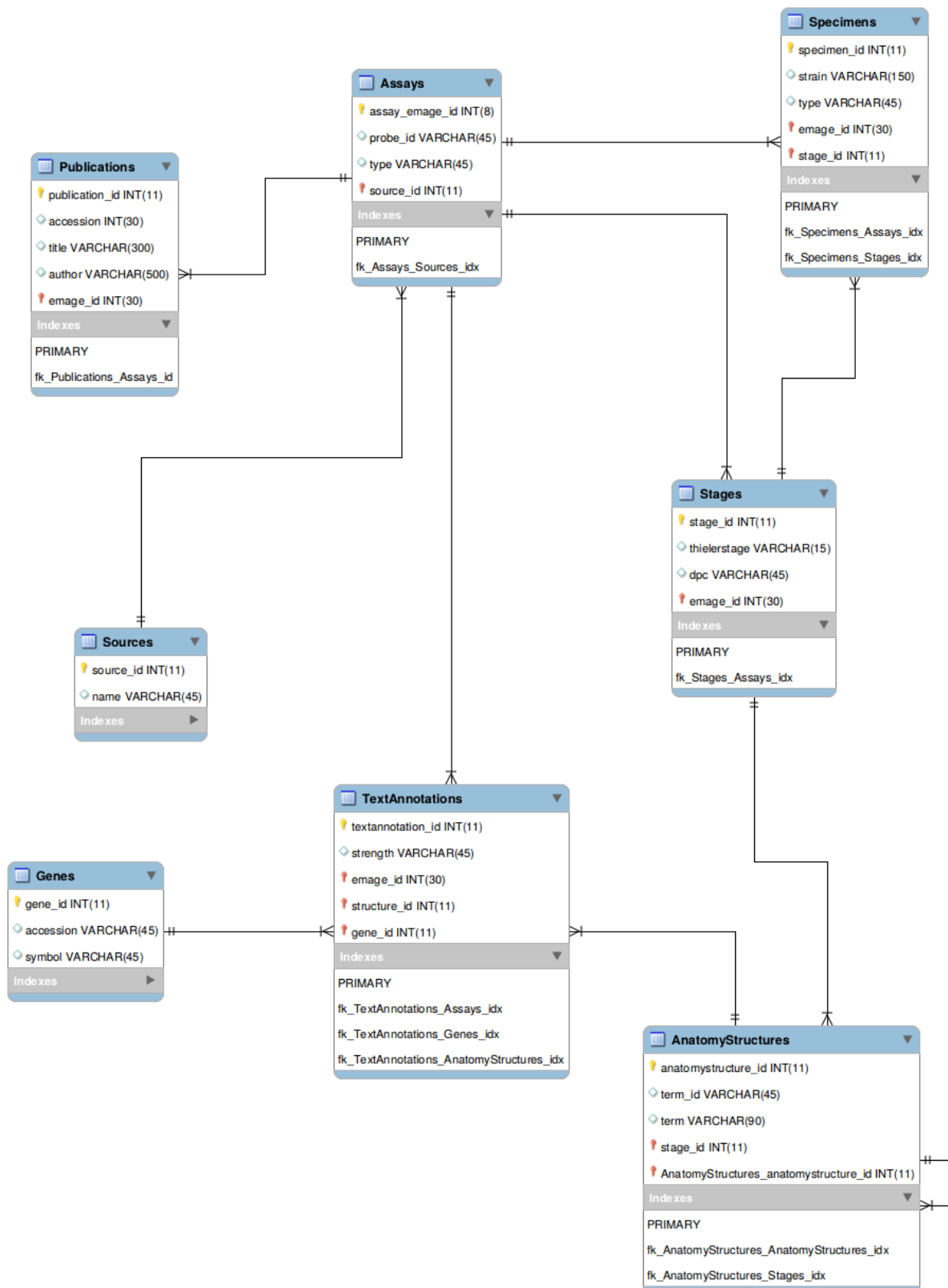


Figure 8.1: MySQL ER table diagram

- **AnatomyStructures** : This table contains the EMAPA ID, and the term which refers to the part of the anatomy.
 - Many to One relationship with the Stages table as one anatomy structure can have the same stage.
 - Many to One relationship with itself on the ID as one structure can have many parts.
- **Assays** : This table contains the EMAGE ID number, the ID of the probe and the type of assay. The *type* field refers to whether the assay is *in situ* or *part of*.
 - Many to One relationship with the Sources table. While one assay can only have one source, many assays can have the same source.
- **Genes** : This table contains the accession number and symbol of each gene.
 - The Genes table does not reference any other table.
- **Publications** : This table contains the accession, title and every author of each assay publication.
 - Many to One relationship with the Assays table as there can be many publications for one assay.
- **Sources** : This table contains the source of the assay.
 - The Sources table does not reference any other table.
- **Specimens** : This table contains the ID, strain and type of each specimen. The *type* field refers to whether the assay is a section, wholemount, sectioned wholemount or unknown.
 - One to One relationship with the Assays table as one assay has one specimen.
 - Many to One relationship with the Stages table as many specimens can have the same Stage.
- **Stages** : This table contains the theiler stage and number of days post conception (dpc) of each assay, specimen and anatomy.

- Many to One relationship with the Assays table as one assay has can have multiple stages.
- **TextAnnotations** : This table contains the structure and strength of each assay.
 - Many to One relationship with the Assays table as one assay can have multiple text annotations.
 - Many to One relationship with the Genes table as one text annotation can have multiple genes.
 - One to One relationship with the AnatomyStructures table as one text annotation can have one structure.

MongoDB

As discussed in section 4.3.1, MongoDB is a homogeneous, schema-less, NoSQL document store database. There are no formal relations between the data which makes modelling the database a little more challenging; especially with data which is so closely bound as the EMAGE dataset.

Data in MongoDB sits in *collections*, a grouping of documents which are stored on a database. A collection exists within a single database and is the equivalent of an RDBMS table. Documents within a collection can have different fields and typically, all documents in a collection have a similar or related purpose.

The MongoDB implementation was the second prototype data model I created for this project. I followed the same structural process which I had undertaken for the previous MySQL data model. When creating a MongoDB data model there are a number of factors and considerations which need to be identified before starting the formal implementation. Firstly the biggest decision I deliberated over was how should the data be connected. As there were a few options I decided to explore all of them to fully comprehend the pros/cons of each.

My initial design was based around using multiple collections to store the various aspects of the data. The design followed the MySQL model, with were 4 collections; Assays, Text Annotations, Anatomy Structures and Genes. To connect the data and bind the values required an additional manually developed ID field for every document. While this was not a complex task, it was one which I felt was unnecessary and added extra unwanted noise to the data. Using this option would have also incurred more overhead when writing the queries for

the database as one would firstly have to connect the data (similar to a RDBMS join) and then include a further query.

After some deliberation I concluded that the best way to implement the data model would be to have all of the data in the one collection. Figure 8.2 illustrates an example document in the developed MongoDB data model. The diagram should be read as follows:

- **id** : This is the EMAGE id of each assay and is the value which binds all of the data together. The id value has been manually configured to correspond with the EMAGE value.
- **specimen** : The specimen value is an array of size 2 which holds data regarding the strain and type of the assay.
- **probe id** : This value is the id of the probe accession.
- **assay source** : The source in which the assay has been retrieved from.
- **assay type** : The type of assay which is being analysed. By type I am referring to whether the assay is *in situ* or otherwise.
- **stage** : An array containing the information regarding the stage of the assay; Theiler stage and DPC.
- **publication** : An array containing all publication information regarding that specific assay; id, title, author.
- **text annotation** : The text annotation array is the grouping of strength, anatomy structure and gene of an assay. An anatomy structure has a term id and the name of the term and a gene has the symbol and id.

```
{
  "_id":"6",
  "specimen":
  {
    "specimen_strain":"Swiss Webster",
    "specimen_type":"wholemount"
  },
  "probe_id":"MGI:1334951",
  "assay_source":"emage",
  "assay_type":"in situ",
  "stage":
  {
    "theiler_stage":"11",
    "User_Stage":"7.5 dpc"
  },
  "publication":
  {
    "publication_id" : "PMID:1409588",
    "publication_author" : "Tanaka A, Miyamoto K, Minamino N, Takeda M, Sato
B, Matsuo H, Matsumoto K",
    "publication_title" : "Cloning and characterization of an androgen-induced
growth factor essential for the androgen-dependent growth of mouse mammary
carcinoma cells."
  },
  "textannotation":
  [
    {
      "anatomystructure":
      {
        "term_id":"16107",
        "term":"allantois"
      },
      "strength":"strong",
      "gene":
      {
        "symbol":"Fgf8",
        "gene_id":"MGI:99604"
      }
    }
  ]
}
```

Figure 8.2: Example MongoDB document diagram

Neo4j

Neo4j is a graph orientated, NoSQL database solution. It uses the Property Graph Model methodology of connecting data by nodes and weighted edges. Nodes are the equivalent of a MySQL table and edges are the equivalent of a relation. A full description of Neo4j can be found in section 4.3.2.

The data model I have constructed for Neo4j, is semantically similar to that of the MySQL implementation. There are 8 nodes, which contain relatively the same data as that of each MySQL table. The main difference between the two systems is how the data is joined. Where MySQL has a foreign key join, Neo4j has an edge, which connects the nodes.

As with MongoDB and indeed many NoSQL system, there is no formal way to diagrammatically convey the database “schema”. To illustrate the Neo4j data model, I have created two diagrams. The first is an entity relationship (ER) diagram - figure 8.3 - and the second - figure 8.4 - is an example visualisation, aiming to convey the look and feel of the graph model. In terms of the ER diagram, it should be translated as, an entity is a node and a join is a relationship. The data within the nodes is:

- **Assay:** This node contains data such as EMAGE ID, probe ID and type e.g. in situ. The Assay node has 4 self-defining relationships.
 - Assay COMES FROM Source
 - Assay HAS Specimen
 - Assay HAS Stage
- **Publication:** This node contains all publication data, which includes; title, author and id of each assay publication. The Publication node has one relationship.
 - Publication DESCRIBES Assay
- **Source:** The source node has just one field, source name. It defines the source of each assay.
- **Specimen:** Each assay has a specimen node. This node stores the specimen strain and specimen type. It has one relationship, which is the link between the stage node.
 - Specimen HAS Stage

- **Stage:** The stage node contains each Theiler Stage and DPC value.
- **Annotation:** This node contains information regarding the strength of each annotation. It is the join between the Gene and Anatomy Structure nodes. The annotation node has two relationships.
 - Annotation REPORTS Assay
 - Annotation HAS AnatomyStructure
- **Gene:** This node contains all data regarding each gene found. Data such as; gene name and gene accession. The Gene node has one relationship.
 - Gene HAS Annotation
- **AnatomyStructure:** This node contains all of the data regarding the respective anatomy structures, such as; structure ID and structure term name

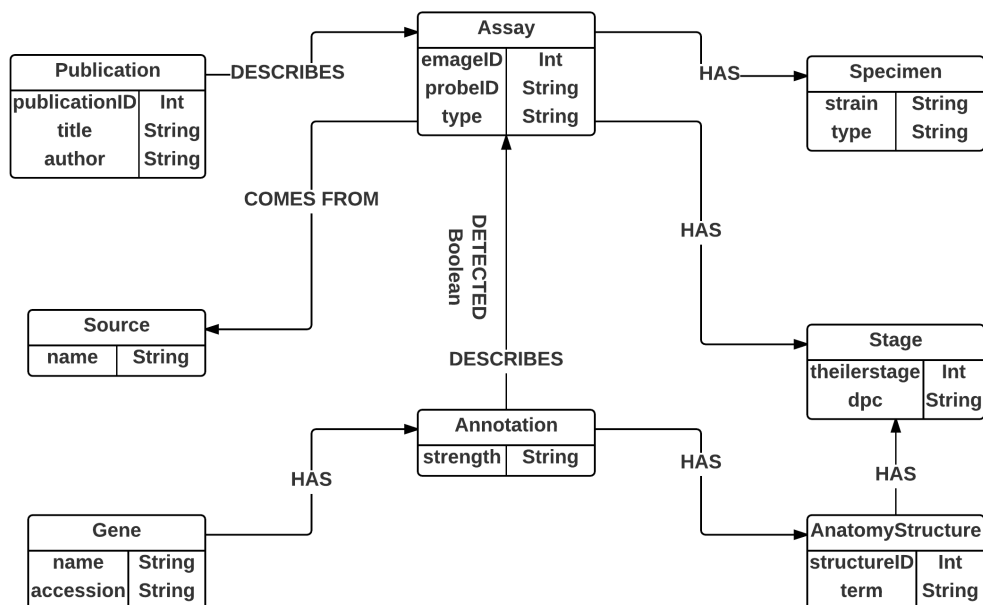


Figure 8.3: Neo4j graph model ER diagram

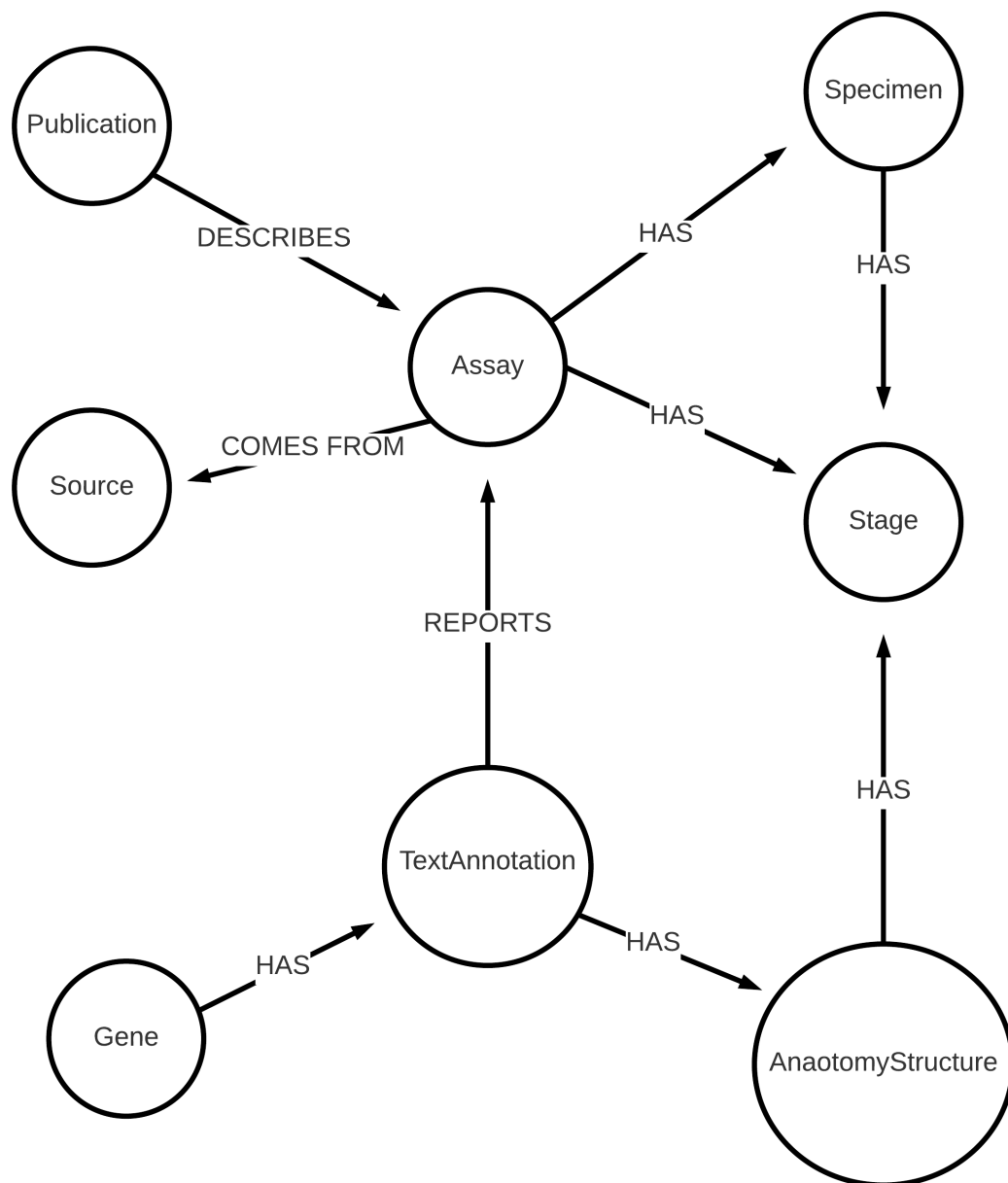


Figure 8.4: Example Neo4j graph model diagram

Apache Cassandra

The Apache Cassandra data model was perhaps the most difficult of all the database system designs to create. This was due to a number of reasons. One of which was, that I had no previous experience of using a Cassandra database, and therefore had to learn a completely new style of working. Secondly, as discussed in section 4.3.3, one of the main aspects of Cassandra family columns and tables is that they do not accept joins. Resulting in tables being created, aiming to satisfy the any potential queries which may be imposed on the database. The repercussions of this concept is discussed in section ??.

Apache Cassandra is a column based data management system. A key characteristic of a column based data store is that they are extremely powerful and can be reliably used to keep important data of very large sizes. Despite not being *flexible* in terms of what constitutes as data, they are recognised as being highly functional and performant [11]. With this in mind, normalisation of a dataset is in fact not the optimal way of developing a Cassandra data model. It is proposed that *denormalisation* and data duplication within the data model returns the best performing output. This is as a result of Cassandra being optimised to perform a high frequency of writes which in turn reduces the more costly reads. This is a trade-off which must be taken into consideration when developing the data model [11].

Chapter 9

Database Implementation

This chapter focuses on the implementation of the data models discussed in chapter 8. Each database management system has their own procedure for instantiating a new collection, table, node or column family. This chapter discusses the methods and strategies I imposed to create the database solution designs; with a focus on any challenges faced in doing so. Section ?? evaluates the process undertaken to physically load the data into the systems.

9.1 Creating database systems

Once the process of modelling of the database systems was complete, the next stage was to transform the model plan into actual databases. For each database system, this was relatively simple. However, with this simplicity, brought limitations and restrictions of which I had to construe, to fully achieve my target model.

MySQL

The MySQL data model consists of 8 tables; AnatomyStructures, Assays, Genes, Publications, Sources, Specimens, Stages and TextAnnotations. Each of which are discussed in detail, in section 8.2. The creation of these tables was a relatively straightforward undertaking. While the ease in which I found this process, may be due to my previous experience of using MySQL, the intuitive and logical way in which relational databases are constructed, make the implementation of a data model, an all round elementary procedure. An example of how a table is created in MySQL can be found in the code snippet 9.1 below. This code illustrates the creation of the Assays table, the indexes and the constraints.

```

1  —
2  — Table structure for table 'Assays'
3  —
4  CREATE TABLE IF NOT EXISTS 'Assays' (
5      'emage_id' int(11) NOT NULL,
6      'type' varchar(255) DEFAULT NULL,
7      'probe_id' varchar(255) DEFAULT NULL,
8      'source_id' int(11) NOT NULL,
9      'specimen_id' int(11) NOT NULL,
10     'stage_id' int(11) NOT NULL,
11 ) ENGINE=InnoDB DEFAULT CHARSET=utf8;
12 —
13 — Indexes for table 'Assays'
14 —
15 ALTER TABLE 'Assays'
16     ADD PRIMARY KEY ('emage_id'),
17     ADD KEY 'source_id' ('source_id'),
18     ADD KEY 'specimen_id' ('specimen_id'),
19     ADD KEY 'stage_id' ('stage_id');
20 —
21 — Constraints for table 'Assays'
22 —
23 ALTER TABLE 'Assays'
24     ADD CONSTRAINT 'fk_Assays_Sources' FOREIGN KEY ('source_id')
25     REFERENCES 'Sources' ('source_id'),
26     ADD CONSTRAINT 'fk_Assays_Specimens' FOREIGN KEY ('specimen_id')
27     REFERENCES 'Specimens' ('id'),
28     ADD CONSTRAINT 'fk_Assays_Stages' FOREIGN KEY ('stage_id')
29     REFERENCES 'Stages' ('id');

```

Code snippet 9.1: Creation of Assays table

As you can see in lines 4 - 11, the creation of each column takes the form of; column name, data type with length and the default attributes and values i.e. null or not null. The character set for each table, by default was set to utf8. You will notice here that the key values were not in fact instantiated at time of creation. This was as a result of an experiment to evaluate the affect the exclusion of index keys and constraints has at time of data load on each database. The findings of this experiment are illustrated in figure ?? with reference to the performance

of the other database solutions for comparison.

This figure clearly illustrates that the time taken to load the data without index keys and constraints had little, to no true affect on load performance. While there is slight variance in load time, this can be expected and attributed to a number of reasons, such as other processes running simultaneously on the CPU for example.

MySQL tables are linked by joining the (unique) primary key of one column to the (unique or non unique) foreign key of another. Lines 15-19 in code snippet 9.1, is where the key columns are created and lines 23 - 29 is where the foreign key constraints are expressed. The notion of keys joining tables can often be a slightly confusing concept to understand on first encounter. Primary and foreign keys are, not always, but in most cases confined to integer values. This is as a result of, data often containing inconsistent, ambiguous and non universal values. For example, a primary key may have the value “Mouse” and a foreign key may have the value “mouse”. Both valid strings however as they do not match exactly the join would fail. The rigidity of these constructs have as many advantages as they do disadvantages. While the concept of joining two tables on matching integers seems logical, many situations occur where there is no unique ID present in the dataset and therefore the ID has to be manually created based on the data available.

The process to create multiple tables and join them together in MySQL is relatively straightforward. While the formality of definitively expressing each term and its data type then stipulating the index keys and constrains, can be a tedious process, it is done so in a logical and objective manner, which makes it coherent and understandable for the programmer.

MongoDB

Creating a document inside a MongoDB collection (the equivalent to a MySQL table) is done by inserting field and value pairs. Each time a new field and value pair is inserted into a collection, a new document is created. By default, each document in a collection is provided with a unique ID which has an object data type. ObjectIds are small, fast to generate, and ordered. These values consists of 12-bytes, where the first four bytes are a timestamp that reflect the ObjectId’s creation [?]. A unique ID can also be manually inserted for each document, if available.

The data types which MongoDB accepts are:

Data type	Definition
String	String in mongodb must be UTF-8 valid.
Integer	Integer can be 32 bit or 64 bit depending upon server.
Boolean	This type is used to store a boolean (true/ false) value.
Double	This type is used to store floating point values.
Min/ Max keys	This type is used to compare a value against the lowest and highest BSON elements.
Arrays	This type is used to store arrays or list or multiple values into one key.
Timestamp	ctimestamp.
Object	This datatype is used for embedded documents.
Null	This type is used to store a Null value.
Symbol	This datatype is used identically to a string however it's generally reserved for languages that use a specific symbol type.
Date	This datatype is used to store the current date or time in UNIX time format.
Object ID	This datatype is used to store the document's ID.
Binary data	This datatype is used to store binay data.
Code	This datatype is used to store javascript code into document.
Regular expression	This datatype is used to store regular expression

Table 9.1: My caption

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