



Investigation of System Architecture, Databases, and Caching systems For backend web development

Independent Study Thesis

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Abstract

Include a short summary of your thesis, including any pertinent results. This section is *not* optional, and the reader should be able to learn the meat of your thesis by reading this (short) section.

This work is dedicated to the future generations of Wooster students.

Acknowledgments

I would like to acknowledge Prof. Lowell Boone in the Physics Department for his suggestions and code.

Vita

Publications

Fields of Study Major field: Major

Minor field: Minor

Specialization: Area of IS research

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Preface

The purpose of this document is to provide you with a template for typesetting your IS using L^AT_EX. L^AT_EX is very similar to HTML in the sense that it is a markup language. What does this mean? Well, basically it means you need only enter the commands for structuring your IS, i.e., identify chapters, sections, subsections, equations, quotes, etc. You do not need to worry about any of the formatting. The `woosterthesis` class takes care of all the formatting.

Here is how I plan on introducing you to L^AT_EX. The Introduction gives some reasons for why one might find L^AT_EX superior to MS WordTM. Chapter 5 will demonstrate how one starts typesetting a document and works with text in L^AT_EX. Chapter ?? discusses the creation of tables and how one puts figures into a thesis. Chapter ?? talks about creating a bibliography/references section and an index. There are three Appendices which discuss typesetting mathematics and computer program code. The Afterword will discuss some of the particulars of how a L^AT_EX document gets processed and what packages the `woosterthesis` class uses and are assumed to be available on your system.

Hopefully, this document will be enough to get you started. If you have questions, please refer to **mgber04**, **kd03**, **ophs03**, **feu02**, **fly03**, or **gra96**.

CHAPTER **1**

Introduction

My first web application was a Flask application with a simple backend, frontend, a database connected to it, and a few API calls. I thought that web development more simple than it sounds like. However, I changed my minds within the few months of learning frontend and backend side of web applications. As I worked on projects, new problems arose as I try to make the scale of the project larger. Also, depending on the project, I had to learn new strategies and technologies to achieve the goal I want. More things were there to learn and I started realizing that several design choices could be made in every situation. Not being able to answer “why this specific choice?” for some of the choices I made realize that I do not have full understanding of decisions that could be made in web development and led me to research this topic.

Covering all the topics in web development was the primary goal, but it could be a lot to process deep understanding by one year of the Independent Study period. I narrowed down my subjects to target the topics I encountered the most and personal interests, with the help of backend roadmap [[Ahmed_2025](#)]. Software architecture choices was a personal choice of interest. Although most of my applications were monolithic due to a smaller scale, I wanted to dig deeper into the structures of monolithic applications and also distributed systems, so that I could apply the knowledge when I start to work with larger scale applications.

The second topic is database systems. I have taken the database class during my sophomore year, but web development required much deeper knowledge. Types of databases to choose, ways to structure the database for performance and scalability were always a confusion for me. To fully understand the decisions I am making, I will research this topic to be able to make the logical decision in the future when creating applications.

The last topic is about caching systems. There were multiple times where my application was slow due to database queries or functions to fetch data from external APIs. There were multiple ways to solve this problem, but the one technology I used was caching. Caching data that calls database queries or API calls often made the application

significantly faster. However, I did not understand which strategies to use and what types of caching systems to use, which led me to research more on this topic.

A web application that uses these three technologies is the best way to show that I have full understanding of the choices I have made. A local cuisine recommender web application shows the application of the knowledge and research done in these areas.

The motivation for creating the application arises from the discomfort of finding local cuisines when traveling to foreign countries. It is a good experience to try out the local cuisines of the area of destination, especially for people who love food. However, searching directly on google map does not accurately show the famous dishes in the specific region, but rather recommend restaurants. Going straight to the restaurants sometimes works, but sometimes it is helpful if there is a set of cuisines to try already layout and choose the restaurant where the cuisines are available. This needs a two step search: first on a search engine such as Google to find the famous food in the area, and second, searching the name of the dish in Google Map. The purpose of the Local Cuisine application aims to make this process of searching restaurants more efficient.

CHAPTER 2

Theoretical Foundations and Literature Review

2.1 Backend Software Design and Architecture Principles

There are multiple architectural styles that could be applied when designing the backend system of a web application. The two main categories are monolithic and distributed. Subcategories such as layered services, microservices, event-driven services, are all under these two architecture styles. Each of these design have their advantages and disadvantages.

2.1.1 Monolithic

A monolithic application is where all the logical components of the application is deployed as one unit. This also means that the application will be run in one process. For example, if there is a stand-alone Python Flask application deployed to a server, this is monolithic application. This means that the UI components should also be included in the same unit. If there is a separate frontend server, this is not a monolithic application anymore. There are multiple reasons to build a project with the monolithic architecture.

One of the benefits of the monolithic architecture is its simplicity. Since a typical monolithic application have a single codebase, it is easier for the developers and collaborators to understand the overall structure. Even when a developer joins in the middle of the development process or reading an older code base, understanding program will be generally easier compared to distributed systems structure. Another advantage of using the monolithic structure is the cost. Since only one unit has to be deployed, which is simple and requires less infrastructure, it is cheaper to operate overall. Because of the cheap cost, developers are able to experiment and deliver systems faster, beneficial in a fast pace environment. Reliability is another aspect, where monolithic applications make few or no network calls, which usually means more reliable application. Lastly, it is easier to find bugs when spotted compared to distributed systems since all the code is in one place.

On the other hand, there are also disadvantages of using the monolithic architecture. As the monolithic application grows, the application becomes harder to scale. Since all the code is in one codebase, it is not possible to adapt different technology stacks to different domains if needed. This also connects to reliability, because incase any bug occurs in the application, this could degrade the service and affect the whole application. Lastly, when deploying the application, Implementing any change will require redeploying the whole application, which could introduce a lot of risk.

2.1.1.1 Layered Architecture

Layered architecture is a sub category of the Monolithic architecture. Applications that are designed with this architecture has three layered parts: the presentation layer, the workflow layer, the persistence layer, and the database layer. Each layer has its own tasks and separated within one application.

- **Presentation Layer:** The presentation layer is where the user interface (UI) is displayed and where the users interact with the system. All components that are related to the UI are included in this layer.
- **Workflow Layer:** The workflow layer consists of all code related to logic such as business logic, workflows, and validations. This is where most of the application's code is contained.
- **Persistence Layer:** The persistence layer encapsulates the behavior required to make objects persistent, such as mapping the architecture or code-base hierarchies into set-based relational databases.
- **Database Layer:** The database layer is optional. This layer includes the database or any mechanism used to persist information.

Each of the layer may contain multiple problem domains. For example, for a restaurant, there could be domains like place order, deliver order, manage recipes, or mange inventory. Different problem domains could exist together in each layer of the application.

An implication of the layered monolithic architecture is the MVC design pattern, which is a abbreviation for model view and context. In MVC, the model represents business logic and entities in the application; the view represents the user interface; and the controller handles the workflow, stitching model elements together to provide the application's functionality, as shown here: (head first software architecture chapter 6)

The layered architecture has several advantages. One of them is the feasability of the application. Since the structure is organized into distinct layers with specific responsibilities, it is clear for developers to understand the overall strcutrue of the code. This separation also allows technical partitioning, which makes it much easier to manage and maintain big projects. The division of each section decreases the possibility of bugs, which could be a crucial disadvange of monolithic applications. Furthermore, the layered architecture is quick to build particuarly among the

projects that have clear relationships among the components since different development teams can work on different layers in parallel.

There are also disadvantages to consider. The layer could add complexity to the application compared to a simple monolithic application. However, this would still be less complicated compared to the complexity of the distributed systems. Testing is another problem since most layers are dependent on each other, testing a specific layer requires mock data or simulation of the related layers, which could decrease the quality of the testing.

Some applications using the layered architecture may have different structure from the original. Some layers might be separated, such as the presentation layer being separated from the other layers. Each structure will have advantages and disadvantages within the layered architecture.

2.1.1.2 Modular Monolith

Modular monolith is when an application is divided into different modules within the monolithic system. A module is one domain of the application, and each domain will have its independent code base. For instance, an application for a restaurant might have different domains such as orders, deliveries, or recipes. In this case, there could be separate databases for each modules, or multiple schemas within a single database. It is important to keep in mind that only the code base is independent in the software structure, meaning that since modular monolithics is still follows the monolithic architecture, the code will be compiled together as a single application and run in one process.

One of the benefits of using the modular monolithic structure is the domain partitioning. Similarly to the layered architecture, this allows to have separate development teams that specialize in one or more of these domains, which will increase the efficiency of the work. Similar to other monolithic applications, the performance of the application will be fast since there are no network calls within the application. Furthermore, since each modules are separated from each other, it is easier to maintain the code.

However, code could be hard to reuse since each module have its own code. The logic and utilities could be tightly coupled to each domain, decreasing the flexibility to reuse the code compared to the modular monolithic structure. Also, similar to other modular monolithic architecture applications, as the application grows, the logics and the databases could become complicated since all the code base is in one single application.

2.1.1.3 Microkernal Architecture

The microkernel architecture is consisted with a core of the application, and plugins. The core of the application is where the main application is being run, and the plugins are connected to the core application. It is used when a lot of customization is needed for the software

There are multiple design choices that could be made within the monolithic architecture. Each structure has its own advantages and disadvantages, so it is important to choose the suitable structure in every situation.

2.1.2 Distributed Systems

Distributed architecture is when the logical components of the application are split up into multiple units. These units each run in their individual process and communicate with each other over the network. This architecture style encourage loose coupling of each services, which could be a huge benifit.

There are multiple advantages by choosing the distributed systems. The one that contrasts with the monolithic architecture is scalability. Since distributed architectures deploy different logical components separately from one another, so it is easy to add new services. Furthermore, similar to modular monolithics, distributed architecture encourage a high degree of modularity. This is because distributed systems have loosely coupled logical components. The benifit of having multiple distributed systems is also shown during the testing phase as well. Since each unit are loosely coupled, they could be tested separatley. This becomes a huge advantage as the size of the application grows compared to monolithic systems. Lastly, fault tolerance is a big difference compared to the monolithic system. Since multiple units are deployed in several units, even though one part of the system is down, the other parts of the system could still be available, depending on the coupling.

On the other hand, there are also disadvantages when choosing to build and distributed systems architecture. Performance is generally slower than an monolithic application since distributed system architectures involve lots of small services that communicate with each other over the network. This can affect performance, but there are ways to improve this. Another aspect is cost, since more servers are needed to deploy multiple units. These services will need to talk to each other, which entails setting up and maintaining network infrastructure. This leads to more complexity in the system, and makes the developers harder to understand the overall design. Also, errors could happen in any unit involved in servicing a request. Since logical components are deployed in separate units, tracing errors could become complicated.

There are both advantages and disadvantages for monolithic and distributed systems and choosing the appropriate architecture for each situation is crucial. After deciding which of the two main architecture will be used, then we could decide on which subcategory of either of the architecture to implement. Same as the monolithic structure, distributed systems architecture has multiple types of subcategories, each having advantages and disadvantages.

2.1.2.1 Microservices Architecture

A microservice is a service that is separately deployed unit of software that performs some business or infrastructure process [Gandhi_Richards_Ford_2024]. Microservices architecture is part of the layered system, where microser-

vices communicate with each other to make an application. Since the system is divided into multiple parts, it is essential how to divide the application, such as deciding how small or how big each microservices could get into. Generally, it is better to make microservices smaller for multiple reasons. Some of the factors that are considered to make microservices smaller are the following: cohesiveness, fault tolerance, access control, code volatility, and scalability.

If a part of the software has lack of cohesiveness and loosely coupled, it is a good idea to separate it into smaller microservices. This will allow higher scalability. If a certain part of the application produces fatal errors, having those part in a separate microservice will decrease the probability to shut down the whole system. For security and authentication, it is important to have these access controlabilities into a single microservice, so it does not get too complicated when managing the information. Finally, if one part of the microservice change, or scale faster than the others, it is good to consider to have a separate microservice for that application, since testing the entire microservice would be much more challenging compared to a small portion of the microservice.

On the other hand, there are times when it is encouraged to make the microservices bigger: Database transactions, data dependencies, and workflow. It is not possible to perform a single database commit or rollback when a request involves multiple microservices. For data consistency and integrity, it is important to combine functionalities that require these kind of behavior into a single microservice. If a part of a microservice has highly coupled data, such as when a database table refers to the key of another database table, it is better to keep these functionalities as a single microservice, to keep the data integrity of the database. If a single request requires separate microservices to communicate with each other, this request is coupled. If too much coupling is occurred between microservices, there are many negative effects. For example, performance is affected by network, security, and data latency. Scalability is affected because each microservice in the call chain must scale as the other microservices scale (something that is hard to coordinate). Fault tolerance is affected because if one of the microservices in the chain becomes unresponsive or unavailable, the request cannot be processed. It is good practice to consider the workflow and decide whether to keep the microservice big.

Balance

Sharing functionalities

There are many times when the same code has to be used in multiple microservices. There are mainly two ways for sharing code when building a microservice architecture. Creating a shared service, or a shared library. A shared service is a separate microservice that contains a shared functionality that other microservices can call remotely. The advantages of using this is that even though a code is changed in the shared microservices, code in other microservices are not required to change. Also, this shared service could be written in any language, which is useful when microservices are implemented in multiple languages. A disadvantage of using a shared service is coupling that happens between the microservices and the shared service. This leads to risks when changing a shared service since it can affect the

other microservices that call it. Furthermore, when the shared service is down for some reason, the microservices that require the shared service would not function. Another disadvantage is network latency,

A shared library is a more common way for code reuse. A library will be built including all the code that are reused in different microservices, and once they microservices are deployed, each microservice will have all the shared functionality available. The biggest advantage of using a shared library is that network performance and scalability is better than shared service, since it is not remote and the code is included in the compile time of the microservice. However, multiple shared libraries will be needed if microservices are written in different programming languages. Also, managing dependencies between microservices and shared libraries could be a challenge if there are multiple microservices using the shared code.

Workflow

Microservices communicate with each other to make the whole application. It is important to know how these are connected, and this is where workflow comes in. The term workflow means when two or more microservices are called for a single request. Workflows are in charge of navigating which microservice to start, which one to call next, and which one to end with. There are two ways to handle workflows: centralized workflow management, and decentralized workflow management.

Centralized workflow management

This workflow management style is where there is a microservice that coordinates all the microservices that are needed to handle a certain single request. This microservice will be responsible for calling all related microservices, knowing the current state of the workflow and what happens next, summarize all data from each microservice, and handling errors.

The advantage of this workflow management style is that the order of microservices for each requests are clear. The central microservice always has the exact routes the request has to take, which allows to track the status where each requests stopped and where to restart. This allows to handle errors efficiently. Also, it is easy to change a workflow since this all changes in one central microservice.

The disadvantage is that tight coupling between the central microservice and the other microservices. This can lead to lower scalability, since changing a microservice will affect the central microservice. Moreover, performance might get delayed since the central microservice is indeed another microservice that requires remote calls and it saves the workflow state data in a database which slows down the performance.

Decentralized workflow management

The decentralized workflow does not have a central microservice, but rather all microservices redirect to another microservice by the given request until the request is complete. It is important to not use one of the microservices as a central microservice.

The advantage of using this workflow pattern is that it is loosely coupled compared to the central workflow management, which has better scalability. Also, since the microservices does not have to connect back to the central microservice, it has better responsiveness, meaning less delay and better performance.

On the other hand, this pattern lacks in error handling, since each microservice is responsible for managing the error workflow, which could lead to too much communication between services. Also, because there is not a central microservice that has the order of microservices that needs to be called, it is hard to tell which state the response is at, which decreases the ability to recover when the request is delayed and needs to be restarted again.

Pros and Cons of microservice architecture.

Microservice architectures are commonly used and it is important when choosing this software architecture. There are multiple advantages when choosing to implement the microservice architecture. Loose coupling is a huge advantage. Since each microservices are single-purpose and they are deployed separately, and easy to maintain. This means that it is easy to change a particular function that needs modification. Also, it is easy to test the application, as the scope is much smaller compared to the monolithic architecture. Fault tolerance is another advantage that comes from loose coupling. Even if a particular microservice fails, it does not break the whole system. Furthermore, microservice architecture is easy to scale and evolve since we just have to add or modify a microservice related to the area.

However, there are also disadvantages of using the microservice architecture. This architecture is complex. It requires multiple decisions(the aspects discussed above: workflow, shared code etc..) depending on the situation. Since it is complex, as microservices communicate with each other, the performance also decreases. The request might have to wait for the network or undergo additional security checks and make extra database calls. Lastly, deploying all of these microservices will increase the cost of the entire application.

2.1.2.2 Event-Driven Architecture(EDA)

What is an Event

An event in computer science is a way for a service to let the rest of the system know that something important has just happened. In EDA, events are the means of passing information to other services [Gandhi_Richards_Ford_2024] (head first chapter11). The event contains data and it is broadcasted to services using topics that are connected to the sender of the event. However, events are asynchronous, which means that although the services are connected, the sender of the event does not wait on the response of the receiving service. This is the key difference between a event and message. Messages includes a command or some kind of a request for the receiving service, and the service sending out the messages require a response, making it synchronous. Messages are also sent to only a single service using queues.

Asynchronous vs Synchronous

Asynchronous communications do not need to wait for the response, even though the receiving services are available or not. These kinds of communications are also called Fire and Forget. On the other hand, synchronous communication needs to stop and wait until the response, which means that the service in response must be available. EDA relies on the asynchronous communication when sending and receiving events.

Advantages, Disadvantages of Asynchronous Communications

Asynchronous communications has advantages in responsiveness compared to synchronous communications. Since responses by the receiving services are unnecessary, it takes less time to complete a request. However, this is also a crucial disadvantage. Since we do not know if the receiving services have successfully completed the request, it is prone to error handling. Here is a diagram.

Advantages of EDA

Event Driven Architecture is highly decoupled, which makes all services independent and easy to maintain. Furthermore, the asynchronous communication increases the performance of the application. Since EDAs are highly decoupled with this type of communication, it is easy to scale and evolve. Disadvantages of EDA Similar to microservices, EDAs are complex. Deciding which database topology for the architecture, asynchronous communications and parallel event processing makes adds complexity to the application. Also, asynchronous communication makes it more difficult to test out the program. Since the request is proceeded without any response or synchronous calls, the context of the test is vague. If the application needs multiple synchronous calls, EDA is not the right choice for the product.

2.2 Databases

2.2.1 Types of Databases

There are mainly two types of database that are used in software engineering: Relational database and non-relational databases. These two databases defer by how they store and data, which influences different aspects of databases including the structure, data integrity mechanism, performance and more.

2.2.1.1 Relational Databases

Relational Databases store data in tables by columns and rows, where each column represents a specific data attribute, and each row represents an instance of that data(aws document). Each table must have a primary key, which is an identifier column that identifies the table uniquely. The primary keys are used to establish relationships between tables, by using the related rows between tables as the foreign key in another table. Once two tables are connected, it is now possible to get data from both tables in a single SQL query.

Advantages and Disadvantages

Relational databases follow a strict structure, which allows users to process complex queries on structured data while maintaining data integrity and consistency. The strict structure also follows the ACID (atomic, consistency, isolation, and durability) properties for enhanced data integrity. However, because of the rigid structure, it is hard to scale compared to nonrelational database.

2.2.1.2 Non-Relational Databases

Nonrelational databases means that there isn't a schema to manage and store data. This means that data does not require constraints that the relational database required, such as fixed schema, primary key constraint, or not null constraints. This allows more flexibility in the structure and size of the database, or anything that may change in the future. There are different types of non relational databases: Key-Value databases, Document database, and Graph database. Key-Value database store data as a collection of key-value pair, where the key is served as the unique identifier. Both the key and values could be anything as objects or complex compound objects. Document databases are used to store data as JSON objects. Since it is readable by both human and the machine, it has the ease of development. Lastly, there are graph databases, where they are used when a graph-like relationships are needed. Unlike the relational databases, which store data in rigid schema, graph databases store data as a network of entities and relationships, providing more flexibility to anything that is prone to change.

Advantages and Disadvantages

Nonrelational databases have a less rigid structure allowing more flexibility. This is useful when the data changes requirements often. For example, when a specific table needs to changes in columns, this would be hard to preform because other tables might be associated with the specific column. However, nonrelational databases are not constraint to fixed schema, which allows easy changes on specific columns or unique identifier. Performance is another strength of nonrelational database. The performance of these databases depend on outer factor such as network latency, hardware cluster size, which is different from relational databases which depends internal factors such as the structure of the schema. However, because of the flexibility in the structure, data integrity is not always maintained. Consistency is an issue since the state of the database changes over time as structures might not be consistent.

2.2.2 Database Design and Evolution

The design of databases and querying the database are the ones that has the most impact on the performance of the database. In this subsection, we will be talking about ways to structure and query efficient database systems.

2.2.2.1 Normalization

Compared to a nonrelational database, relational databases benefit from integrity, with the process of normalization. The definition of normalization is a way of organizing data in a database. During this process, redundant data will be reduced to improve data quality and optimize database performance. There are types of normalization such as 1NF and 2NF, and as the normal form gets higher, it is a better design of the relation. However, most databases tend to be needed until the third normal form, which avoids most of the problems common to bad relational designs.

The First Normal Form(1NF) The two criterias that 1NF meet are the following:

1. The data are stored in a two-dimensional table.
2. There are no repeating groups. (rddI chapt 7)

Here the repeating groups mean that if an attribute that has more than one value in each row of a table [Harrington_2016].

For instance, if there is a column that requires more than one value, such as items (instead of item), this will be a repeating group.

Table 2.1: Order table before 1NF (with repeating groups)

OrderID	CustomerName	Items	TotalPrice
1	Alice	Item1, Item2, Item3	\$45.00
2	Bob	Item1, Item4	\$30.00
3	Charlie	Item2, Item5, Item6, Item7	\$70.00

This table shows the example of a table before the first normalized form. We can see that there are multiple items in the items column separated by a comma. Having three or more dimensions or having repeated groups for a single table results in more complexity and difficulties when querying the database. This is why we need the 1NF normalization. The 1NF is the most simple normalization that could be done in a relational database and it is pretty clear.

Table 2.2: Order table after applying 1NF (no repeating groups)

OrderID	CustomerName	Item	Price
1	Alice	Item1	\$15.00
1	Alice	Item2	\$20.00
1	Alice	Item3	\$10.00
2	Bob	Item1	\$10.00
2	Bob	Item4	\$20.00
3	Charlie	Item2	\$15.00
3	Charlie	Item5	\$10.00
3	Charlie	Item6	\$25.00
3	Charlie	Item7	\$20.00

As we can see on the table above, there is only one item in the items column by creating a new record for each item. However, the first normalization form is not enough from benefiting from using relational databases.

Problems with 1NF

Data could become redundant even though repeated rows are deleted. For example, If there is a table called students with columns(id, name, birthday, course id, course name), every time the same student adds a class, their name will be repeated in each record. Furthermore, there are anomalies in update, insertion, and deletion. Making an update to one of the records (student name) would require to update other records that are associated. Missing out any of the records with the student name will result in data inconsistency. Inserting a new entity could be difficult unless there are related data. For instance, if a new course is to be added to the table, this would be unavailable until there is a student taking the course since the primary key will be the student's id, and there could not be a row without a primary key. Deletion could also be a problem when the row deleted contained the last data for a certain column. For example, if one student is taking a class called CS200, and that record is deleted, the table would not have the information that the class CS200 exists. To solve these problems, we must use higher levels of the normalization form.

The Second Normal Form(2NF)

The two criterias that 2NF meet are the following:

1. The relation is in first normal form
2. All nonkey attributes are functionally dependent on the entire primary key.

Functional dependency is the key term in the 2NF. A functional dependency is a one-way relationship between two attributes, such that at any given time, for each unique value of attribute A, only one value of attribute B is associated with it throughout the relation [Harrington_2016]. In other words, this means that all other columns except the columns of the primary key or keys, are dependent on the primary key or the candidate key.

By using the functional dependencies, we could create the second normal form relations. After analyzing the functional dependencies, primary keys would be decided. It is common to decide attributes that have dependencies for the primary key of the table, and the all the other attributes will be the non-key attributes. For example, going back to the student table example, Student name, and birthday would be dependent on the student id, so the student id will be the primary key. Courses the student takes does not depend on the student id, but rather on the course id. We could create another table using the course id as the primary key, and the course name as the functional dependencies. However, the courses the student takes will be dependent on the courses, so there will be a foreign key to construct that relationship. So far, we can identify the relationship of the tables as the following:

So far, we can identify the relationship of the tables as the following:

- **Student**(*student_id* (PK), *course_id* (FK), *name*, *birthday*, *room_num*)

- **Courses**(course_id (PK), name)

We are assuming that each student can only take one course.

The relationship can be represented as:

$$\text{Student(course_id)} \rightarrow \text{Courses(course_id)}$$

Table 2.3: Student table before applying 2NF (already in 1NF, but with partial dependencies)

Student_ID	Student_Name	Birthday	Course_ID	Course_Name
S001	Alice	2002-03-14	C101	Database Systems
S002	Bob	2001-06-02	C102	Data Structures
S003	Charlie	2002-07-22	C101	Database Systems
S004	Diana	2003-01-18	C103	Operating Systems

Table 2.4: Decomposition into 2NF

Student Table			
Student_ID (PK)	Student_Name	Birthday	Course_ID (FK)
S001	Alice	2002-03-14	C101
S002	Bob	2001-06-02	C102
S003	Charlie	2002-07-22	C101
S004	Diana	2003-01-18	C103

Courses Table	
Course_ID (PK)	Course_Name
C101	Database Systems
C102	Data Structures
C103	Operating Systems

By doing this, some of the problems from the first normal form are solved. The functional dependency solves the insertion, deletion, and update anomalies. We can now insert a new course into the course table without needing to insert a student at the same time, delete a student's course without losing the record of the course itself, and update course information in one place instead of multiple rows, which preserves data integrity. This will provide more stable and consistent database design compared to 1NF.

Problems with 2NF

Although some of the problems with 1NF were solved, there are still anomalies to be resolved. Insertion, deletion, and update anomalies still exist. For example, let us assume we have the following dependencies and the table:

- **Student**(student_id (PK), course_id (FK), name, birthday, room_num)

$$\text{Student(course_id)} \rightarrow \text{Course(course_id, name, room_num(FK))}$$

- **Course**(course_id (PK), name, room_num (FK))

Course(room_num) → Room Number(room_num(PK), name)

- **Room Number**(room_num (PK), name)

Table 2.5: Student Table (same as 2NF)

Student_ID (PK)	Name	Birthday	Course_ID (FK)	Room_Name
S001	Alice	2002-03-14	C101	Database Room
S002	Bob	2001-06-02	C102	CS Lab
S003	Charlie	2002-07-22	C101	Database Room
S004	Diana	2003-01-18	C103	Systems Lab

Table 2.6: Course Table

Course_ID (PK)	Course_Name	Room_Name
C101	Database Systems	Database Room
C102	Data Structures	CS Lab
C103	Operating Systems	Systems Lab

Even though the tables are in 2NF, insertion, deletion, and update anomalies can still occur due to these transitive dependencies.

The functional dependency Course → Room Number introduces anomalies that still remain in 2NF. For example, we cannot record a student's enrollment in a course if the course's room number has not been decided, which creates an insertion anomaly. Also, if we delete the last student enrolled in a course, we also lose the record of the room number for that course, which is a deletion anomaly. Finally, if a course's room number changes, we must update it in every student's record for that course, creating an update anomaly. These problems occur because the room number depends on the course (a non-key attribute) rather than directly on the student ID, and they are resolved by moving the design into 3NF.

The Third Normalization Form(3NF) The two criterias that 3NF meet are the following:

1. The relationship is in second normal form.
2. There are no transitive dependencies.

Transitive dependencies Transitive dependencies exist when the following functional dependency pattern occurs:

$$A \rightarrow B \text{ and } B \rightarrow C, \text{ therefore } A \rightarrow C$$

[Harrington_2016]

This is the same type of relationship where we had problems with 2NF. For example:

- **Student**(*student_id* (PK), *course_id* (FK), *name*, *birthday*, *room_num*)

$$\text{Student}(\text{course_id}) \rightarrow \text{Course}(\text{course_id}, \text{name}, \text{room_num(FK)})$$

- **Course**(*course_id* (PK), *name*, *room_num* (FK))

$$\text{Course}(\text{room_num}) \rightarrow \text{Room Number}(\text{room_num(PK)}, \text{name})$$

Going back to this example, we can see that a non-key attribute in the **Student** table (*room_num*) depends on another non-key attribute (*course_id*).

To remove transitive dependencies, we should break the relations into separate tables. In this case, we can:

- Remove the *room_num* column from the **Student** table to remove the relationship between non-key attributes.
- Alternatively, make the second determinant in a table a candidate key so that no non-key attribute depends on another non-key attribute within the same table.

Applying either method will resolve the anomalies we encountered in the second normalization form (2NF).

Table 2.7: Decomposition into 3NF (removing transitive dependencies)

Student Table			
Student_ID (PK)	Name	Birthday	Course_ID (FK)
S001	Alice	2002-03-14	C101
S002	Bob	2001-06-02	C102
S003	Charlie	2002-07-22	C101
S004	Diana	2003-01-18	C103

Course Table		
Course_ID (PK)	Course_Name	Room_Num (FK)
C101	Database Systems	R12
C102	Data Structures	R14
C103	Operating Systems	R15

Room Table	
Room_Num (PK)	Room_Name
R12	Database Room
R14	CS Lab
R15	Systems Lab

2.2.2.2 Database Evolution

Database design also influences how a database evolves over time. Performance, latency, and fault tolerance are affected by the database designs as the amount of stored data increases. There are multiple techniques to design a database suitable for scaling. Vertical scaling refers to when the physical parts of the computer such as CPU or RAM are upgraded so the database can handle more data and queries. Horizontal scaling is when multiple machines with independent physical parts (CPU and RAM), store the data on an array of disks that are shared among multiple other machines, which is also called nodes. One advantage of using vertical scaling is that the structure is very simple. Only one database needs to be taken care of, which could be easier compared to handling multiple databases. However, there are more disadvantages. Cost increase faster than linearly as higher performance is required. Fault tolerance is problematic as there is only one database running, hardware or software failures on the database host can cause service interruptions. For horizontal scaling, there are mainly two strategies that we will discuss: replication and partitioning. These two strategies have its own sub strategies which will be discussed in the next subsection.

2.2.2.2.1 Replication Replication is when there are multiple copies of the database in different nodes, which could be in different virtual, or physical machines. This leads to redundancy in data, but it also allows for fault tolerance if one of the database hosts is unavailable [Kleppmann_2017]. Another reason to use replication is to increase availability by having databases in different regions to decrease latency. Having multiple database to read queries also help increase the performance of the application.

There are multiple ways to implement this strategy in different situations. The two topics discussed will be Leader and Followers and Multi Leader Replication.

2.2.2.2.1.1 Leaders and Followers Going deeper into how the replicas are actually set up, it is important to make sure that each of the replicas have the same data. For example when a user updates a table, this should include all the other replicas to update the same table. The leader and follower structure has one lead node(leader) that allows writes to the database, and the rest of the nodes are assigned as followers. If there is a change data in the leader, the followers are updated accordingly. Reading the database could be done by any of the nodes including the leader node, but writing the database could only be done by through the leader node. Here is a quick example how the flow might look like (add an example figure)

2.2.2.2.1.2 Multi-Leader Replication One down side of a Leader and Follower replication was that the write queries were only allowed in the leader replica. If the application could not connect to the leader for any reason such as network causes, write queries could not be performed. Multi-Leader replication allows multiple leaders, which means

that write queries could be done in multiple replicas. Although it is rare for a multi-leader replication structure to over weigh the benefits among the complexity added, there are a few use cases for this structure.

- Multi datacenter operation
- Clients with offline operation
- Collaborative editing

However the biggest issue in the multi-leader replication structure is handling multiple write query conflict. For instance, if a same record was modified by multiple users on different leader replicas, there will be different data among replicas resulting in data inconsistency. This was not an issue for a single leader and followers structure since only one leader accepted write queries and they were processed one by one. However, if multiple leaders receive queries at the same time, the conflict should be resolved. There are multiple ways to handle write conflicts.

The simplest strategy is to just avoid the conflicts. If the write queries could be avoided in the application layer, where the application ensures that all write queries for a particular record go through the same leader. This would work until a particular records needs to change its designated leader. In this case, simply avoiding conflicts in the application layer would not work

The next strategy is to converge toward a consistent state. When there is a situation where avoiding conflicts do not work, the conflicts should be handled. There are various ways to converge the replicas into a consistent state. One way could be to simply give each write query a unique ID, and if there is a conflict, the higher unique ID overwrites the conflict. Another way is to give each replica a unique ID, and the higher unique ID overwrites the conflict. Or, there could be another explicit data structure that preserves the information and write application code to resolve the conflict in a certain logic. There are trade offs such as which part of the data is going to be saved over the other, so it is essential to choose the write way to handle write conflicts in a multi-leader replica structure.

Replication is a way to not only have fault tolerance but also improve the performance of the database. This will be useful as the size of the database and the application grows. It is essential to choose the right strategy for replication depending on the situation to support the evolution of databases and maximize performance.

2.2.2.2.1.3 Synchronous vs Asynchronous Replication Communication that happens between the leaders and the followers is also another important factor to decide whether it is a leader and follower setup or multi-leader setup. The two types of communication are synchronous and asynchronous. After the leader receives a write query, synchronous replication waits until all of the followers are updated and synced. The leader will not take any queries before this process is finished. However, asynchronous replication keeps taking queries regardless of the status of the followers. Although handling requests to copy status of the leader on the database replicas are fast, which usually happens less than a second [Kleppmann_2017], there is no guarantee of how long it would take depending on the

physical status of the replica and the network. This is an advantage of synchronous replication, since it is certain that all database replications are up-to-date with the leader database, but it could be a disadvantage in a perspective where the database queries will be slow. If all of the followers are synchronous, the system would be too slow. Most of the times, one of the followers will be set to being synchrounous so that there will be at least two replications(one leader, one follower) up-to-date with all the write queries, and the rest of the followers being asynchronous. This configuration is sometimes also called semi-synchronous.(Designing Data-Intensive App ch5)

Asynchronous replications on the other hand are very fast since the leader does not have to wait until the followers are have synced data. However it does have a disadvantage that all of the followers might not be up-to-date right away, which is also known as the replication lag. This might sound like a huge disadvantage, but asynchronous replication is often times used if there are many followers or if they are geographically distributed. Eventually, all the followers will have a synced replication of the leader, since inconsistency is just a temporary state. This effect is called as eventual consistency [Kleppmann_2017]. If the application that is being created is okay with possibility of inconsistency due to replication lag, asynchrounous replication is perfect. However, if consistency is crucial to the application, other solutions such as synchrounous or semi-synchronous replication will be the go-to when using leaders and followers method.

2.2.2.2 Partitioning Partitioning is when a data is divided into multiple smaller pieces of data such as a record, a row, or a document. Replication was used for scalability and performance, but as the size of the database increases, only replication itself become inefficient since all the data has to be copied to the replicas. In order to scale database applications, partitioning is commonly used. As the data is distributed among multiple partitions, multiple queries could be ran at the same time.

2.2.2.2.1 Partitioning by Key-Value Data Having a key-value data is one way to create partitions. The reason for partitioning was to scale the database by distributing the query load on one node. One way to achieve this is to have a key range for each partition. For example, when we think of a dictionary, we know that words that start with the letter “a” is in the beginning, the letter “m” is somewhere in the middle, and the letter “z” is at the end. By dividing the range of partitions by the key-value data, it will be easier to locate which partition contains the data and distribute the query. In this case, the partitions might not be evenly divided since the each range of key-value pairs could contain a different amount of data. It is important which key-value pair to use. If a key is assigned as a column that is not evenly distributed, this leads to a hot spot (a partition with disproportionately high load) [Kleppmann_2017].

A method that has a lower chance of being affected by hot spots is partitioning by hash of key. A good hash function makes a the key-value pairs evenly distributed among the partitions. However, this loses the efficiency that the key range had. It is now hard to find the range queries efficiently without the key range.

When choosing the strategy, hashing keys and having key ranges to partition data both have advantages and trade-offs, so it is important to choose the one suitable in the situation. Key range could be used if there is a key range that is evenly distributed, and key hash when there are still a lot of hotspots by using the key range.

2.2.2.2.2 Partitioning and Secondary Indexes Partitioning by key-value pairs work nicely with the partitioning strategies discussed above. However things get more complicated with secondary indexes. Secondary indexes will be discussed more in the upcoming sections. A brief introduction for secondary indexes is that they are created to improve the query performance that are based on multiple keys. For example, when searching for a job in a job board, selecting criteria such as industry or experience level could be a situation to use secondary indexes. Secondary indexes makes sharding more complicated since they don't identify a single record, but rather search for records based on the conditions. Partitioning by key-value pairs wouldn't work in this situation.

Scatter/gather is a technique where each partition has its own secondary indexes. In this case, writing data would be efficient since only the partition containing that specific part of the index is where the data is written. However, reading queries are less efficient. If queries require to search on different partitions, each partition is searched separately which is inefficient.

It is also possible to partition secondary indexes by the term. Instead of having distributed secondary indexes across the partitions, this approach has a global index that covers all the partitions. Having a range of secondary indexes partitioned in separate partitions make read queries more efficient from the scatter/gather technique. If write queries are used more often, it is better to use the scatter/gather technique, and if read queries are dominantly used, partitioning indexes by term is the structure to choose.

2.2.2.3 Request Routing After partitioning the dataset into multiple nodes, it is important to make sure the request connects to the right partition. On a high level there are mainly three ways to achieve this.

1. Allow clients to contact any node (e.g., via a round-robin load balancer). If that node coincidentally owns the partition to which the request applies, it can handle the request directly; otherwise, it forwards the request to the appropriate node, receives the reply, and passes the reply along to the client.
2. Send all requests from clients to a routing tier first, which determines the node that should handle each request and forwards it accordingly. This routing tier does not itself handle any requests; it only acts as a partition-aware load balancer.
3. Require that clients be aware of the partitioning and the assignment of partitions to nodes. In this case, a client can connect directly to the appropriate node, without any intermediary [Kleppmann_2017].

The key problem is that how does the component, (which could be the routing tier, the client, or the partition in the node) know about changes in the other partitions in other nodes? If the deciding component is not up to date with the location where data that the client is requesting, this could lead into data inconsistency.

To solve this problem, many distributed data systems use a separate coordination service such as the ZooKeeper to keep track of the data. The whenever a partition changes or a node is added or removed the ZooKeeper is updated to keep data consistency.

2.2.2.2.4 Query Optimization There are multiple factors that affect the performance of the database. The design of the database, including normalization, and partitioning, which was discussed in the previous subsection is one of the factors. Indexing is another huge part of increasing the performance of the database as the amount of data increases. Lastly, changing the physical query of the database is a way optimize the performance of the database. In this section, we will be discussing about specific ways to optimize performance of databases.

2.2.2.2.4.1 Indexing Suppose that there is a table called students with the following keys: id, name, grade. If we want to find students with a certain grade (80%), we could run a SQL query something like this.

```
SELECT *
FROM Students
WHERE grade = 80;
```

This query will visit all the rows and then find the students with grades 80. However this query becomes more inefficient as the size of the table grows, as the time complexity would be $O(n)$. If the table was sorted by grades, this will be much easier, since we could do a binary search to make the search speed $O(\log n)$. This is where indexing is applied.

An index could be created where the grades are sorted in order, each having a reference to the row of the student table. This way, whenever we want to find the name of the students with a certain grade, instead of looking at the Students table, we can look at the index, where the grades are sorted, find rows with the certain grade, for each row find the reference of the student table, and return the name of the student. This shows that Indexes significantly improves the read queries for databases.

There are multiple data structures that could be used to implement indexes, but the most common one are b+trees. B trees are somewhat similar to the binary search trees. However, instead of having one value every node, it contains multiple nodes. This allows multiple partitions, allowing a balanced, and a faster search. Furthermore, as multiple values could be in a single node, the height of the tree would be smaller. This means that there are fewer disk I/O's per file operation as database stores data on disk, resulting in faster query execution [Garcia-Molina_Ullman_Widom_2014]. One down side of b trees is when making range queries, such as finding all students who have grads 20 to 80. If these two data are separated from the root, this could be inefficient. (create diagram). B+trees are a variation of b trees to

solve this issue. B+trees store data only in the leaf node. The other nodes store keys only for navigation. Also, all the leaf nodes are connected to the next leaf node. (create diagram and explain).

B+trees are commonly used in indexes for modern databases management system such as MYSQL, PostgreSQL, and SQLite.

2.2.2.2.4.2 Query Optimization

Optimizing the SQL queries could also increase the performance of the database.

Here are the 6 queries tune SQL queries. <https://www.geeksforgeeks.org/sql/sql-performance-tuning/>

- SELECT fields instead of using SELECT *
- Avoid SELECT DISTINCT
- Use INNER JOIN instead of WHERE for Joins
- Use WHERE instead of HAVING
- Limit Wildcards to the end of a search term
- Use LIMIT for sampling query results

2.2.2.5 N+1 problem The N+1 problem is a common problem when using the ORM. The definition of the problem is when an application retrieves a list then performs additional queries for each item's related data, which results in an inefficient query. (1 + N queries instead of optimized joins). In a nutshell, it is just having too much queries that decreases the performance. This problem usually happens in ORMs.

Similar to the example above, assume there is a students table with keys student_id, student_name, and another table called courses with the keys course_id, student_id, and course_name.

If we were to get all students and courses they are taking in plain SQL, we would write something like this:

```
SELECT s.student_id, s.student_name, c.course_name
FROM students s
JOIN courses c ON s.student_id = c.student_id;
```

2.3 Caching

2.3.1 What is Caching

Caching data means to store frequently accessed data in a location that is easy and fast to access (usually in RAM). The reason why caching is used is to ultimately increase the performance and efficiency when retrieving data. Data in the

database are usually stored in a disk, which could be a hard drive or an SSD, which usually takes more time to process I/O. Caching could help decrease the amount of time to process this data significantly. One might suggest then why not put all the data in the cache, but this would not work since the cache could not store a lot of data as much as the database does. The cost of the hardware of the cache is much more expensive, and as the size of the cache increases, the search time will also increase, decreasing the speed and defeating the whole purpose of caching. Caching can be used at several levels. This article will mainly focus on caching in databases and web pages. There are multiple strategies that could be used when caching these two areas. Another important part of caching is the invalidation strategies. Deciding when the cache expires and when it updates could affect the performance and data consistency. Choosing the right technique in the given situation will be essential.

2.3.2 Database Caching Strategies

There are multiple database caching strategies that could be applied when designing cache systems. Depending on the type of request (read, write) of the user, and which part of the application is responsible for fetching data from the database or managing the cache, there are five main database caching strategies.

2.3.2.1 Cache Aside

Cache Aside is also called Lazy Loading. The application is in control of managing the cache. Let's look at the diagram below.

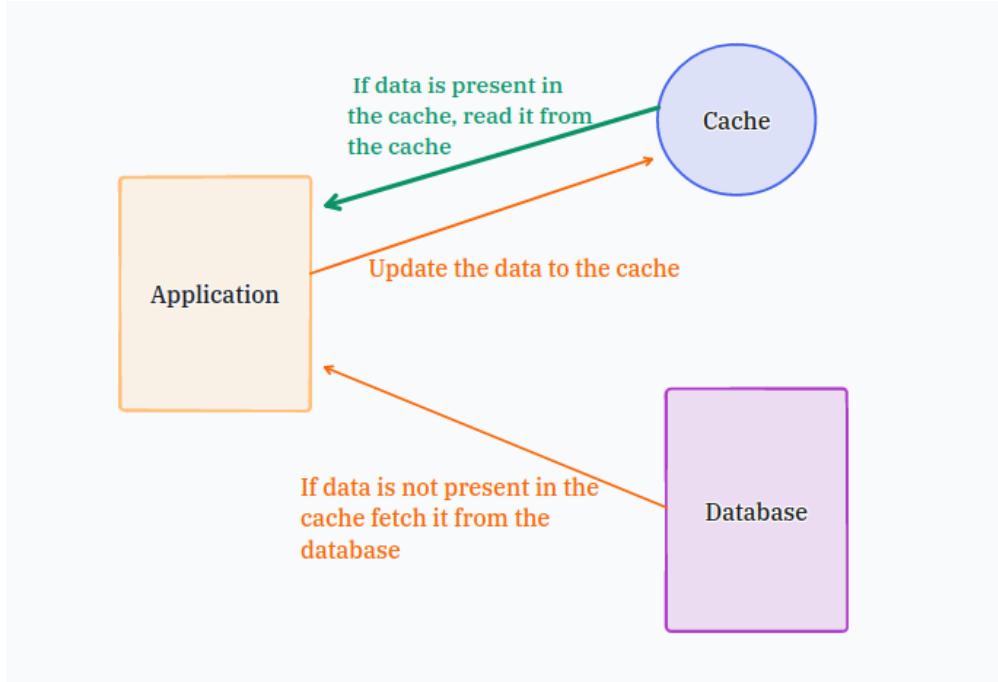


Figure 2.1: Cache-aside Pattern

As the diagram shown above, the client first checks the cache to see if the read request data is in the cache. If the cache exists, this is called a cache hit, and the client uses it right away. If the cache does not exist, this is called a cache miss. When a cache miss occurs, the client then sends a request to the database server to fetch the data. After that, the client transfers the data to the cache, so that there could be a cache hit the next time the data is needed. This will increase the performance of the application when the same data is called multiple times. When there is a write request, the application will first communicate with the database and then update the cache.

This strategy is useful when the application requires a lot of read requests from the database, since the application could just check the cache instead of querying the database. One disadvantage of this approach is that there could be an inconsistency between the cache and the database. Data directly written in the database might not be consistent with the data in the cache, since writing data to the database and writing data to the cache does not happen at the same time.

2.3.2.2 Read-Through

In the read-through strategy, the cache level manages fetching data from the database. Here is a diagram of how the read-through strategy works:

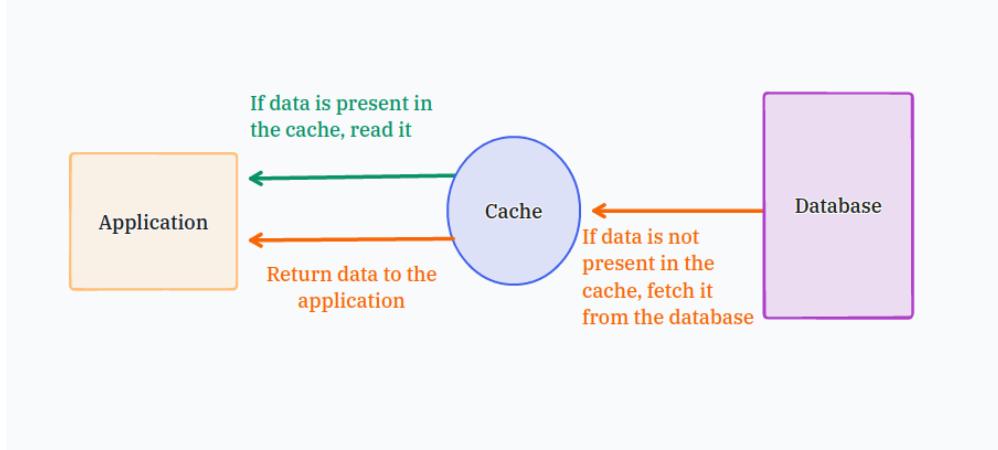


Figure 2.2: Entity-Relationship Diagram

Whenever there is a read request from the application, the application first checks the cache. If there is a cache hit, it simply returns the data back to the application. If there is a cache miss, the cache level fetches the data from the database. Since the cache manages fetching data, it simplifies the application logic when retrieving data compared to when the application handles fetching data.

This strategy only involves read requests from the application, which means that other strategies could be used for write requests. The write-through strategy is generally great to be used with the read-through strategy.

2.3.2.3 Write-Through

The write-through strategy is very similar to the read-through strategy. The diagram is almost identical.

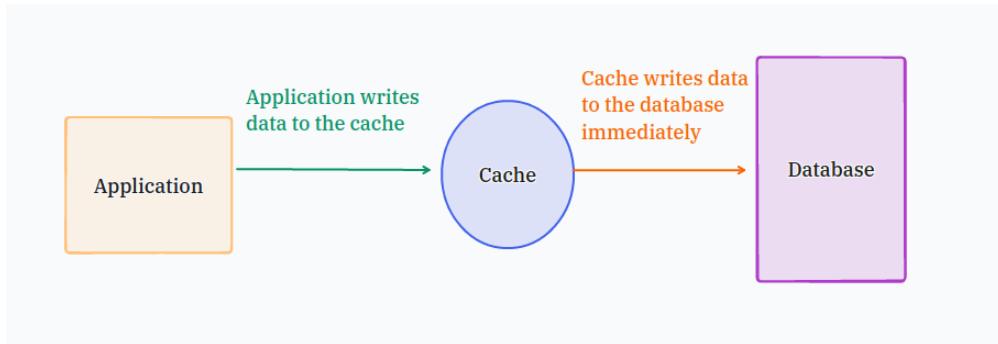


Figure 2.3: Entity-Relationship Diagram

Nothing happens when there is a read request from the application, but when there is a write request, the data will first be written in the cache and then into the database. This ensures data consistency when paired with the read-through

strategy. One downside of this strategy is that since it writes to both the cache and the database layer, the latency of the request increases.

The read-through and the write-through strategies are not meant to be used for all access to data in the application layer. Using these strategies for all database queries could result in a decrease in performance, since the caching layer is not intended to keep every single data.

2.3.2.4 Write-Back

The write-back strategy is similar to the write-through strategy, but the writes to the database happen with a delay. The cache is still in charge of writing data to the database. Let's look at the diagram:

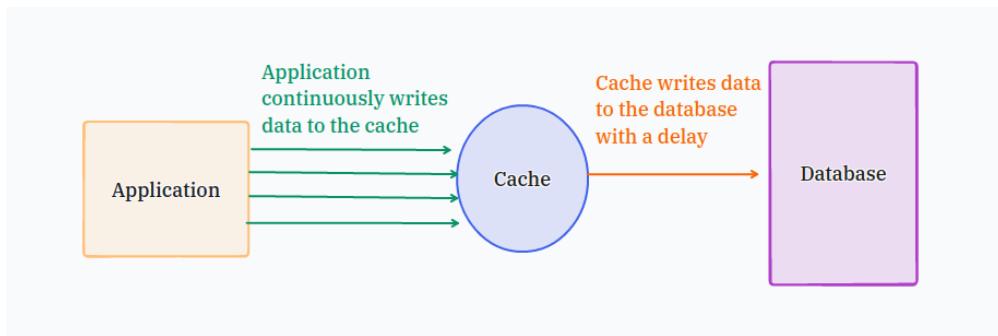


Figure 2.4: Entity-Relationship Diagram

Since the cache only writes to the database after a certain amount of time, this strategy is beneficial when there are multiple write requests to the same data at the application level. This will decrease the write queries from the cache level to the database, which could increase the performance. However, similar to the read-through and write-through strategies, since the data is written to the cache first, writing data to the database could potentially fail if the caching fails.

2.3.2.5 Write Around

This strategy is similar to the cache-aside strategy, but it has more specific instructions for write requests.

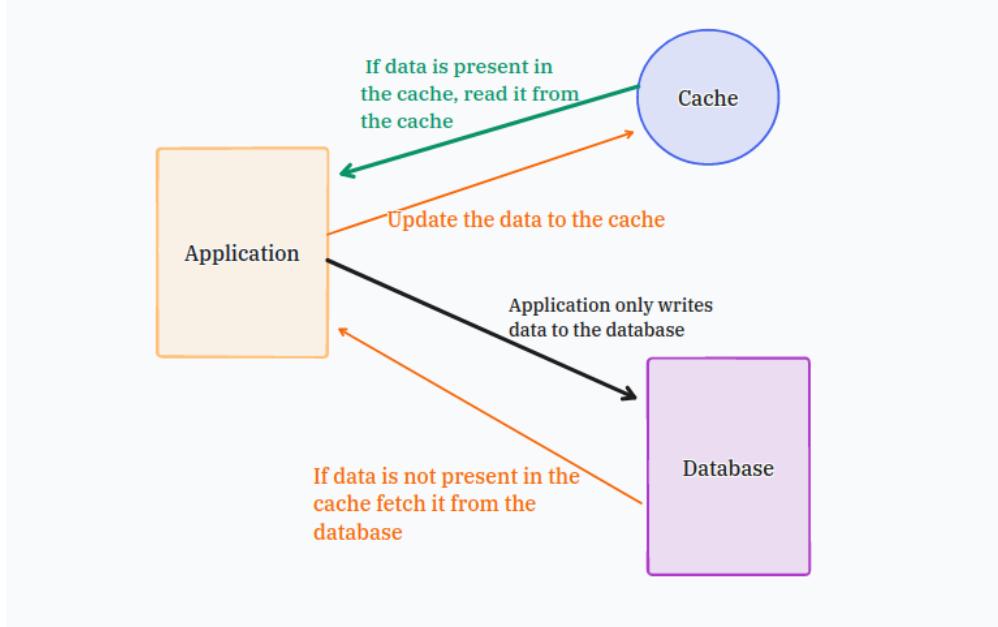


Figure 2.5: Entity-Relationship Diagram

The difference between the write-around strategy and the cache-aside strategy is that when there is a write request, only the data in the database is updated. The data in the cache is only updated when there is a cache miss from a read request. This way, the cache is not overflowed with unnecessary data. The disadvantage of this strategy is that recently written data will always result in a cache miss. This is why the write-around strategy is suitable when the application has a lot of read requests and data is rarely updated.

2.3.3 Client Side Caching

People find it annoying when it takes too long or laggy to load a website they want to access. This is where client side caching could be beneficial. Client side caching is a technique where data is cached inside the client's device unlike the application level caching. Frequently used static data are normally cached on the client side to improve the performance and efficiency of web applications. The reduced time to load the webpages result in enhanced user's satisfaction and the overall experience.

Cache control

One type of client side caching is browser cache. The browser can cache static files such as HTML, CSS, Javascript, and even images and fonts. The browser usually automatically decides what to cache, but this is dependent on the HTTP cache-control header. Here are the 15 types of the headers that are accepted:

Etags

CHAPTER **3**

Implementation

3.1 General Design Choices Made

3.1.1 Backend Design Choices

3.1.2 Frontend Design Choices

CHAPTER

4

Results

CHAPTER **5**

Challenges and Lessons Learned

5.1 What worked well

5.2 What did not work well

