

Software Architecture Course Notes

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A U S T R A L I A

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1 Introduction

An introduction to Software Architecture would be incomplete without the requisite exploration into the term ‘software architecture’. The term is often overloaded to describe a number of completely separate concepts. The overloaded nature of the term makes an introduction quite challenging. Martin Fowler wrestles with this difficulty in his talk on “[Making Architecture Matter](#)¹”. In the talk Fowler settles on the slightly vague definition from Ralph Johnson [?]:

Definition 1. Software Architecture

The important stuff; whatever that is.

In this course, we will try to narrow the scope slightly. We need a definition which encompasses the numerous practical strategies which you need to survive and thrive in industry life. This definition should not be attributed to the term ‘Software Architecture’; that term is much too broad to define succinctly. This is purely the definition used to provide an appropriate scope for the course.

Definition 2. Software Architecture: The Course

The set of tools, processes, and design patterns which enable me to deliver high quality software.

2 High Quality Software

We assume that as software engineers you wish to deliver high quality software systems. What makes life interesting² is that *quality*, like *beauty*, is in the eye of the beholder. As a diligent and enthusiastic software engineer, you may think that *high quality* means well designed software with few defects. On the other hand, your users may think that *high quality* means an engaging user experience, with no defects. While your project sponsor, who is funding the project, may think that *high quality* means the software includes all the features they requested and was delivered on-time and on-budget. Rarely is there enough time and money available to deliver everything to the highest standard. The development team has to balance competing expectations and priorities to develop a software system that is a good compromise and meets its key goals.

From the perspective of designing a software architecture, competing expectations provides what are sometimes called *architectural drivers*.

2.1 Functional Requirements

A seemingly obvious driver is the functional requirements for the software system, i.e. what the software should do. If you do not know what the software is meant to do, how can you design it? You do not need an extensive and in-depth description of every small feature of the software, but you do need to know

¹<https://www.youtube.com/watch?v=DngAZyWMGRO>

²As in the apocryphal Chinese curse “May you live in interesting times.”

what problem the software is meant to solve, who are the key users, and what are the key features of the software. Without this information, you do not know what style of architecture is going to be appropriate for the software system.

For example, consider an application that allows users to write and save notes with embedded images and videos. Say the decision was made to implement it as a simple mobile app that saves notes locally. If it is then decided that web and desktop applications are needed, allowing users to sync their notes across applications and share notes with others, the application will need to be redesigned from scratch. Knowing up-front that the software needed to support multiple platforms, and that syncing and sharing notes was important, would have allowed the developers to design a software architecture that would support this from the start.³

2.2 Constraints

Constraints are external factors that are imposed on the development project. Commonly, these are imposed by the organisation for whom you are building the software system. The most obvious constraint is time and budget. A sophisticated software architecture will take more time, and consume more of the total budget, than a simple but less flexible architecture.

Other common constraints are technology, people, and the organisation's environment. Technology constraints are one of the most common set of constraints that affect the design of the architecture. Even if it is a "greenfields" project⁴ there will usually be restrictions on choices of technology that may or may not be used. For example, if all of the organisation's existing applications are running on the Google cloud platform, there will probably be a restriction requiring all new applications to be built on the same platform to avoid the overheads of working with different cloud providers.

People constraints takes into consideration the skills that are available within the organisation and the availability of developers for the project. Designing an architecture that requires skills that are not available, adds risk to project success and overhead to the project's development cost. If contractors can be hired, or training is available, these may reduce some of the risks, but there will still be budget overhead. The decision needs to be made based on the risks, budget available, and potential benefits.

The organisation's environment may influence other constraints, or add new constraints. An organisation that encourages innovation may be flexible in allowing some technology constraints to be broken. If the project is of strategic value to the business, there may be options to negotiate for a larger budget or to adopt a new technology⁵, if they could lead to a more robust solution with a longer lifespan. Politics can introduce constraints on architectural choices. If there is an influential group who promote a particular architectural style, it may be difficult or impossible to make different choices.

2.3 Principles

Principles are self-imposed approaches to designing the software. Typically these are standards that all developers are expected to follow to try to ensure the overall software design is consistent. From a programming perspective, coding standards and test coverage goals are examples of principles that all developers are expected to follow. Architectural principles typically relate to how the software should be structured and how design decisions should be made to work well with the software architecture. Consequently, principles usually do not influence the architecture⁶, rather the architecture will influence which principles should be prioritised during software design.

³This is different to building a quick-and-dirty prototype to explore options. That is a valid design process, and in that case minimal effort will be put into creating a well-designed app.

⁴This refers to the idea that it is a new project and is not limited by needing to conform to existing system's or expectations.

⁵I have consulted with organisations who have adopted new, and risky at the time, technologies to potentially gain business benefits like easier extensibility.

⁶The exception to this is if some principles are constraints enforced by the organisation.

As an example, if the software architecture is designed to be scalable to accommodate peaks in load, then an architectural principle might be that software components should be stateless to allow them to be easily replicated to share the load. Another principle might be that an architecture that relies on an underlying object model, will adopt the SOLID design principles [?].

2.4 Quality Attributes

While the functional requirements specify what the software should do, non-functional requirements specify properties required for the project to be successful. These non-functional requirements are also termed *quality attributes*.

Often quality attributes are specified by phrases ending in -ility⁷. Medical software needs *reliability*. Social media needs *availability*. Census software needs *scalability*.

Below is a collection of non-exhaustive quality attributes to help give you an idea of what we will be looking at in this course.

Modularity Components of the software are separated into discrete modules.

Availability The software is available to access by end users, either at any time or on any platform, or both.

Scalability The software can handle peaks of high demand by taking advantage of available computing resources.

Extensibility Features or extensions can be easily added to the base software.

Testability The software is designed so that automated tests can be easily deployed.

Quality attributes are one of the main focuses of a software architect. Quality attributes are achieved through architecture designed to support them. Likewise, software architecture quality and consistency is achieved by principles put in place by a software architect and the development team.

Software architects are responsible for identifying the important attributes for their project and implementing architecture and principles which satisfies the desired attributes.

2.5 Documentation

The importance of these architectural drivers means they need to be documented⁸. The extent and format of the documentation will depend on the size of the project, team organisation, and the software engineering process being followed. The larger the team, or if the team is distributed between different locations, the more important it is that the documentation is well-defined and easily accessible. The documentation may be stored as notes in a wiki or as a collection of user stories and other notes. Or, it could be an extensive set of requirements and design specifications following a standard like ISO/IEC/IEEE 15289⁹.

3 Attributes in Tension

One of the defining characteristics of quality attributes is that they are often in conflict with each other. It is a valiant yet wholly impractical pursuit to construct software which meets all quality attributes.

The role of a software architect is to identify which quality attributes are crucial to the success of their project, and to design an architecture and implement principles which ensure the quality attributes are achieved.

⁷Consequently, they are sometimes called the software 'ilities'.

⁸Documentation is the castor oil of programming, managers know it must be good because programmers hate it so much [?].

⁹<https://www.iso.org/obp/ui/#iso:std:iso-iec-ieee:15289>

The first law of software architecture, as defined by Richards [?], reflects the difficulty in supporting multiple quality attributes.

Definition 3. The First Law of Software Architecture

Everything in software architecture is a trade-off.

Galster and Angelov [?] define this as ‘wicked architecture’. They identify the ‘wicked’ nature of architecture as the main difficulty in teaching the subject.

Definition 4. Wicked Architecture

There are often no clear problem descriptions, no clear solutions, good or bad solutions, no clear rules when to “stop” architecting and mostly team rather than individual work.

They stress that “In contrast, other software engineering topics such as programming lead to solutions that can be checked and measured for correctness. Architecture may be the worst-case scenario when it comes to fuzziness in software engineering”.

Despite this difficulty, in this course we intend to expose you to a number of case studies, architectures, and tools which aim to give you experience in tackling the trade-offs involved in software architecture.

4 The World Today

Software architecture today is more important than ever. The importance of architecture can be considered a result of *expectations* and *infrastructure*. Today we expect our software to be available 24/7. To exemplify this point, in October 2021 Facebook went offline for 6-7 hours out of the 8760 hours of the year. Those 6-7 hours of downtime resulted in mass media coverage, \$60 million loss of revenue, and a 5% drop in company shares which caused Zuckerberg’s wealth alone to drop \$6 billion. Interestingly, the outage also caused other sites such as Gmail, TikTok, and Snapchat to slowdown.

Another example of the impact of software faults is the 19 July 2024 faulty update by CrowdStrike. At 04:09 UTC, Crowdstrike distributed a faulty update for its Falcon security software that runs on Windows. The update caused computers to crash and enter a “boot-loop,” where they would restart and crash before completing the boot process. Despite Crowdstrike reverting the update by 05:27 UTC, it affected approximately 8.5 million computers worldwide, including Windows virtual machines on Azure and Google Compute Engine. Companies around the world were paralysed while they manually applied a fix. Almost every sector of business was affected, with financial damage estimated to be at least \$10 billion USD. CrowdStrike stock fell from about \$350 to \$215 USD in the two-weeks after the event.

This is a massive change in public expectations for software availability and reliability. As recently as 2017, human resources at UQ would monopolise the university’s computing resources for an evening each fortnight to calculate the payroll. That lack of availability from even the university’s software systems is now completely unacceptable. The change in expectations has forced developers to adapt by designing architectures capable of supporting this heightened up-time.

In addition to shifting expectations, developers now have access to a range of Infrastructure as a Service (IaaS) platforms. IaaS empowers developers to quickly and programmatically create and manage computing, networking, and storage resources. In part, this enables individual developers to support up-times comparable to technology giants. Of course, to be able to support these up-times software has increased in overall complexity. A website is now commonly spread over multiple servers, marking a change from centralised systems to distributed systems.

5 Conclusion

You should now have some understanding of what software architecture is and that it is, at least in our view, important. Let us return to our definition for the course.

Definition 5. Software Architecture: The Course

The set of tools, processes, and design patterns which enable me to deliver high quality software.

In practical terms, what does this mean you should expect from the course? First, you will learn how to communicate your visions of software architecture through *architectural views*. From there, you will use quality attributes such as extensibility, scalability, etc. to motivate the introduction of common architectural patterns, processes, and tooling which support those attributes.

For example, you can expect extensibility to motivate an introduction to plugin-based architectures. You can expect scalability to motivate our introduction to load balancers. And testability to motivate a look into A/B testing practices.

You can view the planned outline for the course on the [course website¹⁰](#). All the course material can be found on [GitHub¹¹](#). If you think you can explain a concept more succinctly, or find a typo, you are encouraged to submit a pull request to help improve the course. We really hope that you enjoy the course and, perhaps more importantly, benefit from it in your careers as software development professionals!

¹⁰<https://csse6400.uqcloud.net/>

¹¹<https://github.com/CSSE6400/software-architecture>

Layered Architecture

Software Architecture

February 24, 2025

Richard Thomas & Brae Webb

1 Introduction

In the beginning developers created the *big ball of mud*. It was without form and void, and darkness was over the face of the developers¹². The big ball of mud is an architectural style identified by its lack of architectural style [?]. In a big ball of mud architecture, all components of the system are allowed to communicate directly with each other. If the GUI code wants data from the database, it will write an SQL query and send it to directly to the database. Likewise, if the code which primarily talks to the database decides the GUI needs to be updated in a particular way, it will do so.

The ball of mud style is a challenging system to work under. Modifications can come from any direction at any time. Akin to a program which primarily uses global variables, it is hard, if not impossible, to understand everything that is happening or could happen.

Aside

Code examples in these notes are works of fiction. Any resemblance to a working code is pure coincidence. Having said that, python-esque syntax is often used for its brevity. We expect that you can take away the important points from the code examples without getting distracted by the details.

```

1 import gui
2 import database

4 button = gui.make_button("Click me to add to counter")
5 button.onclick(e =>
6     database.query("INSERT INTO clicks (time) VALUES {{e.time}}"))

```

Figure 1: A small example of a *big ball of mud* architecture. This type of software is fine for experimentation but not for any code that has to be maintained. It also does not work well at scale.

2 Monolith Architecture

And architects said, “let there be structure”, and developers saw that structure was good. And architects called the structure *modularity*¹³.

The monolithic software architecture is a single deployable application, running on a computer. There is a single code-base for the application and all developers work within that code-base. An example monolith application would be one of the games developed by DECO2800¹⁴ or CSSE3200¹⁵ students at UQ¹⁶.

¹²Liberties taken from Genesis 1:1-2.

¹³Liberties taken from Genesis 1:3-5.

¹⁴https://my.uq.edu.au/programs-courses/course.html?course_code=DECO2800

¹⁵https://my.uq.edu.au/programs-courses/course.html?course_code=CSSE3200

¹⁶<https://www.uq.edu.au/>

(e.g. [Retroactive¹⁷](#) or [Gardens of the Galaxy¹⁸](#)). A monolith should follow design conventions and be well structured and modular (i.e. it is not a big ball of mud).

Most developers are introduced to the monolith implicitly when they learn to program. They are told to write a program, and it is a single executable application. This approach is fine, even preferred, for small projects. It often becomes a problem for large, complex software systems.

2.1 Advantages

The advantages of a monolith are that it is easy to develop, deploy and test. A single code-base means that all developers know where to find all the source code for the project. They can use any IDE for development and simple development tools can work with the code-base. There is no extra overhead that developers need to learn to work on the system.

Being a single executable component, deployment is as simple as copying the executable on to a computer or server.

System and integration testing tends to be easier with a monolith, as end-to-end tests are executing on a single application. This often leads to easier debugging once errors are found in the software. All dependencies and logic are within the application.

There are also fewer issues to do with logging, exception handling, monitoring, and, to some extent, scalability if it is running on a server.

2.2 Disadvantages

The drawbacks of a monolith are complexity, coupling and scalability. Being a single application, as it gets larger and more complex, there is more to understand. It becomes harder to know how to change existing functionality or add new functionality without creating unexpected side effects. A catch phrase in software design and architecture is to build complex systems, but not complicated systems. Monoliths can easily become complicated as they grow to deliver complex behaviour.

Related to complexity is coupling, with all behaviour implemented in one system there tends to be greater dependency between different parts of the system. The more dependencies that exist, the more difficult it is to understand any one part of the system. This means it is more difficult to make changes to the system or to identify the cause of defects in the system.

A monolith running on a server can be scaled by running it on multiple servers. Because it is a monolith, without dependencies on other systems, it is easy to scale and replicate the system. The drawback is that you have to replicate the entire system on another server. You cannot scale components of the system independently of each other. If the persistence logic is creating a bottleneck, you have to copy the entire application on to another server to scale the application. You cannot use servers that are optimised to perform specialised tasks.

Persistent state is a particular challenge when scaling a monolith. If the system is replicated on multiple servers, the system has to be designed so that changes to the persistent data on one server does not invalidate behaviour executing on another server.



Figure 2: *Gardens of the Galaxy* Deployment Diagram

3 Layered Architecture

And architects said, “let there be an API between the components, and let it separate component from component¹⁹”.

The first architectural style we will investigate is a layered architecture. Layered architecture (also called multi-tier or tiered architecture) partitions software into specialised clusters of components (i.e. *layers*) and restricts how components in one layer can communicate with components in another layer. A layered architecture creates superficial boundaries between the layers. Often component boundaries are not enforced by the implementation technology but by architectural policy.

The creation of these boundaries provides the beginnings of some control over what your software is allowed to do. Communication between the component boundaries is done via well-specified *contracts*. The use of contracts results in each layer knowing precisely how it can be interacted with. Furthermore, when a layer needs to be replaced or rewritten, it can be safely substituted with another layer fulfilling the contract.

3.1 Standard Form

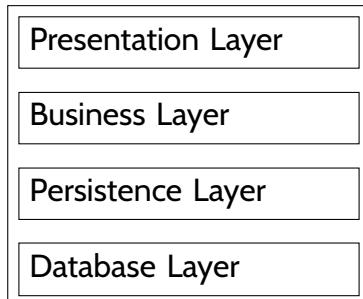


Figure 3: The traditional specialised components of a layered architecture.

The traditional components of a layered architecture are seen in Figure ???. This style of layered architecture is the four-tier architecture. Here, our system is composed of a presentation layer, business layer, persistence layer, and database layer.

The presentation layer takes data and formats it in a way that is sensible for humans. For command line applications, the presentation layer would accept user input and print formatted messages for the user. For traditional GUI applications, the presentation layer would use a GUI library to communicate with the user.

The business layer is the logic central to the application. The interface to the business layer is events or queries triggered by the presentation layer. It is the responsibility of the business layer to determine the data updates or queries required to fulfil the event or query.

The persistence layer is essentially a wrapper over the database, allowing more abstract data updates or queries to be made by the business layer. One advantage of the persistence layer is it enables the database to be swapped out easily.

Finally, the database layer is normally a commercial database application like MySQL, Postgres, etc. which is populated with data specific to the software. Figure ?? is an over-engineered example of a layered architecture.

¹⁹Liberties taken from [Genesis 1:6-8](#).

```

» cat presentation.code

1 import gui
2 import business

4 button = gui.make_button("Click me to add to counter")
5 button.onclick(business.click)

```

Figure 4: An unnecessarily complicated example of software components separated into the standard layered form.

```

» cat business.code

1 import persistence

3 def click():
    persistence.click_counts.add(1)

```

```

» cat persistence.code

1 import db

3 class ClickCounter:
    clicks = 0

6     def constructor():
7         clicks = db.query("SELECT COUNT(*) FROM clicks")

9     def get_click():
10        return clicks

12     def add(amount):
13         db.query("INSERT INTO clicks (time) VALUES {{time.now}}")

15 click_counts = ClickCounter()

```

Figure 4: An unnecessarily complicated example of software components separated into the standard layered form.

One of the key benefits afforded by a well designed layered architecture is each layer should be interchangeable. An example is an application which starts as a command line application, but can later be adapted to a GUI application by just replacing the presentation layer.

3.2 Deployment Variations

While the layered architecture is popular with software deployed on one machine (a non-distributed system), layered architectures are also often deployed to separate machines.

Each layer can be deployed as separate binaries on separate machines. A simple, common variant of distributed deployment is separating the database layer, as shown in figure ???. Since databases have well defined contracts and are language independent, the database layer is a natural first choice for physical separation.



Figure 5: Traditional layered architecture with a separately deployed database.

In a well designed system, any layer of the system could be physically separated with minimal difficulty. The presentation layer is another common target, as shown in figure ???. Physically separating the presentation layer gives users the ability to only install the presentation layer and allow communication to other software components to occur via network communication.



Figure 6: Traditional layered architecture with a separately deployed database and presentation layer.

This deployment form is very typical of web applications. The presentation layer is deployed as a HTML/JavaScript application which makes network requests to the remote business layer. The business layer then validates requests and makes any appropriate data updates.

Some database driven application generators will embed the application logic in the database code so that all logic runs on the database server. The presentation layer is then separated from the application logic, as shown in figure ??.

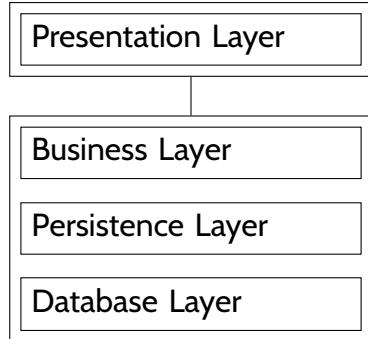


Figure 7: Traditional layered architecture with a separately deployed presentation layer.

An uncommon deployment variation (figure ??) separates the presentation and business layers from the persistence and database layers. An updated version of our running example is given in figure ??, the presentation layer remains the same but the communication between the business and persistence layers is now via REST.²⁰



Figure 8: A contrived example of a deployment variation.

²⁰<https://restfulapi.net/>

```

» cat business.code

1 import http

3 def click():
4     http.post(
5         address="192.168.0.40",
6         endpoint="/click/add",
7         payload=1
8     )

```

```

» cat persistence.code

1 import db
2 import http

4 class ClickCounter:
5     ... # as above

7 click_counts = ClickCounter()

9 http.on(
10     method="post",
11     endpoint="/click/add",
12     action=(payload => click_counts.add(payload))
13 )

```

Figure 9: Code adapted for the contrived example of a deployment variation.

3.3 Layered Principles

Separating software into layers is intended to increase the modularity and isolation of the components within each layer. Isolation is provided by defining a public interface through which all communication with the layer is to be performed.

Definition 6. Layer Isolation Principle

Layers should not depend on implementation details of another layer. Layers should only communicate through well defined interfaces (*contracts*).

Layering should be enforced. One layer should not “reach across” another layer to access behaviour implemented in some other layer. For example, in our standard form of the layered architecture, if the presentation layer uses a component from the persistence layer, it defeats the intent of having a business layer in the architecture.

A consequence of this is chains of message passing. An extreme example would be if the presentation layer needed to display some information from the database, the presentation layer would send a message to the business layer to get the object to be displayed. The business layer would send a message to the

persistence layer to retrieve the object. The persistence layer would then send a message to the database layer to load the object.

Typically, there would not be a need to send messages from the highest to lowest layer. If the business layer knew it had an up-to-date copy of the object, it would return it to the presentation layer without messaging the persistence layer. If the persistence layer had already retrieved the object from the database, it would return it to the business layer without messaging the database layer.

Definition 7. Neighbour Communication Principle

Components can communicate across layers only through directly neighbouring layers.

Layers should be hierarchical. Higher layers depend on services provided by lower layers but not vice versa. This dependency is only through a public interface, so that components in the lower layer may be replaced by another component implementing the same interface. Components in a lower layer should not use components from a higher layer, even if the layers are neighbours.

Definition 8. Downward Dependency Principle

Higher-level layers depend on lower layers, but lower-level layers do not depend on higher layers.

Downward dependency does not mean that data is not passed to higher layers. It does not even mean that control cannot flow from a lower level to a higher level. The restriction is on dependencies or usage, not on data or control flow. A lower layer should not use components from a higher layer, even through the higher layer's interface. Breaking this increases the overall coupling of the system and means it is no longer possible to replace a lower layer with another layer.

Lower layers need a mechanism to be able to notify a higher layer that something has happened, of which the higher layer needs to be aware. A common example of this is the presentation layer wants to be notified if data that it is displaying has been updated in a lower layer. The [observer design pattern²¹](#) is a common solution to this notification issue. The component responsible for displaying the data in the presentation layer implements the *Observer* interface. The object containing data that may be updated implements the *Subject* interface. The subject and observer interfaces are general purpose interfaces that do not belong to the presentation layer. The lower layer uses the observer interface to notify the presentation layer that data has changed and the presentation layer can decide whether to retrieve the new data and display it. This allows the higher layer to be notified of events, without the lower layer using anything from the higher layer.

The same issue occurs with error handling and asynchronous messaging. If a component in a higher layer sends a message, through an interface, to a component in a lower layer, the component in the lower layer needs a mechanism to report errors. A simple boolean or error code return may work in some situations, but often that is not appropriate. If the message is meant to return a value, in most languages it cannot also return an error result. There may also be different types of errors that need to be communicated to the higher layer. (e.g. The call from the higher layer broke the contract specified in the interface. Or, the lower layer is encountering a transient fault and the higher layer should try again later.) Exception handling works, if all layers are within one executable environment, but a key purpose of a layered architecture is to allow separation of the layers, so throwing an exception is not appropriate.

[Callbacks²²](#) are used to deal with this issue for both error handling and asynchronous messaging. A component from a higher layer in the architecture passes a function as a parameter when it sends a message to a component in a lower layer. This function is called by the component in the lower layer of the architecture to report an error or to indicate that an asynchronous call has completed.

²¹<https://refactoring.guru/design-patterns/observer>

²²<https://www.codefellows.org/blog/what-is-a-callback-anyway/>

Definition 9. Upward Notification Principle

Lower layers communicate with higher layers using general interfaces, callbacks and/or events. Dependencies are minimised by not relying on specific details published in a higher layer's interface.

The subject and observer interfaces are examples of supporting logical infrastructure. Logging frameworks are another example of supporting infrastructure. Commonly, all layers will need to use the logging framework. These are typically defined in separate “layers” that can be used by any of the other layers. These are sometimes called *sidecar* or acquaintance layers, as visually they are often drawn on the side of the layered diagram.



Figure 10: Layered architecture with sidecar.

Definition 10. Sidecar Spanning Principle

A sidecar layer contains interfaces that support complex communication between layers (e.g. design patterns like the observer pattern) or external services (e.g. a logging framework).

A purist design approach says that a sidecar layer may only contain interfaces. In some environments, an architecture may decide that multiple sidecars are beneficial, and may even use these for reusable components from broader organisational systems or for objects that hold data passed to higher layers. Figure ?? is an example of using sidecars for both of these purposes in a J2EE²³ application.



Figure 11: Layered architecture with sidecars delivering implementation (figure 2.27 in Clements et al, 2010) [?].

In the example shown in figure ??, the servlets and action classes layer is equivalent to the presentation layer. The controller and service classes layers are a further partitioning of the business layer. The DAO

²³<https://www.oracle.com/java/technologies/appmodel.html>

(Data Access Objects) classes layer is equivalent to the persistence layer. The database layer is not shown in this example, which is common practice to hide it in diagrams focussing on the system's architecture.

The Presentation DTOs (Data Transfer Objects) sidecar contains simple JavaBeans²⁴ that contain data that is to be displayed. This approach takes advantage of J2EE's mechanism that automatically populates and updates data in the presentation layer.

The Corporate DTOs and POJOs (Plain Old Java Objects) sidecar contains classes implemented by corporate-wide systems, and which are shared between systems. These provide common data and behaviour that spans multiple layers in many systems.

3.3.1 Closed/Open Layers

Some textbooks discuss the concept of closed and open layers. This is a way to describe how communication flows between layers. Layers are categorised as either *open* or *closed*. By default layers are *closed*. Closed layers prevent direct communication between their adjacent layers, i.e. they enforce the neighbour communication principle. Figure ?? shows the communication channels (as arrows) in a completely closed architecture.



Figure 12: All layers closed requiring communication to pass through every layer.

An architecture where all layers are closed provides maximum isolation. A change to the communication contracts of any layer will require changes to at most one other layer.

Some architects will advocate that there are some situations where an *open* layer may be useful. Open layers do not require communication to pass through the layer, other layers can “reach across” the layer. The preferred approach is to use general interfaces, callbacks and/or events, as discussed in the sections describing the downward dependency, upward notification, and sidecar spanning principles. This provides mechanisms that allow data and control to flow both up and down in a layered architecture, without breaking the isolation principle that was the original intent of using a layered architecture. Open layers in architecture design should be avoided.

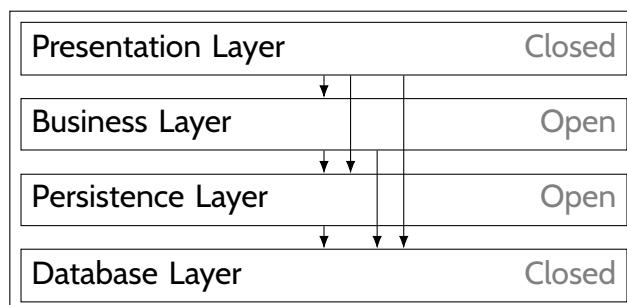


Figure 13: A wolf in layer's clothing [?].

<https://www.educative.io/edpresso/why-use-javabean>

3.4 Advantages

The layer isolation principle means that the implementation of a layer can be changed without affecting any other layer, as long as the interface does not change.

The layer isolation principle also means that a developer only needs to understand the public interface to use a layer, and not its implementation details.

The neighbour communication and downward dependency principles mean that if a layer changes its public interface, at most one other layer needs to change.

The upward notification and sidecar spanning principles mean that complex systems, with sophisticated flows of control and data, can be implemented while maintaining the other layered architecture design principles.

Lower layers in the architecture can be designed to deliver common services that may be reused across multiple applications. (e.g. The persistence layer can be designed to allow general purpose access to the database layer, allowing any type of database to be substituted into the system.)

Layers may be deployed on different computing infrastructure. This enables the hardware to be optimised for the types of services provided by just one layer. It also enables scaling and replication by allowing layers to be duplicated across multiple servers.

3.5 Disadvantages

Poorly designed layers will encourage developers to break the layered architecture design principles in order to get the system to work. This can lead to a system that in detail more closely resembles a big ball of mud, than a layered design.

Layering often introduces performance penalties. Requiring a chain of message passing to obtain a service from a lower layer in the architecture adds to the cost of delivering the behaviour.

Security Principles

Software Architecture

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1 Introduction

One quality attribute which developers often overlook is security. Security can be the cause of a great deal of frustration for developers; there are no comfortable architectures, nor command-line tools to magically make an application secure. While the world depends on technology more than ever, and, at the same time the impacts of cyber attacks become more devastating, it has become crystal clear that security is everyone's responsibility. As users of technology, as developers, and as architects, we all need to ensure we take security seriously.

Learning, and for that matter, teaching, how to make software secure is no easy task. Every application has different flaws and risks, every attack vector and exploit is unique; managing to keep up with it all is daunting. None of us will ever be able to build a completely secure system but that is no reason to stop trying. As developers and architects, security should be an on-going process in the back of your minds. A nagging voice which constantly asks 'what if?'.

We introduce security first to set the example. As we go through this course, the principle of security will recur again and again. With each architecture introduced, we will stop and ask ourselves 'what if?'. In your future careers, you should endeavour to continue this same practice. Each feature, pipeline, access control change, or code review, ask yourself, 'what are the security implications?'.

With that said, there are some useful principles, and a handful of best practices which we will explore. But again, even if you follow these practices and embody the principles, your applications will still be hopelessly insecure, unless, you constantly reflect on the security implications of your each and every decision.

2 You

Before we even fantasise about keeping our applications secure, let's review if you are secure right now. As developers we often have heightened privileges and access, at times above that of even company CEOs. If you are not secure, then nor is anything on which you work. Let's review some of the basics.

Keep your software up to date. Are you running the latest version of your operating system? The latest Chrome, or Firefox, or god-forbid, Edge? If not, then there is a good chance you are currently at risk. Software updates, while annoying, provide vital patches to discovered exploits. You must keep your software up to date.

Use multi-factor authentication. This may be hard to explain to your grandmother but this should be obvious to software developers. One million passwords are stolen every week [?]. If you do not have some sort of multi-factor authentication enabled, hackers can access your account immediately after stealing your password.

Use a password manager. Following from the startling statistic of a million stolen passwords per week, we must seriously consider how we use passwords. Our practices should be guided by the fact that at least one service we use likely stores our password insecurely. We should assume that our password will be compromised. What can we do about this? The first thing is to avoid password reuse, one password per service. Of course, humans have very limited memory for remembering good passwords. So go through and update your passwords with randomly generated secure passwords, and then store them in a password manager.

3 Principles of Securing Software

Okay, now that we are not a security risk ourselves, we can start considering how to secure the software we develop. Before looking at pragmatic practices, we will develop a set of guiding principles. These principles are far from comprehensive but they provide a useful foundation to enable discussion of our security practices. The principles presented in this course are derived from Saltzer and Schroeder [?], Gasser [?], and Viega and McGraw [?]. Some principles have been renamed for consistency and clarity. Refer to Appendix ?? for the comprehensive list of principles from these sources.

3.1 Principle of Least Privilege

Every program and every privileged user of the system should operate using the least amount of privilege necessary to complete the job.

— Jerry Saltzer [?]

The principle of least privilege was identified in 1974 by Jerry Saltzer [?]. This principle is mostly common sense and the benefits should be apparent. If you maintain the principle of least privilege then you minimise your attack surface by limiting the amount of damage any one user can do. This protects software from intentionally malicious actors while also minimising the damage of bugs which occur unintentionally in the software.

Example Consider a web application which lists COVID close contact locations for a state. We will assume that the locations are maintained within an SQL database. Assume that each time the tracing page is loaded, an SQL query is sent to the database to find all current close contact locations. If the developers follow the principle of least privilege, then the account used to query that data would only be able to list the current locations.

For this example, the tracing website had to be developed and rolled out quickly, as such, the developers created only one SQL user which they used for both the tracing website and the portal where the government can log new locations. This user account would have the ability to create new close contact locations, and if done poorly enough, the account might even have access to delete existing locations.

Since the developers have violated the principle of least privilege, their software is now at risk. If a malicious actor is able to gain database access via SQL injection, or, just as likely, if the software has a typo in an SQL query, the integrity of the tracing data could be jeopardised. This could be mitigated by using the principle of least privilege and creating separate user accounts for modifying and subsequently viewing the data.

Exemplar One of the primary examples of a good application of this principle is within Unix operating systems. In the Unix operating system, a sudoer (a user account which can use the `sudo` command) has a lot of destructive power. Commands running at the sudo level can do essentially anything they wish, including wiping the computer. However, a sudoer is not typically using these privileges. The user has to specify that they intend to run a command with elevated privileges, which helps avoid accidental destruction of the computer.

Fail-safe defaults The principle of fail-safe defaults is often presented on its own. Fail-safe defaults means that the default for access to a resource should be denied until explicit access is provided. We include fail-safe defaults as a property of the principle of least privilege given the strong connection.

3.2 Principle of Failing Securely

Death, taxes, and computer system failure are all inevitable to some degree. Plan for the event.

— Howard and LeBlanc [?]

Computer systems fail. As we will see in this course, the more complicated your software, the more often and dramatically it can be expected to fail. The principle of failing securely asks us to stash away our optimism and become a realist for a moment. When designing an architecture or a piece of software, plan for the ways your software will fail. And when your software does fail, it should not create a security vulnerability [?].

Example An interesting example of failing securely comes from Facebook's October 2021 outage which we discussed previously. As you may be aware, one cause of the outage was a DNS resolution issue triggered by Facebook's data centres going offline [?]. The DNS resolution issue meant that the internal Facebook development tools and communication channels went down as well. As you might expect, losing your tools and access to your team members makes resolving an outage far more difficult.

Early reports of the incident indicated that the outage of Facebook's internal infrastructure also meant employees were locked out of the data centres. While it seems that developers were locked out of their buildings, the data centres were not affected. Nevertheless, it is interesting to consider whether an internal outage should, somewhat understandably, lock access to the data centres.

This example highlights the key difference between a system which *fails safely*²⁵ and a system which *fails securely*. In a fail safe system, an internal outage would allow physical access to the data centre to enable maintenance to fix the problem. Whereas in a fail secure system, the outage would cause the data centre to lock and prevent access to maintain the security of the data within. There isn't one correct way to deal with failure. While in this case it would have helped Facebook resolve the issue quicker, if a data breach occurred through an intentional outage there would be equal criticism.

Regardless of the security policy you choose, it is always important to prepare for failure and weigh the pros and cons of each policy.

3.3 Principle of KISS

Simplicity is the ultimate sophistication

— Leonardo Da Vinci²⁶

We will keep this principle simple. The principle of Keep it Simple Stupid (KISS) is needed as complicated software or processes are, more often than not, insecure. Simple means less can go wrong.

3.4 Principle of Open Design

One ought to design systems under the assumption that the enemy will immediately gain full familiarity with them.

— C. E. Shannon [?]

The principle of open design, also known as Kerckhoffs' principle, stresses that security through obscurity, or security through secrecy, does not work. If the security of your software relies on keeping certain implementation details secret then your system is not secure. Of course, there are some acceptable secrets such as private keys, however, these should still be considered a vulnerability. Always assume that if an implementation detail can be discovered, it will be. There is software constantly scanning the internet for open ports, unpublished IP addresses, and routers secured by the default username and password.

²⁵No relation to fail-safe defaults.

²⁶maybe

Example An example which immediately springs to mind is our first and second year assignment marking tools. To date, I am not aware of the tools being exploited, however they are currently vulnerable. The tools currently rely on students not knowing how they work. There are ways to create ‘assignment’ submissions which pass all the functionality tests for any given semester. Fortunately, the threat of academic misconduct is enough of a deterrent that it has yet to be a problem.

The example does illustrate why the principle of open design is so frequently violated. In the short-term security through obscurity can work, and work well, but it is a long-term disaster waiting to happen. It is also common place to violate the principle slightly by trying to build systems which do not rely on secrecy but keeping the systems secret ‘just in case’. In many situations this is appropriate, however, a truly secure system should be open for community scrutiny.

3.5 Principle of Usability

The final principle we should explore is the principle of usability, also known as ‘psychological acceptability’. This principle asks that we have realistic expectations of our users. If the user is made to jump through numerous hoops to securely use your application, they will find a way around it. The idea is that the security systems put in place should, as much as possible, avoid making it more difficult to access resources.

Example The example for this principle includes a confession. The university has implemented a multi-factor authentication mechanism for staff and students. Unfortunately, there was a bug in the single sign-on which means that MFA is not remembered causing the system to re-prompt me at every *single* log in. A direct consequence of this inconvenience is that I have installed software on all my devices which automatically authenticates the MFA, bypassing, in part, the intended additional security.

The university through violating the principle of usability has made it more difficult for users to be secure than insecure. As predicted by the principle, the inconvenience leads straight to bypassing. Violation of this principle often has relatively minimal *visible* impacts, which results in the principle not being considered as often. The long-term implications are that what was an annoyance circumvented by your users, may become the cause of a major security breach long after the security feature was implemented.

4 Practices of Secure Software

With some of the guiding principles of secure software now covered, there are a few useful practices which can be employed to help secure our systems.

4.1 Encryption

In the arms race between hackers and security practitioners *encryption* was one of the first weapons wielded. Encryption is the act of encoding data in a way which is difficult to decode. The most notable early example of encryption was the Enigma Machine in the 1930s, if you trace the history of cryptography back far enough you will eventually end up in World War II Germany [?].

While encryption is outside of the scope of this course, it is well worth having knowledge of available encryption techniques. You should not attempt to design your own encryption algorithms, unless you are an expert in security and encryption. Rather, you should use existing well-known and well-tested encryption algorithms. In the design of a secured software system encryption can play many roles.

4.2 Sanitisation

Another practice which you should endeavour to utilise is sanitisation. If we assume that you cannot tell the difference between your user and a potential attacker, then you cannot trust your user. If you cannot

trust your user, then you should not trust the data they give you. One of the oldest and most common forms of attacks is user input injection. In such an injection attack, a user intentionally or unintentionally provides input which damages your system.



Figure 14: <https://xkcd.com/327/>

When done maliciously, attackers enter characters or sequences of characters which are commonly used to escape a string. The input which follows would then be run as code on the victim's system. The method for preventing against injection attacks is called *sanitisation*, which is simply a process of removing dangerous or unnecessary characters from a user's input.

4.3 Firewalls

A firewall is a piece of networking software which is designed to protect a computer system against unwanted traffic. Firewalls scan incoming and outgoing network packets and are able to drop the packet if it is deemed unwanted. Firewalls can be configured by a set of rules defining which traffic is unwanted. A firewall rule could specify that a computer system drop all packets destined for port 80 or all packets not destined for port 80. They may also be configured to support more advanced packet filtering.

From our perspective the primary advantage of a firewall is to prevent traffic which we did not intend. If we are hosting a web server, only allowing traffic on port 80 and port 443 is desirable, and prevents users accessing a database on the server which we forgot to password protect. The principle for firewalls is to block by default and allow when required.

4.4 Dependency Management

Modern software has a lot of dependencies. Each new dependency a software adopts is a new potential attack surface. Relying on software which is automatically updated is dangerous, the authors can at any point inject malicious code into your system. There is a particularly interesting recent example of dependency injection which is worth reading about [?].

One simple practice to help prevent against dependency injection is by using lock files. Most package managers generate lock files when installing software. Lock files keep track of the exact version of a library that is installed. If you ask a package manager to install version $\geq 2.4.0$ of a library and it actually downloads version 2.5.6, this will be tracked in the lock file. Additionally, lock files track the hash of the dependency so that if someone attempts a dependency injection, the code change will be noticed by the package manager. Lock files should be tracked in version control and updated periodically when a safe and tested version of a dependency is released.

5 Conclusion

We have looked at a few guiding principles for designing and developing secure software. This list of principles is incomplete, security requires constant consideration. Software security is an ongoing arms race for which we are all currently unqualified to enlist. Secure yourself as best you can and, when you are in doubt, consult with or hire an expert.

A Original Security Design Principles

Saltzer and Schroeder

1. Economy of mechanism Principle of KISS
2. Fail-safe defaults Principle of Least Privilege
3. Complete mediation Not covered
Access to resources must *always* be authorised.
4. Open design Principle of Open Design
5. Separation of privilege Not covered
No one user account or role should hold too much power.
Consider multi-role authentication where appropriate.
6. Least privilege Principle of Least Privilege
7. Least common mechanism Not covered
Minimise the amount of resources shared between users.
8. Psychological acceptability Principle of Usability

Gasser

1. Consider Security from the Start Implicit
2. Anticipate Future Security Requirements
3. Minimise and Isolate Security Controls
4. Enforce Least Privilege Principle of Least Privilege
5. Structure the Security-Relevant Functions
6. Make Security Friendly Principle of Usability
7. Do Not Depend on Secrecy for Security Principle of Open Design

Viega and McGaw

1. Secure the Weakest Link
2. Practice Defense in Depth
3. Fail Securely Principle of Failing Securely
4. Follow the Principle of Least Privilege Principle of Least Privilege
5. Compartmentalise
6. Keep It Simple Principle of KISS
7. Promote Privacy
8. Remember That Hiding Secrets is Hard
9. Be Reluctant to Trust
10. Use Your Community Resources

Architectural Views

Software Architecture

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1 Introduction

Understanding software is hard. It is often claimed that reading code is harder than writing code²⁷. This principle is used to explain a programmer's innate desire to constantly rewrite their code from scratch. If software is hard to understand, then understanding software architecture from the detail of the code is near impossible. Fortunately, architects have developed a number of techniques to manage this complexity.

A software architecture consists of many dimensions. Programming languages, communication protocols, the operating systems and hardware used, virtualisation used, and the code itself are a subset of the many dimensions which comprise a software architecture. Asking a programmer's monkey brain to understand, communicate, or document every dimension at once is needlessly cruel. This is where architectural views come in.

Architectural views, or architectural projections, are a representation of one or more related aspects of a software architecture. Views allow us to focus on a particular slice of our multi-dimensional software architecture, ignoring other irrelevant slices. For example, if we are interested in applying a security patch to our software then we are only interested in the view which tells us which software packages are used on each host machine.

The successful implementation of any architecture relies on the ability for the architectural views to be disseminated, understood, and implemented. For some organisations, the software is simple enough, or the team small enough, that the design can be communicated through word of mouth. As software becomes increasingly complex and developers number in the thousands, it is critical for design to be communicated as effectively as possible. In addition to facilitating communication, architectural views also enable architectural policies to be designed and implemented.

2 C4 Model

Simon Brown's C4 model provides a set of abstractions that describe the static structure of the software architecture [?]. The C4 model uses these abstractions in a hierarchical set of diagrams, each leading to finer levels of detail. The hierarchical structure is based on the idea that a software system is composed of containers, which are implemented by components, that are built using code.

Software System Something that delivers functional value to its users (human or other systems).

Containers Deployable 'block' of code or data that provides behaviour as part of the software system.

Components Encapsulate a group of related functionality, usually hidden behind a published interface.

Code Elements built from programming language constructs, e.g. classes, interfaces, functions,

The C4 model does not explicitly identify different architectural views, but views are implicit in the types of diagrams produced to describe an architecture.

²⁷Though evidence suggests that an ability to read and reason about code is necessary to learn how to program well [?] [?].



A **software system** is made up of one or more **containers** (web applications, mobile apps, desktop applications, databases, file systems, etc), each of which contains one or more **components**, which in turn are implemented by one or more **code** elements (e.g. classes, interfaces, objects, functions, etc).

Figure 15: Levels within the C4 model (figure 2.1 from [?]).

The static *structural* view of software architecture is described through four levels of abstraction. Each level providing detail about parts of the previous level.

Context How the software system fits into the broader context around it.

Containers How the containers are connected to deliver system functionality.

Components How the components are structured to implement a container's behaviour.

Code How the code is structured to implement a component.

The *behavioural* view is described via a dynamic diagram that describes how containers and components interact to deliver system features.

The *infrastructure* view is described by a deployment diagram that describes how executable containers, software systems, and other infrastructure services are deployed on computing platforms to instantiate the system.

3 Sahara eCommerce Example

Sahara²⁸ eCommerce is an ambitious company who's prime business unit is an on-line store selling a wide range of products. Sahara provides both web and mobile applications to deliver the shopping experience to customers.

3.1 Architecturally Significant Requirements

Architecturally significant requirements (ASR) are functional or non-functional requirements, or constraints or principles, which influence the design of the system architecture. The structure of a software architecture

²⁸Yes, that is intentionally a dry joke.

has to be designed to ensure that the ASRs can be delivered.

Not all requirements for a system will be architecturally significant, but those that are need to be identified. Once ASRs are identified, an architecture needs to be designed to deliver them. This may require some research, and experimentation with prototypes, to determine which options are appropriate. Tests should be designed to verify that the architecture is delivering the ASRs. Ideally, these should be part of an automated test suite. This may not be possible for all tests. Regardless, the ASR tests should be executed frequently during development to provide assurance that the system will deliver the ASRs.

Inevitably, some ASRs will be discovered later in the project. The existing architecture will need to be evaluated to determine if it can deliver the new ASRs. If it can, new tests need to be added to the ASR test suite to verify delivery of the new ASRs. If the architecture is no longer suitable due to the new ASRs, a major redesign needs to be done to create a new, more suitable, architecture.

The architecturally significant requirements for the Sahara eCommerce system are:

- Customers can start shopping on one device and continue on another device. (e.g. Add a product to their shopping cart while browsing on their computer when they are bored at school. Checkout their shopping cart from their mobile phone on their way home on the bus.)
- The system must be scalable. It must cater for peaks in demand (e.g. Cyber Monday and Singles Day). It must cater for an unknown distribution of customers accessing the on-line store through web or mobile applications.
- The system must be robust. The system must continue to operate if a server fails. It must be able to recover quickly from sub-system failures.
- The system must have high availability. Target availability is “four nines”²⁹ up time.

The following sections will describe the physical and software architecture for this system, and demonstrate how it delivers these ASRs.

3.2 System Context

The system context provides the ‘big picture’ perspective of the software system. It describes the key purpose of the system, who uses it, and with which other systems it interacts. The context diagram is usually a simple block diagram. The software system being designed typically sits in the centre of the diagram surrounded by users and other systems. The intent is to set the context for thinking about the software system’s architecture. It can also be used to communicate basic structural ideas to non-technical stakeholders. Figure ?? is a context diagram for the Sahara eCommerce system. The overall eCommerce system is delivered through two interacting software systems, the on-line store and the data mining service.



Figure 16: Context diagram for the Sahara eCommerce on-line store.

²⁹A number of nines (e.g. four nines) is a common way to measure availability. It represents the percentage of time the system is “up”. Four nines means the system is available 99.99% of the time, or it is not available for less than one hour per year.

Figure ?? is the key to help interpret the context diagram. A key is important for C4 diagrams, as they have a fairly informal syntax and specification.



Figure 17: Context diagram key.

The context diagram situates the on-line store software system in the environment in which it will be used. There are customers who shop at the on-line store, which is part of Sahara eCommerce's software ecosystem. The on-line store uses a data mining service that is also implemented by the company. The two key relationships between the on-line store and the data mining service are that the on-line store sends customer browsing data to the service, and that the on-line store requests the data mining service to recommend products for a customer.

In C4, arrows are used to indicate the main direction of the relationship, not the flow of data. So, in this example, the arrow points from the on-line store to the data mining service as it is the store that manages the communication.

3.3 Containers

Container diagrams provide an overview of the software architecture. They describe the main structure of the software system and the technologies selected to implement these aspects of the system. Containers are 'blocks' of code that can be independently deployed and executed. Examples of containers are web or mobile applications, databases, message buses, It is important to note that containers may be deployed on the same computing infrastructure or on different devices.

Container diagrams focus on the connections between containers and, to an extent, how they communicate. They do not explicitly show computing infrastructure. Decisions about how containers are connected and communicate have major implications for how the components and code will be designed and deployed. Figure ?? is a container diagram for the on-line store. For simplicity, containers managing load balancing and fail-over are not shown in this example.

To provide a link to the context diagram, a container diagram usually shows which containers communicate with which external elements. The text inside the square brackets in a container, and on a relationship, indicates the technology used to implement that container or relationship.

Customers access the on-line store through either web or mobile applications. The Web Application and Interactive Web Pages containers indicate that the web application's behaviour is delivered by two different specialised containers. The Web Application container indicates that it runs in a J2EE³⁰ server. This implements the presentation layer of the web application in Java. It handles browser requests from customers, using the HTTPS protocol over the Internet.

The Interactive Web Pages are JSF³¹ pages and JavaScript code that implement more sophisticated user interactions on web pages. These run within the users' browsers.

The Web Application container uses RMI³² to invoke functional behaviour in the Application Backend

³⁰Jakarta Enterprise Edition [<https://jakarta.ee/>]

³¹Jakarta Faces [<https://jakarta.ee/specifications/faces/>]

³²Remote Method Invocation [<https://www.oracle.com/java/technologies/jpl1-remote-method-invocation.html>]

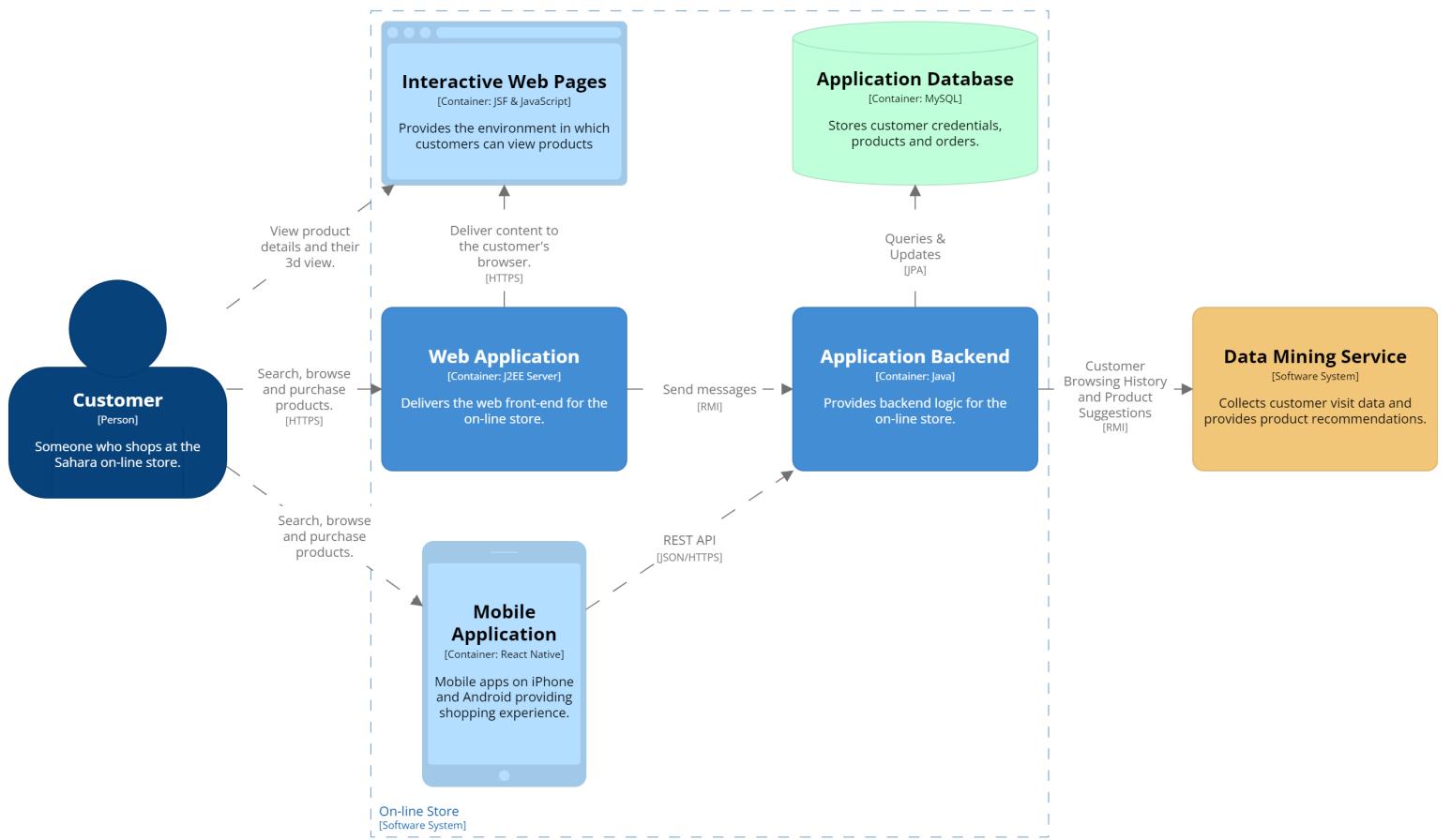


Figure 18: Container diagram for the on-line store software system.

container. It provides the shared logic of the on-line store. This supports implementing the functional requirement that a customer can start shopping on one device and continue on another.

The mobile application communicates with the application backend via a REST API³³. The application backend uses JPA³⁴ to manage persistent data in the application's database. The application backend uses RMI to communicate with the data mining service, sending customer browsing and search history to be used for data mining and receiving product suggestions to present to customers.

While a container diagram does not explicitly show computing infrastructure, some of it can be implied by the types of containers in the diagram. Clearly, the mobile app and the code running in the interactive web pages have to be separate computing platforms to the rest of the on-line store's software system.

Colours and icons can be used to provide further information in the diagrams. The diagram key in figure ?? explains the purpose of each icon and colour.

The data mining service software system (figure ??) has three main containers.

Data Mining Interface provides the interface used to interact with the data mining service. It accepts data to store for future data mining. It returns suggestions based on requests from external systems, such as the on-line store.

Data Mining Process performs the data mining logic.

Data Warehouse stores the data and provides an SQL-based query system to manipulate the data. The data mining interface and process containers use JDBC³⁵ to work with the data in the data warehouse.

³³<https://www.ibm.com/topics/rest-apis>

³⁴Jakarta Persistence API [<https://jakarta.ee/specifications/persistence/>]

³⁵Java DataBase Connectivity [<https://docs.oracle.com/javase/tutorial/jdbc/basics/index.html>]



Figure 19: Container diagram key.

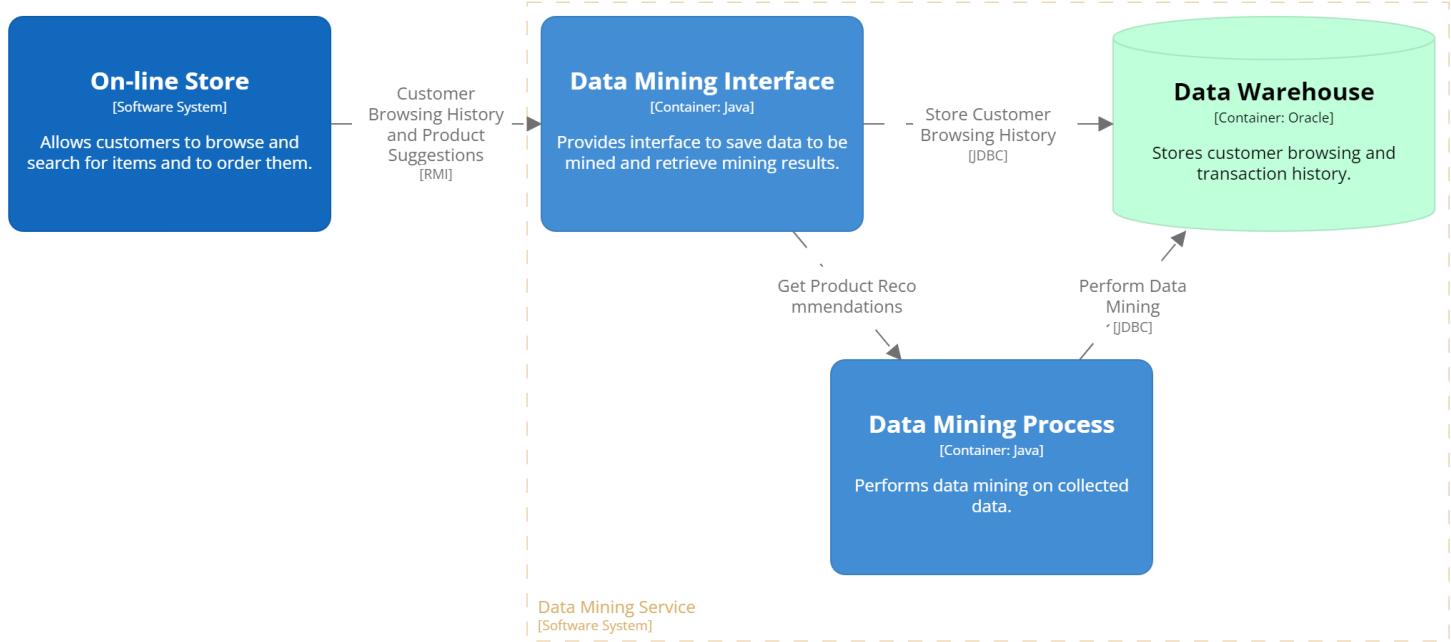


Figure 20: Container diagram for the data mining service software system.

3.4 Components

Component diagrams describe the major parts of containers and how they are connected. Components should describe their important responsibilities and the technology used to implement them (e.g. using React to implement a web frontend component). Like a container diagram, a component diagram can include elements from higher level diagrams to provide context of how the components interact with elements outside of the container.

In figure ??, the application backend is divided into five main components. The Shopping Cart component provides the backend logic of implementing a shopping cart. This includes storing the state of the cart in the application database so that it is available in a later shopping session. The Products component provides information about products in the application database. The Customers component retrieves customer credentials from the application database. The Orders component stores finalised orders in the application database.



Figure 21: Component diagram for the application backend container.

The web application interacts with the Customers, ShoppingCart and Products components via RMI. They would provide interfaces for this interaction. ShoppingCart uses the Products, Orders and Customers components to deliver its behaviour. Together they deliver the logical behaviour of providing information about products, tracking what is in the shopping cart, and placing orders.

The application backend is implemented in Java and uses [JPA Entities³⁶](#) to manage persistent data in the application database.

The mobile applications use a REST API to communicate with the application backend. An example of this is shown by the ShoppingCart Controller component which uses the ShoppingCart to deliver that behaviour to the mobile applications. Other controllers implementing REST APIs are not shown to reduce the complexity of the diagram.

Figure ??, shows the icons and colours used to represent different elements in the component diagrams.



Figure 22: Component diagram key.

³⁶<https://jakarta.ee/specifications/persistence/3.2/jakarta-persistence-spec-3.2.html#entities>

Figure ?? shows the components that provide the frontend behaviour, in the web application, of browsing for products, adding them to the shopping cart, and purchasing them.



Figure 23: Component diagram for the web application container.

Figure ??, shows that the Product Animator component is downloaded from the web application to the customer's browser and that it is implemented in JavaScript. This component provides the code that allows customers to interact with 3D views of products.



Figure 24: Component diagram for the interactive web pages container.

To keep the example manageable, only the components related to implementing the shopping cart are shown at this level of detail.

3.4.1 Component Diagram Detail

There may be some components that are important parts of the software design, but which may not necessarily be included in component diagrams. For example, a logging component is an important part of many software systems. But, due to the nature of a logging component, most other components will use it. Adding it to component diagrams will usually clutter the diagrams without adding much useful information. Usually it is better to add a note indicating which logging component is used in the system. If it is helpful to indicate which components use the logging component, it may be better to colour code these components or use an icon to represent that they use the logging component.

3.5 Code

Code-level diagrams describe the structure of the code that implements a component. The intent is to provide a visual representation of the important aspects of the code's structure.

C4 does not provide a code level diagram. It suggests using diagrams appropriate to your programming paradigm. Assuming the implementation is in an object-oriented language, a [UML diagrams³⁷](#) class diagram would be an appropriate way to model the design of the code.

Figure ?? is a UML class diagram visualising the static structure of the classes that implement the Shopping Cart component. Usually only architecturally significant operations and attributes are shown. (e.g. Operations and attributes needed to understand relationships and behaviour.) Rarely do you need to provide all the detail that replicates the source code. (The source code could be considered a fifth level to the C4 model.) And for simplicity in this diagram, only the classes and interfaces related to adding items to a shopping cart and checking out are shown.



Figure 25: Example static structure for part of the shopping cart component.

The `CartManager` and `Checkout` control classes implement, respectively, the `ManageCart` and `CartCheckout` interfaces. These two classes implement the Façade design pattern and manage how adding products to a shopping cart and checking out are delivered by the classes in this package. Going back to the application backend and web application component diagrams (figures ?? and ??), when a customer, via their web browser, selects to add a product to their shopping cart, the Product Browsing component's logic uses the `ManageCart` interface's `addItem` operation to send a message to the Shopping Cart component.

In the implementation of the Shopping Cart component, the `CartManager` class uses the `EntityManager` to load the product details and the customer's shopping cart from the application database. The `EntityManager` creates the `Product` and `Cart` entity objects, and `CartManager` adds the product to the cart. Once this is done the `EntityManager` is used to save the updated cart data into the database.

When a customer wants to checkout the products in their shopping cart, the Shopping Cart View component uses the `CartCheckout` interface's `products` operation to get a list of the product details to be displayed in the shopping cart. The `ProductDetails` class is a Java bean that is used to pass the data about each product to the Shopping Cart View. Once a customer decides to buy the products in their

³⁷Unified Modeling Language [<https://www.uml.org/>]

shopping cart, the Shopping Cart View sends the checkOut message to the Shopping Cart. Checkout uses the *PaymentGateway* interface to process the payment.

3.5.1 Class Diagram Notation

Formally in UML, rectangles represent *classifiers*. A *class* is one type of classifier. In a class diagram, a rectangle represents a class, unless a keyword is used to indicate that it is a different type of classifier. Classifier rectangles have three compartments. The top compartment contains its name and optionally includes a keyword, stereotypes and properties for the classifier. The middle compartment contains *attributes*. The bottom compartment contains *operations*.

Solid lines represent *associations*, which may optionally have an arrow indicating the direction of the relationship. An association indicates a structural relationship between classes. Typically this means that the target of an association will be an implicit attribute of the class. The end of an association can use *multiplicity* to indicate the number of objects of the class that may take part in the relationship.

A diamond on the end of an association indicates an *aggregate* relationship. The diamond is on the end that is the aggregate, and the other end is the part. The diamond may be filled or not. A filled diamond represents *composition*. This indicates 'ownership', where the aggregate controls the lifespan of the part. A hollow diamond, as in the relationship between Order and Product, indicates *aggregation*. This is a weaker relationship than composition, as the aggregate does not control the lifespan of the part, but it still indicates a strong relationship between the classes.

A dashed line with an open arrowhead (e.g. from CartManager to Product) indicates that one classifier *depends* on (or uses) another. This is meant to indicate a transient relationship.

A dashed line with a closed and hollow arrowhead (e.g. from Checkout to CartCheckout) indicates that the class is *realising* (or implementing) that interface.

Italicised names indicate an abstract classifier. Keywords are used to indicate the type of a classifier. In this example, the keyword «interface» indicates that the classifier is an interface. Stereotypes use the same notation as keywords. Three standard stereotypes for classes in UML are:

«entity» Represents a concept (*entity*) from the problem domain.

«control» Provides logical behaviour from the solution domain.

«boundary» Communicates with something outside of the system. (Not shown in diagram.)

An additional stereotype «bean» is used to indicate that the class is a Java bean.

3.6 Dynamic

Dynamic diagrams in C4 show how different parts of the model collaborate to deliver architecturally significant requirements. Normally dynamic diagrams are used to describe behaviour that is not clear from other diagrams and descriptions. This can include complex interactions between modules, complex concurrency, real-time constraints, or latency constraints.

For example, when Boeing was upgrading the combat control system of the F-111³⁸ for the Australian Airforce, they designed a software architecture that used CORBA³⁹ as middleware. The implementation of the middleware caused a fixed delay in sending messages between components. From an architectural design perspective, it was important to document this delay and enforce a maximum delay on the time taken to complete any process. This type of constraint can be documented with a dynamic diagram and supporting documentation.

Figure ?? provides an overview of how the Product Browsing component in the Web Application container collaborates with the Shopping Cart component in the Application Backend container to

³⁸<https://www.youtube.com/watch?v=xUcpZJE050s>

³⁹Common Object Request Broker Architecture [<https://www.ibm.com/docs/en/integration-bus/9.0.0?topic=corba-common-object-request-broker-architecture>]

deliver the behaviour of a customer adding a product to their shopping cart. It also shows the communication between the Shopping Cart component and the application database.



Figure 26: Dynamic diagram for adding a product to the customer's shopping cart.

A dynamic diagram should provide enough information to clarify any requirements or constraints on the design, but should not be so restrictive as to limit valid implementation choices.

UML provides two types of interaction diagrams that are similar to dynamic diagrams. A communication diagram is very similar to a dynamic diagram. A sequence diagram focusses on the time or ordered sequence of events that occur in a scenario. In documenting a software architecture, there may be some types of constraints that are more clearly expressed through a sequence diagram.

3.6.1 Detailed Behaviour

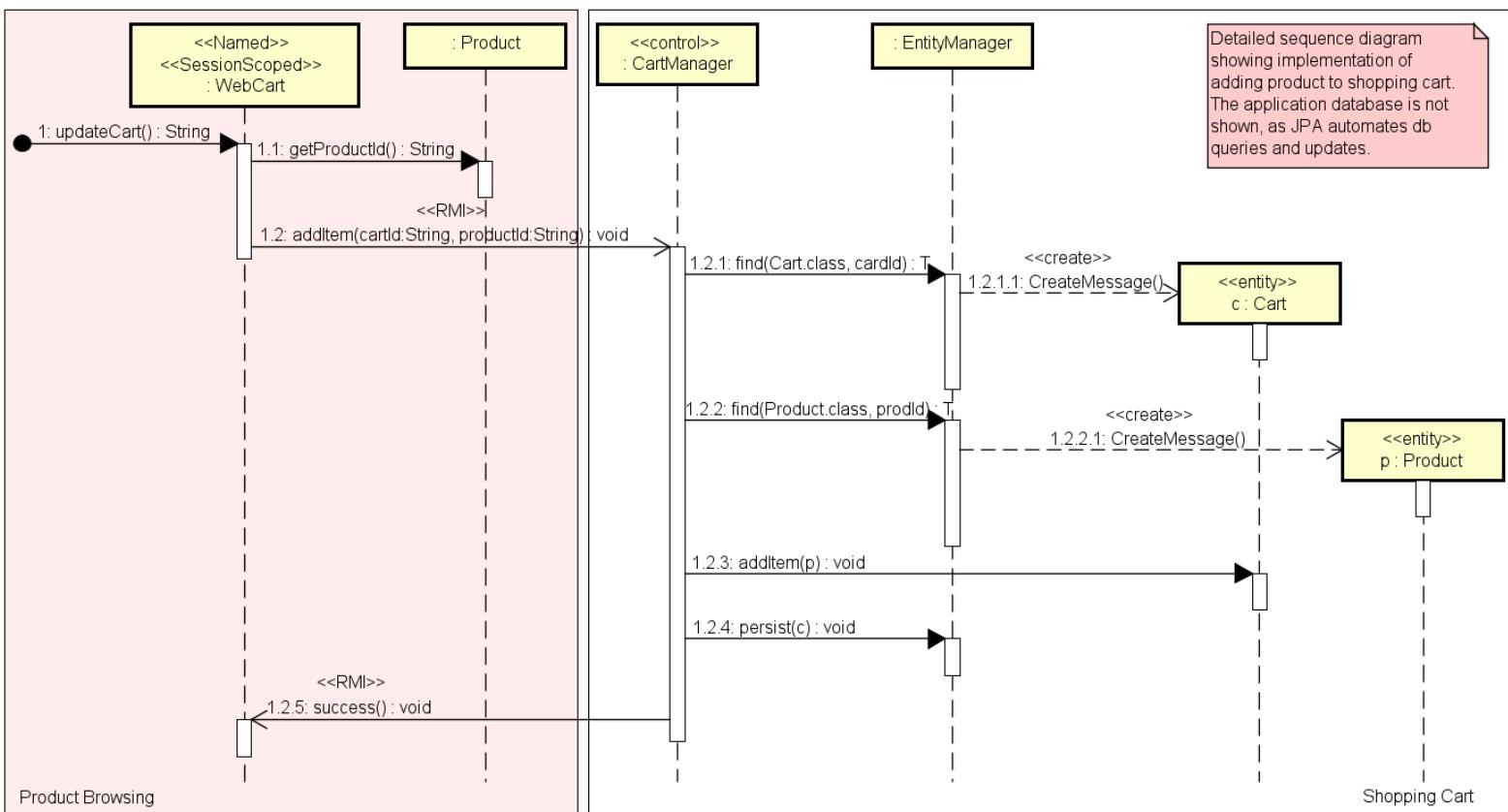


Figure 27: Example detailed sequence diagram showing the implementation of customer adding a product to their shopping cart.

Figure ?? is a detailed sequence showing how the class model in figure ?? implements the behaviour of a customer adding a product to their shopping cart. This is a more detailed, or code-level, view of the

scenario of adding a product to a customer's shopping cart shown in figure ???. You would only provide detailed behavioural diagrams to describe architecturally important details of the detailed design.

The scenario starts with the JSF session-scoped bean WebCart receiving the updateCart message from the browser. WebCart retrieves the product id and uses the ManageCart interface to send it, along with the cart id, to the Shopping Cart component in the application backend. The *ManageCart* interface is implemented by the *CartManager* class in the Shopping Cart component.

The *CartManager* uses the JPA EntityManager to retrieve the cart and product entities from the application database. Once the product is added to the cart, the EntityManager saves the updated cart details to the database. Upon successfully saving the updated cart, the *CartManager* notifies the *WebCart* object in the Product Browsing component in the web application.

3.6.2 Sequence Diagram Notation

Sequence diagrams are read from the top down. The top of the diagram represents the start of the scenario, and execution time progresses down the diagram. The bottom of the diagram is the end of the scenario. Duration constraints can be placed between messages indicating information like the maximum allowed time between the start and end of a message.

Rectangles with dashed lines descending from them are *lifelines*. They represent an instance of a participant in the scenario being described. The name at the top of a lifeline describes the participant. In figure ???, these are objects of classes from the detailed design. The class diagram in figure ?? shows the classes for the detailed design of the Shopping Cart component used in this scenario.

The horizontal lines are *messages* sent between participants. Messages use hierarchical numbers to indicate both nesting and sequence of messages. Message 1.1 is sent by message 1. Message 1.1.1 comes before message 1.1.2. Message 1 in figure ?? is a *found message*, meaning that the sender of the message is not shown in the diagram.

A closed arrowhead on a message (e.g. message 1.1) indicates that it is a synchronous message. An open arrowhead on a message (e.g. message 1.2) indicates that it is an asynchronous message. In figure ??, stereotypes have been placed on messages between containers (i.e. messages 1.2 and 1.2.5) to indicate the protocol used to send the message.

The vertical rectangles sitting on top of lifelines are *execution specifications*. They indicate when an instance is executing logic. For example, after the asynchronous message 1.2 is sent to the *CartManager* object, message 1 finishes executing. When the synchronous message 1.2.1 is sent to the EntityManager, message 1.2 is still active as it is waiting for message 1.2.1 to finish before message 1.2 can continue to the next part of the logic.

The «create» stereotype indicates when an instance is created. When an instance is created, its lifeline starts at the level of the sequence diagram that indicates the point in time when it is created. When an instance is destroyed, its lifeline finishes, with a large X. Lifelines that are at the top of the diagram indicate instances that existed before the start of the scenario. Lifelines that reach the bottom of the diagram indicate instances that still exist after the end of the scenario.

System boundary boxes in figure ?? indicate the components being implemented by the objects. The Product Browsing component is shaded in pink. The Shopping Cart component is white.

3.7 Deployment

While not one of the “four C's”, deployment diagrams are important for most systems. They describe the physical architecture or infrastructure on which the system will be deployed. It shows which containers will run on which computing platforms (*deployment nodes*). Deployment nodes can be nested, as shown in figure ???. They may also contain infrastructure nodes or software system instances⁴⁰.

⁴⁰<https://docs.structurizr.com/dsl/language#deploymentnode>

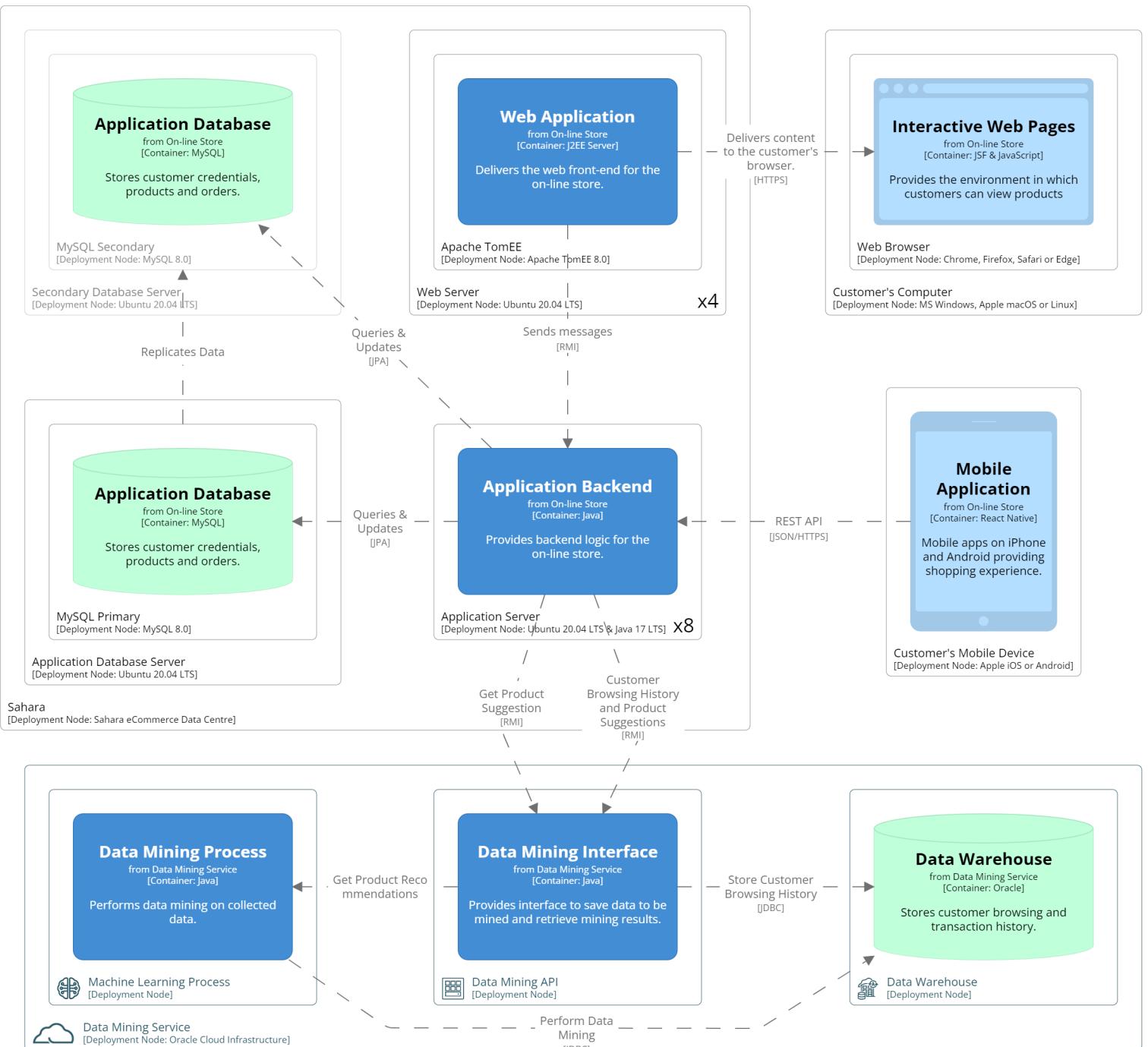


Figure 28: Deployment diagram for the Sahara eCommerce System.

Figure ?? is an example C4 deployment diagram for the Sahara eCommerce system. It shows that the on-line store software system runs in Sahara's data centre. The data mining service runs on Oracle's cloud infrastructure. This approach of a system that uses cloud services for some of its implementation is called a *hybrid cloud* application. There are also the apps running on mobile devices and the code running in the customer's browser.

A software environment is embedded in the hardware environment on which it runs. The web application runs in an [Apache TomEE⁴¹](https://tomee.apache.org/) J2EE server, which is running on a Ubuntu server. The “x4”⁴² inside the

⁴¹<https://tomee.apache.org/>

⁴²It is an unfortunate constraint of C4 that this must be an explicit number. That is fine for a system hosted on an organisation's own infrastructure, as they need to know how many servers need to be provisioned. If you are running virtual servers, this is less informative and does not clearly show capability of spinning up servers as needed, or spinning them down when not needed.

web server deployment node indicates that there will be four of these servers to share the load. The application backend runs on eight Ubuntu servers, providing the core business logic shared by the web and mobile applications.

The application database runs in MySQL on its own Ubuntu server. The application database is replicated on another server, allowing for failover. The application backend can continue to operate if the primary application database fails.

The application backend communicates with the data mining service through an API published by the data mining interface running in a virtual machine on Oracle's cloud infrastructure. The data mining service uses Oracle's machine learning services to perform the data mining. Oracle's cloud-based data warehouse infrastructure is used to hold all the data.

Figure ?? is the key describing the icons and colours used in the deployment diagram.



Figure 29: Deployment diagram key.

3.8 Delivering Architecturally Significant Requirements

In section ??, four ASRs were identified for the Sahara eCommerce system. These were the ability to continue shopping on different devices, scalability, robustness and availability.

Implementing shared logic on an application server, as shown in figure ??, enables the web and mobile applications to share common logic and state. This delivers the functionality of allowing a customer to start shopping on one device and to continue on another device. It also minimises duplication of logic, as it is shared by the frontend applications.

Using separate computing infrastructure for the web server, application server, application database, and data mining service, as shown in figure ??, provides more options to deliver scalability, robustness and availability. For scalability and performance, each computing environment can be optimised for the services it delivers. It also means that new infrastructure can be deployed to target specific bottlenecks. The system follows the *stateless architecture pattern*⁴³. The web and mobile applications do not store any

⁴³<https://www.redhat.com/en/topics/cloud-native-apps/stateful-vs-stateless>

application state (e.g. products currently stored in the shopping cart). Every time the customer performs a transaction (e.g. viewing product details or adding a product to their shopping cart), the web or mobile application sends a message to the application server to perform the action. The application server then saves or loads data to or from the application database.

This means that web and mobile applications can send messages to a different application server for each request. This facilitates scalability, robustness and availability. A new application server can be started to cater for increasing system load, or to replace a failed server. The stateless nature of the application server logic means that no data will be lost if a server fails, or if a frontend application accesses a different application server in the middle of a customer's shopping experience.

Having multiple application servers, web servers, and multiple application databases, means that if one server fails its load can be picked up by other servers. Automating the process of starting or restarting servers improves robustness and availability. Running the data mining service on Oracle's cloud infrastructure means that we can rely on their management of services to guarantee our required level of scalability and availability.

One challenge of a stateless architecture is providing a replicated database that contains up-to-date copies of the system's state. We will look at this issue later in the course.

By designing the architecture as a set of components running on different servers, it is also easier to migrate the application to cloud-based infrastructure. Figure ?? does not constrain the system to run on physical hardware hosted by Sahara eCommerce. Any of the nodes could be provisioned by a service offered by a cloud provider.

4 Tools

We will use C4 as our standard notation in this course, supplemented with UML diagrams when their level of detail is appropriate. C4 is popular because it has a basic structure, but the rules are intentionally loose to make it easy to adopt. You should use tools to aid the creation of your diagrams and documentation.

The important thing is that you should use a modelling tool, not a drawing tool. A few drawing tools provide C4 templates. The issue with drawing tools is that they do not know what the elements of the diagram mean. If a container name is changed in a drawing tool, you will need to manually change it wherever it is referenced in other diagrams. A modelling tool will track the information that describes the model, so that a change to a model element in one place, will be replicated wherever that element appears in other diagrams.

There are a few tools that support C4. Some to consider are [Structurizr⁴⁴](#), [C4-PlantUML⁴⁵](#), [Archi⁴⁶](#), [IcePanel⁴⁷](#), or [Gaphor⁴⁸](#).

Structurizr was developed by Simon Brown as a tool to support generating C4 diagrams from textual descriptions. UQ students may register for free access to the paid version of the [Structurizr Cloud Service⁴⁹](#). You must use your student.uq.edu.au or uq.net.au email address when you register to get free access. Structurizr is an [open source tool⁵⁰](#). You can use a [domain specific language⁵¹](#) to describe a C4 model, or you can embed the details in [Java⁵²](#) code.

C4-PlantUML extends the UML modelling tool PlantUML to support C4.

⁴⁴<https://www.structurizr.com/>

⁴⁵<https://github.com/plantuml-stdlib/C4-PlantUML>

⁴⁶<https://www.archimatetool.com/>

⁴⁷<https://icepanel.io/>

⁴⁸<https://gaphor.org/>

⁴⁹<https://structurizr.com/help/academic>

⁵⁰<https://github.com/structurizr/>

⁵¹<https://docs.structurizr.com/dsl/language>

⁵²<https://docs.structurizr.com/java>

Archi is an open source visual modelling tool that supports C4⁵³ and ArchiMate models.

IcePanel is a cloud-based visual modelling tool that supports C4. There is a limited free license for the tool.

Gaphor is an open source visual modelling tool that supports UML and C4.

4.1 Textual vs Visual Modelling

The tools described above include both graphical and textual modelling tools. Graphical tools, such as Archi and Gaphor, allow you to create models by drawing them. This approach is often preferred by visually oriented learners⁵⁴. Text-based tools, such as C4-PlantUML and Structurizr, allow you to create models by providing a textual description of the model. This approach is often preferred by read/write oriented learners⁵⁵.

Despite preferences, there are situations where there are advantages of using a text-based modelling tool. Being text, the model can be stored and versioned in a version control system (e.g. git). For team projects, it is much easier for everyone to edit the model and ensure that you do not destroy other team members' work. It is also possible to build a tool pipeline that will generate diagrams and embed them into the project documentation.

Text-based modelling tools, such as Structurizr or C4-PlantUML, use a domain specific language⁵⁶ (DSL) to describe the model. These tools require that you learn the syntax and semantics of the DSL. The following sources of information will help you learn the Structurizr DSL:

- language reference manual⁵⁷,
- language examples⁵⁸,
- on-line editable examples⁵⁹, and
- off-line tool⁶⁰.

4.2 Example Diagrams

You may find the Sahara eCommerce C4 model useful as an example of a number of features of the Structurizr DSL. You are able to download the C4 model of the Sahara eCommerce example, from the course website. The C4 model⁶¹ was created using the Structurizr⁶² DSL.

5 Software Architecture in Practice Views

The seminal architecture book, *Software Architecture in Practice* [?], categorises architectural views into three groups. These three groups each answer different questions about the architecture, specifically:

Module Views How implementation components of a system are structured and depended upon.

Component-and-connector Views How individual components communicate with each other.

Allocation Views How the components are allocated to personnel, file stores, hardware, etc.

⁵³<https://www.archimatetool.com/blog/2020/04/18/c4-model-architecture-viewpoint-and-archi-4-7/>

⁵⁴<https://vark-learn.com/strategies/visual-strategies/>

⁵⁵<https://vark-learn.com/strategies/readwrite-strategies/>

⁵⁶<https://opensource.com/article/20/2/domain-specific-languages>

⁵⁷<https://docs.structurizr.com/dsl/language>

⁵⁸<https://docs.structurizr.com/dsl/cookbook/>

⁵⁹<https://structurizr.com/dsl>

⁶⁰<https://github.com/structurizr/cli>

⁶¹https://csse6400.uqcloud.net/resources/c4_model.zip

⁶²<https://www.structurizr.com/>

5.1 Module Views

Module views are composed of modules, which are static units of functionality such as classes, functions, packages, or whole programs. The defining characteristic of a module is that it represents software responsible for some well-defined functionality. For example, a class which converts JSON to XML would be considered a module, as would a function which performs the same task.

The primary function of module views is to communicate the dependencies of a module. Rarely does software work completely in isolation, often it is constructed with implicit or explicit dependencies. A module which converts JSON to XML might depend upon a module which parses JSON and a module which can format XML. Module views make these dependencies explicit.

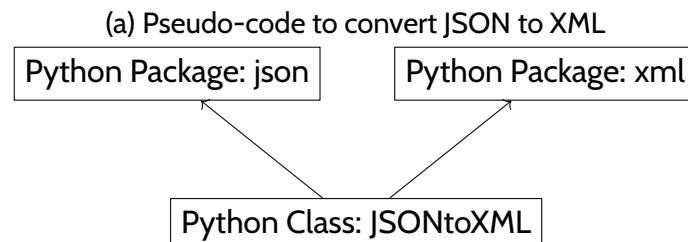
Module views focus on the developer's perspective of how the software is implemented, rather than how it manifests itself when deployed in a computing environment.

```
1 import json
2 import xml

4 class JSONtoXML:
5     def load(self, json_file):
6         with open(json_file) as f:
7             data = json.load(f)
8             self.data = self.convert(data)

10    def export(self, xml_file):
11        xml.write(xml_file, data)

13    def convert(self, data: JSON) -> XML:
14        ...
```



(b) An example of a module view which illustrates the dependencies of the `JSONtoXML` class

Figure 30: A simple module view of a JSON to XML program.

5.2 Component-and-Connector Views

Component-and-connector views focus on the structures that deliver the runtime, or dynamic behaviour of a system. Components are units which perform some computation or operation at runtime. These components could overlap with the modules of a module view but are often at a higher level of abstraction. The focus of component-and-connector views is how these components communicate at runtime. Runtime communication is the connector of components. For example, a service which registers users to a website might have new registrations communicated via a REST request. The service may then communicate the new user information to a database via SQL queries.

When we look at software architecture, component-and-connector views are the most commonly used views. They are common because they contain runtime information which is not easily automatically extracted. Module views can be generated after the fact, i.e. it is easy enough for a project to generate a UML class diagram. (Simple tools will create an unreadably complex class diagram. Tagging important information in the source code, or manually removing small details is required to end up with readable diagrams.) Component-and-connector views are often maintained manually by architects and developers.

5.3 Allocation Views

According to Bass et al, allocation views map the software's structures to the system's non-software structures [?]. They include concepts such as who is developing which software elements, where are source files stored for different activities such as development and testing, and where are software elements executed. The first two points are important for project management and build management. The last point of how the software is executed on different processing nodes is important for architectural design. This is sometimes called the *deployment structure* or the software system's *physical architecture*.

Understanding the physical architecture (simplistically the hardware⁶³ on which the software is executed) is important when designing the software's *logical architecture*. Component-and-connector views describe the software's logical architecture. This design of the logical architecture must contain components that can be allocated appropriately to processing nodes, and these nodes must have communication links that enable the components to interact.

6 4+1 Views

Philippe Kruchten was one of the earliest to advocate the idea of using views to design and document software architectures. In “4+1 View Model of Software Architecture” [?] he describes five different views. These are logical, process, development, physical, and scenario views, which are summarised below.

Logical How functionality is implemented, using class and state diagrams.

Process Runtime behaviour, including concurrency, distribution, performance and scalability. Sequence, communication and activity diagrams are used to describe this view.

Development The software structure from a developer's perspective, using package and component diagrams. This is also known as the implementation view.

Physical The hardware environment and deployment of software components. This is also known as the deployment view.

Scenario The key usage scenarios that demonstrate how the architecture delivers the functional requirements. This is the '+1' view as it is used to validate the software architecture. This is also known as the use case view, as high-level use case diagrams are used to outline the key use cases and actors. A high-level use case diagram provides contextual information, similar to the intent of the C4 context diagram. A use case diagram allows more information to be conveyed and if it is supported with activity diagrams, it provides a significant amount of information that can be used to validate the architecture.

The experience which led to the development the 4+1 View Model was developing the air traffic control management system for Canada. The system provides an integrated air traffic control system for the entire Canadian airspace. This airspace is about double the size of the Australian airspace and borders the two busiest airspaces in the world. The project's architecture was designed by a team of three people led

⁶³Whether it is virtualised or physical hardware

by Philippe. Development was done by a team of 2500 developers from two large consulting companies. The project was delivered on-time and on-budget, with three incremental releases in less than three years⁶⁴. This project also developed many of the ideas that led to the Rational Unified Process [?].

7 Conclusion

Architectural views help developers understand different dimensions and details of a complex software architecture. They are useful both during design and as documentation. During design, views help you to focus on a particular aspect of the software architecture and ensure that it will allow the system to deliver all of its requirements. As documentation, views help developers to understand how different aspects of the architecture are intended to behave.

We have intentionally looked at a few different approaches to helping you describe a software architecture. You should be conversant with multiple different approaches. The hallmark of a professional is to know when to select a particular approach.

If you compare the “4+1 View Model” [?] with the views described in *Software Architecture in Practice* (SAP) [?], you will see that there are obvious similarities but also some differences. The logical, development and process views from the 4+1 view model map closely to the module and component-and-connector (C&C) views from SAP. The physical view corresponds to the allocation view. The 4+1 view model also includes the scenario view, which does not correspond directly to the SAP views.

The scenario view is used to demonstrate how the architecture described in the other views delivers the core functional requirements. It is used while designing a software architecture to validate that it is suitable for the system.

Kruchten intentionally separated the process view from the logical and development views, rather than bundling them together like the C&C view in SAP. This is because for some systems the dynamic details, which are described by the process view, can be complex and important. Dealing with issues such as complex concurrency, real-time interactions or latency, can often be more easily considered by having a separate view for them.

Kruchten’s experience with Canada’s integrated, nation-wide, air traffic control system was such a case. Data from radar systems and aircraft transponders have to be processed and reported to air traffic controllers in near real-time. With thousands of input sources and hundreds of controller stations, understanding concurrency issues is critical. Tracking aircraft from one control space to another means that communication latency is important. Each control space has its own hardware and is separated from neighbouring spaces by hundreds or thousands of kilometres.

The C4 model does not explicitly include the concept of views. Like SAP, it emphasises the structure of the software architecture, adding a hierarchical lens in its structural view. These diagrams map to the 4+1 logical and development views and the SAP module and C&C views. Its behavioural view maps to aspects of the 4+1 process view. Its infrastructure view maps to the 4+1 physical view and the SAP allocation view.

As a software architect you need to choose which views provide meaningful information about your software system. The graphical notation used to describe a view is only one part of the view (though an important part). Ensure you provide enough supporting information so others will know how to work with your architecture and why you made the choices that you did.

⁶⁴Contrast this to the United States Federal Aviation Administration’s Advanced Automation System project from a similar era. The original estimate was \$2.5 billion and fourteen years to implement. The project was effectively cancelled after twelve years. By then the estimate had almost tripled and the project was at least a decade behind schedule [?].

Architectural Decision Records

Software Architecture

February 24, 2025

Richard Thomas

1 Introduction

Documenting reasons why a decision was made about some aspect of the software architecture is important for the long-term maintainability of the system. Architecture decision records (ADR) are a simple but informative approach to documenting these reasons.

Michael Nygard was one of the early proponents of ADRs. His argument is that no one reads large documents but not knowing the rationale behind architecturally important decisions can lead to disastrous consequences, when later decisions are made that defeat the earlier decisions [?]. Nygard created ADRs as a light-weight approach to documenting important architecture decisions, to suit agile development processes. The ideas were based on Philippe Kruchten's discussion of the importance of architecture decisions in his article "The Decision View's Role in Software Architecture Practice" [?]. In this article Kruchten discusses extending his "4+1 View Model of Software Architecture" [?] to capture the rationale for important decisions while designing each view of the architecture.

Architecture decision records should capture important decisions that are made about the design of the architecture. These include decisions that influence the

- structure of the architecture,
- delivery of quality attributes,
- dependencies between key parts of the architecture,
- interfaces between key parts of the architecture or external interfaces, and
- implementation techniques or platforms.

These decisions provide important information for developers who have to work with the architecture, so that they know why decisions have been made and know how to design their code to fit into the architecture. They also provide important information for those who have to maintain the software in the future. ADRs help maintainers to know why decisions were made, so that they do not inadvertently make decisions that result in breaking expectations about the software.

ADRs are short notes about a single decision. The intent is to make it easy to record the information about the decision, so that it is more likely to be documented. ADRs are usually kept with the key project documentation. The argument is often made that this should be within the version control system (e.g. git) holding the project's source code. For example, a directory `doc/architecture/adr` in the project repository to contain the ADRs. The C4 model recommends you create a directory in the project repository to hold the C4 diagrams with a subdirectory for documentation, and another subdirectory for ADRs (e.g. `c4_model`, `c4_model/docs` and `c4_model/adrs`). Note that the C4 modelling tools do not like having the subdirectory containing the ADRs within the documentation subdirectory.

Each ADR is written in a separate file, using a simple notation like markdown. The file names are numbered so the history of decisions can be viewed. It is recommended that the file name describe the decision, to make it easier to scan for information about specific types of architectural decisions. Examples of meaningful file names include:

- `0001-independent-business-logic.md`
- `0002-implement-JSF-webapp.md`
- `0003-choose-database.md`

The directory containing these ADR files is the history of all architectural decisions made for the project.

2 Template

There are a few templates available to help provide consistent formatting of an ADR. The recommended template format contains the following sections.

Title Short phrase that describes the key decision.

Date When the decision was made.

Status Current status of the decision (i.e. proposed, accepted, deprecated, superseded or rejected).

Summary Summarise the decision and its rationale.

Context Describe the facts that influence the decision. State these in value-neutral language.

Decision Explain how the decision will solve the problem, in light of the facts presented in the context.

Consequences Describe the impact of the decision. What becomes easier and harder to do? There will be positive, neutral and negative consequences, identify all of them.

3 ADR Example

The following is an example ADR from the Sahara eCommerce application from section 3 of the *Architectural Views* notes.

1. Independent Business Logic

Date: 2023-01-06

Status: Accepted

Summary

In the context of delivering an application with multiple platform interfaces, facing budget constraints on development costs, we decided to implement all business logic in an independent tier of the software architecture, to achieve consistent logical behaviour across platforms, accepting potential complexity of interfaces to different platforms.

Context

- The system is to have both mobile and web application frontends.
- Marketing department wants a similar user experience across platforms.
- Delivering functional requirements requires complex processing and database transactions.
 - Product recommendations based on both a customer's history and on purchasing behaviour of similar customers.
 - Recording all customer interactions in the application.
- Sales department wants customers to be able to change between using mobile and web applications without interrupting their sales experience.
- Development team has experience using Java.

Decision

All business logic will be implemented in its own tier of the software architecture. Web and mobile applications will implement the interaction tier. They will communicate with the backend to perform all logic processing. This provides clear separation of concerns and ensures consistency of business logic across frontend applications. It means the business logic only needs to be implemented once. This follows good design practices and common user interface design patterns.

The business logic will be implemented in Java. This suits the current development team's experience and is a common environment. Java has good performance characteristics. Java has good support for interacting with databases, to deliver the data storage and transaction processing requirements.

Consequences

Advantages

- Separation of concerns, keeping application logic and interface logic separate.
- Ensures consistency, if business logic is only implemented in one place.
- Business logic can execute in a computing environment optimised for processing and transactions.
 - Also makes load balancing easier to implement.

Neutral

- Multiple interfaces are required for different frontend applications. These can be delivered through different Java libraries.

Disadvantages

- Additional complexity for the overall architecture of the system.

4 Quality

A well written ADR explains the reasons for making the decision, while discussing pros and cons of the decision. In some cases it is helpful to explain reasons for not selecting other seemingly good options. The ADR should be specific about a single decision, not a group of decisions.

The context should provide all the relevant facts that influence the decision. The decisions section should explain how business priorities or the organisation's strategic goals influenced the decision. Where the team's membership or skills has influenced the decision, these should be acknowledged. All consequences should be described. These may include decisions that need to be resolved later or links to other ADRs that record decisions that were made as a result of this decision.

The summary follows the format of a Y-statement [?]. It includes key information about the decision for quick consumption, leaving the details for the rest of the ADR. The template for a Y-statement is:

*In the context of functional requirement or architecture characteristic,
facing non-functional requirement or quality attribute,
we decided selected option,
to achieve benefits,
accepting drawbacks.*

The Y-statement can be expanded to include **neglected alternative options** after the **we decided** clause. A **because** clause providing **additional rationale** can be added to the end of the statement. Some teams use this expanded form of the Y-statement as the complete ADR for simple decisions.

ADRs should be reviewed after about one month. Consider how the consequences have played out in reality. Revise bad decisions before too much has been built based on the decision. The ADR may need to be updated to include any consequences that have been uncovered in practice.

ADRs should be immutable. Do not change existing information in an ADR. An ADR can have new information added to it, like adding new consequences. If the decision needs to be changed, create a new ADR. The original ADR should have its status changed to *deprecated*, and then *superseded* once the new decision is accepted and put into practice. Add a link in the original ADR to the new ADR, and the new ADR should link back to the original.

Sometimes an ADR is not superseded by a new ADR, instead it is extended or amended by another ADR. In these cases, the original ADR still has an *accepted* status but a link is added indicating the other ADR that amends or extends the original ADR. The new ADR then includes a link back to the original ADR, indicating that the new ADR extends or amends the original.

5 What to Put in an ADR?

Only document important decisions that affect the architecture's structure, non-functional characteristics, dependencies, interfaces, or construction techniques. Michael Nygard calls these "architecturally significant" decisions [?]. The types of decisions that usually should be documented are:

- Critical or important to delivering system functionality.
- Helps deliver important quality attributes.
- Unconventional or risky approach to a solution.
- Has expensive consequences.
- Has long lasting effects or will affect a large part of the design.
- Will affect a large number of stakeholders or an important stakeholder.
- Took a long time or significant effort to decide.
- Unexpected decisions that were required late in the project. These may also be important learning experiences.

6 Conclusion

Decisions that affect the software architecture need to be recorded for reference in the future. In a large project it is not possible for everyone to be aware of every decision that is made. ADRs provide a mechanism for team members to find reasons for decisions to help them understand how to work within its constraints. ADRs give new team members a starting point to learn about the architecture and understand how it evolved into its current state. They also provide a reminder for yourself when you are wondering why you did something a particular way, or when you need to explain your decision to someone else, months after you made the decision.

The takeaway is, write an ADR whenever you make an important decision. You, or a colleague, will need to refer to it at some point in the future. Eli Perkins has a good summary of why you should write ADRs at the [GitHub Blog⁶⁵](#) [?].

⁶⁵<https://github.blog/2020-08-13-why-write-adrs/>

Pipeline Architecture

Software Architecture

March 3, 2025

Brae Webb & Richard Thomas

1 Introduction

Pipeline architectures take the attribute of modularity of a system to the extreme. Pipeline architectures are composed of small well-designed components which can ideally be combined interchangeably. In a pipeline architecture, input is passed through a sequence of components until the desired output is reached. Almost every developer will have been exposed to software which implements this architecture. Some notable examples are bash, hadoop, some older compilers, and most functional programming languages.

Definition 11. Pipeline Architecture

Components connected in such a way that the output of one component is the input of another.



Figure 31: An example of using bash's pipeline architecture to perform statistical analysis.

The de-facto example of a well-implemented pipeline architecture is bash, we will explore the philosophy that supports the architecture shortly. The above diagram represents the bash command,

```
$ cat assignment.py | grep "f***" | wc -l | tee anger.txt
```

If you are unfamiliar with Unix processes (start learning quick!).

cat Send the contents of a file to the output.

grep Send all lines of the input matching a pattern to the output.

wc -l Send the number of lines in the input to the output.

tee Send the input to stdout and a file.

2 Terminology

As illustrated by Figure ??, a pipeline architecture consists of just two elements;

Filters modular software components, and

Pipes the transmission of data between filters.

Filters themselves are composed of four major types:



Figure 32: A generic pipeline architecture.

Producers Filters from which data originates are called producers, or source filters.

Transformers Filters which manipulate input data and output to the outgoing pipe are called transformers.

Testers Filters which apply selection to input data, allowing only a subset of input data to progress to the outgoing pipe are called testers.

Consumers The final state of a pipeline architecture is a consumer filter, where data is eventually used.

The example in Figure ?? shows how bash's pipeline architecture can be used to manipulate data in Unix files. Figure ?? labels the bash command using the terminology of pipeline architectures.



Figure 33: Figure ?? with labelled filter types.

3 Pipeline Principles

While the concept of a pipeline architecture is straightforward, there are some principles which should be maintained to produce a well-designed and re-usable architecture.

Definition 12. One Direction Principle

Data should flow in one direction, this is *downstream*.

The data in a pipeline architecture should all flow in the same direction. Pipelines should not have loops nor should filters pass data back to their *upstream* or input filter. The data flow is allowed to split into multiple paths. For example, figure ?? demonstrates a potential architecture of a software which processes the stream of user activity on a website. The pipeline is split into a pipeline which aggregates activity on the current page and a pipeline which records the activity of this specific user.

The One Direction Principle makes the pipeline architecture a poor choice for applications which require interactivity, as the results are not propagated back to the input source. However, it is a good choice when you have data which needs processing with no need for interactive feedback.

Definition 13. Independent Filter Principle

Filters should not rely on specific upstream or downstream components.

In order to maintain the reusability offered by the pipeline architecture, it is important to remove dependencies between individual filters. Where possible, filters should be able to be moved freely. In the example architecture in figure ??, the EventCache component should be able to work fine without the Tag-Time component. Likewise, EventCache should be able to process data if the Anonymize filter is placed before it.



Figure 34: Pipeline architecture for processing activity on a website for later analytics.

Producers and consumers may assume that they have no upstream or downstream filters respectively. However, a producer should be indifferent to which downstream filter it feeds into. Likewise a consumer should not depend on the upstream filter.

Corollary 1. Generic Interface

The interface between filters should be generic.

Corollary ?? follows from definition ???. In order to reduce the dependence on specific filters, all filters of a system should implement a generic interface. For example, in bash, filters interface through the piping of raw text data. All Unix processes should support raw text input and output.

Corollary 2. Composable Filters

Filters (i.e. Transformers & Testers) can be applied in any order.

Corollary ?? also follows from definition ???. If filters are independent they can be linked together in any order. This means that a software designer can deliver different behaviour based on the order in which filters are linked. For example, in bash, applying a tester before or after a transformer can lead to different results.

4 Conclusion

A pipeline architecture is a good choice for data processing when interactivity is not a concern. Conceptually pipelines are very simple. Following the principles of a pipeline architecture will deliver a modular system which supports high reuse.

Containers

Software Architecture

March 10, 2025

Brae Webb

I don't care if it works on your machine! We are not shipping your machine!

– Vidiu Platon

1 Introduction

As developers, we often find ourselves relying on some magical tools and technologies. Version control, operating systems, databases, and containers, to name a few. Containers, and specifically, Docker, are magical tools which have gained wide-spread industry adoption. Over the past decade Docker has enabled some fanciful architectures and developer workflows. Docker is the proposed solution to the age-old programmer proverb, “it works on my machine!”. However, before we subscribe to that belief, let’s see how Docker actually works to learn what it is, and what it is not.

2 History and Fundamentals

Relative to other tools in the magical suite, Docker is new on the scene. Docker was first made available publicly in 2013 at PyCon.⁶⁶ Pitched to deliver the isolation benefits of Virtual Machines (VMs) while maintaining efficient execution. Virtual machines themselves are a much older invention, dating back to the 1960s, around the time that UQ was having its first computer installed.⁶⁷ The concept of a virtual machine, unlike its implementation, is straight-forward — use software to simulate hardware. From there, one can install an operating system on the simulated hardware and start using a completely isolated, completely new computer without any additional hardware. Of course, this process puts great strain on the real hardware and as such, VMs are deployed sparingly.

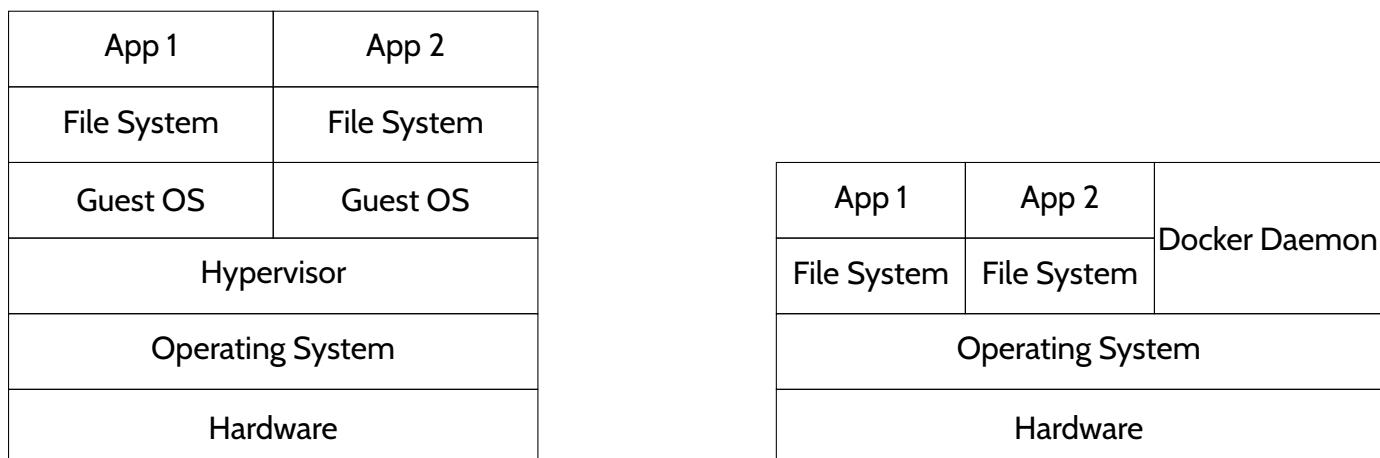


Figure 35: Comparison of virtual machines and containers

Unlike virtual machines, containers do not run on virtual hardware, instead, containers run on the operating system of the host machine. The obvious advantage of this is containers run much more efficiently

⁶⁶<https://www.youtube.com/watch?v=wW9CAH9nSLs>

⁶⁷<https://www.youtube.com/watch?v=DB1Y4GrfrZk>

than virtual machines. Containers however, manage to remain isolated and it is at this point that we should explain how Docker actually works. Docker is built upon two individually fascinating technologies; namespaces, and layered filesystems.

2.1 Namespaces

The first technology, namespaces, is built into the Linux kernel. Linux namespaces were first introduced into the kernel in 2002, inspired by the concept introduced by the Plan 9⁶⁸ operating system from Bell Labs in the 1980s. Namespaces enable the partitioning and thus, isolation, of various concepts managed and maintained by an operating system. Initially namespaces were implemented to allow isolated filesystems (the so-called ‘mount’ namespace). Eventually, as namespaces were expanded to include process isolation, network isolation, and user isolation, the ability to mimic an entirely new isolated machine was realised; containers were born.⁶⁹

Namespaces provide a mechanism to create an isolated environment within your current operating system. The creation of such an isolated environment with namespaces has been made quite easy — you can create an isolated namespace with just a series of bash commands. Niklas Dzösch’s talk ‘Docker without Docker’, uses just 84 lines of Go code (which Docker itself is written in), to create, well, Docker without Docker.⁷⁰ But namespaces are just the first technology which enables Docker. How do you pre-populate these isolated environments with everything you need to run a program? To see what is in the isolated environment, we would run `ls` which, oh, requires the `ls` binary. Furthermore, to even consider running a command we need a shell to type it in, so, oh, we should also have a `bash` binary. And so on until, oh, finally, we have a Linux kernel at least!⁷¹

2.2 Layered Filesystem

A core principle of Unix operating systems is that everything is a file. Naturally then, if we want to start using an isolated environment, all we need to do is copy in all the files which together form an operating system, right? Well, yes, kind of. In principle this is all you need do but this would hardly enable the popularity Docker enjoys today.

Say that you want to send your coworker a Docker container which has nginx (a tool for routing web traffic) setup in just the way you need to pass incoming traffic to various components of your application. Let’s assume that you have setup nginx in Ubuntu. All you would need to do is zip up all the files which compose the Ubuntu operating system (an impressively small 188MB), then all the files installed by nginx (about 55MB) and finally all the configuration files which you have modified, somewhere in the order of 1000 bytes or 1 KB. In total you are sending your coworker about 243MBs worth of data, less than a gigabyte, so they are not too upset.

Now once we have finished developing our application and we are ready to package it up and send it to the world. Rather than trying to support every known operating system, we bundle all our services in Docker containers, one for nginx, one for mysql, one for our web application, etc, etc. If your application’s containers are as popular as nginx, this means one *billion* downloads of your container. At a size of 243MBs, you have contributed 243 *petabytes* to the world’s collective bandwidth usage, and that is just your nginx container.

Docker’s success over other containerisation applications comes from the way it avoids this looming data disaster. A concept known as the layered, or overlayed, or the stacked filesystem solves the problem. First proposed in the early 1990s, layered filesystems enable layers of immutable files to be stacked below

⁶⁸<https://p9f.org/>

⁶⁹Of course, containers in a rudimentary form existed before introduction to the linux kernel but we have to start somewhere. <https://blog.aquasec.com/a-brief-history-of-containers-from-1970s-chroot-to-docker-2016>

⁷⁰https://www.youtube.com/watch?v=7H_eF6hvWg

⁷¹You might be asking yourself, wait but I have a Windows operating system and I can still run Docker, what gives? The answer, ironically enough, is a virtual machine!

a top-level writable system. This has the effect of producing a seemingly mutable (or writable) filesystem while never actually modifying the collection of immutable files. Whenever a immutable file is ‘written to’, a copy of the file is made and all modifications are written to this file. When reading or listing files, the filesystem overlays the layers of immutable files together with the layer of mutable files. This gives the appearance of one homogeneous filesystem.

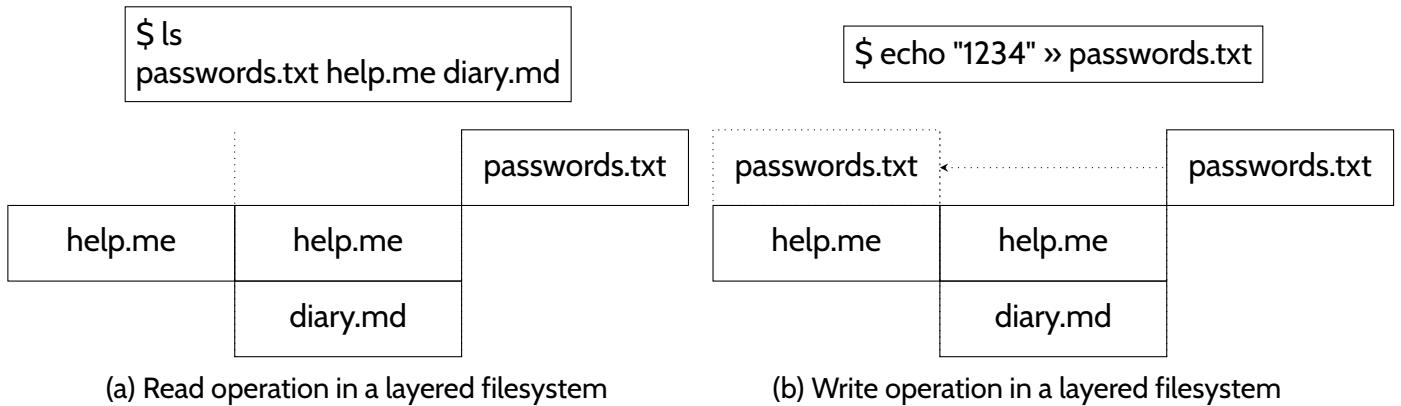


Figure 36: Read and write operations in a layered filesystem. The leftmost column in each diagram represents the most recent ‘writable’ layer.

Docker uses this technique to reduce the amount of duplicated files. If you have Docker containers which run nginx, MySQL, and Python but all containers run on Ubuntu, then your computer will only need to store one copy of the Ubuntu filesystem. Each container will store the changes to the base operating system required to install each application and project that layer over the immutable Ubuntu filesystem.

2.3 Summary

While Docker itself only came out in 2013, the two primary technologies which it is composed of, namespaces and the layered filesystem, were around since the early 1990s. Docker combines these technologies to enable applications to run in an isolated environment which can be efficiently replicated across different host computers. The reproducibility of Docker containers, and the fact that they are so light weight, makes them an ideal target for two important aspects of modern development; developers simulating production environments locally, and duplicating production machines to scale for large loads of traffic.

3 Docker FROM scratch

Now that we understand the fundamentals of how Docker works, let’s start building our very first Docker container. To follow along, you will need to have Docker installed on your computer⁷² and have access to basic Unix command line applications.⁷³

To start with, we will write a Dockerfile which builds a Docker image without an operating system and just prints ‘Hello World’ [?]. The Docker ‘code’ is written in a Dockerfile which is then ‘compiled’ into a Docker image and finally run as a Docker container. The first command in your Dockerfile should always be FROM. This command tells Docker what immutable filesystem we want to start from, often, this will be your chosen operating environment. In this exercise, since we do not want an operating system, we start with FROM scratch, a no-op instruction that tells Docker to start with an empty filesystem.

Let’s get something in this container. For this, we will use the COPY command which copies files from the host machine (your computer) into the container. For now, we will write COPY hello-world /, which says

⁷²<https://docs.docker.com/get-docker/>

⁷³For windows users, we recommend Windows Subsystem for Linux.

to copy a file from the current directory named `hello-world` into the root directory (/) of the container. We do not yet have a `hello-world` file but we can worry about that later. Finally, we use the `CMD` command to tell the container what to do when it is run. This should be the command which starts your application.

```
1 FROM scratch
2 COPY hello-world /
3 CMD ["/hello-world"]
```

Next, we will need a minimal hello world program. Unfortunately, we will have to use C here as better programming languages have a bit too much overhead. For everyone who has done CSSE2310, this should be painfully familiar, create a `main` function, print hello world, with a new line, and return 0.

```
1 #include <stdio.h>
2
3 int main() {
4     printf ("Hello World\n");
5     return 0;
6 }
```

Let's try running this container.

Hint

Try to guess if this is going to work. Why? Why not?

First, the hello world program needs to be compiled into a binary file.

```
1 >> gcc -o hello-world hello-world.c
2 >> ls
3 Dockerfile hello-world hello-world.c
```

Next we will use the `Dockerfile` to build a Docker image and run that image. Images are stored centrally for a user account so to identify the image, we need to tag it when it is built, we will use 'hello'.

```
1 >> docker build --tag hello .
2 >> docker run hello
3 standard_init_linux.go:228: exec user process caused: no such file or
   directory
```

Unless this is Docker's unique way of saying hello world, something has gone terribly wrong. Here we are illustrating the power of Docker isolation as well as the difficulty of not having an operating system. This very simple hello world program still relies on other libraries in the operating system, libraries which are not available in the empty Docker container. `ldd` tells us exactly what `hello-world` depends on. The hello world program can be statically compiled so that it does not depend on any libraries [?].

```
1 >> ldd hello-world
2     linux-vdso.so.1 (0x00007ffc51db1000)
3     libc.so.6 => /lib/x86_64-linux-gnu/libc.so.6 (0x00007fcff8553000)
4     /lib64/ld-linux-x86-64.so.2 (0x00007fcff8759000)
5 >> gcc -o hello-world hello-world.c -static
6 >> ldd hello-world
7     not a dynamic executable
8 >> docker build --tag hello .
9 >> docker run hello
10 Hello World
```

Now we have a Docker image built from scratch, without an operating system, which can say 'Hello World'!

If you are interested in exploring in more depth, try using the 'docker image inspect hello' and 'docker history hello' commands.

Microkernel Architecture

Software Architecture

March 10, 2025

Richard Thomas

1 Introduction

The microkernel architecture aims to deliver sophisticated software systems while maintaining the quality attributes of simplicity and extensibility. This is achieved by implementing a simple core system that is extended by plug-ins that deliver additional system behaviour. Microkernel is also known as a “plug-in” architecture.

Many common applications use the microkernel architecture. Web browsers, many IDEs (notably Eclipse), Jenkins, and other tools all use this architecture. They deliver their core functionality and provide a plug-in interface that allows it to be extended. Eclipse⁷⁴ is famous for being a simple editor that can be extended to become a sophisticated software development tool through its plug-in interface.

Definition 14. Microkernel Architecture

A core system providing interfaces that allow plug-ins to extend its functionality.



Figure 37: Generic structure of the microkernel architecture.

For example, a web browser provides the core behaviour of rendering web pages. Plug-ins extend the browser with specialised behaviour, such as a PDF viewer or dark mode reader.

2 Terminology

The microkernel architecture consists of four elements. The *core system*, *plug-ins* and *plug-in interface* shown in figure ??, plus a *registry*.

Core system implements the system's base functionality.

Plug-ins extend the system by providing independent, specialised behaviour.

Plug-in interface describes how the core system and plug-ins interact.

Registry tracks which plug-ins are available to the core system and how to access them.

⁷⁴<https://www.eclipse.org/downloads/packages/>

The core system implements the minimal functionality that provides the base, or framework, of the system. This may be the core functionality of the system, like the Eclipse editor or a web browser's page rendering engine. Alternatively, the core system may implement a general processing path, like a payroll system's payment process.

The payment process may be simply, identify an employee, calculate their fortnightly pay, and send payment to their bank account. Calculating pay can be a very complex process⁷⁵. There are different pay rates, bonuses, incentives, salaried staff, staff paid commission, staff paid hourly rates, overtime rates, penalty rates, deductions, taxes, and many other pay related calculations to consider for each individual.

Plug-ins are independent components that extend the behaviour of the core system. The simple approach is that the system is delivered as a monolith, including the core system and the plug-ins. In this case the core system uses the plug-ins via a method invocation.

In the payroll example, plug-ins can remove the complexity of different pay adjustment calculations from the core system by moving each calculation to a separate component. This also improves extensibility, maintainability and testability of the system. New calculations can be added to the system by implementing new plug-ins. As each plug-in is independent of the others, it is easier to implement a new calculation, or change an existing one, than trying to do so in a large monolith. New plug-ins can be tested independently and then integrated into the system for system testing.

There is usually a single standard interface between the core system and the plug-ins for a domain. The interface defines the methods that the core system can invoke, data passed to the plug-in, and data returned from the plug-in. A plug-in component implements the interface and delegates responsibilities within the component to deliver its behaviour.

Figure ?? is an example of a possible interface for the pay adjustment calculation plug-ins. Each pay adjustment plug-in returns a `MonetaryAmount` indicating the amount by which the employee's base pay is to be adjusted in the pay period. The amount may be positive or negative. The `employee`, `periodDetails`, `employeeConditions` and `basePay` objects are passed as parameters to the plug-in. The plug-in can request the data it needs from these objects to perform its calculation. The `periodDetails` object provides data about the work performed by the employee during the pay period (e.g. time worked, overtime, higher duties adjustments, ...). The `employeeConditions` set provides data about each of the employee's pay conditions (e.g. before tax deductions, union membership, ...).

```
1 public interface PayAdjustmentPlugin {  
2     public MonetaryAmount adjustPay(Employee employee,  
3                                         WorkDetail periodDetails,  
4                                         Set<Condition> employeeConditions,  
5                                         MonetaryAmount basePay);  
6 }
```

Figure 38: Example plug-in interface for payroll system.

The registry records which plug-ins are available to the core system and how they are accessed. For the simple case of plug-ins being used by method invocation, the registry just needs to record the name of the plug-in and a reference to the object that implements the plug-in's interface. For the payroll example, this could be a simple map data structure. The core system could lookup a plug-in by its name and then apply it by invoking the `adjustPay` method on the plug-in object.

⁷⁵See the Queensland Health payroll disaster

<https://www.henricodolfing.com/2019/12/project-failure-case-study-queensland-health.html>

3 Microkernel Principles

While the concept of a microkernel architecture is straightforward, there are some principles which should be maintained to produce a maintainable and extendable architecture.

Definition 15. Independent Plug-in Principle

Plug-ins should be independent, with no dependencies on other plug-ins. The only dependency on the core system is through the plug-in interface.

Plug-ins should be independent of each other. If a plug-in depends on other plug-ins it increases the complexity of the design. This complexity is called *coupling*⁷⁶, which is a measure of how dependent different parts of a system are on each other [?]. High coupling (many dependencies) makes it difficult to understand the software, which in turn makes it difficult to modify and test the software. Consequently, if a plug-in depends on other plug-ins it requires understanding the dependencies on the other plug-ins to modify or test the plug-in. This can lead to an architecture that resembles a “big ball of mud”.

Plug-ins and the core system should be *loosely coupled*. The core system should only depend on the plug-in interface and data returned via that interface, not any implementation details of individual plug-ins. Plug-ins should only depend on the data passed to them via the plug-in interface. Plug-ins should not rely on implementation details of the core system, nor its datastore. If plug-ins and the core system are not isolated from each other by an interface, then any changes to the core system may require changes to some or all of the plug-ins. Similarly, the plug-in interface should mean that any changes to the plug-in will have no impact on the core system.

Definition 16. Standard Interface Principle

There should be a single interface that defines how the core system uses plug-ins.

To provide an extensible design, the core system needs a standard way to use plug-ins. This means that the plug-in interface needs to be the same for all plug-ins. That way the core system can use any plug-in without needing to know details about how the plug-in is implemented. This again is about reducing coupling between the core system and the plug-ins. The standard interface principle means that there is no additional complexity if the core system uses two plug-ins or two thousand plug-ins.

4 Architecture Partitioning

4.1 Technical Partitioning

The course notes about layered architecture [?] described the idea of partitioning an architecture into layers, as in figure ??.

This approach to partitioning the architecture is called *technical partitioning*. Each layer represents a different technical capability. The presentation layer deals with user interaction. The business layer deals with the application's core logic. The persistence layer deals with storing and loading data. The database layer deals with file storage and access details.

An advantage of technical partitioning is that it corresponds to how developers view the code. Another advantage is that all related code resides in a

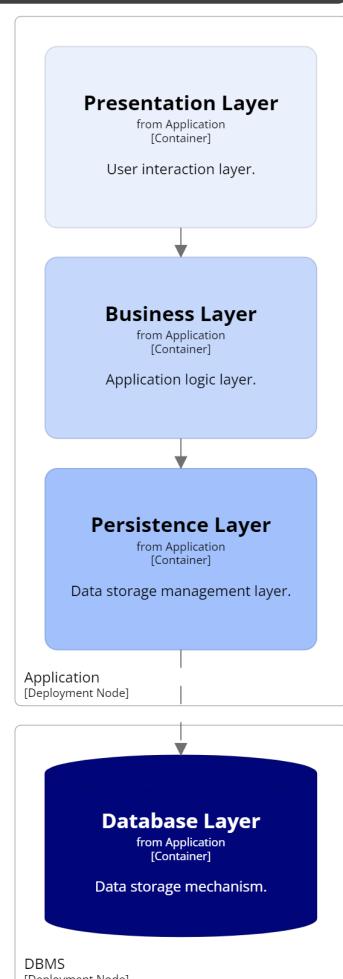


Figure 39: Layered architecture as example of technical partitioning.

⁷⁶<https://leanpub.com/isaqb/glossary/read#term-coupling>

single layer of the architecture, making each layer *cohesive*⁷⁷ from a technical perspective. This makes it easier to work with different parts of the code that deal with the same technical capability. The *layer isolation*, *neighbour communication*, *downward dependency*, and *upward notification* principles help reduce coupling between layers.

A disadvantage of technical partitioning is that business processes cut across technical capabilities. Consider when a customer adds a new product to their shopping cart in the Sahara eCommerce example from the architectural views notes [?]. In a technically partitioned architecture, code to implement this is required in all layers of the architecture. If the team is structured with specialist developers who work on different layers of the architecture, they all need to collaborate to implement the behaviour, which adds communication overheads to the project.

Another disadvantage is the potential for higher data coupling, if all domain data is stored in a single database. If it is decided that the system needs to be split into distributed software containers for scalability, the database may need to be split to have separate databases for each distributed container. If the database was originally designed to cater for a monolith architecture, large parts of the database may need to be refactored.

Note that in figure ??, and most of the following figures, deployment nodes are used to explicitly indicate where components are executing in different environments.

4.2 Domain Partitioning

Domain partitioning is an alternative approach, where the architecture is split into partitions (or major components) corresponding to independent business processes or workflows (the *domains*). The implementation of a domain is responsible for delivering all of that workflow's behaviour. Eric Evans popularised domain partitioning in his book *Domain-Driven Design* [?]. Figure ?? is an example of domain partitioning for an on-line store, similar to the Sahara eCommerce example from the architectural views notes [?].

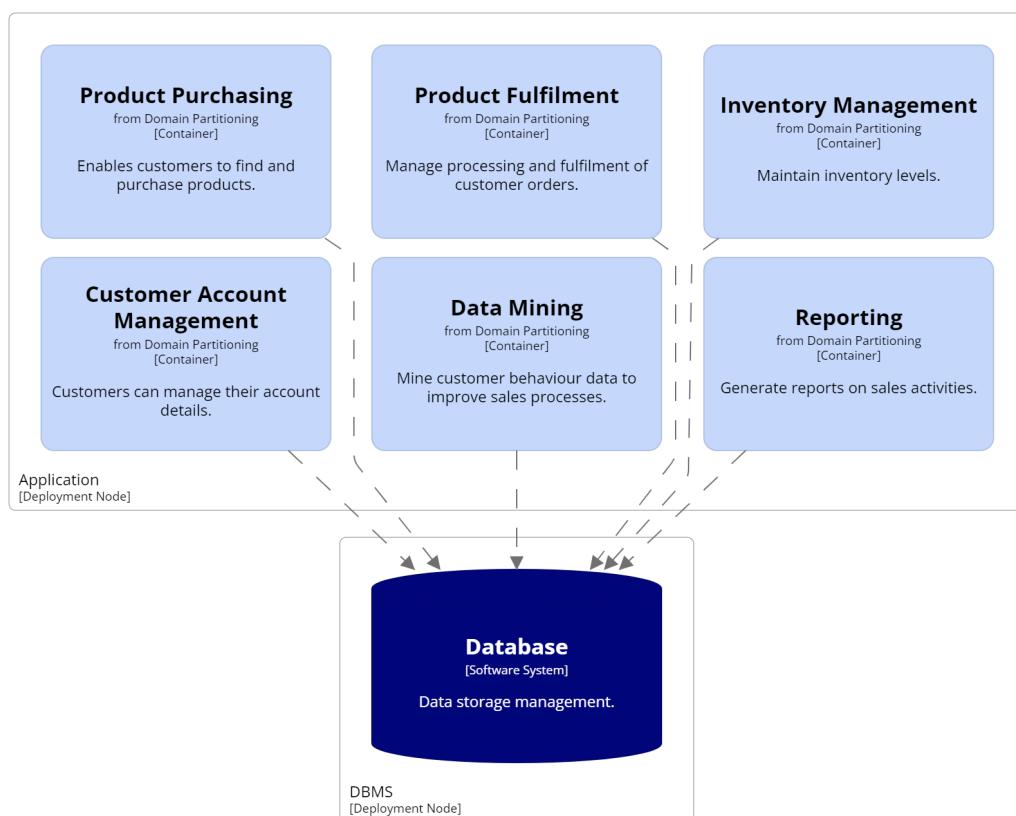


Figure 40: Domain partitioning example.

⁷⁷<https://leanpub.com/isaqbglossary/read#term-cohesion>

An advantage of domain partitioning is that it can model how the business functions, rather than it being structured based on technical decisions. This results in message flows within the software matching how communication happens in the problem domain. This makes it easier to discuss features, and the high-level view of how they are implemented, with business stakeholders who are familiar with how the business operates.

If the domain partitions are independent of each other, it usually makes it easier to split the system into distributed software containers. Even if the system starts with a single database, the independence of domain partitions is likely to lead to a design with lower data coupling, making it easier to split the database.

Another advantage of domain partitioning is that it fits well with an agile or continuous delivery process. A single user story will be implemented entirely within one domain. This also makes it easier to implement multiple user stories concurrently, if they are all from different domains.

A disadvantage of domain partitioning is that *boundary code* is distributed throughout all the partitions. This means that any large changes to a particular boundary (e.g. changing the persistence library) will result in changes to all domain partitions. Boundary code is code that interacts with actors or agents outside of the system. The two common technical partitions of the presentation and persistence layers are examples of boundary code. The presentation layer is the boundary between the system and the users. The persistence layer is the boundary between the system and the storage mechanisms. Other boundary partitions may be for message queues or network communication.

It is possible for each domain partition to use technical partitioning within it, to provide some of the lower coupling benefits of a layered architecture within the domain.

4.3 Architecture Patterns and Partitioning

Different architecture patterns are biased more towards technical or domain partitioning. Those that focus on technical structure are biased towards technical partitioning (e.g. layered architecture). Those that focus on message passing between components are biased towards domain partitioning (e.g. microservices architecture). The core system of the microkernel architecture can follow either technical or domain partitioning. A consequence of this leads to a variation of principle ??.

Definition 17. Domain Standard Interface Principle

Each *domain* should have a single interface that defines how the domain uses plug-ins.

Some domains may share a plug-in interface, but allowing domains to have different plug-in interfaces means that each business process can be customised independently by a set of plug-ins.

In figure ??, deployment nodes are used to explicitly indicate that the core system and plug-ins are conceptually separate from each other. They are all contained within the Application node to indicate that they are still all part of one monolithic application.

5 Extensions

While the microkernel architecture often implements the core system as a monolith and it, along with all its plug-ins, is often deployed as a single



Figure 41: Microkernel architecture with domains.

monolith (e.g. a web browser), that is not the only approach to using the microkernel architecture.

5.1 Distributed Microkernel

The internal partitions of the core system can be distributed to run on different computing infrastructure. Figure ?? is an example of implementing a distributed microkernel architecture using three computing tiers.



Figure 42: Microkernel architecture distributed by technical partitions.

The presentation layer runs on a frontend such as a web or mobile application. It is possible that the presentation layer could have its own set of plug-ins. The business and persistence logic run on a backend server and have their own set of plug-ins. The database runs on a separate database server, and typically does not have any plug-ins from the application's perspective.

5.2 Alternative Contracts

Figure ?? was an example interface that could be used if plug-ins were invoked directly within the core system. This is possible if the plug-ins are implemented within the application or are loaded as code modules at run time (e.g. via JAR or DLL files).

There may be times when plug-ins are external services used by the core system. In these situations communication is via some communication protocol. Remote method invocation would still allow the core system to use a compiled interface. Registration of components would become a little more complicated, as the core system would need a communication interface to be notified of the availability of plug-ins.

More commonly, the communication protocol will be some other mechanism (e.g. REST, as shown in figure ??). In this case, the registry needs to record more information than just the name and interface of a plug-in. The registry will need information about the communication pathway (e.g. URL of the REST endpoint). It will also need details about the data structure passed to the plug-in and returned by the plug-in.



Figure 43: Microkernel architecture – separate plug-in services using REST.

5.3 Plug-in Databases

As mentioned in the discussion of principle ??, plug-ins should not use the core system's data directly. The core system should pass to the plug-in any data that it needs. For sophisticated plug-ins, they may need their own persistent storage. They should not request the core system to manage this. Rather, these plug-ins should maintain their own databases, as shown in figure ??.



Figure 44: Microkernel architecture with plug-ins maintaining their own databases.

5.4 Non-Standard Interfaces

Principles ?? and ?? indicate that each domain, or the entire core system, should use a single plug-in interface. This is not always possible when the plug-ins are services provided by external agencies. In these situations you would use the [adapter design pattern](#)⁷⁸ to isolate the external service's interface from the core system.

As shown in figure ??, an adapter plug-in is implemented that manages communication with the external service. From the core system's perspective, the external system is just like any other plug-in.

⁷⁸<https://refactoring.guru/design-patterns/adapter>



Figure 45: Adapter plug-ins to work with third party services.

6 Conclusion

The microkernel architecture is a suitable option for systems where extensibility is a key quality attribute. Following the microkernel design principles will lead to a design where the core system and plug-ins are not affected by changes to each other. Existing plug-ins can be replaced and new plug-ins added with no impact on the core system.

Service-Based Architecture

Software Architecture

March 17, 2025

Richard Thomas

1 Introduction

Service-based architecture is one of the simpler, but still flexible, distributed architectural styles. It provides good support for delivering quality attributes of modularity, availability, deployability, and simplicity (in the context of a distributed system). The key characteristic of a service-based architecture is that it uses domain partitioning, and each domain becomes its own distributed service. This partitioning provides high-level modularisation that helps ensure the domain partitions are independent of each other. The distribution of domains means that multiple instances of a service can be made available through a [load balancer](#)⁷⁹, providing better availability and some level of scalability.

Many medium-sized bespoke systems⁸⁰ are built using a service-based architecture. For example, an on-line store might be partitioned into services such as Product Browsing, Product Purchasing, Product Fulfilment, Inventory Management, and Customer Account Management. Each of these could be independent distributed services that use a shared database.

Definition 18. Service-Based Architecture

The system is partitioned into business domains that are deployed as distributed services. Functionality is delivered through a user interface that interacts with the domain services.

2 Terminology

The service-based architecture consists of four elements. The *user interface*, *services*, *service APIs*, and *database*, as shown in figure ??.

User Interface provides users access to the system functionality.

Services implement functionality for a single, independent business process.

Service APIs provide a communication mechanism between the user interface and each service.

Database stores the persistent data for the system.

The user interface runs as a standalone process to manage user interactions. It communicates with the services through their service APIs to invoke system behaviour. This requires a remote access communication protocol, such as REST, a message transport service, remote method invocation, [SOAP](#)⁸¹ or some other protocol.

⁷⁹<https://www.cloudflare.com/en-gb/learning/performance/what-is-load-balancing/>

⁸⁰Bespoke systems are custom designed and built for a single organisation.

⁸¹https://www.w3schools.com/xml/xml_soap.asp



Figure 46: General structure of a service-based architecture.

To reduce coupling between the user interface and the service APIs, and to provide easier extensibility, the user interface often uses a [service locator design pattern](#)⁸² to manage access to the services⁸³. This provides a registry of the services and the details of the API of each service. The user interface uses the registry to retrieve an object that communicates with a service through its API. This also makes it easier to add new services to the application, as the details of the new service are encapsulated in the registry.

Services implement the application logic for independent business processes. These are often called “coarse-grained” services, as each one implements a significant part of the system’s functionality. Each service is deployed on its own computing infrastructure. Commonly, there is a single instance of each service but it is possible to run multiple instances of services. Multiple instances of services improves availability because if one instance goes down, other instances can handle future requests from the user interface. To provide higher reliability, in the context of running multiple instances of a service, it should implement the [stateless service pattern](#)⁸⁴. A system running multiple instances of a service, that does not implement the stateless service pattern, would still have higher availability if a service instance went down, as other instances could handle future requests. But, any user in the middle of performing a business process would need to restart their activity, thus lowering system reliability.

Services implement their own service API using the [façade design pattern](#)⁸⁵. This defines the commu-

⁸²<https://www.baeldung.com/java-service-locator-pattern>

⁸³Martin Fowler provides good commentary about using the service locator pattern at <https://martinfowler.com/articles/injection.html#UsingAServiceLocator>. He expands further on some tradeoffs of the pattern, than other more superficial descriptions of the pattern.

⁸⁴<https://www.oreilly.com/library/view/design-patterns-and/9781786463593/f47b37fc-6fc9-4f0b-8cd9-2f41cb36xhtml>

⁸⁵<https://refactoring.guru/design-patterns/facade>

nication protocol used between the user interface and the service. For simplicity, usually all services use the same communication protocol. The façade design pattern reduces coupling between the user interface and the services, as the user interface does not depend on the implementation details of the services.

The service API provides the benefit that different user interfaces can all use the same services. For example, an application with web and mobile interfaces could use the same set of distributed domain services.

The database stores persistent data for the system. Often, a single database is shared by all the services as it is common that some data will be shared between services. A shared database makes it easier to maintain data integrity and consistency. This is because each service implements a single business process and can usually perform all transaction management related to the data involved in the process. For example, the Product Purchasing service for an on-line store can manage the entire database transaction for making an order. If the product is no longer available or payment fails, the service can rollback the transaction to ensure data integrity.

3 Design Considerations

A service-based architecture is typically used for medium-sized systems. This is because the user interface interacts with all services through their APIs. The user interface becomes more complicated when it has to deal with many services. If the services follow the common approach of using a shared database, it means the greater the number of services, the more complicated the database design becomes. There is also a potential performance bottleneck if many services are using a shared database. Strategies to improve database performance, like replicated databases, defeat some of the benefits of a shared database (e.g. consistency). Typically a service-based architecture will have six to twelve domain services. There is no specific upper or lower limit on the number of services allowed, it is a tradeoff that architects make based on all the requirements for the system.

Coarse-grained services will usually have some internal complexity that requires some architectural structure. This internal structure may follow either technical or domain partitioning. Technical partitioning will typically consist of three layers, the API façade, business logic and persistence. Domain partitioning will break the service domain into smaller components related to each part of the domain's behaviour. For example, the Product Purchasing service domain may have components for the internal behaviours of checking out, payment and inventory adjustment. Payment would use an API to process payment through a financial service gateway. Figure ?? provides an example of the structure for both technical and domain partitioning of a service.

Consequences of a shared database are increased data coupling between the services and lower testability. Increased data coupling means that if one service changes its persistent data, then all services that share that data need to be updated, as well as the tables storing the data in the database. Lower testability is the consequence of shared data and services implementing complete business processes. A small change to one part of the service requires the entire service to be tested, and all other services that share data with the service also need to be tested.

To mitigate data coupling, design a minimal set of shared (or common) persistent objects and their corresponding tables in the database. Implement a library containing the shared persistent classes that is used by all services. Restrict changes to the shared persistent classes and their database tables. Changes may only occur after consideration of the consequences to all services. A variation is to not only have shared persistent objects, but other persistent objects that are only shared with a subset of services.

Each service may have its own set of persistent objects and corresponding database tables. These are independent of other services, so there are no external consequences to changing these within a service. Figure ?? is an example of shared persistent objects and a service with its own persistent objects.



Figure 47: Partitioning options for a service domain.



Figure 48: Database logical partitioning example.

4 Service-Based Principles

There are a couple of principles which should be maintained when designing a service-based architecture to produce a simple, maintainable, deployable and modular design.

Definition 19. Independent Service Principle

Services should be independent, with no dependencies on other services.

Services should be independent of each other. If a service depends on other services they either cannot be deployed separately, or they require communication protocols between services, which increases the

coupling and complexity of the system design.

Definition 20. API Abstraction Principle

Services should provide an API that hides implementation details.

The user interface should not depend on implementation details of any services. Each service should publish an API that is a layer of abstraction between the service's implementation and the rest of the system. This provides an interface through which the service can be used and reduces coupling between the service and its users. In a service-based architecture, the user interface is the primary client of service APIs but it is not necessarily the only client. Auditing services may also need to use domain services. In more sophisticated environments, services may be shared across different systems.

5 Extensions

There are a few common variations of the service-based architecture to consider.

5.1 Separate Databases

The first variation we will consider is having separate databases for each service. This extends the idea of logical partitioning your database, as described in section ???. Figure ?? shows a few options of how this can be implemented.

In figure ??, there is a shared database that contains the entity data that is shared across services. Service 1 and 2 are deployed on separate servers but share a single database server that hosts different tables for each service. Service 3 communicates with its own database server that hosts its tables. Service 4 uses a database that is running on the same server as the service.

Each of these approaches have their own advantages and disadvantages. A key consideration is whether a service has enough unique data to make it worth creating a separate database for just the service. If most data is shared between services, it may be easier to implement the system with just a single shared database. If there is some data that is unique to some services, a single database server with either logical partitioning of the data or even independent database services, may provide enough performance for the system. A separate database server for some or all services provides greater flexibility for scaling, if database performance is likely to become a bottleneck for the service. Running an independent database on the same server as the service provides easier communication with the database and may suit cases where an independent database is useful but it is not large enough to warrant running on its own server.

5.2 Separate User Interfaces

A similar variation can be applied to the user interface, so that there are separate user interfaces for some services. This allows separate interfaces to be implemented for different user interface domains (e.g. standard users, power users, administrators, ...). Figure ?? shows some options of how this can be implemented.

In figure ??, the mobile and web user interfaces interact with two services. They both use the same API interfaces to use those services. This is like the single user interface in the general structure shown in figure ???. The admin user interface interacts with the admin service. This example demonstrates a service API that provides services for a specialised user domain (i.e. administrators). It also shows that service APIs can be used to allow multiple user interfaces to work with the backend services.



Figure 49: Separate databases example.

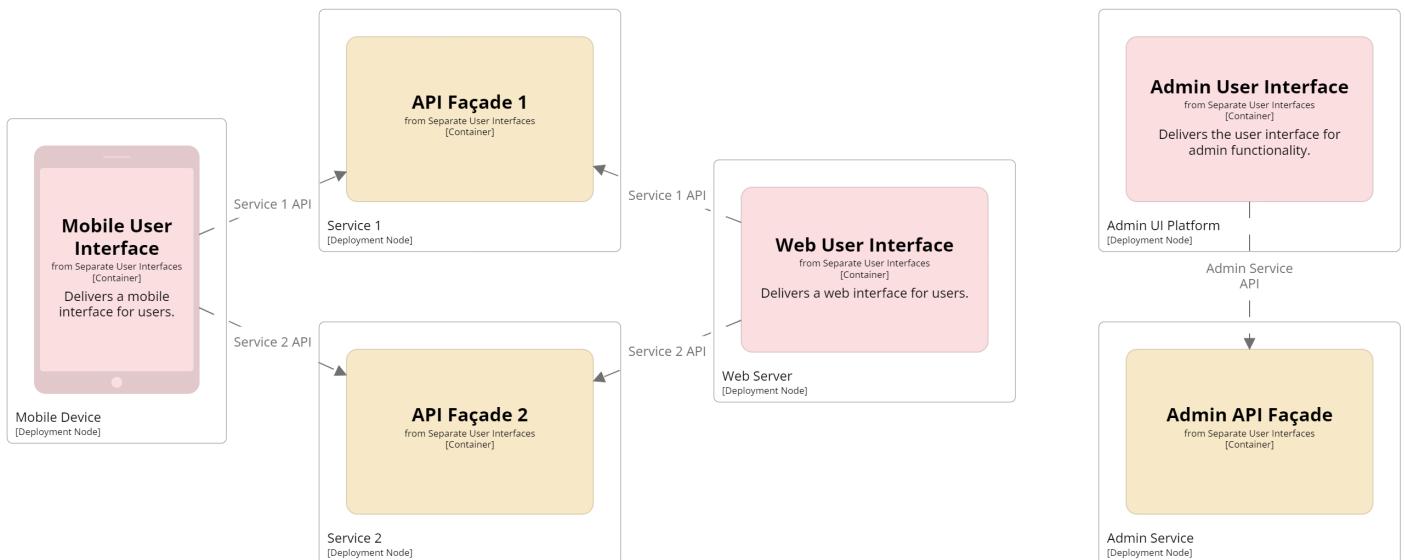


Figure 50: Separate user interfaces example.

5.3 API Layer

It is possible to place an API layer between the user interface and the services, as shown in figure ???. The API layer is a [reverse proxy](#)⁸⁶ or [gateway](#)⁸⁷ that provides access to the services, while hiding details of the services.

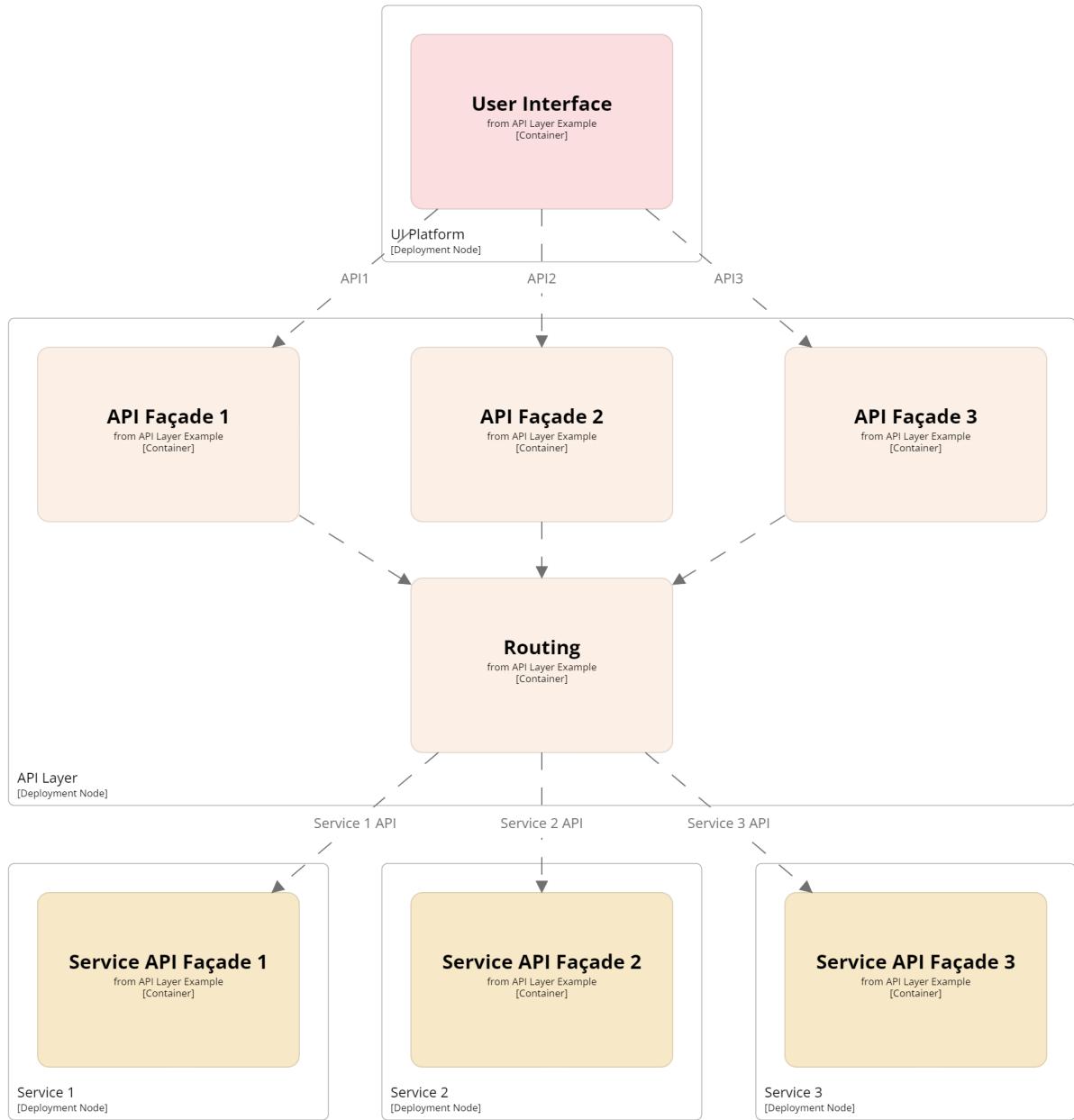


Figure 51: API layer separating the user interface from services.

If any domain services are used by external systems, a reverse proxy hides the internal network structure of your system's architecture. This extra layer of abstraction means that you can expose a different interface to external systems than to internal systems. This facilitates delivering the security principle of least privilege.

A gateway adds “intelligence” to the reverse proxy. It provides similar characteristics regarding hiding the internal network structure, but also processes requests and responses. This can be translating protocols or orchestrating, or aggregating, requests or responses to improve performance.

⁸⁶ <https://www.cloudflare.com/en-gb/learning/cdn/glossary/reverse-proxy/>

⁸⁷ <https://www.baeldung.com/cs/api-gateway-vs-reverse-proxy>

The API layer allows the implementation of *cross-cutting* concerns to be separated from the user interface. For example security policies, user access logging, or service discovery could be implemented in the API layer.

Service discovery allows new services to be registered and provides a mechanism for clients to “discover” the new services. The API layer would provide an interface that allows services to be registered, including information about their interface. The API layer would also provide an interface to clients that allows them to query what services are available and to retrieve an interface that the client can use to access the service through the API layer.

The API layer can also perform load balancing by delegating service requests to different servers running the same domain service.

6 Service Oriented Architecture

Service Oriented Architecture ([SOA](#))⁸⁸ is an extension of service-based architecture. In SOA, each service implements a single business process and provides one or more interfaces that allow access to its functionality. The primary purpose of the API layer is to provide a robust service discovery platform and to implement security policies. Systems are implemented by integrating a set of services to deliver the required functionality. Consequently, the user interface is part of the system being implemented and not part of the service architecture. SOA requires each service to be independent of the others, including very low data coupling. Typically in SOA, each service would have its own database.

SOA sounds like a good idea, but in practice many organisations made compromises that neutered much of the expected benefits. Business processes are often not perfectly independent and there is often data dependencies between processes. If these dependencies are not managed well, the services are not independent. This results in services having to be used together, which reduces their reusability and composability.

Another common issue was a poor service discovery implementation. One problem was that the mechanism to discover new services required too much knowledge about the services. This results in the clients needing to know the services, before they can discover them. Another problem was poor interface design, that caused dependencies on some implementation details of the services.

Microservices were designed to deliver the promised benefits of SOA without some of the implementation issues. In particular, well designed microservices break a system up into independent contexts that have strictly defined boundaries. This reduces the likelihood of tight coupling between services, as each microservice can have its own independent model of its perspective of the problem domain. There are challenges in designing and delivering microservices to achieve the benefits. These will be explored later in the course.

7 Conclusion

Service-based architecture is an approach to designing a distributed system that is not too complex. Domain services provide natural modularity and deployability characteristics in the architecture design. Well designed service APIs improve the encapsulation and hide implementation details of the services.

⁸⁸<https://www.ibm.com/topics/soa>

Infrastructure as Code

Software Architecture

March 17, 2025

Brae Webb

1 Introduction

Configuration management can be one of the more challenging aspects of software development. In sophisticated architectures there are roughly two layers of configuration management: machine configuration; and stack configuration.

Machine configuration encompasses software dependencies, operating system configuration, environment variables, and every other aspect of a machine's environment.

Stack configuration encompasses the configuration of an architecture's infrastructure resources. Infrastructure includes compute, storage, and networking resources.

In a sense, machine configuration is a subset of the stack configuration, however, stack configuration tends to be focussed on a higher level of abstraction. In this course, our focus when looking at Infrastructure as Code (IaC) is *stack configuration*. We rely on containerization tools, such as Docker, to fill the hole left by the lack of treatment of machine configuration.

2 Brief History

In the 'Iron Age' of computing, installing a new server was rate limited by how quickly you could shop for and order a new physical machine. Once the machine arrived at your company, some number of weeks after the purchase, someone was tasked with setting it up, configuring it to talk to other machines, and installing all the software it needed. Compared to the weeks it takes to acquire the machine, a day of configuration is not so bad. Furthermore, because so much physical effort was needed to provision a new machine, a single developer would only be responsible for a few machines.

With virtualization one physical machine can be the home of numerous virtual machines. Each one of these machines requires configuration. Now, with new machines available within minutes and no physical labour involved, spending a day of configuring is out of the question — introducing: *infrastructure code*.

3 Infrastructure Code

Infrastructure code arose to ease the burden of the increased complexity where each developer configured and maintained many more machines. Infrastructure code encompasses any code that helps manage our infrastructure. Infrastructure code can often be quite simple. A shell script which installs dependencies is infrastructure code. There's an assortment of infrastructure code out in the world today, ranging from simple shell scripts up to more sophisticated tools such as Ansible and Terraform.

Definition 21. Infrastructure Code

Code that provisions and manages infrastructure resources.

Definition 22. Infrastructure Resources

Compute resources, networking resources, and storage resources.

To explore the range of infrastructure code available, skim the below examples of infrastructure code in BASH, Python, and Terraform. Each snippet performs the same functionality. Infrastructure Code does not have to be strictly tools such as Terraform, although the two are often conflated. One thing which should be noted is that Infrastructure Code specific languages, unlike most traditional software, is tending towards a declarative paradigm.

```
1 #!/bin/bash
2
3 SG=$(aws ec2 create-security-group ...)
4
5 aws ec2 authorize-security-group-ingress --group-id "$SG"
6
7 INST=$(aws ec2 run-instances --security-group-ids "$SG" \
8     --instance-type t2.micro)
```

```
1 import boto3
2
3 def create_instance():
4     ec2_client = boto3.client("ec2", region_name="us-east-1")
5     response = ec2.create_security_group(...)
6     security_group_id = response['GroupId']
7
8     data = ec2.authorize_security_group_ingress(...)
9
10    instance = ec2_client.run_instances(
11        SecurityGroups=[security_group_id],
12        InstanceType="t2.micro",
13        ...
14    )
```

```
1 resource "aws_instance" "hextris-server" {
2     instance_type = "t2.micro"
3     security_groups = [aws_security_group.hextris-server.name]
4     ...
5 }
6
7 resource "aws_security_group" "hextris-server" {
8     ingress {
9         from_port = 80
10        to_port = 80
11        ...
12    }
13    ...
14 }
```

4 Infrastructure as Code

In this course, we have chosen to make a distinction between *Infrastructure Code* and *Infrastructure as Code*. We define *Infrastructure Code* as above, as code which manages infrastructure. We separately define *Infrastructure as Code* as the practices of treating Infrastructure Code as if it were traditional code. In the real world no distinction is made. We now introduce *Infrastructure as Code* and clarify why this distinction is important.

Definition 23. Infrastructure as Code

Following the same good coding practices to manage Infrastructure Code as standard code.

Given the above definition of IaC, the natural follow-up question is ‘what are good coding practices?’ Before reading further, pause for a moment and consider what coding practices you follow when developing software that you would consider good practice. Got some ideas? Good, let’s enumerate a few that we think are important.

4.1 Everything as Code

Everything as Code is a good coding practice which seems so obvious in regular programming that it is rarely discussed. The idea is to ensure that your code does not depend on manual tasks being performed. Unfortunately, as developers are already familiar with their cloud platform’s UI, it can be easy to take the easy way and to quickly provision a resource in the UI.

Introducing manual changes outside of your Infrastructure Code creates *configuration drift*, infrastructure configuration which has diverged from your Infrastructure Code. Configuration drift can produce *snowflake* machines, unique machines which your project depends on but no one can safely recreate. Once you introduce just one snowflake machine into your infrastructure, the benefit of reproducibility afforded by IaC is lost.

4.2 Version Control

We hope that everyone can agree that version control in regular code is a luxury we would not wish to live without. It should then be common sense to apply the benefits of version control; restorable code, accountable code, and working collaboratively to Infrastructure Code.

There is however, one significant catch with versioning infrastructure code: *state*. Most Infrastructure Code tools utilize some form of state. In Terraform, applying changing updates a file called *terraform.tfstate*. The state is important to map the resources specified in Infrastructure Code to their real-world counterparts. However, the state is updated frequently and needs to be kept in live-sync between all developers. These requirements make version controlling state a generally bad idea. The solution is counter-intuitively a remote state which exists outside of Terraform controlled infrastructure and out of reach of version control. A remote state might exist on an S3 bucket which all developers can access and update in real time. An non version controlled file such as this might seem like a step backwards, however, if you consider it as a cache sitting between your Infrastructure Code and your infrastructure it is a *slightly* nicer pill to swallow.

4.3 Automation

The goal of Infrastructure Code is to help developers manage the complexity of resource management via automation. In order to maximize our confidence that Infrastructure Code is reflected in reality, it is

important that our build pipelines provide an assurance of consistency.

There are two methods for achieving consistency through automation: fail the pipeline if the Infrastructure Code would change the reality; or make changes to reality in our pipeline. Either of these options would ensure that the checked-in Infrastructure Code is an accurate reflection of reality that developers can safely build atop.

4.4 Code Reuse

A good developer should embody the practice of working smarter not harder — it's the core practice of our industry. When developing Infrastructure Code it is important to remember that you are (likely) not the first to solve this problem. You're not the first person to connect a public EC2 instance to an S3 bucket. A good coding practice that happens to be a win-win for everyone is code reuse. You can't copy and paste another developer's mouse clicks to configure their server via a UI, but you can, and in most cases should, import the Terraform module they published to configure servers in just the way you needed.

4.5 Testing

We'll cover testing in the lecture :)

5 Conclusion

We have looked at Infrastructure Code which enables developers to manage the vast amount of infrastructure resources necessitated by the Cloud Age. Then we explored the benefits of applying the good coding practices we know and love from regular programming to Infrastructure Code. We termed this practice Infrastructure as Code despite the tools (Infrastructure Code) and practices (Infrastructure as Code) being combined in the real world as Infrastructure as Code. It is important to note that IaC is still in relatively early stages, there are a number of issues which need to be addressed, such as: importing existing infrastructure; improving state management; and enabling proper refactoring. Despite these issues, it is the best system we have to date and a significant improvement on manual management.

Infrastructure as Code is the worst form of infrastructure management except for all those other forms that have been tried from time to time.

— Paraphrased Winston Churchill

Distributed Systems I

Software Architecture

March 17, 2025

Brae Webb & Richard Thomas

1 Introduction

We have started looking at distributing our applications. Service-based architectures distribute business processes such that each process is deployed on separate machines [?]. The distributed machines act as if they are the one system, giving us our first look at a distributed system.

Definition 24. Distributed System

A system with multiple components located on *different machines* that communicate and coordinate actions in order to *appear as a single coherent system* to the end-user.

Recall that during our investigation of service-based architectures we outlined the following pros and cons:

Simplicity For a distributed system.

Reliability Independent services spreads the risk of fall-over.

Scalability Coarse-grained services.

Let us take a moment now to reflect deeper on each of these attributes.

2 Simplicity

We said that a service-based architecture was simple ‘for a distributed system’. This stipulation is doing a lot of heavy lifting. It can be easy to forget, given the wide-spread usage and demand for distributed systems, that they are not simple. Let us investigate some logical fallacies that make distributed systems more complicated and less appealing than they might initially appear.

Definition 25. Fallacy

Something that is believed or assumed to be true but is not.

3 Fallacies of Distributed Computing

The first four fallacies of distributed computing were introduced by Bill Joy and Dave Lyon and called ‘The Fallacies of Networked Computing’ [?]. Peter Deutsh introduced three more fallacies and named the collection ‘The Fallacies of Distributed Computing’ [?]. James Gosling (lead developer of Java) later introduced a final eighth fallacy [?].

3.1 The Network is Reliable

The first fallacy assures us that the network is reliable. Developers like to believe that this is a fact which can be relied upon, but networks are certainly not reliable. They are more reliable than they used to be but they are far from reliable.

Often we are quite capable of remembering this requirement in obviously unreliable contexts. For example, building a mobile application, it is easy enough to remember that the mobile will occasionally lose network access and we should plan for that. Developers can often get the client-server connection correct but neglect server-server connections, assuming they are reliable.

When building distributed systems which need to communicate with each other, we often assume that the connection between servers will always be reliable. However, even in the most tightly controlled network we cannot guarantee that no packets will be dropped. It is important to remember that the reliability of network communication is a fallacy and that we need to build-in error handling between any two machines. We will see later in our distributed systems series that processing network errors can be extremely challenging.⁸⁹

3.2 Latency is Zero

This course is being run in Australia, no one who is taking this course in Australia *should* believe this fallacy. Again, this fallacy does not exist as much with client-server communication, we are all intimately familiar with having videos buffer.

This fallacy still lingers with server-server communication. Each time an architect makes a decision to distribute components onto different machines, they make a trade-off, they are making a non-trivial performance sacrifice. If you are designing a system with distributed calls, ensure that you know the performance characteristics of the network and deem the performance trade-offs acceptable.

3.3 Bandwidth is Infinite

Similar to the previous fallacy, the fallacy of infinite bandwidth is a plea for architects to be mindful and conservative in their system designs. We need to be mindful of the internal and external consumption of bandwidth for our systems. There are hard limits on bandwidth. A dubious statement from Wikipedia⁹⁰ claims that Australia has a total trans-Pacific bandwidth of around 700 GB/s.

Internally, data centres such as AWS allow impressive bandwidths and it is therefore becoming less of a problem. However, when working at scale, it is important to be mindful to not be wasteful with the size of data communicated internally. Externally, bandwidth usage comes at the cost of the end-user and the budget. End-users suffer when bandwidth usage of an application is high, not all users have access to high bandwidth connections, particularly those in developing nations. There is also a cost on the developers end, as infrastructure providers charge for external bandwidth usage.

3.4 The Network is Secure

Developers occasionally assume that VPCs, firewalls, security groups, etc. ensure security. This is not the case. The moment a machine is connected to the internet it is vulnerable to a whole range of attacks. Known and unknown vulnerabilities enable access, bypassing network security infrastructure. Injection attacks are still prominent; if a distributed system does not have multiple authentication checkpoints then an injection attack on one insecure machine can compromise the entire system. We tend to incorrectly assume we can trust the machines within our network, and this trust is a fallacy.

⁸⁹<https://youtu.be/IP-rGJKSZ3s>

⁹⁰https://en.wikipedia.org/wiki/Internet_in_Australia: I cannot find a supporting reference, let me know if you are able.

3.5 The Topology Never Changes

The topology of a network encompasses all of the network communication devices, including server instances. This includes routers, hubs, switches, firewalls, etc. Fortunately, in modern cloud computing we have more control over these network devices. Unfortunately, this control also gives us the ability to rapidly change the topology. The churn of network topologies in the cloud age makes us less likely to make previously common mistakes like relying on static IP addresses. However, we still need to be mindful of network changes. If network topology changes in such a way that latency is increased between machines then we might end up triggering application timeouts and rendering our application useless.

3.6 There is Only One Administrator

This is a fallacy which is encountered infrequently but it is worth pointing out. Imagine you have an application deployed on AWS. To prevent an overly eager graduate developer from taking down your application, your build pipeline does not run on the weekend. Sunday afternoon you start getting bug reports. Users online are unhappy. Your manager is unhappy. You check the logs, there have been no new deployments since Friday. Worse still you can access the application and it works fine. Who do you contact? AWS? The users? Your ISP? Your users ISP's? Who is the mythical sysadmin to solve all your problems? There isn't one; it is important to account for and plan for that. When things start failing, can you deploy to a different AWS region? Can you deploy to a different hosting provider? Can you deploy parts of your application on-premise? Likewise we need to be aware of this fallacy when trying to resolve less drastic failures, for example, high latency, permission errors, etc.

3.7 Transport Cost is Zero

When architecting a system it can be easy to get carried away with building beautiful distributed, modular, extensible systems. However, we need to be mindful that this costs money. Distributed systems cost far more than monolithic applications. Each RPC or REST request translates to costs. We should also mention that under-utilised machines cost money. Distributing our application services can seem like a beautiful deployment solution but if you are running 10 different service machines for an application with 100 users, you are burning money both hosting the machines and communicating between them.

3.8 The Network is Homogeneous

This fallacy has gotten both better and worse over time. The network has become even more heterogeneous over time. There are more types of networks over which most systems need to operate. There are more communication protocols to consider when designing a distributed system. But, a judicious selection of a small set of standard protocols can hide this complexity.

A simple example of this is accessing a system from a desktop computer with a wired connection to a router, from a laptop over WiFi, and from a phone over 5G. This system is obviously operating over a heterogeneous network, but if you have designed the system using standard communication protocols, the complexity of its heterogeneous network is hidden behind the layer of abstraction provided by the protocols.

4 Reliability

We said previously that a service-based distributed architecture was reasonably reliable as it had independent services which spreads the risk of fall-over. We should look a bit more into why we need reliable software, what reliable software is, how we have traditionally achieved reliable software, and how we can use distributed systems to create more reliable software.

4.1 Reliable Software

We want, and in some cases, need, our software to be *reliable*. Our motivation for reliable software ranges from life or death situations all the way to financial motivations. At the extreme end we have radiation therapy machines exposing patients to too much radiation and causing fatalities [?]. On the less extreme end, we have outages from Facebook causing \$60 million of lost revenue [?]. Regardless of the motivation, we need reliable software. But what does it mean for software to be reliable?

4.2 Fault Tolerance

In an ideal world we would produce fault-proof software, where we define a fault as something going wrong. Unfortunately, we live in an extremely non-ideal world. Faults are a major part of our software world. Even if we could develop bug-free software, hardware would still fail on us. If we could invent perfectly operating hardware, we would still be subject to [cosmic bit flipping⁹¹](#).

Instead, we learnt long ago that fault tolerance is the best way to develop reliable systems. John von Neumann was one of the first to integrate the notion of fault tolerance to develop reliable hardware systems in the 1950s [?]. Fault tolerant systems are designed to be able to recover in the event of a fault. By anticipating faults, rather than putting our heads in the sand, we can develop much more reliable software.

A part of this philosophy is to write defensive software which anticipates the *likely* software logic faults (bugs). The *likely* modifier is important here, if we write paranoid code which has no trust of other systems, our code will become incredibly complex and ironically more bug prone. Instead, use heuristics and past experience to anticipate systems which are likely to fail and place guards around such systems.

Aside from software logic faults, we have catastrophic software faults and hardware faults. These types of faults cause the software or hardware to become unusable. This occurs in practice far more often than you might expect. Hard disks have a 10 to 50 year mean time to failure [?]. We would only need 1,000 disks to have one die every 10 days. How should we tolerate this type of fault?

4.3 Distributing Risk

For faults which cause a system to become unusable we cannot program around it. We need a mechanism for recovering from the fault without relying on the system to work at all as expected. One approach is to duplicate and distribute the original system. If we duplicate our software across two machines then we have halved our risk of the system going completely down.⁹² If we replicate our software across thousands of machines then the likelihood of a complete system failure due to a hardware failure is negligible. Google does not go down over a hardware failure. We know that Google servers have many hardware failures per day but this does not cause a system outage.

This gives us one very important motivation for creating distributed systems, to ensure that our software system is *reliable*.

5 Scalability

Thus far we have foreshadowed a number of the complexities inherit to distributed systems, we have also reasoned that somewhat counter-intuitively distributing our system can offer us greater overall reliability. Finally, let us shallowly explore the ways cloud platforms can offer us reliable systems via replication.

⁹¹https://www.youtube.com/watch?v=AaZ_RSt0KP8

⁹²In a simple ideal world.

5.1 Auto-scaling

Auto-scaling is a feature offered by many cloud platforms which allows dynamic provisioning of compute instances. Kubernetes is a non-cloud platform specific tool which also offers auto-scaling. Auto-scaling is specified by a scaling policy which a developer configures to specify when new instances are required, and when existing instances are no longer required.

Auto-scaling policies will specify a desired capacity which is how many instances should currently be running. The actual capacity is how many instances are currently running, this is different from the desired capacity as instances take time to spin up and down. The desired capacity can be based on metrics such as CPU usage, network usage, disk space, etc. configured via the scaling policy. We should also specify minimum and maximum capacity. Our minimum capacity prevents spinning down too many instances when load is low, for example we do not want to have zero actual capacity as a user will need to wait for an instance to spin up to use the service. Likewise the maximum capacity prevents over-spending when load is high.

5.2 Health Checks

In addition to using auto-scaling to respond to dynamic load we can utilise health checks to ensure all running instances are functional. Health checks allow us to build reliable software. A health check is a user specified method for the auto-scaling to check if an instance is healthy. When a health check identifies that an instance is not healthy, it will spin the instance down and replace it with a new healthy instance.

5.3 Load-balancing

An auto-scaling group will allow us to automatically provision new instances based on specified metrics. In combination with health checks we can keep a healthy pool of the correct amount of instances. However, the question arises, how do we actually use these instances together? If we are accessing these instances via network connections we can use a load-balancer. A load-balancer is placed in front of an auto-scaling group. All traffic for a service is sent to the load-balancer and as the name implies, the load-balancer will balance the traffic sent to instances within the auto-scaling group. This allows a group of instances to assume the same end-point with the load-balancer forwarding traffic to individual instances.

6 Conclusion

We have revisited three of the important quality attributes of a service-based architecture. Namely; simplicity, reliability, and scalability. For simplicity we have seen that there are a number of challenges implicit with any distributed system. For reliability we have seen how using a distributed system can increase the reliability of a system. Finally, we have briefly looked at the techniques which make a distributed system more reliable and more scalable. Our treatment of scalability has only scratched the surface when scaling is just straight-forward replication of immutable machines. For the rest of the distributed systems series we will explore more complex versions of scaling.

Distributed Systems II

Software Architecture

March 31, 2025

Brae Webb & Richard Thomas

1 Introduction

In the previous course notes [?] and lecture [?] on distributed systems, we explored how to leverage distributed systems to increase the reliability and scalability of a system. Specifically, we saw that when working with stateless services, which do not require persistent data, auto-scaling groups and load-balancers can be used to scale-out the service — distributing the load to arbitrary copies of the service. In the lecture, we applied this technique to the product browsing service of our Sahara example, as illustrated in Figure ??.

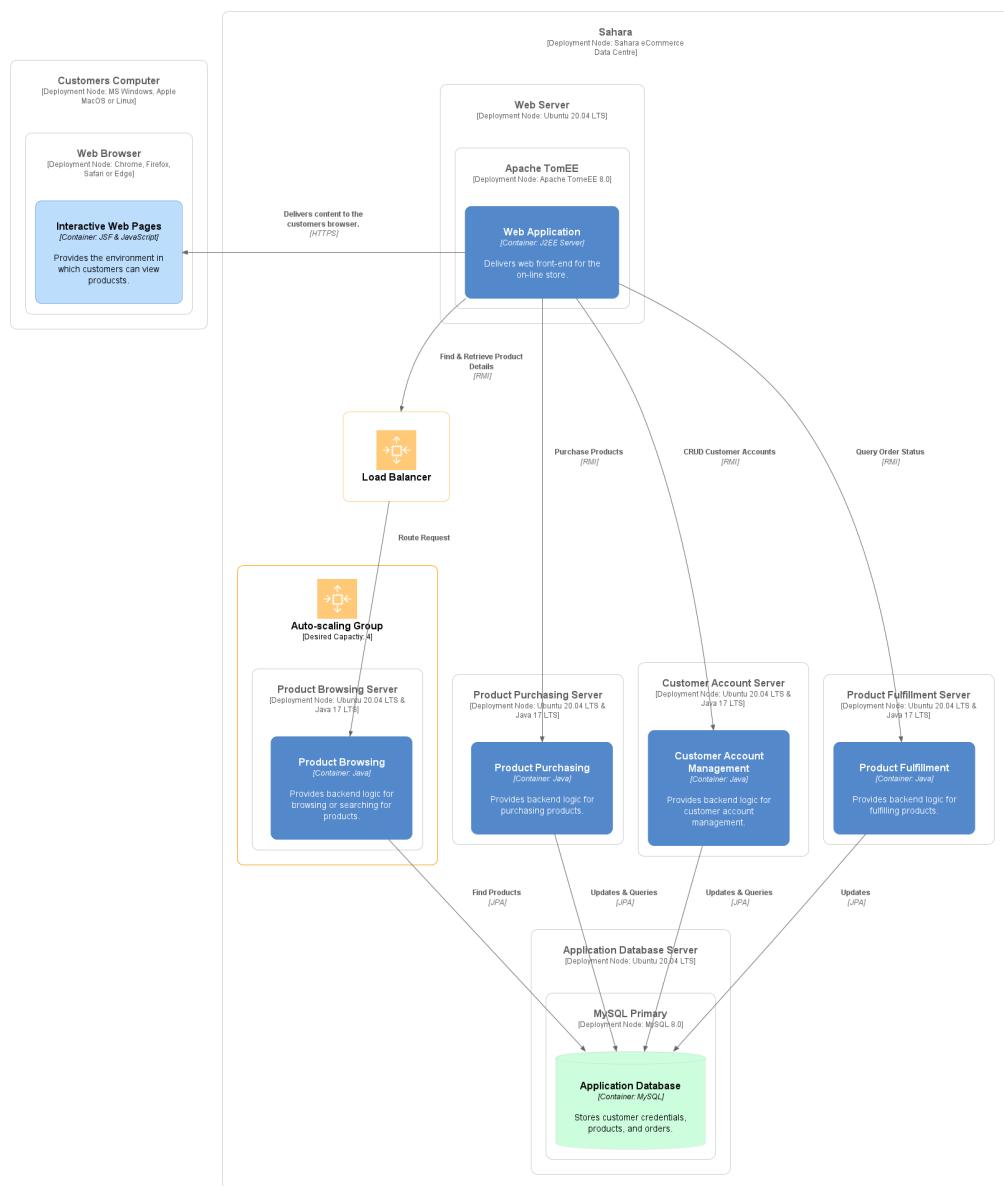


Figure 52: A service-based implementation of Sahara with stateless scaling techniques applied to the product browsing service.

One might correctly identify that by scaling the product browsing service, we have only increased the maximum load that the database can expect. The database becomes a major bottle-neck. We might attempt to scale-up the database, purchasing more powerful machines to host the database on, but this approach is limited.

In this part of our distributed systems series, we look at how to scale stateful services which *do* require persistent data. We focus on state stored in a database and thus, how databases can be made more reliable and scalable. In these lecture notes we only outline the scope of our treatment of database scaling. For a detailed treatment of these topics, please refer to the *Designing Data-Intensive Applications* textbook [?].

2 Replication

Replication is the most straight-forward approach to scaling databases. In many applications, read operations occur much more frequently than write operations, in such cases replication can enable improved capacity for read operations whilst keeping the write capacity roughly equivalent. Replication involves creating complete database copies, called replicas, that reduce the load on any single replica.

2.1 Leader and Followers

The most common implementation of replication is leader-follower replication. Fortunately, it is also the simplest.

Leader a replica that accepts write operations and defines the order in which writes are applied.

Follower replicas that are read-only copies of the data.

When writes occur, they must be sent to the leader replica. Leader replicas propagate updates to all followers. Read operations may occur on any of the follower replicas.

For our example, we might create two followers, or read replicas, of the Sahara database. As the product browsing service is likely to primarily perform read queries, it may send those requests to one of the read replicas. Write operations, which are likely to be the majority for the product purchasing service, must still be sent to the lead replica⁹³. The resulting system might look like Figure ??.

⁹³Realistically, queries would be forwarded based on their type rather than their service of origin.

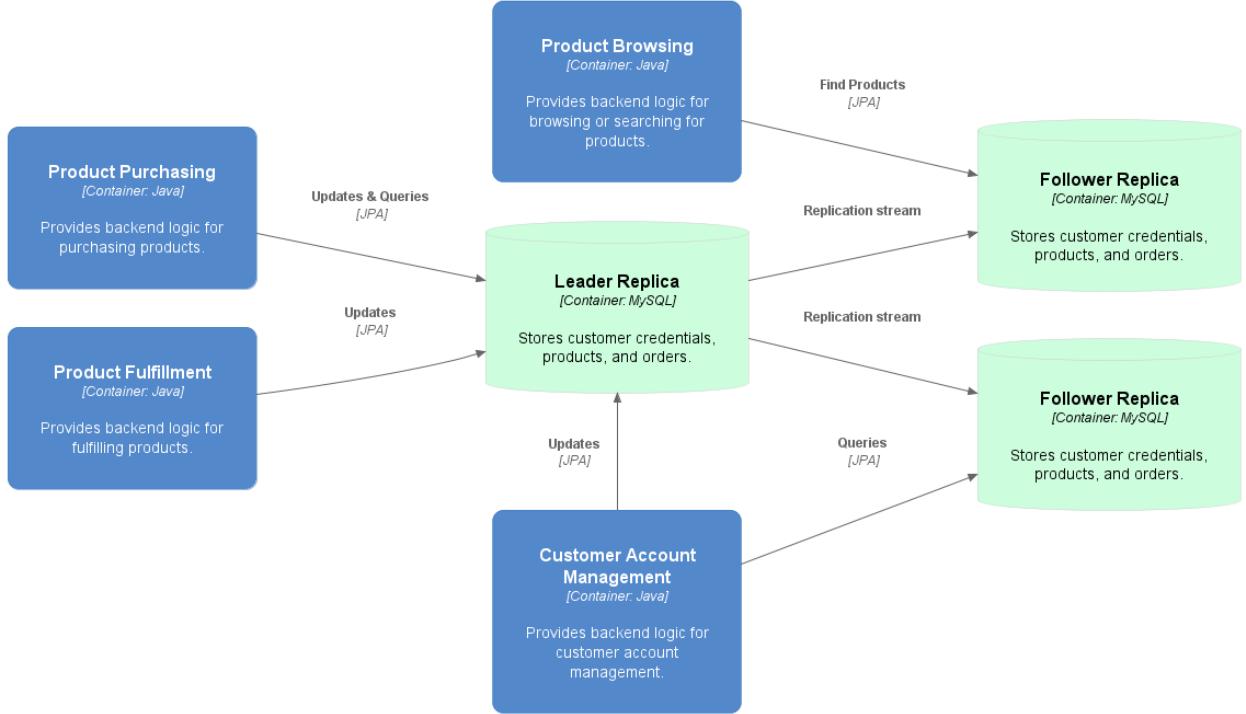


Figure 53: A leader-follower replication of the Sahara database.

Replication Lag

For leader-follower replication to be practical, write updates from the leader to the followers need to be *asynchronous*⁹⁴. However, asynchronous propagation introduces an entirely new suite of issues. If we do not wait for write updates to be propagated to all replicas, then there will be times where the data retrieved from a read replica will be out-dated, or *stale*. Eventually, all writes will be propagated to every read replica, so we call this an *eventually consistent* system.

We have grown fairly accustomed to eventually consistent systems. Consider the last time you or a friend of yours updated their display picture. Did everyone start seeing the updated picture immediately, or, did it take a number of hours or even days to propagate through? Despite our increased exposure to eventually consistent systems, there are a few common practices to keep in mind when implementing such a system to preserve your users sanity.

Read-your-writes Consistency Ensures that the user who wrote the database change will always see their update reflected, though other users will still have to wait for the change to be propagated. This type of consistency avoids upsetting users and making them think they must redo their write.

Monotonic Reads Ensures that once a user reads the updated data, they do not later see the older version of the data, i.e. they do not travel back in time.

Consistent Prefix Reads Ensures that sequential writes are always read in the same order. Consider a Twitter feed, each post is a write. Consistent Prefix Reads guarantees that those readers do not see the posts out of order.

2.2 Multi-leader Replication

Leader-follower replications are sufficient for most use cases as reads often occur far more frequently than writes. However, there are situations where leader-follower replication is insufficient. For systems which

⁹⁴We need not wait for writes to propagate to all followers before accepting that a write has succeeded

need to be highly available, having a single point of failure, the leader replica, is not good enough. Likewise, for systems which need to be highly scalable, a write bottle-neck is inappropriate. For these situations, a multi-leader replication scheme may be appropriate. It is worth noting that multi-leader replications introduce complexity that often outweighs their value.

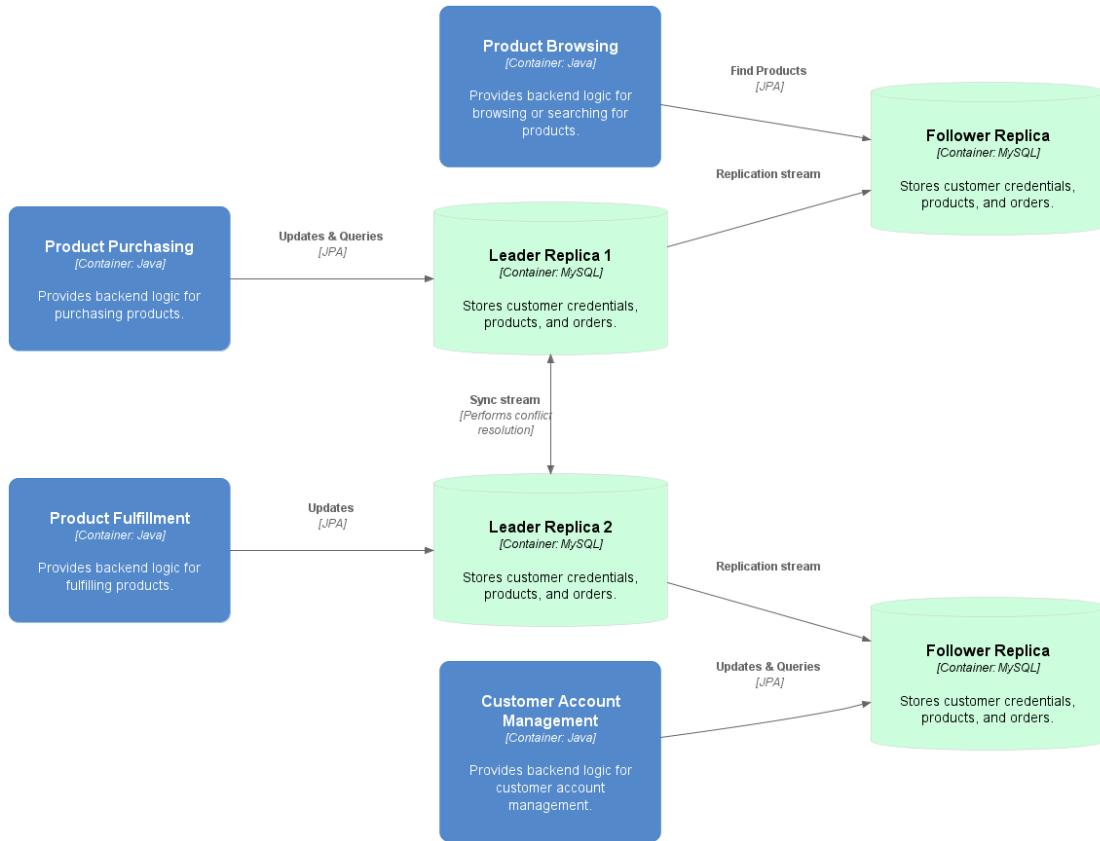


Figure 54: A multi-Leader replication of the Sahara database.

For our example, we might naively introduce a system such as Figure ???. Here we have introduced a second leader, and each leader has their own follower. This type of separation might make sense. We might find it beneficial to have a separate database replica in the warehouse which can be interacted with via the fulfillment service. Such a system would isolate the warehouse operations team from the potential latency of the external customer load.

However, we now have a system where writes can occur in parallel. This can cause several problems. Consider a situation where the fulfillment center has noticed a defective [Nicholas Cage Reversible Pillow](#). They promptly update their system to reflect the decreased stock. However, at around the same time, the CSSE6400 tutors placed a bulk order for all of Sahara's remaining stock. Both write operations appear successful to the fulfillment team and the tutors but a conflict has occurred — this is known as a *write conflict*, and it is a common problem in multi-leader replications.

Write Conflicts

Write conflicts occur when two or more leaders in a multi-leader replication update the same piece of data. In relational systems this is normally the same table row. There are a few mechanisms for resolving write conflicts, but the recommended approach is to avoid conflicts altogether. Conflicts can be avoided by ensuring that a piece of data is only ever updated by the same leader, for example, we might implement that all Nicholas Cage related products are written to Leader Replica 1.

If we are not fortunate enough to be in a situation where conflicts can be avoided, there are a few techniques we can use.

- Assign IDs to writes, and decide which conflicting write to accept based on the ID via some strategy (i.e. highest ID). This results in lost data.
- Assign an explicit priority to leader replicas. For example, if there is a merge we might accept Leader Replica 1 as the source of truth. This also results in lost data.
- Merge the values together via some strategy. This works for data such as text documents but is inappropriate for stocks of products.
- Application code resolution. As most conflict resolution is application dependent, many databases allow users to write code which can be executed on write of a conflict or read of a conflict to resolve the conflict, where appropriate our application could even ask the user to resolve the conflict.

2.3 Leaderless Replication

Leaderless replication does not rely on writes being sent to and processed by a single designated leader, instead reads and writes may be sent to any of the database replicas. To accomplish this, leaderless databases introduce a few additional constraints on both read and writes operations to maintain relative consistency.

A core aspect of leaderless replication is that clients need to duplicate both write and read operations to multiple replicas. This may be implemented by each client communicating directly with the database replicas, as in Figure ??, or one of the replica nodes can act as a coordinator node and forward requests to other database replicas, as in Figure ??.

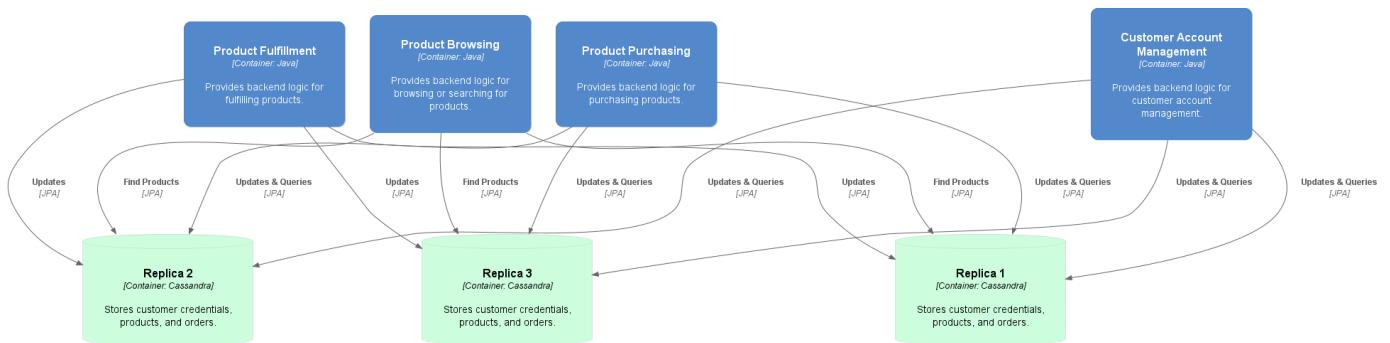


Figure 55: A leaderless replication of the Sahara database.

In leaderless databases, any database node may go offline at any point and the system should continue to function, assuming only a few nodes go offline. This type of database gives us excellent reliability and scalability as we can keep adding extra replicas to increase our capacity. But how can we support this?

Quorum

To support the extensibility of leaderless databases, we need to duplicate our read and write requests. As a simple example, take Figure ??, we have three replicas of our database. When making a write request, if we send our write to just one replica then at most two replicas can have outdated data. Therefore when we read, we need to read from all three replicas to ensure one will have the most recent writes. If instead, we write to two replicas then at most one replica will have outdated data. Then we need only read from two replicas to ensure that at least one will have the most recent writes.

To generalise, if we have a leaderless database of n replicas, we need to satisfy that,

$$w + r > n$$

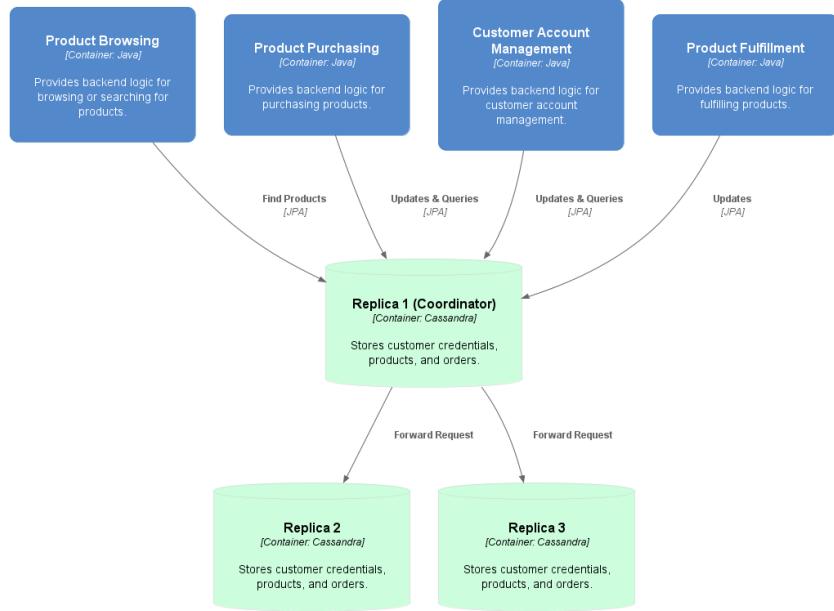


Figure 56: A leaderless replication using a coordinator node of the Sahara database.

where w is the amount of replicas to write to and r is the amount of replicas to read from. By satisfying this equation we have quorum consistency, the set of writes and reads must overlap, which means that reading stale data is *unlikely*⁹⁵.

3 Partitioning

Partitioning involves distributing the contents of a database across multiple nodes. It differs from replication as nodes do not store complete copies of the database. Often partitioning is combined with replication to prevent the loss of data if one of the partitions fails. Partitioning is required when we have a large amount of data to store.

When we start partitioning data onto multiple nodes, we need to consider how we decide which data belongs to which node. There are two primary approaches to this decision.

Partition by Key Range

We assume that data is given a key, with a key-value database this is required, in relational databases the schema should specify a primary key column. One approach to partitioning is to divide the range of key values and partition based on that. Consider the UQ student database, the key would be the student ID. We can then partition the database based on student ID, say all student numbers between s0000000 and s1000000 are stored on partition 0, all numbers between s1000001 and s2000000 are stored on partition 1, etc.

This approach appears practical, each partition has an equal share of database entries. However, as time goes on certain partitions become less used while others become very popular. We might imagine that at the moment, partitions 5 and 6 would be used far more frequently than partition 0. This is known as *skewed partitioning*.

⁹⁵The cases where stale data can still be read are enumerated in M. Kleppmann [?].

Partition by Hash

Consider hash maps, we use hashes of the keys to allocate values into buckets. A good hashing algorithm minimizes the amount of collision (a value stored in the same bucket). We can apply the same process to database partitioning, hashing the key of a record allows us to maximize the spread of partition usage. The disadvantage of partitioning by hash is that only queries by key are efficient, queries by ranges of keys are no longer efficient as they require *all* partitions to be queried.⁹⁶

Secondary Indices

Databases often rely on secondary index to perform a range of useful queries. In our UQ student database example, a database field which is often useful to query might be the degree of a student record. We might want this query to run efficiently as schools could need to frequently query for these collections to implement their own services.

The two approaches to this are local or global indices. With local indices, each partition stores an index for their own partition of the data. With global indices, a partition is assigned to manage a particular secondary index value. For example, partition 2 might store the index for all Bachelor of Software Engineering students.

Local indices allow efficient writing, as a write only has to update the index of the partition to which it is writing. However, it introduces slower reads as all partitions must be queried for their index. Global indices slow down writing as all relevant partitions need to have their partition updated. Although it can increase read speeds as a query only needs to look at the relevant partitions.

3.1 Rebalancing

Over time some partitions may get more frequent use than others. We might also add or remove nodes. This can require the data to be rebalanced to update the range of values stored on any partition. Rebalancing can be an automated or a manual process. It is important to consider the effects of rebalancing automatically as they are costly operations and if triggered at an inappropriate time they can greatly impact the performance of a database.

3.2 Routing

Much like auto-scaled stateless services, we need a way to route traffic that is fair. However, unlike stateless services, only one node of the system is capable of processing our request. We need a mechanism for choosing the appropriate node to which our request is sent.

We might implement a naive load balancer which just balances the load regardless of the request. This load balancer will send requests to the wrong nodes. In such a system, it is the responsibility of the node to forward the request to the node which is capable of answering the query.

A more sophisticated solution would be to deploy a load balancer which is request aware. This load balancer can forward requests to the appropriate node.

Finally, we might offload the problem to the client. Requiring that our database clients are aware of how to map their query to the appropriate node.

4 Transactions

All of the various failure cases and considerations when working with scalable databases can be overwhelming. The complexities of distributed databases make reasoning about the logic of an application

⁹⁶Databases such as Cassandra use compound primary keys to help resolve this issue.

challenging, which in turn leads to more bugs and faults. Fortunately, database developers have a technique to assist in this complexity and allow us to reason about our interactions with the database, *transactions*.

Transactions bundle related groups of read/write operations together and guarantee useful properties. Traditionally, these properties are referred to as ACID properties, Atomicity, Consistency, Isolation, and Durability.

4.1 Atomicity

Atomicity guarantees that when performing multiple operations, if one operation cannot be completed successfully then the effects of all operations are aborted. For example, consider the purchasing process. When purchasing a product we may wish to both update the stock of the product and reduce the funds of a customer's account. If either of those operations occurred on their own, someone would be very unhappy. Atomicity guarantees that either all operations in a transaction succeed or none do.

4.2 Consistency

Consistency guarantees that any application specific invariants of the database are preserved by transactions. For example, we might introduce the invariant that the stock of an item cannot be below zero. This invariant must then be maintained by all transactions.

4.3 Isolation

Isolation allows transactions to pretend that they are the only operation performing on the data. Transactions appear to perform sequentially even though they may in reality be performing concurrently. This allows transactions to ignore a whole host of issues related to concurrency.

4.4 Durability

Durability provides a guarantee that once transactions are completed, their updates are preserved. In distributed databases this is often an assurance that the updated data has been copied to other machines.

5 Conclusion

Scaling out services that have persistent data requires far greater care than stateless services. We have seen approaches for coping with undue load on individual nodes via replication. We have seen approaches for handling greater volume of data than can be stored on a single machine via partitioning. We have noted that often one might want to combine the approaches of replication and partitioning for the one database system. Both of these techniques introduce a new range of complexity for programmers to deal with. In our final section we briefly introduced how transactions, and the guarantees they provide, can help developers in reasoning about their database interactions.

This lecture note has been a very brief introduction into the topics of replication, partitioning, and transactions. The content has been structured around Chapters 5, 6, and 7 of *Designing Data-Intensive Applications* [?]. You are strongly encouraged to read these chapters of the book for a more in-depth coverage of these topics.

Event-Driven Architecture

Software Architecture

March 31, 2025

Richard Thomas

1 Introduction

Event-driven is an asynchronous architectural style. It reacts to events, which is different to the common procedural flow of control of many designs where messages are sent as requests. It is a distributed event handling system, which is conceptually similar to event handling used in many graphical user interface libraries.

Events provide a mechanism to manage asynchronous communication. An event is sent to be handled, and the sender can continue with other tasks while the event is being processed. If necessary, an event handler can send an asynchronous message back to an event initiator indicating the result of the event processing.

Each event handler can be implemented in its own independent execution environment. This allows each type of handler to be easily scaled to handle its load. Asynchronous communication means that event generators do not need to wait for the handler to process the event. Handlers can generate their own events to indicate what they have done. These events can be used to coordinate steps in a business process.

Figure ?? shows the conceptual structure of an event-driven architecture. A client of some form sends the initiating event to a central event broker or mediator. That event is picked up by an event handler that processes the event. That may lead to the event handler generating a processing event to move to the next step of the process. The processing event is sent to the central broker and is picked up by another event handler. This continues until the business process is completed.

diagrams/conceptual-architecture.png

Figure 57: Conceptual deployment structure of an event-driven architecture.

An auction system, as shown in figure ??, could be implemented as an event-driven architecture.

- When a customer bids on an item, they initiate a *bid event*.
- Upon receiving the *bid event*, the event broker notifies the bid handler, which checks the bid against the current high bid and determines the new high bid.
- The bid handler generates a new *high bid event*.
- The event broker notifies the page update handler of the *high bid event*, which sends the new high bid to all pages displaying the item.

diagrams/auction-architecture.png

Figure 58: Auction bidding example event-driven architecture.

- The bid notification handler is also notified of the *high bid event* and it sends an email to the bidder with the result of their bid.
- And, the rebid notification handler is also notified of the *high bid event*. If the previous high bidder is no longer the high bidder, they are sent an email asking if they would like to make another bid.

There are two basic approaches to implementing an event-driven architecture. They have different high-level structures or *topologies*. The *broker topology* is the simpler of the two and is optimised for performance, responsiveness, scalability, extensibility, fault tolerance, and low coupling. The *mediator topology* is more complex but is designed to provide process control, error handling, and recoverability.

2 Broker Topology

The broker topology consists of five elements.

Initiating Event starts the flow of events.

Event Broker has *event channels* that receive events waiting to be handled.

Event Channel holds events waiting to be processed by an event handler.

Event Handler accepts and processes events.

Processing Event sent by an event handler when it has finished processing an event.

In figure ??, the *Client* sends the *Initiating Event* to the *Initiating Event Channel* in the *Event Broker*. *Event Handler A* accepts the event and processes it. Upon completion of handling the *Initiating Event*, *Event Handler A* sends *Processing Event 1* to the appropriate channel in the event broker. *Event Handlers B* and *C* accept this processing event and perform their actions. When *Event Handler C* finishes processing, it sends *Processing Event 2* to its channel. No event handler is designed to accept *Processing Event 2*, so it is ignored.

Different event channels in the event broker provide a simple mechanism to coordinate the flow of events in a business process. As shown in figure ??, there is a separate channel for each type of event. This allows event handlers to register to be notified of only the type of events they can process. This reduces the overhead of broadcasting events to handlers that cannot process them. The consequence is that event sources need to send their events to the correct channel. For a simple broker topology, this could be by sending event messages directly to a channel or, for better abstraction and reduced coupling, the event broker may implement a façade that directs events to the correct channel.

Definition 26. Event Handler Cohesion Principle

Each event handler is a simple cohesive unit that performs a single processing task.

The *event handler cohesion principle* minimises the complexity of each handler and improves the ability of the system to scale only the tasks that need additional computing resources.

Definition 27. Event Handler Independence Principle

Event handlers should not depend on the implementation of any other event handler.

Dependencies between event handlers limit the processing throughput of the system, and increases the complexity of implementing event handlers. The only dependency should be the event that is processed by the event handler.

2.1 Extensibility

There may be multiple event handlers for a single type of event, shown by *Processing Event 1* being sent to both *Event Handler B* and *C* in figure ???. This allows more than one action to be performed when an event is sent. This means that new event handlers can be added to the system as it evolves. A new feature can be added by implementing an event handler to do something new when an event is received by the event broker.

In figure ??, when *Event Handler C* finishes processing its event it sends *Processing Event 2* to the event broker. The diagram indicates that the system does not handle this event. The purpose of doing this is to make it easier to extend the system. Currently, the system may not need to do anything when *Event Handler C* finishes processing, but because it sends an event to indicate it has finished it means other tasks

diagrams/broker-components.png

Figure 59: Basic broker topology.

can be added to the system following *Event Handler C*. Because event handlers are independent of each other, *Event Handler C* does not need to be modified to cater for this later addition of functionality.

If there are events that are not handled by the system, the event broker façade can ignore them, it does not need a channel to manage them. If the system is extended and needs to process one of the ignored events, the event broker can create a new channel to manage them.

Event Handler B, in figure ??, does not send an event when it finishes processing the event it accepted. This is a valid design choice when implementing the system, if there is nothing foreseeable that might

need to know when *Event Handler B* is finished processing. The drawback is that if the system later needs to do something else when *Event Handler B* is finished, it will need to be modified to send an event to the event broker. The tradeoff is reducing asynchronous communication traffic with unnecessary events, versus providing easy extensibility later.

2.2 Scalability

As was mentioned in section ??, the broker topology is optimised for performance. Each event handler is a separate container that can be deployed independently of other handlers. A load balancer and an automated scaling mechanism ensures that each event handler can scale to manage its load.

There may be multiple clients sending events to be processed, and each event handler may itself be a source of events. This requires the event broker and its channels be able to handle the event traffic load. The event broker itself can be deployed on multiple compute nodes, with its own load balancing and auto-scaling. The challenge is to implement this in such a way that the event handlers do not need to know about the event broker's deployment structure.

A simple distributed event broker could deploy each channel on a separate compute node. The event broker façade is deployed on its own node and manages receiving events and sending them to the appropriate channel. The façade also manages how event handlers register to receive notification of events from channels. This works until the event traffic to the façade or a single channel exceeds their capacity.

A more robust approach, which scales to very high traffic levels, is to federate the event broker. This allows the façade and channels to be distributed across multiple nodes but provides an interface that the clients and event handlers can treat as a single access point. The complexity of implementing a federated computing system is beyond the scope of this course. There are several libraries (e.g. [ActiveMQ⁹⁷](#) or [RabbitMQ⁹⁸](#)) and cloud-computing platforms (e.g. [AWS SQS⁹⁹](#), [AWS MQ¹⁰⁰](#) or [Google Cloud Pub/Sub¹⁰¹](#)) that provide this functionality. They can still be used when the system does not need to scale to a federated event broker, as they provide the underlying implementation for the event broker.

2.3 Queues

The other issue that the channels need to manage to allow scalability is holding events until they are processed by an event handler. The simple approach is that a channel implements a queue. Events are added to the end of the queue as they are received. When an event reaches the front of the queue, all the event handlers for the channel are notified that the event is available. The channel queue needs to be configured to cater for different implementation choices. The simple option is that when an event handler accepts the event, it is removed from the queue. This means that only one type of event handler listening to the channel will process the event.

If the system needs all the different types of event handlers to process the event, the queue needs to be configured so that the event is not removed from the queue until all the event handlers have retrieved it. This can be implemented in the queue by having multiple *front of queue pointers*, one for each type of event handler listening to the channel. This allows different event handlers to process through events in the queue at different rates. The queue should be implemented to pass queue size or the amount of time events are in the queue to the auto-scaling mechanism for each event handler. This can be used as part of the logic to determine when to deploy new event handlers, or to scale-back when traffic decreases.

To increase reliability, the queue can be implemented to only remove the event from the queue once the event handler has finished processing it, rather than when it has been received by the handler. This

⁹⁷ <https://activemq.apache.org/>

⁹⁸ <https://www.rabbitmq.com/>

⁹⁹ <https://aws.amazon.com/sqs/>

¹⁰⁰ <https://aws.amazon.com/amazon-mq/>

¹⁰¹ <https://cloud.google.com/pubsub/docs/overview>

allows another event handler to process the event if the first event handler to accept the event fails. A timeout mechanism can be used to provide this functionality. If the queue does not receive notification that the event has been processed within a certain amount of time, it notifies the event handlers that the event is available.

Another consideration to increase reliability is dealing with when the event broker, or one of its queues, fails. If queues are implemented as in-memory queues, events in the queue will be lost when the event broker or queue fails. Queues can be implemented to persistently store events until they have been processed. A federated event broker will further improve reliability by making it less likely that a single queue will fail between receiving an event and storing it persistently.

2.4 Streams

An alternative to channels using queues to manage events, is to use streams instead. Event sources send events to the event broker and they are added to the appropriate stream. Each channel becomes a stream and events are added to the stream. The observer pattern is used where the channel is the subject and the event handlers are the observers. When an event is added to a stream, the channel notifies all its observers that an event has been added. The event handlers then decide whether to retrieve the event and process it.

The most important difference of using streams versus queues is that the events are stored permanently in the stream. Event handlers can process events at their own pace. Because the events are stored permanently, history is maintained. This allows the system to go back and redo past processing or for an audit to be conducted of what happened during processing.

2.5 Queues vs. Streams

Queues work well when there are known steps in the business process being implemented. Queues ensure that all preceding events in the business process are completed before the next step. Queues can ensure that events are only processed once (known as “exactly once” semantics). An ecommerce website is an example of the type of system suited to using queues. This is because there is a fixed set of rules about which event handlers process which events.

Streams work well when there are multiple event handlers responding to events, particularly when event handlers may choose to ignore some events based on certain conditions. Streams mean that the event broker or channels do not need to be notified if an event handler wants to ignore an event. Because streams store events permanently, data analysis of the system’s behaviour can be done by processing past events. Streams work well for social media platforms as monetisation of the platform depends on analysing user behaviour. If user generated events are stored permanently in streams, new analyses can be performed on past data.

Streams also work well for systems that generate a vast number of events, or that have a large number of event handlers. A health monitoring system, taking advantage of the Internet of Things¹⁰² (IoT), would be an example of such a system. There could be a very large number of monitoring devices that generate frequent events to notify the system of physiology changes. Streams make it practical to process different events at an appropriate pace. Some events may need almost immediate processing (e.g. a monitor reporting heart failure). Other events may need periodic processing (e.g. analysing patient blood pressure over a period of time). Streams can accept and store events and different event handlers can be optimised for how they process data in the stream.

The health monitoring system would also have a large number of event handlers, because many devices would process some events (e.g. a heart rate display or a patient alarm). Streams have less overhead to manage their events, so can more easily cope with many event handlers retrieving events for processing.

¹⁰²<https://www.oracle.com/au/internet-of-things/what-is-iot/>

Streams also enable *event sourcing* as a persistence mechanism. Event sourcing stores every event, and its associated state, rather than storing and updating system state. System state at any earlier point in time can be recreated from the event history. This makes it easier to analyse how the system is used and what changes happen to the state over time.

3 Mediator Topology

The mediator topology extends the broker topology by adding an *event mediator*. The event mediator manages the flow of events to implement the business process. There are six elements that make up the mediator topology.

Initiating Event starts the flow of events.

Event Queue holds initiating events sent to the event mediator.

Event Mediator coordinates sending events to the event handlers to implement a business process.

Processing Event sent by the event mediator to start the next step in the process.

Event Handler accepts and processes events.

Event Channel holds events waiting to be processed by an event handler.

In figure ??, the *Client* sends the *Initiating Event* to the *Event Queue*. The *Event Queue* notifies the *Event Mediator* that an event has been enqueued. The *Event Mediator* dequeues the next *Initiating Event* and starts the business process to deliver the behaviour for that event. The *Event Mediator* adds a *Processing Event 1* to its channel. The channel notifies the event handlers listening for this type of event. The event handlers retrieve the event from the channel and process it.

When an event handler finishes processing it does not send a processing event to the *Event Mediator* to be handled. Rather, the event handler usually sends an asynchronous message to the *Event Mediator* indicating that the handler has finished processing. When the *Event Mediator* receives a completion message from an event handler, the mediator determines what is the next step in the process and sends a processing event to the appropriate channel to continue the logic.

The event mediator allows the system to implement more sophisticated logic to deliver the business process. Based on the result received from an event handler, when it finishes processing an event, the mediator can decide which processing event to send next. This allows conditional or iterative logic to be implemented in the business process. Unlike the broker topology, which only has a sequential flow through the business logic based on event handlers sending new events when they finish processing.

3.1 Implementation

Commonly, the mediator topology will implement multiple event mediators. Each one deals with a subset of events. These are usually related to a particular part of the problem domain. For example, in the Sahara eCommerce system, there could be event mediators for:

Customer Events – registering, updating profile, viewing order history, ...

Browsing Events – searching, browsing by category, requesting product detail, ...

Order Events – adding product to shopping cart, checking out, cancel order, ...

Inventory Events – viewing inventory levels, reporting on popular products, ordering new stock, ...

diagrams/mediator-components.png

Figure 6O: Basic mediator topology.

This allows different mediators to be scaled independently, based on their load. It also improves reliability, as one mediator can fail but others can continue to operate.

Like with the broker topology, there are many libraries and cloud-computing platforms that support implementing the mediator topology. Different libraries focus on different aspects of event coordination within the event mediator.

If the event coordination and error handling that needs to be implemented are relatively simple, it is

often easiest to implement the logic in code. Libraries such as [Apache Camel¹⁰³](#) or [Spring Integration¹⁰⁴](#), provide the messaging infrastructure to support this type of implementation.

If the event coordination and error handling are fairly complex, involving a lot of complex conditional processing or dynamic path determination with complex error handling, it is often easier to use a declarative DSL¹⁰⁵ to implement the logic. One such language is [Business Process Execution Language¹⁰⁶](#) (BPEL). It describes the steps involved in processing an event, along with error handling, multicasting and other features. Libraries such as Oracle's [BPEL Process Manager¹⁰⁷](#), provide infrastructure to support the description and execution of the process.

BPEL is not suited to event coordination and error handling that may require human intervention, due to the long run times of this type of processing. A more sophisticated Business Process Management (BPM) execution engine may be more appropriate in this context. These engines use multiple DSLs to provide more sophisticated process automation. Libraries such as [jBPM¹⁰⁸](#) provide the infrastructure that enable this type of event mediator implementation.

Figure ?? is an example of extending the idea of implementing multiple event mediators to have different types of mediators based on the complexity of the event. This is because most large systems will have a mix of simple and complex events, and some of the complex events may have long durations. It is usually more efficient in developer time and effort to apply different strategies for different types of events. Describing and verifying the process for a simple event using BPEL or a BPM execution engine may cost more developer effort than implementing the logic programmatically. To minimise coupling, the client still only sends initiating events to a single event queue. An event mediator retrieves the events from the event queue and classifies them, adding the events to a queue for the appropriate type of mediator.

4 Broker vs. Mediator Topologies

One way to think of the differences between the broker and mediator topologies is:

Broker is a *dumb pipe*.

Mediator is a *smart pipe*¹⁰⁹.

An event broker only provides a messaging service to notify event handlers of events. The broker does not control the logic of business process. Consequently, it cannot maintain any state related to the process. It also cannot perform any error handling if an error occurs in the middle of the process.

An event mediator coordinates the implementation of the business process by sending events to start each step of the process. This allows a mediator to implement complex logic. This can include maintaining state for the process and performing error handling. In the auction example, once a bidder wins an auction they have to pay for the item. *Pay for item* would be the initiating event to begin the process of paying for the item. *Notification sent* and *order fulfilled* would be other events in the payment process. If the payment failed, the event mediator could store the state of the process and once payment was successfully processed it could restart the process.

A conceptual difference between the broker and mediator topologies is that the broker topology is a pure form of event handling. Events represent things that have happened. Once an action has occurred, the event is published and event handlers react to it. In the auction system, events in a broker topology would be *bid placed*, *new high bid*, *payment started*, *payment accepted*,

¹⁰³<https://camel.apache.org/>

¹⁰⁴<https://spring.io/projects/spring-integration>

¹⁰⁵Domain Specific Language

¹⁰⁶<https://www.oracle.com/technical-resources/articles/matjaz-bpel.html>

¹⁰⁷<https://www.oracle.com/middleware/technologies/bpel-process-manager.html>

¹⁰⁸<https://www.jbpm.org/>

¹⁰⁹This is a corruption of the original usage of “smart” pipes, which was related to complex Enterprise Service Buses. Though, using BPEL processors or BPM engines is moving into the same territory of intelligence.

diagrams/complex-mediator-components.png

Figure 61: Complex mediator topology.

The mediator topology is more like a command driven process. The events are commands sent by the event mediator to perform the next step in the business process. In the auction system, events in a mediator topology would be *place bid*, *notify bidders*, *notify previous high bidder*, *pay for item*,

Consequently, in the broker topology, because events represent actions that have occurred, some events can be ignored. In the mediator topology, because events are commands to perform the next step in the business process, they must be executed.

Broker Advantages

- Greater scalability because the broker just distributes event notifications and does not have state, it is easier to federate the broker to provide greater throughput.
- Greater reliability because the broker does not coordinate the business process. If the broker is federated and a broker compute node fails, another node can accept the next processing event and the process can continue.
- Lower coupling because the only dependency between parts of the system are the events.

Mediator Advantages

- Allows for more complex business process logic and error handling.
- Can store process state and restart a process after recovering from an error.

This is not to say that the mediator topology scales poorly, it is just easier to scale to extreme loads with the broker topology. The broker topology takes independence to the extreme to reduce coupling. To provide process control, the mediator topology requires some coupling between the event mediator and the event handlers. The trade-off to consider is whether the business process logic is complex enough that it is easier to implement with the mediator topology.

Reliability versus recoverability is another trade-off to consider. If the event broker is federated and there are multiple instances of each event handler, it is extremely unlikely that some part of the system will fail and not be available. But, this does not deal with errors that occur within a business process. The event mediator can recover from errors and complete a business process.

It is possible to have a hybrid architecture that uses both broker and mediator topologies. Event mediators can implement complex business processes in the system. Event brokers can handle events related to simpler business processes.

5 Conclusion

Event-driven architecture enables delivering a highly scalable and extensible distributed system. Implementation is complex, though this is offset to a certain degree by the availability of libraries or services that implement much of the event broker or event mediator behaviour. The event handler cohesion and event handler independence principles help reduce the complexity of the event handlers. It is the event logic coordination, along with asynchronous communication and inevitable communication failures, that adds to the complexity of the architecture.

Testing and debugging asynchronous communication is a difficult task. The scale of most event-driven architecture tends to exacerbate this difficulty.

The event-driven architecture can be combined with other architectural styles. This allows other architectures to take advantage of the scalability and responsiveness of the event-driven approach. Two architectures that commonly are combined with the event-driven architecture are space-based and microservices. They are not the only hybrid approaches, many other architectures use or borrow from event-driven (e.g. event-driven microkernel).