Healthcare Data Lake

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Abstract

Digital healthcare provided by the NHS in England typically operates in silos. GPs have electronic systems to manage patient care which are distinct from hospital systems which are distinct from the ambulance service, 111, mental health services etc. Each data owner has a wealth of data that, if combined, would generate a more valuable resource than it does in isolation. While there are solutions to integrate this data for direct care purposes, there is no centralised solution to use this data to inform future care or service provisioning. This project is designed to explore the benefits of cloud technologies to produce a prototype secure, scalable health data storage platform that can underpin local healthcare analytics.

1 Overview

1.1 Client

Dr. Philip D Harfield, Health Data Scientist (Informatics) at NIHR Bristol Biomedical Research Centre, University of Bristol.

1.2 Domain

The domain of our Healthcare Data Lake project is the Healthcare Analytics Environment team who will design, implement and test a set of candidate cloud-hosted analytics environments that provide sufficient functionality while also maintaining a secure data environment.
The overall domain of the three teams is NHS Healthier Together Sustainability Transformation Partnership Bristol, North Somerset, and South Gloucestershire (BNSSG) & Bristol Biomedical Research Centre, University of Bristol Medical School.

1.3 Project

The project entails combining a wealth of data from data owners(GPs Patient data, ambulance services, 111, mental health services .etc) into a data lake. This will be used to inform clinical

decisions making by providing more advanced insights into the longitudinal health of the patient on arrival and understand the merits of previous clinic decisions taken.
The project will explore the benefits of cloud technologies and produce a prototype secure, scalable health data storage platforms that can underpin local healthcare analytics.
The project is one of three designed an end-to-end proof of concept to the local NHS. We will be working alongside the "Healthcare Data Visualisation" and "Healthcare Analytics Environment" teams.

1.4 Vision

The Healthcare Data Lake Project is envisioning a future integrated data storage solution, one that is scalable and portable, while using the latest cloud-based technologies. Starting with a prototype, the final scope is to create, alongside the Simulation and Analytics Projects, a system that is going to change how data is handled and used in the healthcare system. There is the real possibility that this three projects will represent the cornerstone of a future solution used and developed extensively by the NHS, which will bring immediate aid to the average medical worker and improve the quality of the service provided to the patients.

2 Stakeholder and Requirements Analysis

2.1 Primary Stakeholder and User Story

Philip Harfield at Bristol, North Somerset and South Gloucestershire CCG (BNSSG). Philip Harfield is our client, and this software is being developed for him at BNSSG. The user story for this stakeholder is that BNSSG require a piece of software that can be used to allow long-term healthcare data analytics from multiple data sources to inform clinical and strategic decisions. The reason for this is understanding the longitudinal health of a patient allows understanding of the merits of previous clinical decisions taken. In addition it can be used to inform strategic commissioning decisions using data on how effective services offered to patients have been.

2.1.1 Flow steps

Considering the user story above, we can breakdown the story into a sequence of steps of user flow.

1. Local healthcare service authenticates their identity.
2. Local healthcare service provides information to the data lake.
3. Data is transformed and loaded into the data lake.
4. The data is catalogued in the data lake and stored in structured data marts as required.
5. The data lake allows access to a data analytics environment.
6. An analytics environment can run queries on the data lake and report results to analytics environment.
7. Clinical and strategic decisions can be taken based on analysis.

We can also identify alternative or exceptional flows.

Exceptional Flow:

1. Local healthcare service is authenticated.
2. Local healthcare services provide data to the data lake.
3. Data is not provided in an acceptable format to the API.
4. The healthcare service receives an error message to provide data in standard format.

Exceptional Flow:

1. Local healthcare service fails to be authenticated.
2. The service receives an error message to provide valid credentials.
3. Incoming data is not accepted.

2.1.2 Atomic Requirements

We can breakdown these steps into atomic requirements of the software.

1. An identity authentication process provides healthcare providers with credentials to supply data to the API.
2. An API takes in data from local healthcare providers as a HL7 FHIR message. We have chosen HL7 FHIR as it is the UK standard for transferring healthcare messages.
3. These data messages are stored in a cloud solution in a well structured data model.
4. Ingested data is catalogued.
5. An ETL tool is used to curate data marts.

6. These data marts can be queried by the analytics environment.

There are also additional requirements specified for the software:

1. Medical data is to be stored independently from pseudonymised patient identifiers.
2. Provide a user console to monitor automated ETL jobs.
3. Provide full audit trails.

2.2 Additional stakeholders and User Stories

This software will provide services to a number of local healthcare organisations such as NHS trusts and the Healthier Together STP and such all these additional users are secondary stakeholders to this project. These organisations will need to be able to provide healthcare information to the software which will need to be able to load and store the data for future analysis.

2.2.1 Flow Steps

Considering the user story above, we can breakdown the story into a sequence of steps of user flow.

1. Healthcare provider (e.g. Hospital Trust) provide data to the data lake by a HL7 FHIR message.
2. The data is stored in the data lake.

We can also consider the stakeholder of a developer and their user story of accessing a user control to monitor automated ETL jobs to identify live support issues.

Flow Steps This can be broken into the following user flow.

1. Developer authenticates identity.
2. Developer accesses user interface which logs all automated ETL jobs carried out on the data lake.
3. Developer can use information to identify issues and provide support.

3 Personal Data, Privacy, Security and Ethics Management

3.1 GDPR

The data lake solution developed by the "Healthcare Data Lake" project team is an integrating part of the larger prototype system, alongside "Healthcare Data Visualisation" and "Healthcare Analytics Environment" teams *(section 1.3)*. The proposed system is going to be used in compliance with the *NHS Digital GDPR* compliance implementation and the liability for the personal data stored falls onto the respective primary stakeholder, Philip Harfield at Bristol, North Somerset and South Gloucestershire CCG (BNSSG) *(section 2.1)*. The team developing the data lake infrastructure is responsible for creating a prototype secure, robust and scalable health data storage platform used for ingesting and interrogating patient's data under the HL7 FHIR standard *(section 4.1)*. As a client-specified requirement, medical data is going to be stored independently from the pseudonymised patient identifiers, thus protecting the identity and integrity of the patients whose data is stored in the data lake. The security of the data ingested as described in *section 3.2* is aligned with the *NHS Digital GDPR* compliance and practice.

3.2 Security

The security requirements for this project are extremely high, and thus this implementation will enforce protections at every layer in the stack. The principle of least privilege (`PoLP`) applies with isolation and strong encryption to ensure data storage, access and communication is safeguarded from unauthorised processes in any event. The entire infrastructure is written in testable code to catch any mistakes before they hit production in the first place.

There will be no outbound (egress) communication from inside the data lake and the only inbound connection is data ingestion from the client API, which may in fact reside within a Virtual Private Network (`VPN`) to begin with rather than accessed over a public gateway. So that internet access is forbidden inside the Virtual Private Cloud (`VPC`) from our standpoint - so data exfiltration becomes challenging for an attacker that compromises any user account. All curated data marts are accessible via a peering link with the Data Analytics team who are responsible for the security of their environment in which they spawn their processes. All access to these will be logged and anomalies, violations and exceptions will be flagged for alerts and auditing. Furthermore, this storage of curated data marts is in a private network separate from the rest of the data lake in any case. A comprehensive look at this architecture is included in Section 4.5 and Section 4.6 of this paper.

3.3 Ethics

Ethics pre-approval was applied for on 19 November 2020, 12:00 GMT.

The data handled in the project is simulated patients data supplied by the Healthcare Data Simulation project. The Healthcare Lake project does not collect any data from any real person nor handles any consent, as the scope of the project is to create a secure infrastructure for storing patients data.

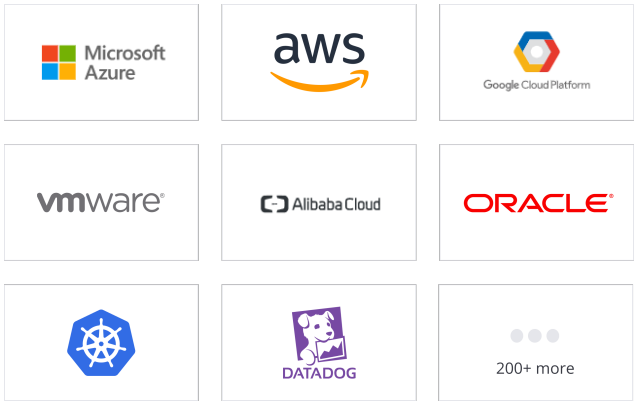
In case of future development and testing with actual patients data, separate ethics approvals will be required, NHS REC review as it involves patients and governance approvals (e.g. Health Research Authority HRA). *–client approvals and testing to be added–*

4 Architecture

4.1 Introduction

We propose a modular, (cloud)platform-independent solution that offers high scalability and performance at a low cost for maintenance, development and deployment. The key to achieving this is leveraging the practises of infrastructure-as-code (IaC), serverless architectures and open standards. Therefore, development expense is focused on providing the most value, security and flexibility to the user.

IaC By building infrastructure through extensible configuration files, we make it easy to build, test, secure, update and rollback versions of architecture which can combine multiple cloud or on-premise services. Terraform is an IaC framework that supports all major cloud providers in addition to self-hosted options such as Kubernetes. This makes it a popular choice for a modern infrastructure team that seeks to avoid vendor lock-in and easily protect the security of it with robust tests and auditing.



Serverless Serverless computing is a cloud computing execution model in which the cloud provider runs the server, and dynamically manages the allocation of machine resources. Pricing is based on the actual amount of resources consumed by an application, rather than on pre-purchased units of capacity [1]. The benefits of this approach are the huge reduction in infrastructure and development expense. Engineers can focus on shipping their microservices and have secure, scalable infrastructure taken care of for them.

The Serverless Framework is also an example of IaC and provides developers with the ability to develop and deploy their serverless application to different cloud providers or simply Kubernetes (using **Knative**) if they wanted to run it on-premise or avoid code exposure to a cloud native service such as AWS Lambda or Google Cloud Functions.

This also provides quicker developer on-boarding and flexibility as a broad array of popular languages are supported. Given that the Function as a Service (`FaaS`) model is centred around the

principles of loosely coupled microservices, this enables easy migration out of serverless architecture to a VM or container-based deployment. This may make sense in scenarios where there are cost savings to be made which typically applies to long-running, memory intensive tasks as opposed to short-lived and resource-light stateless services.

Open standards Open Standards allow people to share all kinds of data freely and with perfect fidelity. They prevent lock-in and other artificial barriers to interoperability, and promote choice between vendors and technology solutions. [2]

OpenAPI The OpenAPI Specification (OAS) defines a standard, language-agnostic interface to RESTful APIs which allows both humans and computers to discover and understand the capabilities of the service without access to source code, documentation, or through network traffic inspection. When properly defined, a consumer can understand and interact with the remote service with a minimal amount of implementation logic. An OpenAPI definition can then be used by documentation generation tools to display the API, code generation tools to generate servers and clients in various programming languages, testing tools, and many other use cases. [3]

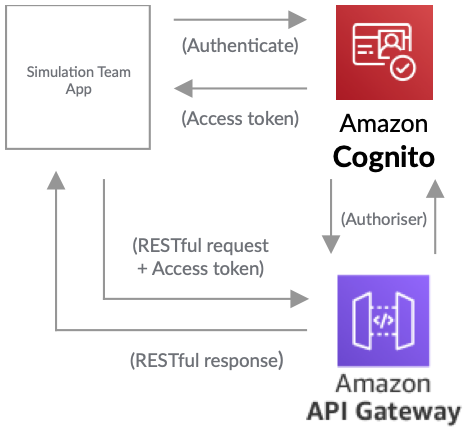
HL7 FHIR *Fast Healthcare Interoperability Resources* (`FHIR`, pronounced "fire") is a standard describing data formats and elements (known as "resources") and an [API] for exchanging electronic health records (`EHR`). The standard was created by the Health Level Seven International (`HL7`) health-care standards organization. One of its goals is to facilitate interoperation between legacy health care systems, to make it easy to provide health care information to health care providers and individuals on a wide variety of devices from computers to tablets to cell phones, and to allow third-party application developers to provide medical applications which can be easily integrated into existing systems. [4]

4.2 Data ingestion

The system will expose a RESTful endpoint for FHIR HL7 messages. It will not offer the full CRUD, only the Create and Update (when authorised). This accepts any structured or unstructured data when contained in a valid HL7 message. There is scope to build on this to add other data ingestion methods by building an API Facade that accepts other kinds of standards the client wants - such as medical IoT streaming data. This API will be accessible over a public gateway at first, with the intent to encourage developers to use a private link.

4.2.1 API management

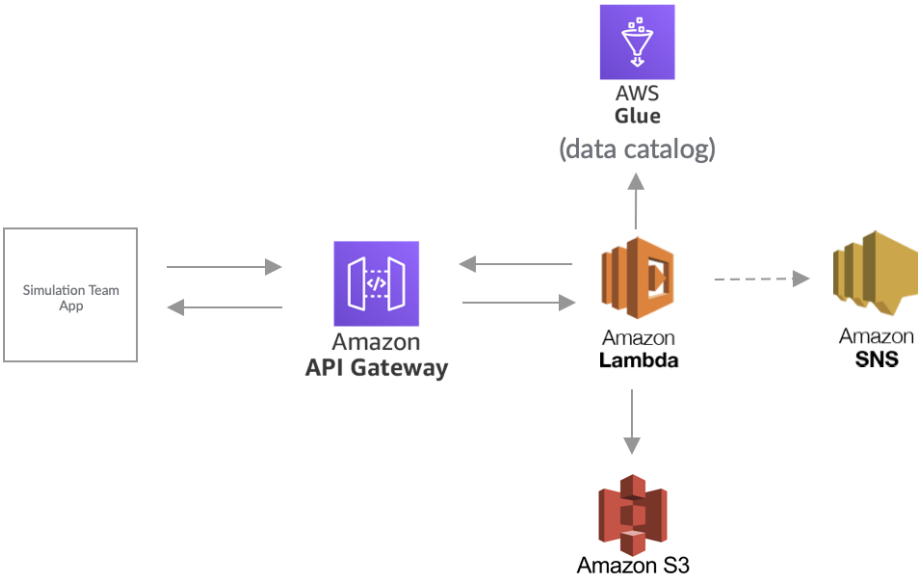
Gateway AWS API Gateway automatically handles the caching, authentication, rate-limiting, routing, logging, validation, integration, scaling, versioning, mocking, documentation and usage plans of APIs defined with the OpenAPI specification. It also offers an affordable, flexible pricing model in exchange for handling these very challenging aspects of API development. Cutting time and cost, enabling teams to focus on shipping their code that actually matters.



Authentication A healthcare service/simulation team app will first authenticate their identity with AWS Cognito which will supply the service with a secure access token. This token may be time-scoped and resource-scoped. The service can then use this token to access the API Gateway. This gateway uses strictly the latest version of TLS and requires the `Authorization` header to be set. This uses the AWS4-HMAC-SHA256 algorithm to calculate a signature for the secret key (access token). This is provided as a hexadecimal representation along with the other required parameters of access key (identity key) and requested resource. The Authorization header is added to all requests that contain the HL7 body for ingestion into the data lake. The API Gateway can then confirm with AWS Cognito to ensure the token is valid. If so then the HL7 FHIR message will be accepted.

4.2.2 Microservices

The API Gateway will forward requests to an AWS Lambda function that stores the data in S3, may send a notification using AWS Simple Notification Service (`SNS`) and writes metadata to the Glue catalogue. SNS notifications may trigger other microservices that prepare ETL jobs. These are yet to be scoped by the client but by default everything will be thrown into the lake where an EMR cluster can process.



4.2.3 Metadata cataloguing

AWS Glue AWS Glue [5] is a fully managed ETL (extract, transform, and load) service that makes it simple and cost-effective to categorize data, clean it, enrich it, and move it reliably between various data stores and data streams. AWS Glue consists of a central metadata repository known as the AWS Glue Data Catalog, an ETL engine that automatically generates Python or Scala code, and a flexible scheduler that handles dependency resolution, job monitoring, and retries. AWS Glue is serverless, so there's no infrastructure to set up or manage.

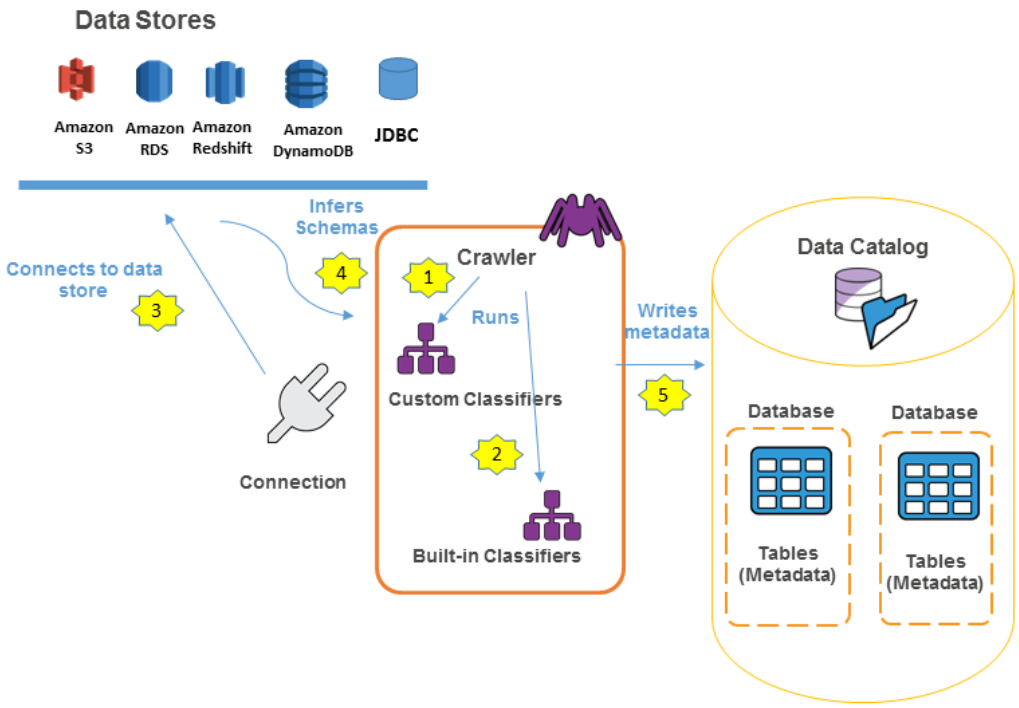
How it works When used for metadata cataloguing, AWS Glue handles essential tasks:

- Discovers and catalogs metadata about data stores into a central catalog. Semi-structured data can be processed, such as clickstream or process logs.
- Populates the AWS Glue Data Catalog with table definitions from scheduled crawler programs. Crawlers call classifier logic to infer the schema, format, and data types of data. This metadata is stored as tables in the AWS Glue Data Catalog and used in the authoring process of the ETL jobs.
- Detects schema changes and adapts by preference.

The data is stored in a Data Catalog made up Databases and Tables (Metadata). Databases are used to organize metadata tables in the AWS Glue. When a table is defined in the AWS Glue Data Catalog, it is added to a database. A table can be in only one database.

What is a crawler and how do they work? A table can be defined using a crawler. Running a crawler connects to one or more data stores, determines the data structures, and writes tables into the Data Catalog. The crawler uses built-in or custom classifiers to recognize the structure of the data. A crawler can be ran on a schedule. To be noted that this is not the only way for creating tables, as the AWS Glue console can be used to manually create a table in the AWS Glue Data Catalog, or by using the CreateTable operation in the AWS Glue API. [6]

- A crawler runs any chosen custom classifier to infer the format and schema of your data. As the ingested data comes as HL7 FHIR messages through the RESTful endpoint, a custom classifier will be needed.
- The crawler connects to the data store. Some data stores require connection properties for crawler access.
- The inferred schema is created for the data.
- The crawler writes metadata to the Data Catalog. A table definition contains metadata about the data in the data store. The table is written to a database, which is a container of tables in the Data Catalog. Attributes of a table include classification, which is a label created by the classifier that inferred the table schema.
- If the crawler runs more than once, perhaps on a schedule, it looks for new or changed files or tables in the data store. The output of the crawler includes new tables and partitions found since a previous run.



Example: General workflow for how a crawler populates the AWS Glue Data Catalog

DataBrew

4.2.4 Schema-less object store

S3

4.3 Data warehousing

4.3.1 Federated querying

4.3.2 Common models

4.4 ETL & data marts

4.4.1 EMR cluster

4.4.2 Scheduling

4.4.3 Developers

4.4.4 Console

4.5 Secure access

4.5.1 Encryption

When data is received, it will require a key to encrypt the data. This key is typically generated by a key manager. When data is being retrieved or queried it will then use the same key to decrypt the data to be used.

A key manager is used to generate, exchange, use, replace and delete cryptographic keys. It's able to deal with asymmetric and symmetric keys. Some key managers encrypt keys after generation to add another layer of security.

Client-side encryption is an alternative option to encrypt the data locally in the application before it gets to the lake. This means the lake is not involved in the cryptographic process of the data, as the application will use its own encryption key which the lake cannot access. This is beneficial for the users as it provides them peace of mind.

Solutions Cloud computing services *Azure*, *GCP* and *AWS* all provide options for client and server-side encryption.

We will be looking at AWS Simple Storage Service (`S3`) [7], AWS Redshift [8] and AWS Key Management Service (`KMS`) for an example of the implementation of encryption.

AWS S3 Server-side encryption uses three different modes of server-side encryption: SSE-S3, SSE-C, or SSE-KMS. The following will be an example of SSE-KMS.

SSE-KMS enables the choice of a customer-managed Customer Master Key (`CMK`) or the AWS managed CMK for Amazon S3 in the account. AWS KMS and Amazon S3 perform the following actions on encryption:

- Amazon S3 requests a plaintext data key and a copy of the key encrypted under the specified CMK.

- AWS KMS generates a data key, encrypts it under the CMK and sends both the plaintext data key and the encrypted data key to Amazon S3.
- Amazon S3 encrypts the data using the data key and removes the plaintext key from memory as soon as possible after use.
- Amazon S3 stores the encrypted data key as metadata with the encrypted data.

Amazon S3 and AWS KMS perform the following actions when data is requested to be decrypted:

- Amazon S3 sends the encrypted data key to AWS KMS.
- AWS KMS decrypts the key by using the same CMK and returns the plaintext data key to Amazon S3.
- Amazon S3 decrypts the ciphertext and removes the plaintext data key from memory as soon as possible.

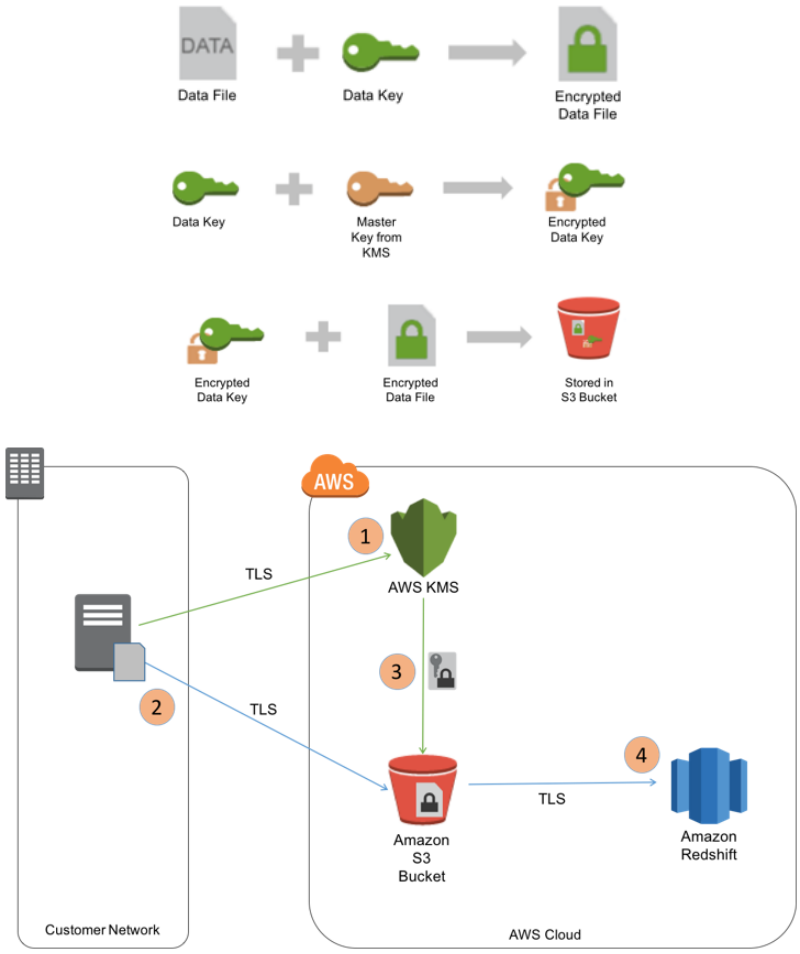
Client-Side Encryption with AWS can use Amazon S3 Encryption Client in the AWS SDK of an application to encrypt objects and upload them to Amazon S3. This method ensures its security as it passes to the Amazon S3 service. The Amazon S3 service receives the encrypted data; it does not play a role in encrypting or decrypting it.

AWS Redshift Amazon Redshift uses a four-tier, key-based architecture for encryption. The architecture consists of data encryption keys, a database key, a cluster key and a master key.

1. Data encryption keys encrypt data blocks in the cluster. Each data block is assigned a randomly generated 256-bit AES key. These keys are encrypted by using the database key for the cluster.
2. The database key encrypts data encryption keys in the cluster. The database key is a randomly generated AES-256 key. It is stored on disk in a separate network from the Redshift cluster and passed to the cluster across a secure channel.
3. The cluster key encrypts the database key for the Redshift cluster. KMS, AWS CloudHSM, or an external hardware security module (`HSM`) can be used to manage the cluster key.
4. The master key encrypts the cluster key. KMS CMK can be used as the master key for Redshift.

AWS KMS AWS Key Management Service (`KMS`) allows you to create and manage cryptographic keys and control their use across a wide range of AWS services and in the applications. AWS KMS uses hardware security modules that have been validated under FIPS 140-2, or are in the process of being validated, to protect keys. AWS KMS is integrated with AWS CloudTrail to provide logs of all key usage to help meet applicable regulatory and compliance needs. [9]
What is going on when S3 handles the process of server-side encryption [10]

- When an object is uploaded into S3 and specified SSE, a unique 256-bit key (a data key) is generated and the data is encrypted using that key with AES-256.
- The data key is then encrypted using a master key, which S3 retrieves from KMS using the master key ID that was supplied in the s3 cp command.
- The encrypted data key is then stored with the encrypted data in the S3 bucket.



Overview The major steps in this process are

1. You create a master key in KMS
2. You load the data into S3.
3. S3 retrieves the key from KMS and encrypts the data.
4. You run the COPY (`cp`) command in Redshift to load the data from S3.

4.5.2 IAM

Concept Identity and Access management (`IAM`) is used to make sure authorised users have the right to services while preventing access to non-authorised users (guaranteeing secure access). It does this by defining and managing the roles, the access privileges of individual users and the circumstance users are granted those privileges.

IAM allows access management over computing, storage, database and application services. It gives one identity per individual. Once that identity has been introduced, it must be maintained, modified and monitored throughout each user's access lifecycle. [11]

Solution We will be examining AWS IAM [12]. IAM is a feature of an AWS account offered at no additional charge.

The use cases of AWS IAM include finite-grained access control to AWS resources, multi-factor authentication for high privilege users, analysis of access across the AWS environment and ability to integrate with the corporate directly (integration of current IAM system).

How it works AWS IAM allows us to:

- Manage IAM users and their access – Create users in IAM, assign them individual security credentials (access keys, passwords and multi-factor authentication devices), or request temporary security credentials to provide users access to AWS services and resources. Manage permissions in order to control which operations a user can perform.
- Manage IAM roles and their permissions – Create roles in IAM and manage permissions to control which operations can be performed by the entity, or AWS service, that assumes the role. Define which entity can assume the role. In addition, you can use service-linked roles to delegate permissions to AWS services that create and manage AWS resources automatically.
- Manage federated users and their permissions – Enable identity federation to allow existing identities (users, groups and roles) in the enterprise to access the AWS Management Console, call AWS APIs and access resources, without the need to create an IAM user for each identity. Enable the use of any identity management solution that supports SAML 2.0.

4.5.3 Logging

Concept A Log is data that can describe application information, system performance and user activity, for example, might include Timestamp, Application, User, Session ID etc.

Using logs to monitor the use of the system provides security to check for violations and unpredicted behaviour from users and the system. Analysing, searching and filtering logs discovers and alerts these incidents. It enables access to historic information for debugging and forensic investigations. [13]

Examples The example which will show the use of logs is AWS CloudWatch. CloudWatch can be used to monitor, store and access the log files from AWS Services.

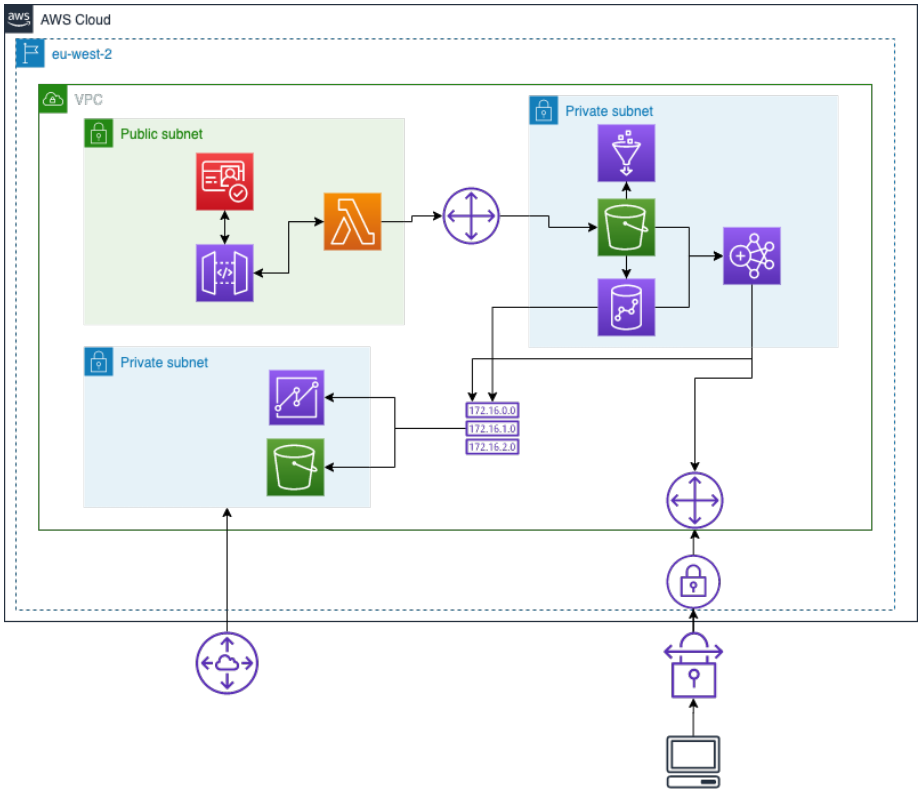
CloudWatch enables the centralization of the logs from all over the systems, applications and AWS services that are used, in a single, highly scalable service. You can then easily view them, search them for specific error codes or patterns, filter them based on specific fields, or archive them securely for future analysis. [14]

Features

- Querying – CloudWatch Insights can be used to interactively search and analyse log data. CloudWatch provides sample queries, command descriptions, query autocompletion and log field discovery to help get started.
- Monitor AWS CloudTrail Events – You can create alarms in CloudWatch and receive notifications of particular API activity as captured by CloudTrail and use the notification to perform troubleshooting.

- Log Retention – By default, logs are kept indefinitely and never expire. You can adjust the retention policy for each log group, keeping the indefinite retention, or choosing a retention period between 10 years and one day.
- Archive Log Data – CloudWatch Logs can be used to store log data in highly durable storage. The CloudWatch Logs agent makes it easy to quickly send both rotated and non-rotated log data off of a host and into the log service. You can then access the raw log data when needed.

4.6 Network



4.6.1 Public subnet (API)

The client API is accessible over the WAN on all IPv4 and IPv6 addresses (0.0.0.0/0, ::/0). In future versions, it may be decided to make this a private network though. In front of the Lambda sits the API Gateway, forwarding requests to and fro. Lambdas may not be directly invoked. The Lambda only has the following IAM permissions: `PutObject` and `UploadPart`. This would ideally be replicated across at least two availability zones in the region so that downtime is prevented.

4.6.2 Private subnet A (Data Lake)

The lake itself contains the S3 bucket, Glue instance, Redshift instance and EMR cluster. These are needed for all the ETL jobs and federated querying. Optionally, an AWS Athena instance could be added here for SQL querying across the lake. The EMR cluster can be accessed securely via a VPN client connection.

4.6.3 Private subnet B (Trusted Research Environment)

Once big data tasks are run across the lake to cleanse and prepare data marts, they are written to an S3 bucket inside a private subnet for use in the analytics environment. Additionally, Redshift can provide Business Intelligence tools with data. An example of AWS QuickSight has been included here, but most BI tools are compatible with S3 anyway and if not, then Redshift solves that problem by providing data warehousing so that models are there for querying.

4.6.4 VPC peering

Private subnet B, or the Trusted Research Environment (hereinafter "`TRE`"), is accessible to the Data Analytics team via a VPC peering connection. This assumes the VPCs are held in the same AWS Organization account, ensuring IAM roles can be used across VPCs.

4.7 Streaming data (Optional)

4.7.1 Kinesis Fire Hose

4.7.2 Medical IoT

4.7.3 Wearables / sensors

4.7.4 EHR

4.7.5 Digital medical imagery

4.7.6 Real-time analytics

4.8 Extensible

4.8.1 Databricks integration

4.8.2 Multi-vendor

5 Development Testing

5.1 Local environment

5.1.1 API

Serverless The Serverless Framework enables developers to run an emulated environment locally instead of needing to deploy that serverless app for testing. This comes with over 1,000 plugins that can emulate services such as AWS Lambda and API Gateway.

Therefore, developers are expected to build and test their code locally with identical behaviour to that of the deployment environment. As any microservice can be done in a number of languages, it is not decided which framework is chosen for unit tests of those.

Postman Postman is a very popular tool used by developers that want to conveniently test and build APIs in a collaborative way.

As we are implementing the OpenAPI specification, Postman enables the import of Swagger files to automatically generate a Postman environment. This makes developer on-boarding much easier as versioned mock endpoints and documentation are hosted for us as part of the DevOps deployment. It enables tests to be written as well (JavaScript), but we may opt to use a different RESTful testing framework such as REST-assured (Java).

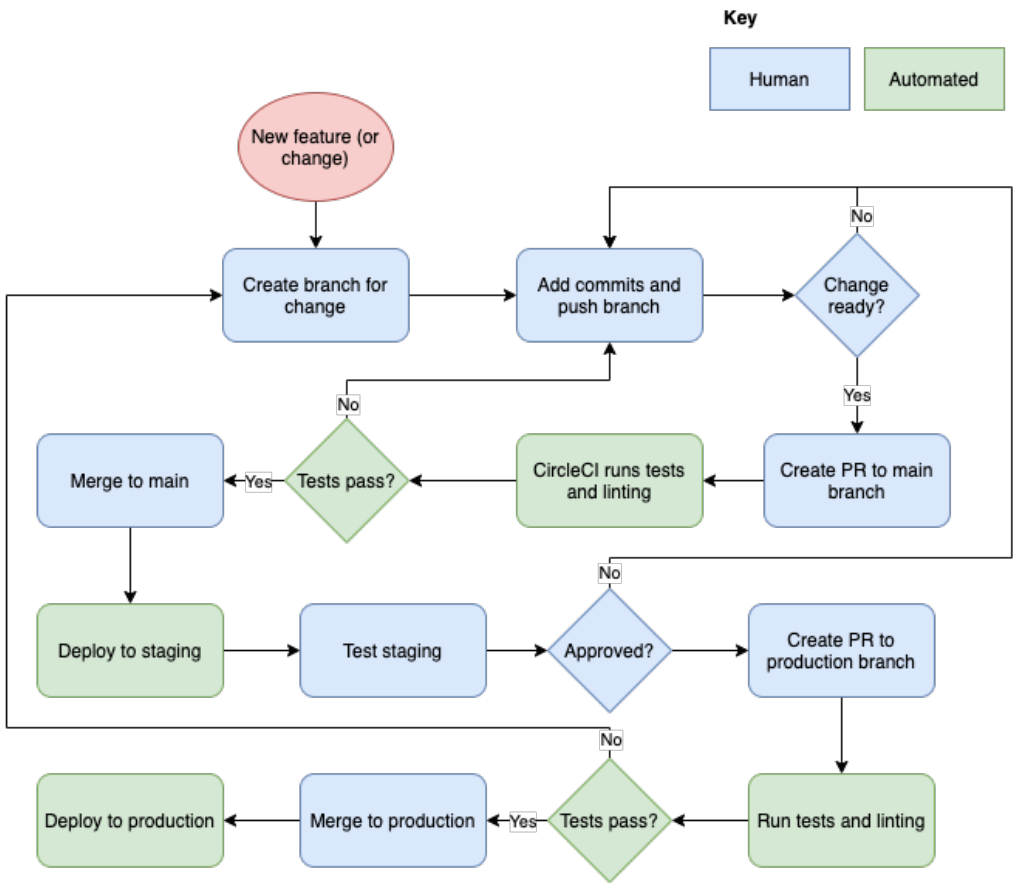
5.1.2 Infrastructure

The shared infrastructure differs from that of the application infrastructure (in this case referring to the serverless API). The shared infrastructure can be built, updated, reverted and destroyed easily using the Terraform command-line tools (`cli`). Terraform formats and validates your plan before applying it, so writing unit tests around the migration itself doesn't make sense in this context. What does make sense is testing the enforcement of user-defined standards. This can be written with Terraform Validate (Python) or Terratest (Go). Furthermore, compliance controls could be generated with Chef InSpec profiles ("Compliance-as-Code").

Docker To achieve consistency across developers' local machines and avoid headaches, Docker containers will be used for the local development environments.

Terraform Terraform workspaces are utilised to isolate development, staging and production environments. It also gives developers the option to work on their own accounts without breaking global state. However, a global state backend will be configured with S3 and a state lock with DynamoDB to enable a team to work on the same infrastructure.

5.2 DevOps



5.2.1 GitHub

The git repository is hosted on GitHub in the custody of the organisation. However, the repository will be MIT licensed.

5.2.2 CircleCI

The Continuous Integration & Continuous Delivery pipelines are run by CircleCI servers. This decision was made by the university. Jenkins (self-hosted) would be preferred to reduce overall cost constraints and just generally to reduce vendor lock-in and improve security. The workflows of jobs are defined in a YAML configuration file.

5.2.3 Terraform

Terraform handles the deployment by using the relevant APIs - in this case it will use the AWS API but may use any other providers as required - such as if we decided to integrate Azure or Google for a multi-vendor infrastructure.

6 Release Testing

6.1 Staging

6.2 Production

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