

Malware Detection within Object Storage

Author: Matthew Battagel, Supervisor: Theodoros Spyridopoulos

Acknowledgments -

I would like to extend my sincere gratitude to my supervisor Theo, my colleague Harry, parents, and Lo for their unwavering support and encouragement during my project. Their combined expertise and guidance provided were critical in the shaping and execution of the project. I am truly thankful to all of them for their contributions.

Abstract

The rapid increase in data production has amplified the necessity for robust and secure data storage systems. MinIO, an open-source object storage platform, offers cost-effective and scalable solutions but lacks an integrated malware detection feature, thereby posing potential risks to user data. This project seeks to augment MinIO by incorporating a scalable malware detection system, with the goal of maintaining MinIO's performance and scalability. In essence, this project aspires to enhance the security features of MinIO while offering a valuable experience in deploying production-grade solutions within a microservice framework.

Contents

1	Introduction	4
1.1	Overview	4
1.2	Motivation	4
1.3	Project Aims	5
2	Background	5
2.1	Signature Detection	5
2.2	Malware Detection with ClamAV	5
2.3	Microservices	6
2.4	Amazon S3 Malware Detection	6
3	Specification	7
3.1	Functional Requirements	7
3.2	Non-Functional Requirements	9
3.3	Constraints	9
4	Architecture	9
4.1	Candidate Design 1 - Post-Write	10
4.2	Candidate Design 2 - Upload Queue	11
4.3	Candidate Design 3 - Write Interception	12
4.4	Candidate Design 4 - Per Node	13
4.5	Selected Candidate Design	14
5	Implementation	15
5.1	Service Selection and Creation	15
5.2	Aegis Module Design and Creation	18
5.3	External Package Integration	21
5.4	Aegis' Internal Workflow	24
5.5	Testing	30
5.6	Kubernetes Deployment	31
6	Results and Evaluation	35
6.1	Solution Workflow	37
6.2	Benefits of Metric Collection	37
6.3	Performance Evaluation	38
6.4	Comparing Functional Requirements	42
6.5	Comparing Non-Functional Requirements	43
6.6	Project Aims Evaluation	44
6.7	Testing Evaluation	45
7	Product Issues / Future work	45
8	Conclusions	46
8.1	46

9	Reflection on Learning	47
	9.1	47
10	Appendix	48

1. Introduction

1.1. Overview

The exponential growth of data generation has made data storage an increasingly important aspect for both individuals and organisations alike (John and David, 2012). Object storage has emerged as a promising solution due to its ability to store vast amounts of unstructured data in a cost-effective and scalable manner (Ot, 2022). Object storage improves upon traditional storage ideas by moving lower-level functions inside of the storage device itself to raise the level of presented abstraction to the user (Michael *et al.*, 2005). Functions such as, space management and access control are handled by the device while objects are accessed through a storage interface (Michael *et al.*, 2005).

One of the most widely used object storage platforms is Amazon S3, which provides a highly scalable and reliable solution for storing data (Vlad *et al.*, 2018). However, an open-source alternative called MinIO has emerged as a promising contender, providing similar features to Amazon S3 while giving customers greater control over their data (MinIO, 2023c). MinIO is written in Go and is available for free under the Apache License 3.0 or, for commercial and enterprise purposes, at a reduced cost compared to Amazon S3 (MinIO, 2023d). MinIO offers a wide range of features, including high performance, data replication, encryption and erasure coding (MinIO, 2023c). Most importantly, MinIO is designed to scale out horizontally to ensure that it can handle the demands of large-scale applications (MinIO, 2023c).

With MinIO, scalability is made simple by allowing multiple types of hardware platforms to work together in separate nodes each with their own compute and storage within a microservice architecture (MinIO, 2023c). This is extremely attractive for customers who want to utilise their existing hardware without being tied down to a specific provider. This also applies for customers looking to migrate their data from Amazon S3 to cheaper solutions without compromising on the high performance, reliability and scalability of the S3 platform.

While MinIO is a great alternative to Amazon S3, it does not offer any form of integrated malware detection. This could deter potential customers from choosing MinIO as a viable platform to migrate to from Amazon S3 or leave existing users data vulnerable to malware attacks. This project aims to address this issue by integrating a malware detection system into MinIO without negatively impacting the scalability or performance such that MinIO is still an effective alternative to Amazon S3.

1.2. Motivation

Due to the high amount of unstructured data expected to be both written to and read from the object store, and the increasing amount of malware being produced (Ormandy, 2011), there are increased risks of encountering malicious files. Therefore malware detection within object storage is crucial in modern cloud storage scenarios. Most popular off-the-shelf object storage platforms, such as AWS, already have integrated third-party antivirus software, such as ClamAV and Sophos (Srinivasan *et al.*, 2022), to mitigate security risks. MinIO on the other hand is vulnerable to malware attacks as it currently does not have any native antivirus integration (MinIO, 2023c). This forces customers who require complete virus protection to either not use MinIO or to use

potentially costly third-party software. As antivirus scanning is inherently resource intensive, if the software is integrated incorrectly, it could reduce the ability for the storage solution to scale horizontally. The purpose of this project is to implement malware detection within MinIO while being mindful to not impact the scalability or performance of the platform.

1.3. Project Aims

The primary objective of this project is to integrate malware detection into MinIO without compromising the platform's scalability or performance. The solution must be able to detect malware within files uploaded to MinIO and deal with them accordingly. The solution should also be as production-ready as possible and offer the required features customers desire in the real-world. This includes; the ability to configure the solution, provide both metric collection and audit logging for monitoring, and the ability for it to scale to meet the users demand.

From a personal standpoint, this project serves as an opportunity to enhance my knowledge of the Go programming language and the MinIO platform. Additionally, it aims to expand my experience in designing and implementing production-ready solutions within a microservice environment. Lastly, this project seeks to develop my proficiency in managing time, scope, and resources for large-scale projects.

2. Background

2.1. Signature Detection

Signature-Detection is a method used to detect malware within files. A signature is a string that represents a malicious file (Liao *et al.*, 2013). These signatures come in multiple forms; including MD5 hashes, to represent whole-files (Aslan *et al.*, 2020), byte sequences, which can be matched internally or regex patterns, often written in YARA (Nitin *et al.*, 2019), to allow for more fuzzy matching. If malware were to have a different signature than the one present in the virus database, fuzzy matchers like YARA could be used to compare more abstract properties of the file using a set of rule (Nitin *et al.*, 2019). These rules are reverse engineered from known malware to include common indicators of compromise (IOC) like text or hex strings (Nitin *et al.*, 2020).

However, signature detection is not foolproof. It is ineffective against unknown malware or significantly modified variants of existing malware (Liao *et al.*, 2013). This requires frequent updates to the signature database to ensure that knowledge of new malware is kept up to date. In addition, YARA rules can be generated automatically but are often not as effective as manually generated ones (Nitin *et al.*, 2019).

2.2. Malware Detection with ClamAV

ClamAV uses the latest signature-based detection techniques to scan files located on the disk (Kil *et al.*, 2011). It is the most popular open-source antivirus software and has already been optimised to use less memory and to speed up signature matching (Kil *et al.*, 2011). ClamAV pulls its signatures from an online database which contains two types of signatures, MD5 whole-file

signatures and multi-part patterns (Po-ching *et al.*, 2006). ClamAV uses both of these signatures in its detection process, firstly prioritising the single sequence signatures and if no match then using the multi-part patterns (Po-ching *et al.*, 2006). ClamAV has frequent updates to its signature database to negate the disadvantages of signature detection (ClamAV, 2023a).

2.3. Microservices

Microservices are a software development technique that structures an application as a collection of loosely coupled services with high internal cohesion. This allows for each service to be independently deployable into logical business functions providing a high level of scalability and flexibility (Nuha *et al.*, 2016). Cloud-native applications are often built using a microservice architecture to take advantage of scaling for variable demand (Nuha *et al.*, 2016). Developing a microservice also comes with challenges that should be addressed, such as service discovery, load balancing, and inter-service communication (Nuha *et al.*, 2016).

Microservices are often deployed using containerisation technologies, orchestrated by tools such as Kubernetes (Abdollahi Vayghan *et al.*, 2018). These containers are housed within pods, the smallest and simplest unit in the Kubernetes object model that encapsulates an application's container (or group of tightly-coupled containers), storage resources, a unique network IP, and options that govern how the container(s) should run (Abdollahi *et al.*, 2019).

Each pod is deployed onto a node, which represents a single machine in a Kubernetes cluster. This node could be a physical machine in a datacenter or a virtual machine in a cloud environment (Abdollahi *et al.*, 2019). Nodes host one or multiple pods and provide the runtime environments for those pods' containers.

For larger deployments, multiple nodes are organised into a cluster, managed by a master node that coordinates activities across worker nodes (Abdollahi *et al.*, 2019). This setup allows a microservice architecture to fully leverage the scaling and resiliency features offered by Kubernetes (Abdollahi Vayghan *et al.*, 2018).

Communication within and across these nodes, pods, and containers is a vital aspect of a microservice architecture. Internally, containers within a pod can communicate with each other directly, while inter-pod communication is managed via the Kubernetes networking model (Narūnas, 2020).

Kubernetes facilitates exposure of services outside of the cluster through methods like NodePort, LoadBalancer, Ingress, and ExternalName, each offering different capabilities and trade-offs (Abdollahi *et al.*, 2019). For instance, NodePort opens a specific port on every node, while LoadBalancer and Ingress are typically used in cloud environments to route incoming traffic, and ExternalName maps a service to a DNS name (Abdollahi *et al.*, 2019).

2.4. Amazon S3 Malware Detection

As MinIO's largest competitor, this project draws a lot of inspiration from Amazon S3's integrated malware detection article (Srinivasan *et al.*, 2022). The article explains Amazon's current approach for managing malware detection within their service. Amazon S3 uses a combination of ClamAV and Sophos as their third-party scanning engines due to their out-of-the-box nature

(Srinivasan *et al.*, 2022). Amazon then gives you the option to use either of these engines or both. The article goes on to describe the three main interaction mechanisms that Amazon S3 uses to flag files for scanning. Firstly, an API endpoint is provided to handle all uploads. This forms a queue of uploads which are then scanned before entering the bucket. Next, event-driven scanning is used keep track of all regular file uploads. The antivirus will then scan each file after they have been written to the bucket. Finally, retro-driven scanning is used to scan all existing files within the bucket. The user then has the flexibility to define what types of files should be scanned including defining time windows. This article has given some useful methodologies of how to keep track of both incoming and previously scanned files. Creating a system that can match these methods is important for offering a matching level of scalability and security within MinIO.

3. Specification

The purpose of the project specification is to guide the project towards achieving the goals outlined in the previous section. The specification is divided into three main categories; functional requirements, non-functional requirements and constraints.

The MoSCoW method is employed to prioritize the projects requirements. It is a prioritisation technique utilised in business analysis and software development to establish a shared understanding among stakeholders regarding the significance assigned to the delivery of each requirement (Gita *et al.*, "2018"). The acronym stands for:

- Must have: Critical for the project's success and must be included in the final solution.
- Should have: Important but not absolutely necessary for the project's success. They should be included if possible, but the project can proceed without them.
- Could have: Desirable but not essential. They can be included if time and resources permit but can be left out without impacting the project's success.
- Won't have: Not necessary for the current project and will not be included. They may be considered for future development.

3.1. Functional Requirements

Functional requirements are provided in the table 1. The requirement is given with a MoSCoW priority and a description to justify the priority.

Requirement	Description	Priority
Provide a way of detecting the latest uploads to the object store.	Key aspect of automatically dispatching scans based on upload. Must keep track of all uploads with no loss of data to ensure that all files get scanned.	Must
Record the results of the malware detection within the object store.	Must provide feedback to the user informing them of the result from the scan. Relevant information must be provided such as, result and time scanned.	Must
Provide the ability to measure key performance and analysis metrics.	Metric collection is very attractive for satisfying production-ready status. Also vital for viewing overall system health and proving that no data has been lost.	Must
Scale alongside MinIO to ensure that it does not bottleneck the object store at high loads.	To handle maximum throughput, the solution should scale alongside MinIO. This prevents the object store from being bottlenecked by the solution.	Must
Provision for future expansion and ongoing maintenance.	Having the ability to build on-top of the project will increase the attractiveness to users looking to migrate from AWS.	Must
Must be cost effective and legally viable for commercial use.	As the solution is targeted towards industry use, it must only use software that allows it to be used in production. This include compliance with licenses and regulations, cost-effective software and redundancy if an external software were to become unusable.	Must
Have a high level of customisability to allow for different use cases.	Gives flexibility to the user but is not a requirement for proof of concept.	Should
Allow for efficient and transparent debugging in the event of failure	Creating a robust product mitigates the priority of debugging.	Should
Add more complex metrics - Histogram, Gauges, etc.	Additional metrics are more beneficial in a production environment but unnecessary for size of project scope.	Should
Provide the choice of multiple antivirus engines	Not necessary for the proof of concept as it requires too much time.	Could
Provide a warning when under “delete” cleanup policy.	Not necessary for the proof-of-concept as it requires too much time.	Could
Automatically setup bucket notifications to be sent to the event queue.	Can be completed manually with instructions instead. Removes customisability from the user if done automatically.	Could
Supply the MinIO policies the solution will use e.g. “put” and “get”.	MinIO denies by default and therefore operations could fail when MinIO is not run with admin permissions.	Could
Prevent the downloading of files if flagged as infected.	Is covered by cleanup policies. Would also require GUI changes.	Won't
Protection from “inside man” attacks.	The system will be maintained by an admin. The admin could attempt to compromise the system. Protection against this is significantly harder without reducing extensibility.	Won't
Provide multiple types of scanners e.g. hash or server based AV scanner.	These would have different workloads and requirements. Not achievable in project scope.	Won't

Table 1: Functional Requirements

3.2. Non-Functional Requirements

Requirement	Description	Priority
Speed	The solution must be able to keep up with the rate of uploads made to MinIO. This can be measured by including a metric that records the scan time of each request which can then be used to find average scan time.	Must
Scalability	The solution must scale to meet the demand of the incoming requests. This can be done with scaling up, across or both.	Must
Availability	Over a long period of time, the solution must be able to handle all requests. This can be measured by comparing the number of requests made to the number of requests completed over a large time frame.	Must
Reliability	100% of the files uploaded to MinIO must go through the scanning process. The recorded metrics can be used to compare MinIO uploads with the number of objects scanned. It is worth noting that checking the clean and infected results add to the total sum of scanned objects.	Must
Capacity	The solution should be able to handle the maximum number of simultaneous requests that MinIO can handle. This can be measured by monitoring the amount of cache used by the solution under load.	Should
Usability	Future additions, maintenance, and debugging should be as simple as possible. This requirement is more subjective and therefore an explanation of how this has been achieved will be discussed in the implementation section. Prolonged use of the solution should be enabled by recording dependency versions.	Should
Security	The solution could implement the best practices for security, including data protection and secure communication between components. This is less of a priority as sensitive information is kept within the Kubernetes deployment and all external interaction is handled by MinIO's internal authentication.	Could
Privacy	The solution is not directly responsible for following privacy laws and regulations, such as the DPA (Government, 2018).	Won't

Table 2: Non-Functional Requirements

3.3. Constraints

The primary constraint for this project is the strict 12-week timeline, which significantly restricts the project scope. To overcome this constraint, careful prioritisation of features and efficient time management for their implementation is crucial.

Another constraint is the requirement that all external software used must be open source, available for commercial use under a license, or require a fee. This ensures the project's legal viability if the solution is to be employed commercially.

Lastly, my personal knowledge and experience pose constraints on the project. The learning curve for new technologies may extend the average time needed to achieve milestones. Moreover, potential errors could result in unforeseen delays. As a result, when selecting technologies, factors such as ease of use, documentation, and community support should be considered to minimise the impact of these constraints.

4. Architecture

Choosing the correct architecture for the project is critical for ensuring that the solution is scalable, performant and maintainable. Given the specification above, various potential architec-

tures can be created and evaluated based my own thoughts and from reading the background material. The best candidate design will then be chosen based on which design satisfies the most requirements with as little compromise as possible. Thought will also be given to which architecture fits within the constraints of the project.

Project Naming

Due to the defined functionality of the solution, an suitable name can be chosen. “Aegis” is the name of the shield that Zeus used to protect himself in Greek mythology and is also a noun synonymous with protection (Dictionary, 2023). This is appropriate given that the solution is designed to protect the MinIO object store from malware. Aegis will be used synonymously with the solution throughout the rest of the report.

4.1. Candidate Design 1 - Post-Write

The first candidate design makes use of the performance benefits of MinIO by allowing puts to be initially written to the bucket without being scanned. The design then uses a event queue compatible with MinIO to keep track of all the files that have been uploaded. The queue is then used to trigger a scan of the file once an antivirus engine is available. The candidate design is shown in Figure 1.

This design has many benefits over other potential implementations. Firstly, it uses the storage provided by MinIO to store all incoming files without having to manage a large temporary storage. This removes complexity from the solution by not having to account for a number of failure conditions that could occur with a high availability, production ready storage solution. For example, the solution would not be responsible for handling partial writes, loss of data, or data corruption. Removing this responsibility allows the solution to focus on the core functionality of the project, the scanning of files, which is essential for keeping the project within the time constraints.

Secondly, the design also makes use of the integrated event queue provided by MinIO. This again removes responsibility from the solution by differing the scalability and reliability requirements to the event queue and MinIO.

Lastly, having Aegis dispatch the files to a scalable number of antivirus engines allows the solution to scale to meet the demands of the system. This meets a key requirement as the solution is expected to have the capacity for a large number of operations. This method require the use of a load balancer to effectively distribute the load across the available antivirus scanners.

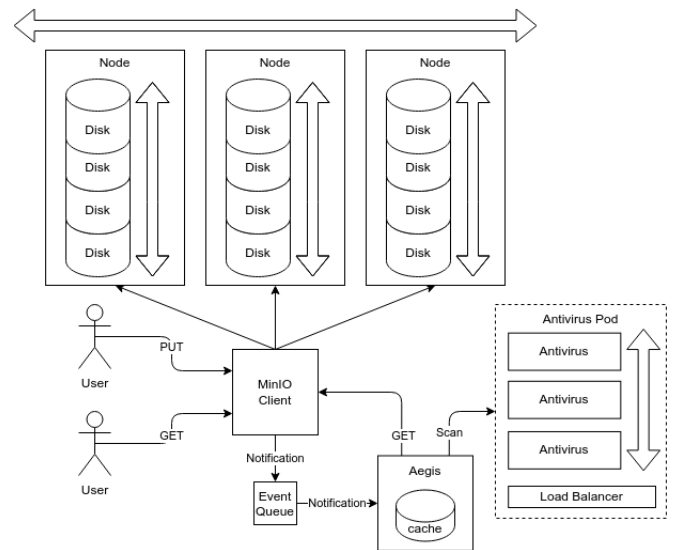


Figure 1: Post-Write Architecture

The candidate design also has a number of drawbacks. Firstly, the design still requires a small amount of cache to temporarily store the object when it is being dispatched to the antivirus. Provisioning of this cache has to be large enough to handle the largest file possible to be uploaded to the object store. In reality, this cache would be provisioned even larger to allow for the temporary storage of multiple objects while multiple scans are being performed asynchronously. In addition, the cache needs to be large enough to ensure that the system does not become overwhelmed by the number of objects being scanned as the system scales. This is a minor issue as store capacity is cheap and the provisioning of the cache easy to scale up. Additionally, a higher priority can be given to scaling up and out antivirus engines to ensure that the smallest number of files are being cached, while being scanned, at any point.

The second drawback is that, for each event, Aegis makes a get request for the object to be scanned. This effectively doubles the number of requests made to the object store. This also means that Aegis must have the ability to get any file expected to be scanned and therefore must have access to the whole storage network. The impact of this drawback is mitigated as the solution is expected to be deployed on the same network as the object store which should reduce the latency of each request made by Aegis. However, this still leaves MinIO to handle twice as many requests with the performance loss being noticed mainly on more distributed storage topologies.

Thirdly, the candidate design only allows for a single Aegis instance to dispatch all incoming objects to available scanners and antivirus engines. This is a potential bottleneck for the system as this instance could become overwhelmed by the number of requests it is receiving. This is a minor issue as the dispatching of objects to scanners is not as performance intensive as other areas of the solution, such as the actual scanning, and therefore it is not expected to be a major bottleneck.

Lastly, any object uploaded to the store will have a certain period of time where it remains unchecked. In this time, the user could potentially download an unscanned object or the object could cause harm to the store before it is detected. Although displaying warnings when downloading unscanned or infected objects is out of scope, in an actual implementation of the solution, GUI changes would be needed to display these warnings.

This design is similar to the event-driven architecture used by Amazon S3 (Srinivasan *et al.*, 2022).

4.2. Candidate Design 2 - Upload Queue

This candidate design created a wrapper around MinIO that the user interacts with instead of MinIO. This means that all puts go through Aegis before being uploaded to the object store. The candidate design is shown in Figure 2.

The main benefit of this design is that the user interacts only with Aegis when uploading files. This means that all incoming files can be stored within a temporary storage before ever entering the object store. This offers the best protection against malicious files as the user cannot ever download an unscanned or infected file as it is never uploaded to the object store. Infected files can then either be deleted or moved to a separate quarantine store for analysis.

This candidate designs main advantage also comes with a major drawback. This design requires Aegis to handle the full throughput of all the puts to the system. Aegis then has the full responsibility of being available to all puts and, in a failure scenario, to handle the recovery of the system. Additionally, the cache provisioned must be large enough to handle the largest files at maximum throughput with extra room for unexpected delays. This negatively affects the scope of the project by requiring the solution to prioritise features that are already covered by MinIO. Because MinIO is dependent on Aegis to handle the puts, MinIO must wait to be passed incoming objects sequentially after Aegis has finished processing the previous object. Therefore, all the performance benefits that MinIO offers are lost to time spent scanning. This leads to users waiting longer when uploading files before they are available to download.

This candidate design is similar to the API endpoint approach used by Amazon S3 (Srinivasan *et al.*, 2022).

4.3. Candidate Design 3 - Write Interception

Candidate Design three is very similar to the second candidate design, however, instead of wrapping outside the MinIO service, it intercepts the writes from the client before objects are written to the object store. With this interception, Aegis can scan the object and decide whether to allow the object to be written to the store or to quarantine the object. The candidate design is shown in Figure 3.

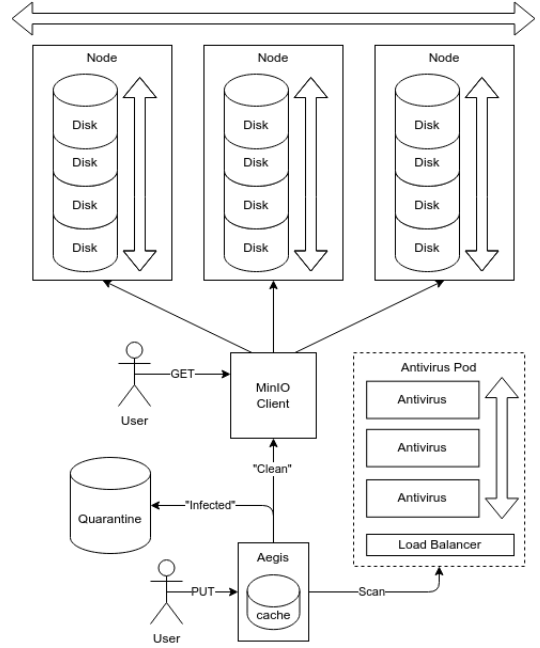


Figure 2: Upload Queue Architecture

This candidate design has similar benefits as the second candidate design. It offers the most protection against malicious files by never allowing either un-scanned or infected objects to be stored in the object store. However, it also has similar drawbacks. This is because Aegis is still in sequence with MinIO meaning that for optimal throughput, Aegis would need to match the performance of MinIO.

Similar to the upload queue candidate design, this design also requires Aegis to have a large cache to handle the largest files at maximum throughput. This cache must also be large enough to handle the number of objects being put by MinIO into the store. This issue cannot be mitigated without the risk of compromising performance at increased loads.

However, this design does have an advantage over the second candidate design as there is less responsibility placed on Aegis to be as failure tolerant. MinIO is still directly responsible for accepting objects into the store and therefore is still responsible for the recovery of the system in a failure scenario. This allows the scope to focus on more related features to malware scanning.

4.4. Candidate Design 4 - Per Node

The final candidate design distributes Aegis onto each node in the object store. This means that each node has a local instance of Aegis that is responsible for scanning objects before they are written to the store. The candidate design is shown in Figure 4.

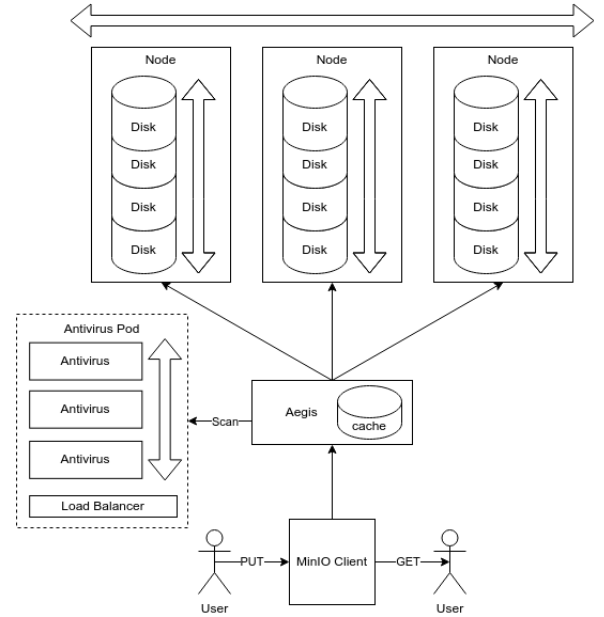


Figure 3: Write Interception Architecture

This candidate design makes use of the distributed nature of MinIO to match the demand when scaling out the system. As more nodes are added, more Aegis instances are added to handle the increased scanning demand. This removes the need for having a cache repository as Aegis already has access to the files that need scanning. By removing this single point of failure, in theory, the system only relies on the antivirus pod to be able to scale out on its own.

Independent scaling of the antivirus pod allow for efficient usage of available hardware. A simple load based auto-scaler can be used to scale the number of pods based on the current load. This allows for the system to scale with the demand of the system or to reduce usage of valuable resources, such as power. There is also the opportunity to use intelligent scaling techniques to predict the load on the system and prematurely scale the system to meet the demand. For example, to scale the number of pods depending on the time of day or the day of the week.

The major drawback of this candidate design is that it relies on the ability to scan whole files by only using data on a single node. In actual implementations, MinIO makes use of erasure coding to add increased redundancy to the store (MinIO Erasure Coding, 2023). Erasure coding splits objects into multiple parts known as blocks, and then calculates corresponding parity blocks. These data and parity blocks are then distributed among all nodes in the system allowing for on-the-fly data recovery even with the loss of multiple drives or nodes. This means that the Aegis instance on each node only has access to the part available on their node and therefore will not be able to reconstruct the whole file for scanning. This makes this candidate design unsuitable for MinIO as erasure coding is one of its key data protection features.

4.5. Selected Candidate Design

Given the above evaluations of each candidate design, design one best meets the requirements and constraints of the project. It makes the most use of the existing features that MinIO provides in order to handle failure scenarios and to scale out. This also means that this design has less critical responsibility and will better fit the scope constraints allowing for more time to be spent on supplementary features, such as testing, logging, and metric collection. Because of this, the produced solution will be closer to production-ready than the other candidate designs.

This candidate design keeps the user in control by giving them the ability to store unscanned files / known malware without wasting resources on a scan. Protection can be added per bucket

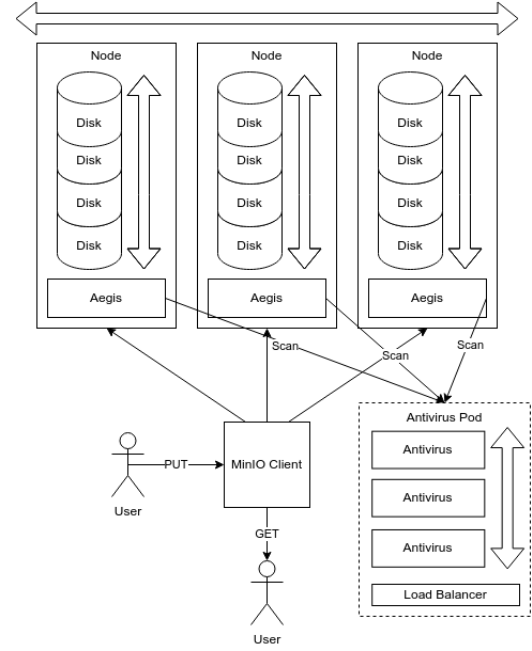


Figure 4: Antivirus per Node Architecture

therefore a user could have a known malware bucket and a clean bucket within the same object store. This allows for the system to be more flexible and to be able to handle more use cases. Candidate Designs two and three would not be as able to handle this use case as they both scan all objects before they are written to the store.

The size of the cache required is smaller than all other candidate designs as it only needs to store the objects actively being scanned. This is in opposition to upload queue and write interception candidate designs as they have to be prepared to handle the full demand placed on the store. This makes candidate design one the most lightweight of all the candidate designs which should lead to a smaller resource footprint.

In the event of an error or high demand, a backlog of requests would be stored on the event queue enabling system to recover from a failure scenario without losing any scan requests. This is in contrast to the other candidate designs where the incoming requests are directly handled by Aegis and in the event of a failure or high demand, the requests would be lost. This is an example of event driven architecture (EDA), the asynchronous processing of events, being used to improve the reliability of the system (Svetoslav and Anna, 2019).

5. Implementation

5.1. Service Selection and Creation

Throughout the implementation, the development of the solution followed a waterfall approach. The project's progress was determined by milestones outlined in the project plan Gantt chart, which can be found in the appendix at Figure 18. As this is a solo project with a limited timeline, the waterfall methodology is a better fit than an agile methodology as agile caters more to larger teams with longer timelines where the requirements are less concrete.

Before beginning to implement the solution, it was necessary to research, create, configure, and understand each external service that would be used. Up to this point, the types of services needed were identified, but the specific services to be used had not been determined. This section will describe the process of selecting each service and then initially configuring them to form a bare-bones proof of concept.

Object Store - MinIO

The object store is the only service that did not require further research or comparison as it is already the subject of this project. However, creating and configuring a local instance of MinIO for development was necessary. MinIO itself is available from various sources, including Docker, Homebrew, and the MinIO website. Homebrew, a MacOS package manager, was chosen as it is the easiest to install and update. The MinIO documentation was then used to create a local instance of MinIO accessible through the web client at <http://localhost:9000>. This allowed for the creation of buckets, uploading objects to the store, and familiarisation with MinIO's features. An image of the MinIO console is available in the appendix at Figure 19.

MinIO has integrated the ability to send notifications to event queues depending on the operation performed on the store. This makes it quick and easy to set up a locally running instance of an event queue to read messages sent by MinIO. MinIO offers wide support for many different event queues, such as Kafka, Webhook, Redis, PostgreSQL, and many more.

Event Queue

An event queue is needed to store the incoming events produced from MinIO whenever a put event is triggered. The event queue must be able to handle a high throughput of events and be able to scale out to meet the demand of the system (Svetoslav and Anna, 2019).

Kafka is a popular and well-supported event queue that is used in many different industries (Svetoslav and Anna, 2019). It offers many features that make it a good choice for this project, such as high-throughput, low latency, and open-source. Kafka is also available from both Docker and Homebrew, making it easy to install and run locally. Most modern event queues offer similar high throughput and low latency, but Kafka is lighter in resource usage than other queues, such as RabbitMQ (Levy, 2022). This is beneficial as it will be easier to implement and not overuse resources when it has a simple use case.

Kafka has a dependency on Zookeeper, which is a distributed coordination service (Svetoslav and Anna, 2019). Zookeeper must be installed as a separate service but is available from the same sources as Kafka. Kafka can be run in Kafka Raft mode (KRaft), which will eventually replace Zookeeper, but as of writing KRaft, has not been fully adopted yet (M, 2022).

With Kafka and Zookeeper set up, the Kafka command line interface (CLI) was used to start the service and create a topic. The MinIO documentation was then used to configure MinIO to send all put notifications to the Kafka topic. The Kafka CLI was used to read messages from the topic and see the messages sent by MinIO. This demonstrated that the event queue is working and that MinIO is sending messages to it whenever a put operation is performed. An example Kafka message is available in the appendix under listing 1.

Antivirus

The antivirus chosen needed to meet a list of requirements for it to be suitable for use in this project. Firstly, it must be able to scale with the solution in order to keep up with the demand placed on the system. Secondly, it must have a CLI that the program can interact with in order to scan files. Finally, it must be free or as inexpensive as possible to make it viable for commercial use. This narrows down the available options to a few contenders.

Sophos is a popular antivirus that is used by many businesses and is available for free for personal use. However, it has some major downsides. It is more costly for commercial use than ClamAV and uses more naive signature detection techniques as stated in (Ormandy, 2011). This makes it less suitable for this project.

ClamAV, on the other hand, is completely free and open-source. It comes with a scalable and multi-threaded daemon that can be accessed via CLI for high-performance and on-demand file scanning (ClamAV, 2023a). It is capable of scanning many different file types, including archives and mail files. Built-in is freshclam, a tool for automatically updating the virus database definitions. The virus database itself is also open-source and is updated regularly by the open source community. Although ClamAV is not the fastest or most accurate antivirus, it offers a good starting point to building a solution with multiple antivirus engines for higher accuracy as stated in (Omer, 2017). ClamAV has a docker image and is available from Homebrew.

ClamAV was chosen for this project because it is entirely free for commercial use, open-source, and has a CLI that can be used to scan files. It is also very well documented and has a large community of users who regularly update and maintain the virus database.

ClamAV comes with a daemon, `clamd`, that can be run in the background and can be accessed via a CLI using `clamscan`, the `clamd` client. A configuration file is needed to point `clamscan` to the IP address that the daemon is running. In this case, it is running locally on port 3310. Performing the `clamscan` command and providing a file will scan the file and return the result. An example of this is available in the appendix in listing 2.

Aegis will be designed so that it can be easily extended to support multiple antivirus engines aggregated together for higher accuracy (Omer, 2017). Initially, only ClamAV will be implemented.

Metric Collection

As the project is expected to be as production-ready as possible, a system for collecting metrics is needed. This will allow the system to monitor its activity for easier maintenance, debugging and to aid in the evaluation section of this report. A few different options are available for metric collection, such as Prometheus, InfluxDB, and Graphite with Prometheus being the best option as it is open-source and the most popular metric server. It uses a pull model which periodically scrapes metrics from a specified address and endpoint. Prometheus then aggregates the results from the scrape and stores them in a time-series database (Prometheus, 2023). This database can be queried through Prometheus or exposed to another graphing service, such as Grafana.

Prometheus also has the ability to gather metrics short-term processes via a push gateway which pushes metrics on completion instead of waiting for the scrape period. However, this is not needed for this project as centralised metric collectors will be used to continually aggregate and expose metrics. Prometheus is available for download from Homebrew as well as a Docker image available.

Prometheus is currently unusable as it is not being sent any metrics to collect. However, the Prometheus server can still be launched, and the web interface can be accessed on port 9090 (Prometheus, 2023). In the meantime, a configuration file can be created, defining the address and endpoint expected to be exposing metrics to, in this case, address `localhost:2112` and `/metrics`.

Audit Log Store

Production-ready software should have a method to store logs for auditing and analysis purposes. A central database can be used due to the relatively low amount of data needing to be written and stored. The audit log's purpose is to store information about the scans performed by the system, such as the time and result of the scan, as well as the antivirus used. In the case that the scan returns an infected result, the type of malware found should be recorded. This allows the system to review previous scans, which can aid in debugging and maintenance.

PostgreSQL is an open-source object-relational database management system compliant with SQL standard queries (Joshua and John, 2002). Since the use case is simple, SQL queries can be used to perform all actions needed when recording audit logs shown in the PostgreSQL guide (Bruce, 2001). PostgreSQL is also available from both Docker and Homebrew.

At this stage, PostgreSQL is not yet storing any data. However, the PostgreSQL server can be launched, and the database accessed via the PostgreSQL shell prompt (`psql`). A database and a user for the database can be created. The database can then be exposed to port 5432 on the `localhost`, making it ready for Aegis to use.

Data Visualisation

The final dependency that needs to be configured is a data visualisation tool. This will not directly be implemented into the microservice but instead will be connected to Prometheus to display the metrics collected. Grafana is a popular open-source data visualisation tool that allows you to visualise and query the metrics produced (Vivek, 2022). Grafana enables the creation of dashboards that can display multiple relevant metrics in a single view. Data visualisation will be an important part of this project for both the evaluation section and for the system's ongoing maintenance.

5.2. Aegis Module Design and Creation

Now all of the dependencies have been downloaded, initialised and configured, the Aegis Go module can be created. The most common language to use for microservice based projects is GoLang. Go is a compiled language that is statically typed and high concurrency support. This makes it a perfect fit for this project to ensure that the system is as performant as possible. MinIO is also written in Go should allow for easier integration. Go has certain standards and guidelines for clean architecture that should be followed to ensure high usability and efficiency.

Go introduces some specific language that are commonly used during the project (Go, 2023). A list of common terms and their definitions are available in table 3.

Go Specific Term	Definition
Go keyword	Launches a function as a goroutine, which is a lightweight thread managed by the Go runtime, enabling concurrent execution.
Select	Waits on multiple communication operations, typically used with channels, to handle different cases depending on which operation is ready.
Switch	Multi-way branching statement that allows conditional execution of code blocks based on the evaluation of an expression or comparisons.
Goroutine	Lightweight thread managed by Go runtime, allowing concurrent execution of functions without the overhead of managing traditional threads.
Channel	Communication mechanism between goroutines, allowing them to synchronise and share data, providing a way to safely pass data between them.
Struct	Composite data type for creating custom structures composed of different fields, useful for grouping related data together.
Package	Collection of related Go source files organised under a specific namespace, allowing code organisation, reuse, and dependency management.
Module	Collection of related Go packages, providing versioning and dependency management, simplifying the process of building and sharing Go code.
Capitalised first letters	All functions, variables and types that are intended to be exported outside of a package must be capitalised.
Defer	Defers the execution of a function until the surrounding function returns.

Table 3: Go Specific Terms and Their Definitions

Project Structure

In Go you should separate the code into different packages, where each package represents a distinct function of the system. This allows for easier maintenance and debugging in the future. These packages are then grouped into different directories depending on their intended scope and function. There are three main directories that are used in GoLang projects, cmd, pkg and internal. The cmd directory is used to store the main.go file which manages the workflow and is the entry point of the program. The pkg directory is used to store all of the packages that

are intended to be used by external applications, in this case our other services. The internal directory is used to store all of the packages that are intended to be used by the application itself. This is where the packages in the pkg directory will be consumed to perform the Aegis' core actions as follows:

- Listen for PUT events on the event queue
- Read the message from the event queue and extract the bucket and object path
- GET the object from the object store and store in cache
- Initiate a scan on the object using the antivirus software
- Collect the result of the scan and add tags to the object
- Collect metrics throughout the process
- Store the result of the scan in the audit log
- Expose metrics to Prometheus

From these requirements, the internal design of Aegis can be planned. We can visualise this plan using various UML diagrams such as, class, sequence and flow diagrams. Class diagrams are useful for understanding the relationships between different classes - in this case packages - and what attributes and methods they require (Doaa *et al.*, 2022). It is worth noting that Go itself does not have classes but instead uses structs which can be used to achieve the same effect. Sequence diagrams are also valuable for understanding the timeline of the system during the execution of a workflow (Yang, 2009). Flow diagrams are useful for visualising the flow of processes and decisions during a workflow. This class diagram is shown in the appendix at Figure 20 along side with a both the sequence and flow diagram at Figures 21 and 22 respectively.

From this diagram a file structure can be created inline with Go standards. Go comes with a CLI tool used to initialise a new go module, which is a collection of packages that are intended to be used together. This tool will create a go mod file which is used to define the module and its dependencies. This tool will also create a go sum file which is used to store the hashes of the dependencies to ensure that the same version is used across all environments. Now go commands can be used to install go dependencies and then download them to a local vendor folder for use in building. Building the project is also done with the go CLI. All binaries are stored within the build folder. The initial project structure is shown by the Figure 5.

Version Control

Considering the size of this project, version control is necessary to ensure maintainability and the availability of a backup. Git, in combination with GitHub, was chosen for version control due to its widespread use, familiarity, and cost-free nature. The Git CLI was used to initialise a new repository within the

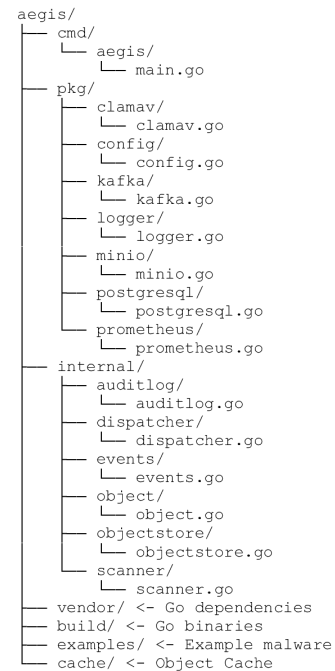


Figure 5: Aegis' Initial File Structure

root directory of the Go module. Additionally, a `.gitignore` file was created to prevent unnecessary files from being tracked by Git, such as, the vendor or build folder.

To maintain usability, commits to the remote GitHub repository will be made after each significant change to the project, accompanied by relevant commit messages. This approach facilitates easier tracking of changes for debugging and maintenance purposes.

Structured Logging

Structured logging is a method of logging that allows for easier parsing of the log messages by adding structure to the message (Dileepa, 2012). This is done by adding key value pairs containing relevant information to the log message. This enables for easier filtering and searching of the logs. This is especially useful when using a log aggregation tool such as, Splunk or LogRhythm (Dileepa, 2012).

Go has many external modules that can handle this type of logging including Zap by Uber. Zap is a very fast and efficient logging library that can be configured to change the level of logging output, such as for info or debug useful for production or development respectively (Uber, 2023). Zap also has the ability to change between structured and unstructured logging depending on the use case. Structured logging comes with the drawback of being less human readable than unstructured logging and therefore Zap offers the ability to change between the two (Uber, 2023).

As Zap is an external module, it must be added as a dependency and all code contained in the pkg folder. A package called logger is created to encapsulate all logging functionality. This package contains two go files, one for interacting with the Zap and one for defining the structure of the log commands inside of an interface. In Go, it is idiomatic to keep the interface as close to the implementation as possible. Keeping the interface in the same package as the implementation allows for easier mocking of the package when testing. This package goes against this by containing the interface within the repository because multiple packages will need to use the same interface when interacting with them. This reduces code duplication as we don't have to define the interface in each package that uses it, which in this case would be every package.

Configuration

As Aegis is a microservice, it is important that it is configurable to allow for easy deployment to different environments. This is done by using a configuration file in tandem with Viper, a Go module that can read in the configuration file (Francia, 2023).

This configuration file contains all of the values that are likely to change between environments. This includes values such as the endpoints, ports and credentials of external services, logging options and database names. This configuration file will be a dotenv file which is a key value store of environment variables. This is beneficial as Viper has the ability to automatically override the config file with environment variables if the same key is found. This allows for easier configuration of the application when it is built locally or deployed in a Kubernetes cluster. This gives the user the ability to tailor the deployment to their needs or existing implementation.

Much like the logger package, the configuration package contains two go files. A repository file that defines the interface and a config file that contains the Viper configuration.

Adding both the configuration and structured logging as the first packages reduces the need for

refactoring in the future. No hard coded values are needed for initial development as all values can be stored in the configuration file from the start.

Makefile

A Makefile is a file that contains a set of instructions that can be run from the command line (GNU, 2023). These instructions are used to automate processes such as building, testing and deploying. Through the project, longer workflows will be automated and put into the Makefile to reduce the amount of time spent on running commands. Makefiles also simplify the usage of program by users by encapsulating complex commands into an explicit action the user can understand. Makefile commands can also be used by the Dockerfile when building the application in a container.

5.3. External Package Integration

With the dependency services still running, the next step is to integrate them into the Aegis application using Go. This is done by creating a new package for each of the services within the pkg folder. Each package will contain a go file for each of the services that will later be consumed by Aegis' internal workflow.

One significant advantage of separating external services from internal implementation is that it allows for a higher level of abstraction from the services used. This abstraction provides flexibility in the use of multiple external services that fulfill the same purpose, such as multiple antivirus scanners. The creation of external packages allows for the use of a single internal implementation for all of these services. This reduces the need for extensive changes in the future, making the application more maintainable and scalable.

MinIO

The initial external service to be incorporated is MinIO. The MinIO package manages interactions with the MinIO service. For this project, the required operations include getting, putting, and removing objects, as well as getting and putting tags. MinIO provides a Go Software Development Kit (SDK) that already supports these operations in Go (MinIO, 2023a). The SDK simplifies the complexities of making requests and offers straightforward methods for operations such as putting and getting, as well as accessing type definitions like tags.

Once the MinIO SDK is imported, a new MinIO client object is generated to communicate with the MinIO service. The `CreateMinio` function accepts essential connection parameters, such as a context, an endpoint, access and secret keys, and an SSL usage flag, and initialises the MinIO client using the `minio.New` function. This client object is then incorporated into a custom `Minio` struct, along with a logger. Various methods are implemented for the `Minio` struct to execute different object storage operations:

- `GetObject`: Retrieves an object from a specified bucket and returns its data as a byte slice.
- `PutObject`: Takes in a byte stream and uploads it to a specified bucket with a specified object name.
- `RemoveObject`: Removes a specified object from a specified bucket.

- `GetObjectTagging`: Fetches the tags associated with an object and returns them as a map of key-value pairs.
- `PutObjectTagging`: Replaces the existing tags of an object with a new set of tags provided as a map of key-value pairs.
- `AddObjectTagging`: Adds new tags to an object by first fetching the existing tags, updating them with the new key-value pairs, and then setting the updated tags back to the object. Necessary for not overriding existing object tags that may exist.

All of these methods take in a context which is used in the shutdown process to close the connection to the MinIO service. This context is passed in during the creation of the `MinIO` struct so that all methods have access.

Kafka

The next external service to be integrated is Kafka. The Kafka package will handle the interactions with the Kafka service. For this project, the operations needed are to consume messages from a specified topic. Kafka provides a Go library, *kafka-go*, which simplifies the consumption of messages in a Go application (Segmentio, 2022).

The package imports necessary dependencies and creates a custom `KafkaConsumer` struct, which embeds a `kafka.Reader` object and a logger. The `CreateKafkaConsumer` function initialises a new `KafkaConsumer` instance by taking connection parameters such as the list of brokers, the topic to be consumed, a group ID, and a maximum number of bytes per message.

- `ReadMessage`: Uses the Kafka library to halt until a message is received from the specified topic. It then decodes it using the `decodeMessage` function, and returns the bucket name and object key.
- `decodeMessage`: Decodes a Kafka message by unmarshalling its JSON payload and extracting the bucket name and object key. If the message event is *s3:ObjectCreated:PutTagging*, it returns. This is required to break out of the infinite loop that is created when reading put events. Scanning and tagging an object will trigger another put event, which initiates another scan and tag. Specifically ignoring put tagging events prevents this feedback cycle.

During the shutdown process, the `ReadMessage` function is halted by closing the context passed in. This closes the connection to the Kafka service and therefore stops the reading of any new Kafka messages, leaving unprocessed messages in the event queue.

ClamAV

ClamAV is another external service to be integrated into the project. The primary operation needed for this project is scanning a file and returning the scan results. The ClamAV daemon can be interacted with through the command-line interface (CLI) using the `clamscan` command (ClamAV, 2023b).

Initially, a `ClamAVScanner` struct is created, embedding a logger. The `CreateClamAV` function initialises a new `ClamAVScanner` instance. Methods for the `ClamAVScanner` struct are implemented to perform various file scanning operations:

- `ScanFile`: Accepts a file path as an argument and scans the file using the built-in Go `exec` library to run the `clamscan` command with the `--config` flag set to use a custom

configuration file located at `clamav.conf`. The `exec` library enables the execution of external commands, providing the ability to interact with the ClamAV antivirus daemon. A process attribute is added, which starts the process in a different process group than the main execution. This approach aids in achieving a graceful shutdown later on, as calling a system interrupt terminates the entire process group (McKusick *et al.*, 2014). As a result, `ScanFile` can continue executing after the shutdown, ensuring that no scans are interrupted. The method returns `false` if the file is clean, `true` if infected, and the type of malware detected. If any errors occur during the execution, it returns `true` (infected) along with an error message, ensuring that the worst-case scenario is assumed when it comes to security.

- `findVirusType`: Takes the output from the `clamscan` command, extracts the virus type using regular expressions, and returns it as a string.
- `GetName`: Returns the name of the antivirus engine, in this case, "clamav". The name must be accessed through a method, as ClamAV will implement an interface that does not have access to any attributes.

This package can now implement the `Antivirus` interface given in the internal scanner package and be used as an antivirus engines. More external antivirus services can be created in the same way, as long as they implement the `Antivirus` interface, if they are needed in the future.

Prometheus

The Prometheus package is in charge of creating and managing an HTTP server that exports metrics from Aegis. It does this by providing a plaintext response containing the metrics in the Prometheus exposition format. The exposed endpoint is then used by the Prometheus server to collect metrics from Aegis.

- `CreatePrometheusServer`: Initialises a new Prometheus exporter by setting up a new HTTP server with the specified endpoint and path. The Prometheus handler, provided by the `promhttp.Handler()` function from the Prometheus Go client library, is linked to the given path, which serves the plaintext. Read and write timeouts for the HTTP server are established using constants since these values are not expected to be configurable.
- `Start`: Initiates the Prometheus server by calling the `ListenAndServe()` method on the HTTP server. An example of the generated plaintext output can be found in the appendix at listing 3.
- `Stop`: Handles the graceful shutdown of the Prometheus server by invoking the `Shutdown` method to close the HTTP server.

PostgreSQL

The package imports necessary dependencies and creates a custom `PostgresqlDB` struct, which embeds a `pgxpool.Pool` object and a logger. The `CreatePostgresqlDB` function initialises a new `PostgresqlDB` instance by taking connection parameters such as the user, password, endpoint, and database name. It also returns a `CloseFunc` function to close the connection when needed.

- `CreatePostgresqlDB`: Is responsible for establishing a connection to the PostgreSQL database and returning a `PostgresqlDB` instance. The function takes in connection parameters such as the user, password, endpoint and database name. Additionally, it returns

a `CloseFunc` function to facilitate a graceful shutdown of the connection pool when necessary. Instead of connecting straight to the database, the function uses a connection pool to manage connections. This allows multiple concurrent clients to perform operations on the database without having to wait for other clients to finish their transactions. In this case, when multiple files are being scanned at the same time and the results are being saved to the database, the connection pool ensures that a database connection is always available.

- `CreateTable`: Uses the connection pool to create a new table with the specified name if it does not exist. The table schema includes columns for ID, ObjectKey, BucketName, Result, Antivirus, Timestamp, and VirusType. The SQL query used to execute this operation is available in the appendix at listing 4.
- `Insert`: Uses the connection pool to insert a record into the specified table with values for ObjectKey, BucketName, Result, Antivirus, Timestamp, and VirusType. The SQL query used to insert is available in the appendix at listing 5.

The PostgreSQL instance is provided with a context to close the connection to the database when the application is shutting down.

5.4. Aegis' Internal Workflow

The internal workflow is the inner packages that make up the Aegis microservice. Previously, the packages created were for interacting with external services but now those services need to be utilised. The following packages are split up into logical processes for handling different parts of the workflow. A breakdown of these internal packages can be found in the appendix in Figures 20, 21 and 22.

Metrics and Collectors

The internal metrics collection comprises two primary components: the metric manager and various metric collectors specific to each package. The metric manager is responsible for managing interactions with Prometheus, which includes executing the `Start` and `Stop` methods for handling the starting and graceful shutdown of Prometheus respectively.

Each package contains a metric collector in a file named `metrics.go`. These collectors define the available metrics that can be collected and exported by the respective packages. The `promauto` library facilitates the creation of a global registry when the metric manager is initialised. This registry is accessed by all metric collectors to record the metrics they collect and is also utilised by the Prometheus exporter for publishing these metrics.

Object

The object package presents the `Object` struct as the internal representation of an object within the object store. It includes all methods and attributes related to an object, such as the object key (the path of the object within a bucket) and bucket name. Operations involving an object are performed within the object instance itself.

Since the object represents a concrete entity, there is no need for an interface when using it. This design choice allows the object to have attributes that can be accessed directly, without the need for getter functions.

The `CreateObject` function enables the creation of a new `Object` instance, given a specified object key and bucket name.

The `SetCachePath` method defines the cache path for an object by concatenating the cache path, bucket name, and object key, separated by slashes. This method is called when an update to the cache path is needed.

The `SaveByteStreamToFile` method stores an object's byte stream in a file. First, it checks if the path attribute is empty since, by default, no path is provided. It returns an error if this is the case, as other types of scanners may not always require this information to perform a scan. Next, it ensures that the file's parent directory exists, creating it if necessary. Lastly, the method writes the byte stream to the file using Go's built-in IO writer.

The `RemoveFileFromCache` method is responsible for deleting an object file from the cache. It tries to remove the file specified by the object's path attribute. If the removal is unsuccessful, it logs an error message and returns the error.

Events Manager

The events package includes the event manager, which is responsible for reading messages from the event queue and forwarding scan requests to the scanner. The `Kafka` interface provides methods for reading messages from the Kafka queue and closing the connection. The `EventManager` struct consists of four fields: a logger, a `kafka` instance for interacting with Kafka, a `scanChan` channel to forward scan requests and an `eventsCollector` for gathering metrics.

The `CreateEventManager` function creates a new `EventManager` instance, accepting the necessary arguments. The `Start` method of the `EventManager` takes in a context and then enters a loop that uses a switch statement to first check if the context has been canceled. If it has, it closes the `scanChan` channel, closes the Kafka connection and returns. Otherwise, it invokes the `ReadMessage` method of the `kafka` instance to read a message from the Kafka queue. Upon confirming that there is no error and the message is not nil, it increments the `eventsCollector` counter and creates a new `object.Object` instance with the received bucket name and object key. It then forwards the object to the `scanChan` channel for scanning.

Since the event manager runs within a goroutine, if an error occurs, it sends the error to the provided `errChan` channel.

Object Store

In the object store package, several structs and interfaces are defined to handle object storage operations. The `Minio` interface contains the abstract object store operations, such as; get, put and remove objects, as well as get and put object tags. These are also reflected by the `ObjectStoreCollector` in the form of metric counters that track the number of each operation performed.

Once the object store is created by the `CreateObjectStore` function, it can be used by the rest of the application to perform object storage operations. In addition to the standard object storage operations, two more operations are added to the object store: `MoveObject` and `AddObjectTagging`. These both combine multiple standard operations into one as follows:

- `MoveObject`: Retrieves an object from the source bucket, puts it into the destination bucket, and removes it from the source bucket.
- `AddObjectTagging`: Retrieves the object tags from the source bucket, adds the new tags to the existing ones, and puts the combined object tags onto the object.

Object Scanner

The scanner package provides the functionality for multiple workflows when it comes to scanning an object. In this instance, an object scanner refers to process of downloading the object from the object store, performing a scan with its antivirus engines, and then passing the result to the cleaner which will execute the cleanup policy. Having the ability to use multiple types of scanners allows for flexibility in the system as in the future, the workflow for scanning an object might change. For example, if one of the antivirus engines could require the hash of the file. In this case, another scanner called `HashScanner` could be created to handle this alternate workflow. For this project, the `ObjectScanner` will be the only type of scanner implemented.

The `CreateObjectScanner` function creates a new `ObjectScanner` instance with the following arguments:

- `logger`: A logger instance for logging messages.
- `objectStore`: An object store instance for downloading objects.
- `antiviruses`: An array of antivirus instances for scanning objects.
- `cleaner`: A cleaner instance for cleaning up objects.
- `auditLogger`: An audit logger instance for logging scan results.
- `scanCollector`: A scan collector instance for collecting metrics.
- Various configuration values, such as, `removeAfterScan`, `datetimeFormat`, and `cachePath`.

All instances passed to the `CreateObjectScanner` function are interfaced to both allow for future mocking and to allow for other abstract implementations of the interfaces. Namely, the `Antivirus` interface is implemented by the external antivirus engines.

The `ScanObject` method handles the workflow for downloading and scanning an object. It takes in an `object.Object` instance, which it fetches from the object store, and an `errChan` for returning errors. It then sets the object cache path by calling `SetCachePath` on the object. With this set, the scanner can perform a `GetObject` on the object store to retrieve the byte stream of the object and call `SaveByteStreamToCache` with the byte stream to save it to the cache.

The scanner can now perform a scan on the object by calling `Scan`, with the cache location, on every antivirus engine. If any of the antivirus engines detect the object as infected, then using the assume the worst mentality, the file is deemed infected. The object is then passed to the cleaner to execute the cleanup policy. During this execution various metrics are being collected by the `scanCollector` about the scan, such as, the number of clean or infected files, total files scanned and total errors encountered. In addition, audit logs are also generated by the `auditLogger` for each scan by each antivirus recording the object key, bucket name, antivirus name, scan result, timestamp and if infected, the virus type.

After performing the scan and dealing with the results, if the `removeAfterScan` flag is set to true, the object is removed from the cache after scanning.

The `ObjectScanner` is will be run within a goroutine, if an error is encountered during the scan, it will be sent to the provided `errChan`.

Cleanup Policies

As mentioned in the previous section, the `ObjectScanner` passes the object to the cleaner to execute the cleanup policy. The cleaner package defines how to react given a clean or infected result from the antivirus engines. Multiple policies are available in the `config.env` file to give the user flexibility in how they want to deal with infected objects. These policies include:

- Tag: Adds a tag to the object in the object store based on the scan result.
- Remove: Removes the object from the object store if it is deemed infected.
- Quarantine: Moves the object to a quarantine bucket if it is deemed infected.

In `CreateCleaner` function, a new `Cleaner` instance is created with a logger, object store, metrics and audit loggers, and various configuration parameters such as the cleanup policy and quarantine bucket.

The `Cleanup` method is called by the `ObjectScanner` where is passes the object after it has been scanned. This method uses a switch statement, shown in Figure 6, to determine which policy to implement and executes the appropriate cleanup method. If no policy is specified, the switch statement has a default case. In the case that a user wants only the audit log, only a logger message will be provided. However, when a cleanup policy is given, the corresponding cleanup method is called. Each of these use the object store and object store to perform the cleanup.

```
switch c.cleanupPolicy {  
case "tag":  
    err = c.TagInfected(object, result, scanTime)  
case "remove":  
    err = c.RemoveInfected(object, result, scanTime)  
case "quarantine":  
    err = c.QuarantineInfected(object, result, scanTime)  
default:  
    c.logger.Warnln("No cleanup policy found")  
}
```

Figure 6: Cleanup policy switch statement

Dispatcher

The dispatcher package is responsible for managing the scanning of objects using multiple scanners concurrently. It defines a `Scanner` interface with a single method, `ScanObject`, that will be implemented by one of the available scanners. The `Dispatcher` struct contains three fields: a logger for logging messages, a `scanChan` channel for receiving object scan requests, with a `scanners` slice to hold the available scanners.

The `CreateDispatcher` initialises a new `Dispatcher` instance with the required fields. The `Start` method enters into a loop where it ranges over the `scanChan` channel. If the channel is empty, the loop will block until a new object is sent through the channel. If the channel has an object, the dispatcher will spawn a new goroutine to handle the scan. However, if the channel is closed, the loop will continue to process the remaining objects in the channel and then exit (Go by Example, 2022b). This is because when channels are closed, no more values can be sent to them, but the values that have already been sent can still be received (Go by Example, 2022a). This is shown in the provided dispatcher loop code in Figure 7.

```
func (d *Dispatcher) Start(errChan chan error, done chan struct{}) {
    var wg sync.WaitGroup

    for request := range d.scanChan {
        for _, scanner := range d.scanners {
            wg.Add(1)
            go func(req *object.Object, sc Scanner) {
                defer wg.Done()
                sc.ScanObject(req, errChan)
            }(request, scanner)
        }
    }
    wg.Wait()
    done <- struct{}{} //Send empty done message
}
```

Figure 7: Dispatcher loop

When the program receives a termination signal, there should be no loss of information about incoming scan requests. This is a security risk as it could lead to objects not being scanned. To prevent this, the dispatcher uses a `sync.WaitGroup` to wait for all goroutines to finish before exiting the program. This is done by calling `wg.Add(1)` before starting a new anonymous goroutine to increment an active goroutine counter, and using `defer wg.Done()` when the goroutine has finished to decrement the counter. The `wg.Wait()` call will block until the counter is zero, meaning all goroutines will have finished processing (Go by Example, 2022c). This ensures that all scans that are currently being processed since `scanChan` was close will be completed before the program exits.

Main

The main package orchestrates the top-level workflow that Aegis executes throughout its operation. The entry point of the program is the `main` function, which performs one task - calling the `run` function and exiting the program based on its return value. This design choice enhances extensibility and testability since alternate workflows can be implemented while maintaining a single entry point. Furthermore, the `run` function can be tested without running the entire program (Ryer, 2020). The `run` function serves as an abstraction from `main`, as it encompasses Aegis' main workflow.

The `run` function is divided into three distinct sections: Initialisation and configuration, the main loop, and cleanup. The initialisation and configuration section is responsible for initialising all the

components Aegis requires and configuring them with the values provided by the configuration package.

- The configuration is loaded from `config.env`, and the logger is created. An initial context is also created and passed to everything that requires it, apart from the event system.
- The metric manager and various metric collectors are created, with the metric manager taking in the Prometheus exporter.
- The audit logger is implemented by the PostgreSQL database.
- The object store is implemented by the Minio client.
- The event system is implemented by the Kafka consumer with the `scanChan` passed in as well.
- The scanning workflow is created. This includes creating the antivirus engines, in this case ClamAV, creating the cleaner with the configured policy and passing both of them to the scanners, namely the object scanner. The scanners are then passed to the dispatcher alongside the `scanChan`.

The main loop is the continuous execution of the goroutines that handle Aegis' asynchronous operations. These are the event manager, dispatcher, and metric manager. The goroutines are started using the `go` keyword, which spawns new goroutine to execute the functions in a separate thread. An additional context is created and passed into the `Start` method of the `EventManager`. Multiple channels are then created to handle errors, shutdown command, and the shutdown complete with `errChan`, `shutdownChan` and `done` respectively. The `Start` methods of the `EventManager`, `dispatcher` and `metricManager` are called to begin the main workflow of the program. An error channel (`errChan`) is created to handle errors generated by the event manager and metric manager goroutines.

Finally, the shutdown section ensures a smooth termination when the program receives an interrupt signal or encounters errors from the goroutines. The shutdown sequence is vital as it allows Aegis to maintain the progress of processed objects when receiving messages, enabling it to resume scanning objects from where it left off upon restart. The shutdown sequence unfolds as follows:

When an interrupt signal or an error from any goroutine is received, Aegis starts its graceful shutdown sequence. A `select` statement is used to wait for a message from either the `errChan` or `shutdownChan` channels. If any of these channels receive a message, a message or error is logged, and the shutdown sequence begins by canceling the context passed to the event manager. This action halts the event manager from consuming messages from the Kafka consumer and subsequently closes the `scanChan` channel. As a result, incoming notifications remain in the Kafka queue and can be consumed by Aegis upon restart leading to no scans lost.

The code then waits for the `done` channel to send a message, signaling that the goroutines have completed processing the remaining objects in the `scanChan` channel. Once this process is finished, the program stops the Prometheus metric exporter and exits with a status code of 0, indicating a successful operation. To better indicate the graceful shutdown process, a sequence diagram is available in the appendix at Figure 23.

5.5. Testing

Unit Tests

Unit testing is an essential aspect of software development that focuses on testing individual units or components of a software application. The objective of unit testing is to ensure that each component functions correctly in isolation, thus improving the overall quality and reliability of the software.

In this project, unit tests were developed for each internal package, ensuring that the core functionality of each package was thoroughly tested. Unit tests were created using the built-in `testing` library. This package allows for the easy creation and execution of test cases, as well as the measurement of code coverage.

To facilitate the process of unit testing and ensure that the focus remains on the functionality of the components under test, the mocking technique was employed using the Mockery framework (vektra, 2023). This approach allows for the isolation of individual components by replacing dependencies with mock implementations.

Mocking

Mocking is a technique employed in unit testing to replace dependencies that packages rely on for their functionality. This allows for the testing of individual packages in isolation, minimising the impact of potential errors from external sources and ensuring that tests focus solely on the functionality of the component being tested.

A mocking framework called Mockery is utilised for this purpose. Mockery is a tool that generates mocks implementing each interface within a package (Miguel, 2021). It offers the ability to override methods, enabling the mock to return a predetermined output for specific inputs. This capability can also be extended to accommodate any input of a specific type.

To generate the mocks, mockery has a configuration file in which defines where the mock files are created. I opted to create the mocks in the same package as the interface to avoid any import conflicts. Creation of the mocks can be done by the corresponding makefile command.

Code Coverage

The command `go test` is used to run tests, which outputs the results of all unit tests and the code coverage for the package. Code coverage is computed as the ratio of the number of lines of code executed to the total number of lines of code in the package, as illustrated in Equation 1. Code coverage serves as a valuable metric for assessing the thoroughness of package testing.

$$\text{Code Coverage Percentage} = \frac{\text{Number of lines of code executed}}{\text{Total Number of lines of code in an application}} \times 100 \quad (1)$$

By combining unit tests and mocking techniques, thorough testing of each component's functionality was possible. Unit tests were continually updated and refined throughout the development process, contributing to the overall quality and reliability of the solution.

5.6. Kubernetes Deployment

To turn the solution into a microservice, a process is required to turn Aegis into a self-contained business unit. This process is called containerisation and is achieved by packaging the application and its dependencies into a single container image. This image can then be deployed to a container orchestration system such as Kubernetes.

Kubernetes

Kubernetes (K8s) is an open-source container orchestration system for automating deployment, scaling, and management of containerised applications (Kubernetes, 2023). It groups containers into logical units called "pods" and manages their lifecycle, networking, and storage. Kubernetes enables the scaling of applications using multiple decentralised nodes controlled by internal and horizontal load balancers. Kubernetes supplies a CLI tool called `kubectl` for interacting and managing Kubernetes clusters.

Docker

Docker is a platform for developing, shipping, and running applications in containers (Docker, 2022). Containers are lightweight, portable, and provide a consistent environment for applications, simplifying deployment and scaling. Docker allows developers to build and package applications and their dependencies into containers that can run on any system with Docker installed. These smaller, self-contained business units can be networked together to form a microservice architecture.

K3d

K3d is a lightweight Kubernetes distribution designed for local development and testing (K3d, 2023b). It runs Kubernetes clusters inside of Docker containers, making it easy to create, delete, and manage clusters using the provided CLI. K3d provides a convenient way to test Kubernetes deployments and configurations before deploying them to a production environment. K3d uses a configuration file called `k3d.yaml` to define the cluster's configuration, including creating a registry for storing Docker images, exposing ports, and mounting volumes (K3d, 2023a). The configuration file is available in the Figure 10.

Registries are used to store Docker images that will be available for Kubernetes to use. In this case, I create a local registry using K3d which I can then later upload the Aegis Docker image to using the k3d CLI.

Aegis Containerisation

For the Aegis solution to be deployed on Kubernetes, it needs to be containerised using Docker. A Dockerfile is used to describe the steps required to build the Docker image (Docker, 2023) (Baresi *et al.*, 2022). It contains 2 major sections. Firstly, for building the Aegis application, it defines the base docker image, in this case `golang:1.19`, and the instructions to compile the application. These instructions include copying the source code to the container along with any configuration files, such as the `config.env` and `clamd.conf` and building the application using the `makefile` command.

The second stage is for the execution of the program. This stage downloads the `clamscan` dependency, copies over the config files and the binary from the previous stage and then runs

the application. This separation is beneficial because after the binary is built, the source code can be deleted which reduces the size of the image, therefore saving resource demand. Once the Docker image is built, it can be uploaded to the local container registry, ready for use by Kubernetes.

Kubernetes uses `CrashLoopBackOff` to restart containers that have crashed (Kubernetes, 2023). Each time the pod crashes, the time between restarts increases. This is beneficial because if Aegis launches before all of its dependencies are online, it will enter a `CrashLoopBackOff` until the dependencies are online.

Helm

Helm is a package manager for Kubernetes that simplifies the deployment and management of applications on a Kubernetes cluster (Helm, 2023). It uses "charts" as templates for Kubernetes resources allowing for easy configuration, versioning, and sharing of applications. Helm charts define the application's networking, services, and dependencies, making it easy to deploy and maintain applications in a Kubernetes environment.

Helm can be used to streamline the installation and management of all the dependencies required for the solution. This approach saves time compared to manually installing and configuring each dependency, as described in the "Service Selection and Creation" section. Each of these dependencies has its own Helm chart, which can be found using the online Helm chart repository Artifact Hub (Artifact Hub, 2022). Artifact Hub stores the Helm charts that can be installed and managed using Helm, along with documentation on how to configure them.

Service Configuration

Using this documentation, environment variables can be configured for each deployment. Within the Helm chart, a `values.yaml` file holds the default values for these variables, which will be passed into several template files. These template files are used in Kubernetes to generate the appropriate configuration settings for each deployment. By customising the `values.yaml` file, you can tailor the deployments to suit the specific requirements of your environment. As we have already allowed the overriding of variables in Aegis by using environment variables, this means that configuring the solution to work within Kubernetes is an easy task. In Figure 8, these environment variables are overridden to configure Aegis, in the `env:` key and all other services in their corresponding fields.


```

env:
  MINIO_ENDPOINT: aegis-minio.default.svc.cluster.local:9000
  KAFKA_BROKERS: "aegis-kafka.default.svc.cluster.local:9092"
  PROMETHEUS_ENDPOINT: 0.0.0.0:2112
  PROMETHEUS_PATH: /metrics
  POSTGRESQL_ENDPOINT: aegis-postgresql.default.svc.cluster.local:5432

minio:
  auth:
    rootUser: minioadmin
    rootPassword: minioadmin

postgresql:
  auth:
    enablePostgresUser: true
    postgresPassword: postgres
    database: aegis_antivirus

kafka:
  auth:
    clientProtocol: plaintext
  provisioning:
    topics:
      - minio-put-events

clamav:
  service:
    milter:
      enabled: false

```

Figure 8: Overriding Environment Variables

Internal Communication

In Kubernetes, service endpoints are represented by DNS names that are automatically generated upon service creation. These DNS names resolve to the corresponding service's ClusterIP and remain stable throughout the service's lifecycle. To enable communication between services, these DNS names can be used as cluster internal addresses instead of the localhost address.

Utilising DNS names instead of ClusterIPs offers several advantages, including the abstraction of the ClusterIP. This abstraction allows Kubernetes to change the ClusterIP without requiring any reconfiguration of the deployment to locate the updated IP. This is viewable in the `env:` field of Figure 8 where new internal addresses are used to configure the services to communicate with each other within the cluster.

Exposing Services

ClusterIP services are only accessible within the node, so to access the services outside of the cluster, say to upload files to MinIO, a different type of service must be used (Martínez, 2022).

NodePort services expose the service on a static port on every node. NodePort has ports available in the range 30000-32767. NodePort can be used with all TCP or UDP traffic and therefore fits

the purposes of all three services that need to be exposed; the MinIO console, Prometheus metric server and PostgreSQL audit log database. The main drawback with NodePort is that it offers no load balancing customisation between nodes and by default round-robins traffic. This is not ideal for a multi-node production environment but is less important as the solution is deployed on a single node. A diagram of how NodePort is used can be found in Figure 9.

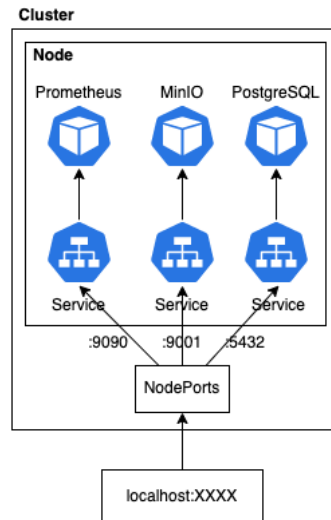


Figure 9: NodePort Diagram

The alternative to NodePort is LoadBalancer, which uses ClusterIP and NodePort services in combination to balance traffic to all nodes in the cluster. LoadBalancer can be configured with various algorithms to better route traffic based on load. As this is a single node cluster, there is no need to create a load balancer between them, so NodePort is sufficient. This can be changed in the Helm chart if need in the future.

Below is the `k3d-conf.yaml` file that configures the NodePort services for MinIO, Prometheus and PostgreSQL.

```
registries:
  create:
    name: registry.localhost
    host: "0.0.0.0"
    hostPort: "12345"
ports:
  # Expose MinIO
  - port: 9001:30001
    nodeFilters:
      - server:0
  # Expose Prometheus
  - port: 9090:30090
    nodeFilters:
      - server:0
  # Expose Postgresql
  - port: 5432:30080
    nodeFilters:
      - server:0
```

Figure 10: Exposing of Services

In the appendix is an output log displaying all services, pods and cronjobs from the command `kubectl get all` available in the Listing 9.

Connecting Prometheus Metrics

The Prometheus deployment must be configured to know where to scrape metrics from. This can be done by adding annotations to the deployment, which can be seen in Figure 11. These annotations tell the Prometheus deployment to scrape metrics from the Aegis service on the port 2112.

```
podAnnotations:
  prometheus.io/scrape: "true"
  prometheus.io/path: /metrics
  prometheus.io/port: "2112"
```

Figure 11: Adding Annotation for Prometheus

6. Results and Evaluation

Virus Database Updates

On deployment, the Helm chart deployment of ClamAV automatically creates a cronjob that downloads the latest version of the virus database. Initially, this cronjob downloads the entire database but on subsequent runs only downloads the updates in daily releases. Upon completion, ClamAV has access to a total of almost 8.7 million virus signatures shown in Figure 12. Alongside the number of signatures, the figure also shows the active configuration of ClamAV, namely the maximum file size, the recursion level and the file types that are scanned.

During development, the database was downloaded multiple times, resulting in the cluster being rate-limited and unable to update its signature definitions. Consequently, the antivirus returned a clean result for every file, as no matching signatures were found in its empty database. In a production environment, this issue should not arise if the database is pulled infrequently. However, if the system suddenly scales out to meet increased demand, the cluster IP could be rate-limited again.

```
Starting Freshclamd
Starting ClamAV
Socket for clamd not found yet, retrying (0/1800) ...
ClamAV update process started at Wed May 10 11:43:49 2023
daily.cvd database is up-to-date (version: 26902, sigs: 2034320, builder: raynman)
main.cvd database is up-to-date (version: 62, sigs: 6647427, builder: sigmgr)
bytecode.cvd database is up-to-date (version: 334, sigs: 91, builder: anvillleg)
Socket for clamd not found yet, retrying (132/1800) ...
Wed May 10 11:46:04 2023 -> Limits: Global time limit set to 120000 milliseconds.
Wed May 10 11:46:04 2023 -> Limits: Global size limit set to 419430400 bytes.
Wed May 10 11:46:04 2023 -> Limits: File size limit set to 104857600 bytes.
Wed May 10 11:46:04 2023 -> Limits: Recursion level limit set to 17.
Wed May 10 11:46:04 2023 -> Limits: Files limit set to 10000.
Wed May 10 11:46:04 2023 -> Limits: MaxEmbeddedPE limit set to 41943040 bytes.
Wed May 10 11:46:04 2023 -> Limits: MaxHTMLNormalize limit set to 41943040 bytes.
Wed May 10 11:46:04 2023 -> Limits: MaxHTMLNoTags limit set to 8388608 bytes.
Wed May 10 11:46:04 2023 -> Limits: MaxScriptNormalize limit set to 20971520 bytes.
Wed May 10 11:46:04 2023 -> Limits: MaxZipTypeRcg limit set to 1048576 bytes.
Wed May 10 11:46:04 2023 -> Limits: MaxPartitions limit set to 50.
Wed May 10 11:46:04 2023 -> Limits: MaxIconsPE limit set to 100.
Wed May 10 11:46:04 2023 -> Limits: MaxRecHWP3 limit set to 16.
Wed May 10 11:46:04 2023 -> Limits: PCREMatchLimit limit set to 100000.
Wed May 10 11:46:04 2023 -> Limits: PCRERecMatchLimit limit set to 2000.
Wed May 10 11:46:04 2023 -> Limits: PCREMaxFileSize limit set to 104857600.
Wed May 10 11:46:04 2023 -> Archive support enabled.
Wed May 10 11:46:04 2023 -> AlertExceedsMax heuristic detection disabled.
Wed May 10 11:46:04 2023 -> Heuristic alerts enabled.
Wed May 10 11:46:04 2023 -> Portable Executable support enabled.
Wed May 10 11:46:04 2023 -> ELF support enabled.
Wed May 10 11:46:04 2023 -> Mail files support enabled.
Wed May 10 11:46:04 2023 -> OLE2 support enabled.
Wed May 10 11:46:04 2023 -> PDF support enabled.
Wed May 10 11:46:04 2023 -> SWF support enabled.
Wed May 10 11:46:04 2023 -> HTML support enabled.
Wed May 10 11:46:04 2023 -> XMLDOCS support enabled.
Wed May 10 11:46:04 2023 -> HWP3 support enabled.
Wed May 10 11:46:04 2023 -> Self checking every 600 seconds.
Wed May 10 11:46:04 2023 -> Set stacksize to 1048576
```

Figure 12: ClamAV Virus Database Size

6.1. Solution Workflow

The solution is now ready for deployment. Provided below is the workflow of a standard deployment of the solution.

- 1) Ensure all dependencies are installed.
- 2) Launch the cluster with `make create-cluster`.
- 3) Connect to the MinIO web console at `localhost:9000`. You can perform all standard actions here, such as creating buckets and uploading files.
- 4) Add the event queue configuration to MinIO, pictured in the appendix in Figure 24. You will need to restart the MinIO server for the change to update.
- 5) Configure a bucket to send put events to the event queue. Pictured in the appendix at Figure 25.
- 6) Upload a file to the bucket. This will trigger Aegis to download and scan the file. The logs can be viewed in the appendix in Listing 6.
- 7) Depending on the cleanup policy, Aegis will perform the appropriate cleanup action which can be seen on the web console.
- 8) In addition, you can connect to the Prometheus web console at `localhost:9090`. You can view the metrics collected by Prometheus here. Example is available in the appendix in Listing 26. To use the metrics you can also connect Grafana to the same address.
- 9) Connect to the PostgreSQL database at `localhost:5432` using the `psql --localhost` command. You can view an example of the audit log in the appendix in Listing 7.

6.2. Benefits of Metric Collection

Because of the metrics collection we implemented earlier, getting values such as files scanned and total infected files already present. Using the exposed Prometheus, Grafana can be used to visualise these metrics. These graphs can help us evaluate the performance of the solution. In Figure 13 a dashboard has been created to visualise the use of the solution. Its worth noting that for a successful solution, the total events messages, total scanned objects and total cleaned objects must all be equal. This ensures that all objects have been processed to completion through Aegis. Ideally, event errors, scanner errors and cleaner errors should all be zero but a value of 12 is displayed for demonstration purposes.



Figure 13: An Example Grafana Dashboard

6.3. Performance Evaluation

To access the performance of the solution, various metrics can be used. Many of these are already available using Prometheus and Grafana. However, extra metrics will be collected to aid the evaluation process. All of the metrics collected were gathered from consumer grade hardware that is not fit for a production environment. This will negatively impact the performance of the solution and should be taken into account when evaluating the results. For this evaluation, the cluster is deployed on an Apple M1 Macbook Pro with 16GB of RAM and a 10 core CPU giving 10GB and 8 cores to Docker.

Setup Time

This metric is less important as it is only performed once. However, it is still valuable for our analysis as it represents the time taken to deploy the a single node in a cluster. This is measured from the time the `make create-node` to first being able to perform a scan in Table 4. This includes the time taken to download the virus signature database.

Setup Task	Time mm:ss
Cluster started	00:00
Cluster building complete	00:20
Docker Image pulled	00:27
Dependency repositories checked	01:39
Dependencies downloaded	02:40
Pods starting	04:41
Aegis first online	06:42
MinIO online	11:13
Kafka online	14:31
Virus database downloaded	16:38
First scan performed	16:45

Table 4: Cluster Setup Times

The majority of the working time is waiting for the dependencies to come online, namely ClamAV to download its virus signature database. Aegis is the first pod to come online but enters into CrashLoopBackOff until all other pods are online.

Scan Throughput

Over a longer period of time, the scan throughput can be measured. This could be interpreted as two separate metrics, the total number of files scanned and the total size of files scanned. Both are valuable metrics to measure to assess the sustained performance of the solution. Calculating throughput in Equation 2 can be done by uploading a known number of files with a known size and measuring the time taken to complete the scan. The results from scanning a two folders, containing various media types, will be added in the Table 5 with average throughput calculated.

$$Throughput = \frac{Total\ Scanned\ Size}{Time\ Taken} \quad (2)$$

Metric	Folder 1	Folder 2	Average Throughput
Files Scanned	280	1218	1.48 Files/s
Size of Files Scanned	7370MB	7200MB	14.37 MB/s

Table 5: Scan Throughput

Folder one took 8.5 minutes and folder two took 8.4 minutes to complete. Overall, the system is able to scan at the rate of 14.37MB/s or 50.5GB/h. For a single node setup this is a good result as this covers the average network speed of most home users. However, scaling up of the hardware is need for it to achieve evaluate the full performance capabilities of the solution. The number of files per second is less informative as the folder used contained a multitude of different file sizes and types therefore is not a good representation of the performance.

Scan Speed

Unfortunately the intended inclusion of a scan time metric through Prometheus became out of scope. However, calculating the scan speed can still be done using the output logs from Aegis. This can be done as scan time is logged for each file scanned, it is just not collected. Using a grep and awk in Figure 14, all scan times can be extracted and averaged to give the average scan time.

```
kubectl logs aegis-d564b7ddb-fvvmj | \
grep -o 'Time: [0-9]*.[0-9]* sec' | \
awk '{ for (i=1; i<=NF; i++) { sum+=$i; count++ } } END { print sum/count }'
79.4085
```

Figure 14: Calculate Scan Time Commands

The result of 79.4085 seconds is a very long amount of time. This result was from a system under maximum load on restricted hardware. If the same commands are run on a system not under constant load the results change dramatically. For a single scan, time taken is at 0.39 seconds. This shows that very quickly the antivirus engine gets overwhelmed by a queue of files to scan.

Scan Lag

Scan lag is the time taken between uploading file and its scan completing. This can be visualised by measuring the time taken between receiving a put event and the scan completing. Grafana can be used to generate this graph as shown in the Figure 15. Note the folder used is different to the one used in the previous example.

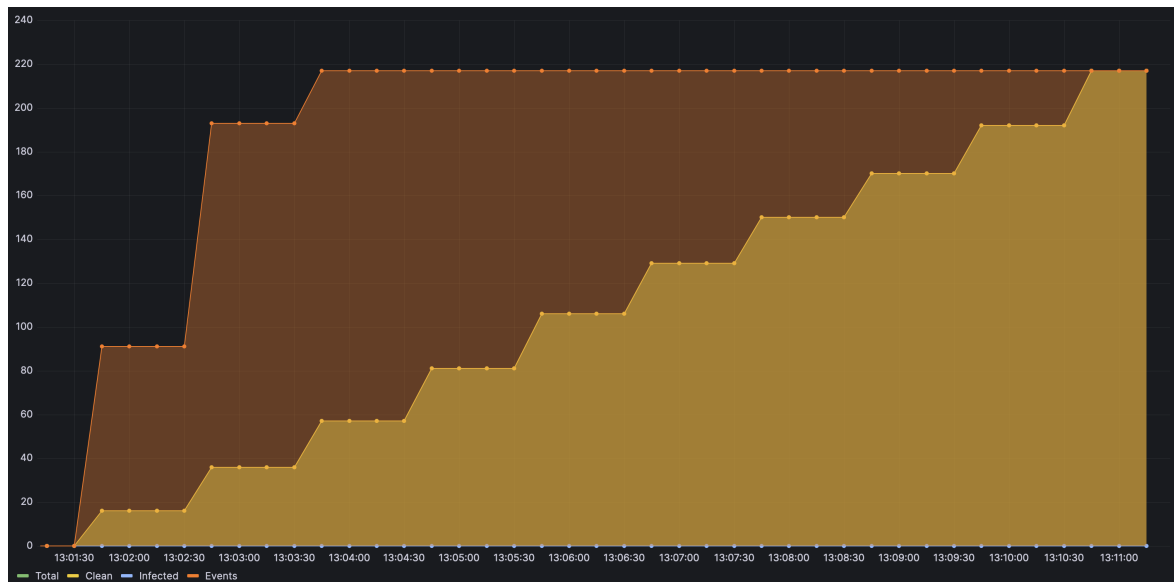


Figure 15: Scan Lag Graph - Scans vs Time

This figure shows that there is a moderate amount of scan lag. This is due to the high scan request load and the intensive nature of virus scanning against large signature databases. In the graph the orange areas represents scan lag. This is the time difference between Aegis receiving a put event and the scan completing. The yellow area is the current scan progress. Overtime, the yellow area matched the orange area as all the scan requests are processed. With the process starting at 13:01:30, the peak of the orange area is at 13:03:45 which is only 2m:15s after the first upload. The peak yellow area is at 13:10:45 showing that it took a total of 9m:15s to complete the scan of the whole folder, a difference of 7 minutes scan lag time. Its worth noting that the

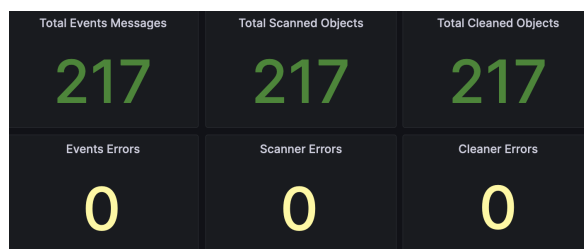


Figure 16: Scan Reliability

processing of the scan requests is linear meaning that the process is never being bottlenecked at any point. This backs up the previous assumption that the evaluation is limited by hardware and not the capabilities of the solution.

If the users upload rate to MinIO stays below 14.37MB/s, the scan lag should be minimal as the scan will be able to keep up with the upload rate. However, if the upload rate exceeds this, the incoming scans will start to queue up and scan lag will increase exponentially.

Scan Reliability

Throughout the performance evaluation above, Grafana has displayed a running total of all scan requests, scanned files and any error occurred in Figure 16. This is a good indicator of the reliability of the solution as no scans are being missed and no errors have been recorded.

Scan Accuracy

Scan accuracy is redundant to measure as the solution only uses ClamAV to scan files. If higher accuracy than what ClamAV provides is required, adding more antivirus engines is possible with the aggregate scan results being determined by the union of positive scan results (Omer, 2017). This is shown in Figure 17.

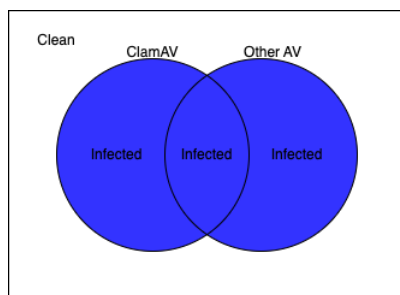


Figure 17: Combined AV Effectiveness

Shutdown Reliability

During an unexpected error or graceful shutdown process, reliably stopping the scanning process is essential to ensure that no files are left unprocessed. To evaluate this, a set of scans will be requested with known malicious files. These files should be removed under the corresponding cleanup policy and therefore no files should be left in the object store. Mid-scan, an interrupt signal will be given to Aegis causing it to enter graceful shutdown. The results of running the test are available in the appendix in Listing 10.

As expected, zero files are left in the object store after Aegis had restarted and continued processing the scan requests. This shows that there are no gaps in the execution of the solution if any error conditions would occur.

6.4. Comparing Functional Requirements

By comparing the functional requirements defined at the beginning of the report, a conclusion can be made on whether the solution has met the requirements. Each requirement is evaluated in Table 6.

Requirement	Evaluation
Provide a way of detecting the latest uploads to the object store.	This requirement has been achieved. Kafka has been successfully connected to MinIO and can read all put events given by MinIO. It can also hold events if Aegis is not ready to receive scan requests in the event of an error or shutdown.
Record the results of the malware detection within the object store.	Provided are three cleanup policies, remove, tag or quarantine. This requirement has been met and over achieved as there are multiple options for the user to choose from.
Provide the ability to measure key performance and analytic metrics.	As shown by 13, various metrics have been collected throughout the Aegis' lifetime. These have also been consumed and analysis has been performed. This requirement has been met.
Scale alongside MinIO to ensure that it does not bottleneck the object store at high loads.	This requirement has been partially met. Aegis never bottlenecks the object store during execution due to the use of an event queue. However, Aegis does not effectively scale with MinIO to keep up with the incoming uploads.
Provision for future expansion and ongoing maintenance.	The solution fully meets this requirement for many reasons. Firstly, structured logging, configuration files metric collection and audit logging means that active maintenance of the solution should be as easy as possible. In addition, Aegis has been designed to be as extensible as possible with room for multiple types of scanning workflows and multiple antivirus engines.
Must be cost effective and legally viable for commercial use.	This requirement has been met as all external software used is open-source and freely available. If in production use, additional antivirus engines are used then paid software can be included.
Have a high level of customisability to allow for different use cases.	This requirement has been met as a configuration file is available for Aegis that allows customisation of all endpoints, name of the topic, database details, the cleanup policy and make more. There is also room to add different types of scanning workflows and antivirus engines.
Allow for efficient and transparent debugging in the event of failure.	Structured logging is included that provides insightful feedback at various levels. In addition, metric collection and audit logging make it easy to keep track of errors and scan history. Including a log aggregation tool, such as Splunk, could improve the satisfaction of this requirement.
Add more complex metrics - Histogram, Gauges, etc.	Although many useful metrics are collected, no complex metrics have been added. These have a minimal impact on the overall solution so have not been prioritised.
Provide the choice of multiple antivirus engines.	No other antivirus engines have been added to the solution. However, the structure is in place to allow for additions in the future.
Provide a warning when under "delete" cleanup policy.	This requirement was partially met as selecting the delete policy is done within the <code>config.env</code> file. In the file a commented warning is provided. In the future, if the configuration is available via GUI this requirement would move up in priority from could to should.
Automatically setup bucket notifications to be sent to the event queue.	In practice, manually setting up the solution must only be done once. This lead the decision that thorough documentation was a better use of the limited time available.
Supply the MinIO policies the solution will use e.g. "put" and "get".	This requirement is relatively simple but has remained out of scope. This will need to be completed to be fully production-ready to provide information to inform any future users of the access it requires
Prevent the downloading of files if flagged as infected.	This requirement was not met as it involved making changes to the MinIO web console. This was determined to be out of scope due to the additional time required to research the implementation for a insignificant change to the solution.
Protection from "inside man" attacks.	No protection from "inside man" attacks has been added. This is still not a priority for systems where users will have a wide range of abilities already, such as deleting or reading files.
Provide multiple types of scanners e.g. hash or server based AV scanner.	Only a single workflow for scanning files has been provided. However, provisions for implementing this in the future has been put into place, if required.

Table 6: Functional Requirements with Evaluation

6.5. Comparing Non-Functional Requirements

Additionally, the non-functional requirements have been evaluated in the table 7.

Requirement	Evaluation
Speed	As seen in the scan throughput section, if the incoming scan requests stays at or below 14.37MB/s, then the solution will keep up with MinIO. However, it suffers dramatically under high load with average scan times rising to 79. This does not satisfy this requirement under maximum throughput conditions. In a less intensive scenario, scans are performed within 0.39 which is a very good result. More focus in the future should be placed on quickly scaling out the antivirus engines to meet high demand.
Scalability	The solution lacks to achieve this requirement. Provisions for scaling out have been added but the scope constraints prevented them from being fully implemented. This negatively affects the project as this requirement was a priority.
Availability	Scan reliability has shown that throughout benchmarking the cluster has not become unavailable. While object store availability is the responsibility of MinIO, the stability of the cluster is apart of the solution. As there were no unexpected downtime, this requirement has been met.
Reliability	The reliability of the solution has proven to be good. No unexpected errors happened during the evaluation process. When performing a test of Aegis' graceful shutdown procedure, zero files were left unprocessed.
Capacity	As Aegis only uses one temporary cache file, the maximum capacity needed can be calculated by multiplying the average throughput by the average scan time. This results in an average capacity required as $14.37\text{MB/s} \times 79.4\text{s} = 1.14\text{GB}$. This is highly achievable for the majority of production environments.
Security	The security of the system is largely reliant on MinIO's built-in authentication. This stops unwanted puts / gets from the system without Aegis getting involved. All files scanned do not leave the cluster and therefore are sheltered from external access.
Privacy	As the scanned files remain inside of the cluster, privacy is preserved. In addition, the only metrics collected are counting occurrences and never interpret the contents of any file. ClamAV does look at internal contents but apart from virus signature database downloads, does not have any outside access.

Table 7: Non-Functional Requirements with Evaluation

6.6. Project Aims Evaluation

Upon reviewing the functional and non-functional requirements, it can be said that the project aim of "implementing malware detection into MinIO without compromising the platform's scalability or performance" has been achieved to some extent. While a malware detection component has been successfully integrated, certain compromises were required to remain within the project scope. The current solution does not dynamically scale the antivirus engines in response to increased demand on the object store, resulting in substantial scan latency that could potentially affect user experience.

Despite this, the developed solution serves as a solid foundation for a production-grade malware detection system for MinIO, boasting high availability, reliability, and security. With further time and resource investment, it has the potential to scale efficiently alongside MinIO without compromising performance.

Through the course of this project, I have made significant strides towards achieving my personal aims. Specifically, I have successfully deepened my understanding of the Go programming language and the MinIO platform. Creating a complete and high quality Go application has taught me the value of effective design architecture to maximise cohesion and minimise coupling. At a few points in the project, refactoring was required which could have been avoided with a more informed planning phase.

Furthermore, I have increased my experience in designing and implementing production-ready solutions within a microservice environment. Through the practical application of microservice design principles and deployment strategies, I have gained insights into the complexities and rewards of this architectural style.

Yet, perfecting the management of time, scope, and resources in large-scale projects remains

a field needing more development. The wide scope of this project introduced considerable challenges, such as juggling competing priorities and resolving unforeseen issues. Even with these challenges, it illuminated the vital importance of effective project management skills and has motivated me to target continued growth in this area.

6.7. Testing Evaluation

In Aegis, every internal package is accompanied by a set of unit tests. These tests can be executed using the Go CLI, and their coverage varies across different packages. The overall test coverage for Aegis is a good indicator of the effectiveness of the tests in place. This also supports the reliability of the solution as errors should be caught before deployment.

The average test coverage for Aegis is 64%. Supplied in the appendix in the output from performing the tests in Listing 8.

For future development, achieving 100% coverage over all packages is a worth while goal, especially to claim production-ready status. This will ensure that every piece of code is thoroughly tested, improving the overall robustness and reliability of the system. One way to achieve this is through test-driven development (TDD), a software development methodology that involves writing tests before implementing the actual code. By adopting TDD, testing becomes the priority, and each package's level of quality and encapsulation will be constantly assessed, therefore catching more errors before deployment.

7. Product Issues / Future work

Although the solution is working, it is not without its limitations. From the evaluation, two categories of issues have been identified. Firstly, the hard constraint of the project deadline has meant that some features have not been implemented or compromises have had to be made. This will have negatively affected the quality of the solution These issues are listed below.

- Lack of scalability from load balancing antivirus engines. This impacts the scalability of the solution as no scanning can happen in parallel when the system is under load. This could be solved by implementing a horizontal pod auto-scaler to adaptively scale number of concurrent pods available based on the demand of compute resources (David *et al.*, 2020).
- Diversify metric collection so that a larger range of metrics are collected. For example, the average scan time of a file and the average time a file is in the cache. This could provide more insights into the performance of the solution.
- The testing code coverage could be improved to achieve 100% coverage for both internal and external pkg packages. This would ensure that all code going into production has had some level of testing. Using table driven tests could help improve the coverage of edge cases and error conditions (Samuel, 2021).
- While the scanned files are removed (if AEGIS_REMOVE_AFTER_SCAN is true), the sub-folders under the buckets are not. This is a hard issue to solve as it is possible to delete a folder while another file is being downloaded to it. The impact of retaining all folders is small as an empty folder uses minimal storage space but over time writing to the store could slow down. One possible solution is to store all files in a single folder. This could lead to naming conflicts which a UUID could solve (Scott *et al.*, 2017). Another solution

could be having a retention policy on each folder which would delete the folder after a given time or under a given condition.

-

Secondly, new opportunities have identified themselves during the development of the solution. These could be implemented in future projects related to this area. Below is a list of the issues identified.

- MinIO has the ability to integrate Audit logging and Prometheus metrics into its existing metric collection service. Combining the two could provide a more complete picture of the system to draw conclusions from.
- No feature tests have been written for this solution. Feature tests would test multiple packages together to ensure that the overall workflow of the system is correct. This testing would be valuable for ongoing production use.
- The solution only deploys to a single node cluster running on a single machine. In a production environment, this would not be the case and therefore more work is needed to ensure that the solution can be deployed to a multi node cluster.
- Using the MinIO web console, the results of the scan could be viewed. In addition, warning messages could be added to inform the user of infect files. Depending on the production use, this feature could be valuable.
- Store the scan result in metadata rather than tagging to improve immutability of tags. This might also raise the ability for bad actors to edit object metadata outside of MinIO.
- Unscanned files are currently not tagged with anything to indicate that they have not been scanned. This could be useful for auditing or user feedback purposes.
- Calculate the hash of a object, upon performing put, inside of MinIO using lambda functions (MinIO, 2023b). This reduces the size of the download required to scan a file. However, removes the ability for any antivirus engine to use any fuzzy matching.
- Have a selection of ready-to-go antivirus engines that the user can choose from to improve overall scanning accuracy (Omer, 2017).
- Put tagging messages are ignored by the event queue. This could potentially cause a security issue where a change in tags are not scanned. The risk of this is minor as only a user with access to the system can modify the tag which could be classed as an inside man attack which was not in the scope of the project.
- Queue deduplication could be used to ensure that the same file is not scanned multiple times while in the event queue. This would improve the performance of deployments that are receiving a large number of puts involving the same file.

8. Conclusions

8.1.

As this project concludes, further work remains to ensure the solution aligns with the standards delineated in the project specification. Despite making considerable progress, the current solution does impact the scalability and performance of the MinIO object store. However, it's important to recognize the significant accomplishments of the project; the successfully development of a microservice capable of scanning uploaded files for malware. The Aegis service operates

efficiently, requiring minimal cache for object scans and never acting as a bottleneck in the workflow.

Moreover, the solution integrates numerous production-level features necessary for enterprise deployment. It also maintains compatibility with existing MinIO features, including erasure coding and object encryption. These successes affirm the potential of the solution, even as we acknowledge areas that need further development.

Additionally, throughout the development process, numerous potential research avenues have been identified. Given more time, these could be thoroughly explored and capitalised upon.

9. Reflection on Learning

9.1.

Throughout the course of this project, I have dramatically improved on my knowledge and experience. The project provided a valuable opportunity for me to further my understanding of the Go programming language and the MinIO platform. The endeavor of creating a microservice application using Go was challenging at points, but it served as an enriching exercise that will improve my grasp of effective system design and software engineering principles.

Furthermore, the project has shown me the importance of various non-technical skills when working on large-scale developments. Particularly, project management skills were brought to the forefront given the broad requirements and restrictive scope of the project. I have recognized the crucial role of effective time management, clear goal-setting, and efficient resource allocation in ensuring the project's success. While I did encounter a few setbacks, I managed to adapt my approach and implement necessary changes to facilitate the project's progression.

Despite the overall success of the project, I recognize that certain areas require further refinement. Notably, maintaining the scalability and performance of the MinIO object store while staying within scope present many issues. Nevertheless, these hurdles have served as invaluable learning experiences, offering insight into areas of potential future focus. Moving forward, I am eager for another opportunity to apply the skills and knowledge I've gained from this project to new challenges and projects.

10. Appendix

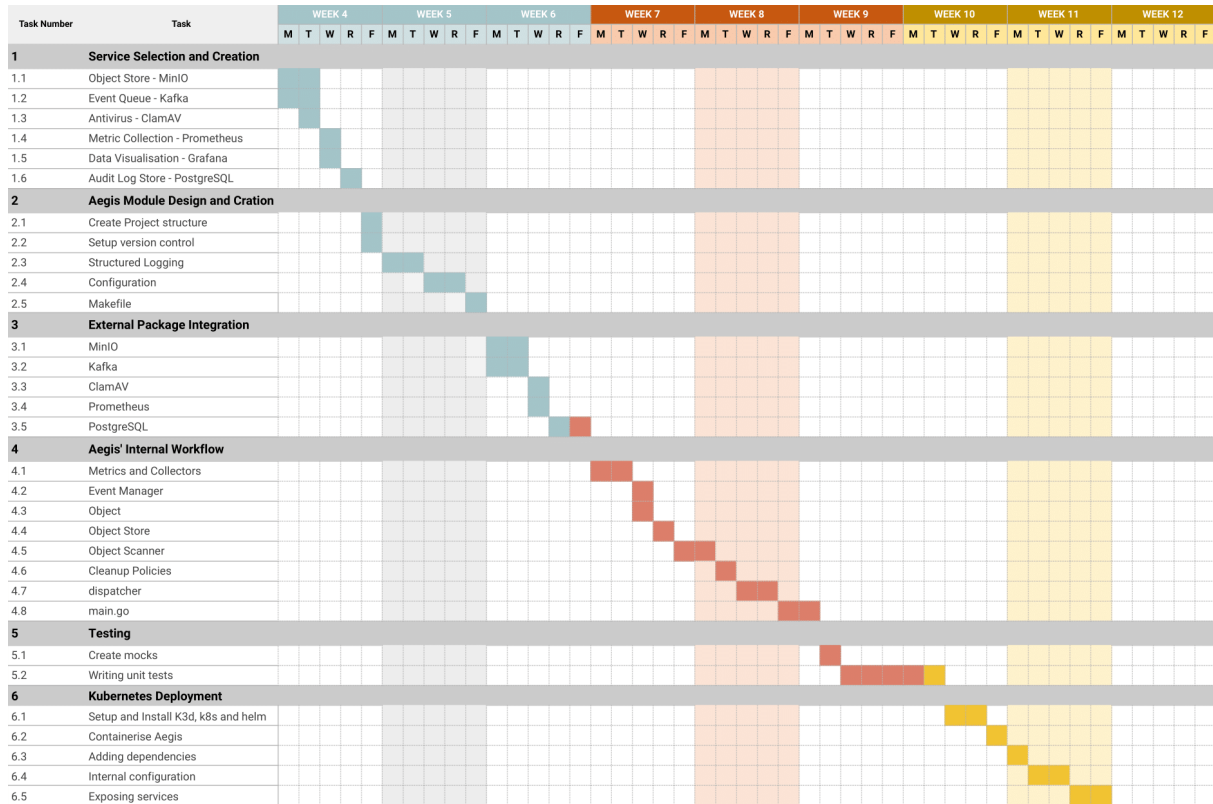


Figure 18: Timeline of Aegis' Development

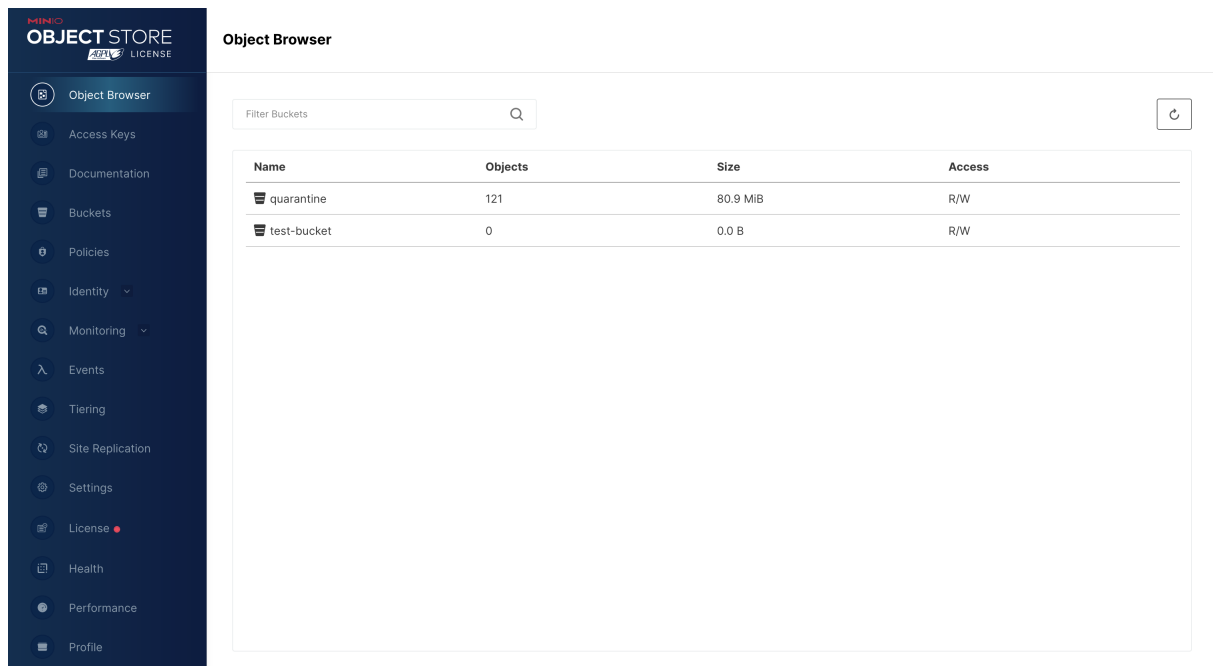


Figure 19: Image of MinIO's Web Console

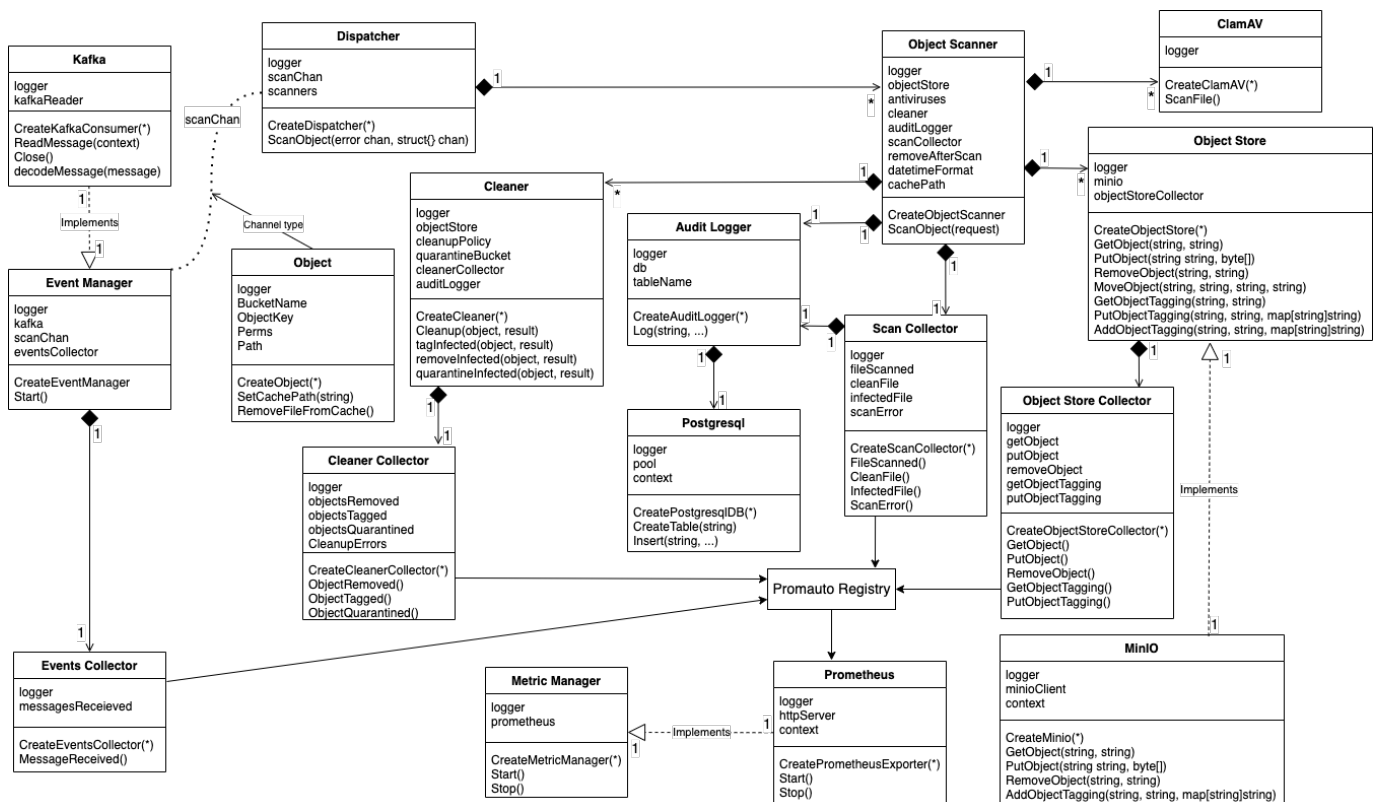


Figure 20: Plan of Aegis' Internal Packages

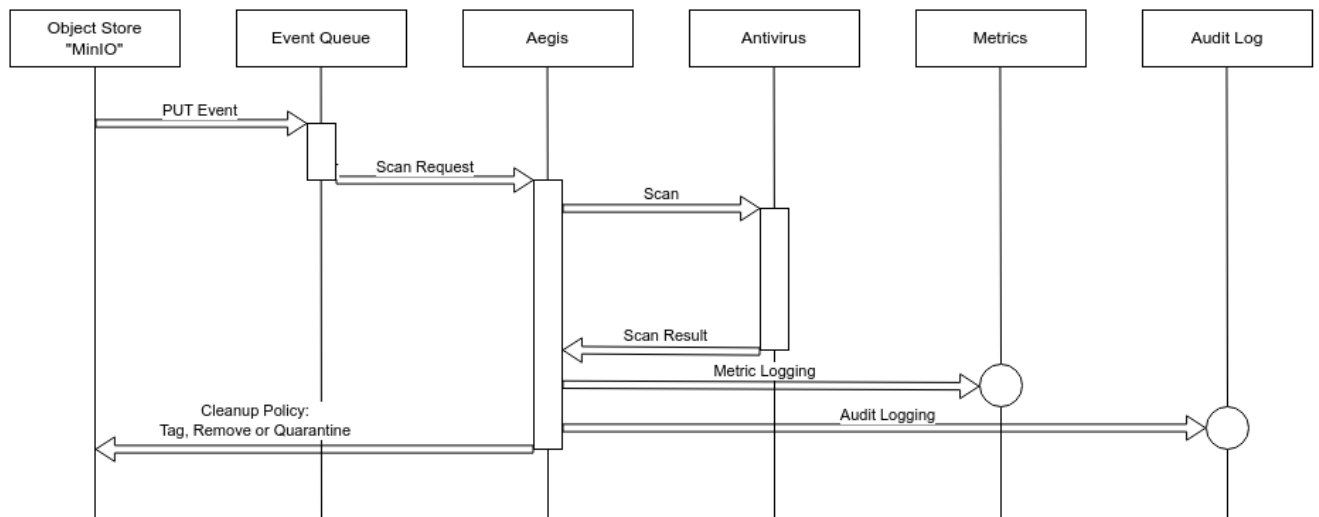


Figure 21: Aegis General Sequence Diagram

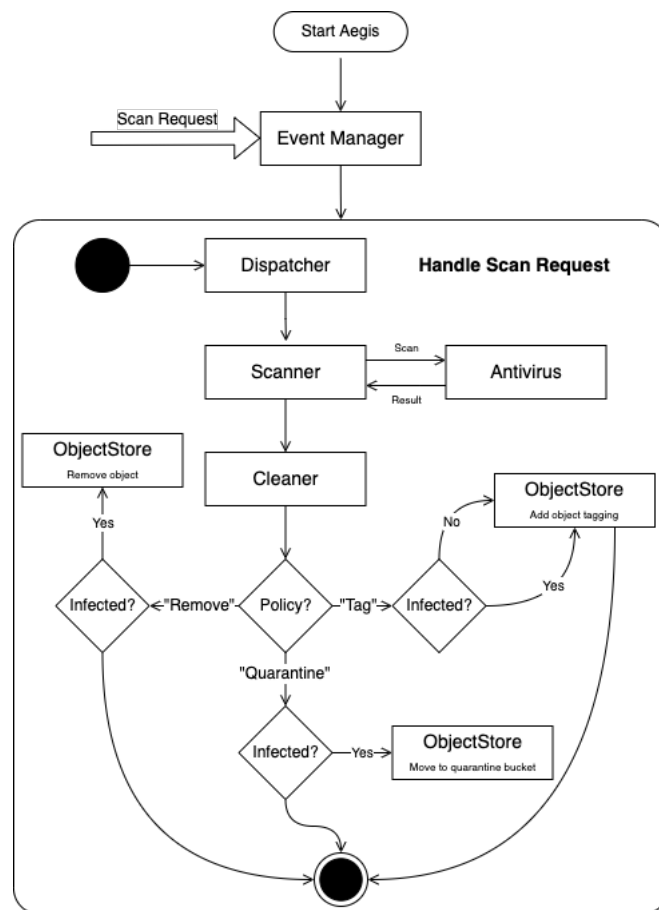


Figure 22: Aegis Scan Request Flow Diagram

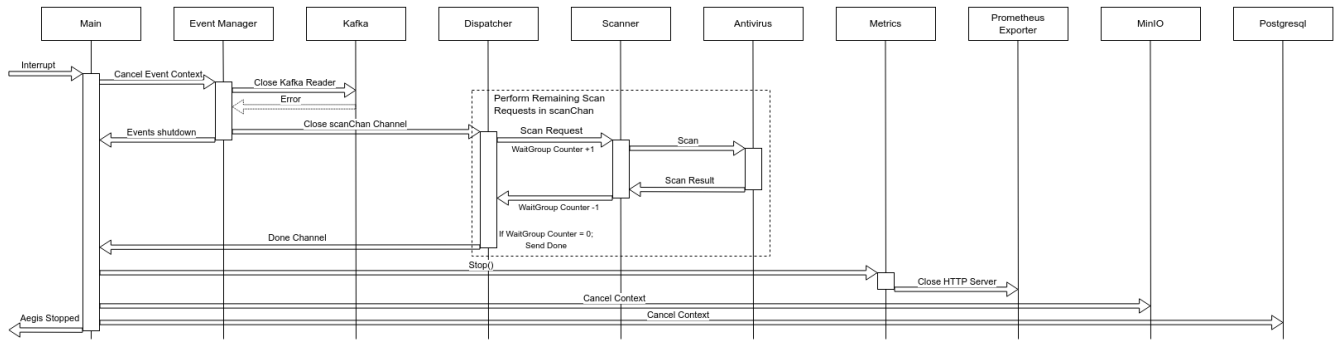


Figure 23: Aegis Shutdown Sequence Diagram

Listing 1: Example Kafka Notification

```

1 {
2   "eventName": "s3:ObjectCreated:Put",
3   "key": "test-bucket/gantt.png",
4   "Records": [
5     {
6       "eventVersion": "2.0",
7       "eventSource": "minio:s3",
8       "awsRegion": "",
9       "eventTime": "2023-03-24T12:23:27.844Z",
10      "eventName": "s3:ObjectCreated:Put",
11      "userIdentity": {
12        "principalId": "minioadmin"
13      },
14      "requestParameters": {
15        "principalId": "minioadmin",
16        "region": "",
17        "sourceIPAddress": "127.0.0.1"
18      },
19      "responseElements": {
20        "content-length": "0",
21        "x-amz-id-2": "...",
22        "x-amz-request-id": "174F5A6C715ECB50",
23        "x-minio-deployment-id": "439d9d33-3cca-42ae-b778-d703cbf9bbf7",
24        "x-minio-origin-endpoint": "http://192.168.1.138:9000"
25      },
26      "s3": {
27        "s3SchemaVersion": "1.0",
28        "configurationId": "Config",
29        "bucket": {
30          "name": "test-bucket",
31          "ownerIdentity": {
32            "principalId": "minioadmin"
33          },
34          "arn": "arn:aws:s3:::test-bucket"
35        },
36        "object": {
37          "key": "gantt.png",
38          "size": 92704,

```

```

39         "eTag": "22c4ae87e652bce0865536964cb8bb8d",
40         "contentType": "image/png",
41         "userMetadata": {
42             "content-type": "image/png"
43         },
44         "sequencer": "174F5A6C71C977E8"
45     }
46 },
47     "source": {
48         "host": "127.0.0.1",
49         "port": "",
50         "userAgent": "MinIO (darwin; arm64) minio-go/v7.0.49 MinIO Console /(dev)"
51     }
52 }
53 ]
54 }

```

Listing 2: Example Kafka Notification

/Users/username/test.jpg: OK

```

----- SCAN SUMMARY -----
Infected files: 0
Time: 0.332 sec (0 m 0 s)
Start Date: 2023:03:27 11:53:15
End Date: 2023:03:27 11:53:16

```

Listing 3: Example Exposed Metrics

```

# HELP aegis_kafka_total_messages Kafka total messages received
# TYPE aegis_kafka_total_messages counter
aegis_kafka_total_messages 0
# HELP aegis_objectstore_get_objects Object Store total get objects
# TYPE aegis_objectstore_get_objects counter
aegis_objectstore_get_objects 0
# HELP aegis_objectstore_get_objects_tagging Object Store total get objects tagging
# TYPE aegis_objectstore_get_objects_tagging counter
aegis_objectstore_get_objects_tagging 0
# HELP aegis_objectstore_put_objects_tagging Object Store total put objects tagging
# TYPE aegis_objectstore_put_objects_tagging counter
aegis_objectstore_put_objects_tagging 0
# HELP aegis_scanner_clean_files Total of clean files scanned by Aegis
# TYPE aegis_scanner_clean_files counter
aegis_scanner_clean_files 0
# HELP aegis_scanner_errors Total number of errors encountered during scans by Aegis
# TYPE aegis_scanner_errors counter
aegis_scanner_errors 0
# HELP aegis_scanner_infected_files Total of infected files scanned by Aegis
# TYPE aegis_scanner_infected_files counter
aegis_scanner_infected_files 0
# HELP aegis_scanner_time Time taken to perform a scan
# TYPE aegis_scanner_time histogram
aegis_scanner_time_bucket{le="0"} 0
aegis_scanner_time_bucket{le="125"} 0

```

```

aegis_scanner_time_bucket{le="250"} 0
aegis_scanner_time_bucket{le="500"} 0
aegis_scanner_time_bucket{le="1000"} 0
aegis_scanner_time_bucket{le="2000"} 0
aegis_scanner_time_bucket{le="4000"} 0
aegis_scanner_time_bucket{le="8000"} 0
aegis_scanner_time_bucket{le="16000"} 0
aegis_scanner_time_bucket{le="+Inf"} 0
aegis_scanner_time_sum 0
aegis_scanner_time_count 0
# HELP aegis_scanner_total_scans Total number of scans performed by Aegis
# TYPE aegis_scanner_total_scans counter
aegis_scanner_total_scans 0
# HELP go_gc_duration_seconds Pause duration of garbage collection cycles.
# TYPE go_gc_duration_seconds summary
go_gc_duration_seconds{quantile="0"} 0
go_gc_duration_seconds{quantile="0.25"} 0
go_gc_duration_seconds{quantile="0.5"} 0
go_gc_duration_seconds{quantile="0.75"} 0
go_gc_duration_seconds{quantile="1"} 0
go_gc_duration_seconds_sum 0
go_gc_duration_seconds_count 0
# HELP go_goroutines Number of goroutines that currently exist.
# TYPE go_goroutines gauge
go_goroutines 17
# HELP go_info Information about the Go environment.
# TYPE go_info gauge
go_info{version="go1.19.4"} 1
# HELP go_memstats_alloc_bytes Number of bytes allocated and still in use.
# TYPE go_memstats_alloc_bytes gauge
go_memstats_alloc_bytes 1.363496e+06
# HELP go_memstats_alloc_bytes_total Total number of bytes allocated, even if freed.
# TYPE go_memstats_alloc_bytes_total counter
go_memstats_alloc_bytes_total 1.363496e+06
# HELP go_memstats_buck_hash_sys_bytes Number of bytes in profiling bucket hash table.
# TYPE go_memstats_buck_hash_sys_bytes gauge
go_memstats_buck_hash_sys_bytes 4941
# HELP go_memstats_frees_total Total number of frees.
# TYPE go_memstats_frees_total counter
go_memstats_frees_total 2757
# HELP go_memstats_gc_sys_bytes Number of bytes in garbage collection system metadata.
# TYPE go_memstats_gc_sys_bytes gauge
go_memstats_gc_sys_bytes 3.745832e+06
# HELP go_memstats_heap_alloc_bytes Number of heap bytes allocated and still in use.
# TYPE go_memstats_heap_alloc_bytes gauge
go_memstats_heap_alloc_bytes 1.363496e+06
# HELP go_memstats_heap_idle_bytes Number of heap bytes waiting to be used.
# TYPE go_memstats_heap_idle_bytes gauge
go_memstats_heap_idle_bytes 3.678208e+06
# HELP go_memstats_heap_inuse_bytes Number of heap bytes that are in use.
# TYPE go_memstats_heap_inuse_bytes gauge
go_memstats_heap_inuse_bytes 3.8912e+06
# HELP go_memstats_heap_objects Number of allocated objects.

```

```

# TYPE go_memstats_heap_objects gauge
go_memstats_heap_objects 16646
# HELP go_memstats_heap_released_bytes Number of heap bytes released to OS.
# TYPE go_memstats_heap_released_bytes gauge
go_memstats_heap_released_bytes 3.678208e+06
# HELP go_memstats_heap_sys_bytes Number of heap bytes obtained from system.
# TYPE go_memstats_heap_sys_bytes gauge
go_memstats_heap_sys_bytes 7.569408e+06
# HELP go_memstats_last_gc_time_seconds Seconds since 1970 of last garbage collection.
# TYPE go_memstats_last_gc_time_seconds gauge
go_memstats_last_gc_time_seconds 0
# HELP go_memstats_lookups_total Total number of pointer lookups.
# TYPE go_memstats_lookups_total counter
go_memstats_lookups_total 0
# HELP go_memstats_mallocs_total Total number of mallocs.
# TYPE go_memstats_mallocs_total counter
go_memstats_mallocs_total 19403
# HELP go_memstats_mcache_inuse_bytes Number of bytes in use by mcache structures.
# TYPE go_memstats_mcache_inuse_bytes gauge
go_memstats_mcache_inuse_bytes 12000
# HELP go_memstats_mcache_sys_bytes Bytes in mcache structures obtained from system.
# TYPE go_memstats_mcache_sys_bytes gauge
go_memstats_mcache_sys_bytes 15600
# HELP go_memstats_mspan_inuse_bytes Bytes in mspan structures.
# TYPE go_memstats_mspan_inuse_bytes gauge
go_memstats_mspan_inuse_bytes 95184
# HELP go_memstats_mspan_sys_bytes Bytes in mspan structures obtained from system.
# TYPE go_memstats_mspan_sys_bytes gauge
go_memstats_mspan_sys_bytes 97632
# HELP go_memstats_next_gc_bytes Heap Bytes when next garbage collection happens.
# TYPE go_memstats_next_gc_bytes gauge
go_memstats_next_gc_bytes 4.194304e+06
# HELP go_memstats_other_sys_bytes Number of bytes used for other system allocations.
# TYPE go_memstats_other_sys_bytes gauge
go_memstats_other_sys_bytes 1.300043e+06
# HELP go_memstats_stack_inuse_bytes Number of bytes in use by the stack allocator.
# TYPE go_memstats_stack_inuse_bytes gauge
go_memstats_stack_inuse_bytes 819200
# HELP go_memstats_stack_sys_bytes Bytes obtained from system for stack allocator.
# TYPE go_memstats_stack_sys_bytes gauge
go_memstats_stack_sys_bytes 819200
# HELP go_memstats_sys_bytes Number of bytes obtained from system.
# TYPE go_memstats_sys_bytes gauge
go_memstats_sys_bytes 1.3552656e+07
# HELP go_threads Number of OS threads created.
# TYPE go_threads gauge
go_threads 12
# HELP promhttp_metric_handler_requests_in_flight Current scrapes being served.
# TYPE promhttp_metric_handler_requests_in_flight gauge
promhttp_metric_handler_requests_in_flight 1
# HELP promhttp_metric_handler_requests_total Total scrapes by HTTP status code.
# TYPE promhttp_metric_handler_requests_total counter
promhttp_metric_handler_requests_total{code="200"} 0

```

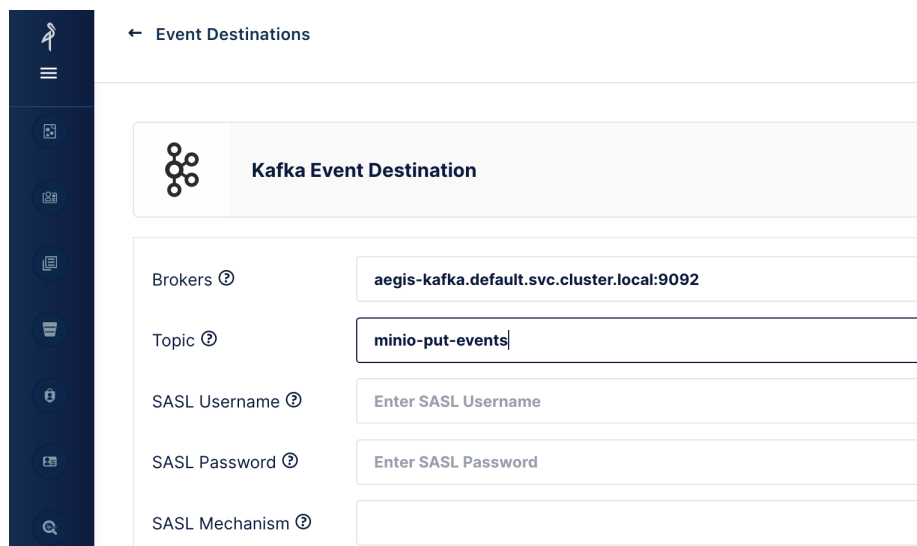
```
promhttp_metric_handler_requests_total{code="500"} 0
promhttp_metric_handler_requests_total{code="503"} 0
```

Listing 4: Create Table SQL Query

```
CREATE TABLE IF NOT EXISTS %s (
    ID SERIAL PRIMARY KEY,
    ObjectKey TEXT NOT NULL,
    BucketName TEXT NOT NULL,
    Result TEXT NOT NULL,
    Antivirus TEXT NOT NULL,
    Timestamp TIMESTAMP NOT NULL,
    VirusType TEXT
);
```

Listing 5: Insert into Table SQL Query

```
INSERT INTO %s (ObjectKey ,
    BucketName ,
    Result ,
    Antivirus ,
    Timestamp ,
    VirusType) VALUES ($1 ,
    $2 ,
    $3 ,
    $4 ,
    $5 ,
    $6
)
// Where %s = tableName
```



← Event Destinations

Kafka Event Destination

Brokers ⓘ aegis-kafka.default.svc.cluster.local:9092

Topic ⓘ minio-put-events

SASL Username ⓘ Enter SASL Username

SASL Password ⓘ Enter SASL Password

SASL Mechanism ⓘ

Figure 24: Configuring MinIO to Send Events to Kafka

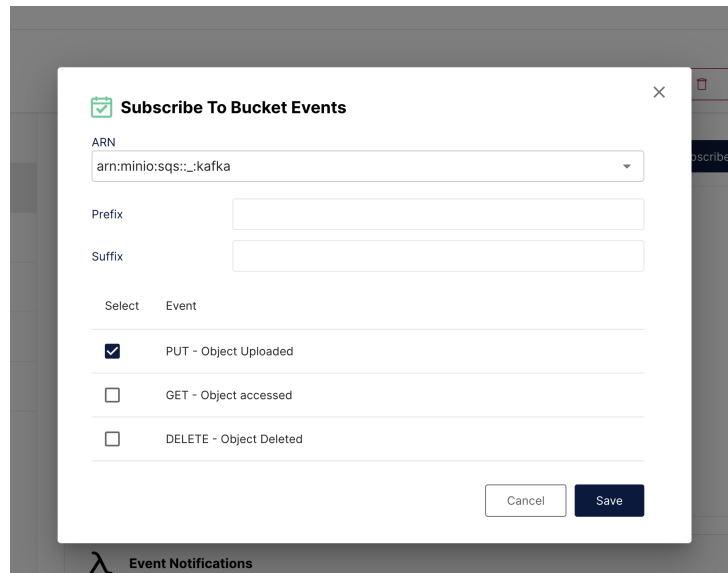


Figure 25: Registering Bucket to Send Events to Kafka

Listing 6: Aegis Scan Log

```

2023-05-09T17:50:12.983Z INFO Starting Aegis\
2023-05-09T17:50:12.984Z INFO Config \{"config": \{"..."\}\}
2023-05-09T17:50:12.984Z DEBUG Creating metric manager and collectors\
2023-05-09T17:50:12.984Z DEBUG Creating Prometheus Server\
2023-05-09T17:50:12.984Z DEBUG Creating Metrics Manager\
2023-05-09T17:50:12.984Z DEBUG Creating audit logger\
2023-05-09T17:50:12.984Z DEBUG Connecting to Postgresql DB \{"database": "aegis_antivirus"\}
2023-05-09T17:50:12.998Z DEBUG Table is created \{"table": "aegis_audit_logs"\}
2023-05-09T17:50:12.998Z DEBUG Creating object store\
2023-05-09T17:50:12.998Z DEBUG Creating MinIO client\
2023-05-09T17:50:12.998Z DEBUG Creating object store\
2023-05-09T17:50:12.998Z DEBUG Creating events system\
2023-05-09T17:50:12.998Z DEBUG Creating Kafka Consumer \{"brokers": ["..."], "topic": "..."\}
2023-05-09T17:50:12.998Z DEBUG Creating Event Manager\
2023-05-09T17:50:12.998Z DEBUG Creating scanning workflow\
2023-05-09T17:50:12.998Z DEBUG Creating dispatcher\
2023-05-09T17:50:12.998Z DEBUG Starting dispatcher loop...
2023-05-09T17:50:12.998Z DEBUG Listening for activity on Kafka...
2023-05-09T17:50:12.998Z DEBUG Starting Metrics Manager\
2023-05-09T17:50:12.998Z DEBUG Exposing metrics at \{"endpoint": "0.0.0.0:9090"\}
2023-05-09T17:50:12.998Z DEBUG Reading message from Kafka\
2023-05-09T17:50:41.285Z INFO Message \{"message": "..."\}
2023-05-09T17:50:41.286Z DEBUG Incrementing kafka message received counter\
2023-05-09T17:50:41.286Z DEBUG Reading message from Kafka\
2023-05-09T17:50:41.286Z DEBUG Getting object from object store \{"bucketName": "...", "objectKey": "..."\}
2023-05-09T17:50:41.286Z DEBUG Getting object \{"bucketName": "test-bucket", "objectKey": "..."\}
2023-05-09T17:50:41.299Z DEBUG Incrementing get object counter\
2023-05-09T17:50:41.299Z DEBUG Saving byte stream to file \{"bucketName": "test-bucket", "objectKey": "..."\}
2023-05-09T17:50:41.299Z DEBUG Cache path \{"cachePath": "..."\}
2023-05-09T17:50:41.301Z DEBUG Scanning file with antiviruses \{\}
2023-05-09T17:50:41.361Z DEBUG clamscan output \{"output": "..."\}
2023-05-09T17:50:41.361Z DEBUG Incrementing files scanned counter\
2023-05-09T17:50:41.361Z DEBUG Adding audit log\
2023-05-09T17:50:41.369Z INFO Clean file \{"bucketName": "test-bucket", "objectKey": "..."\}
2023-05-09T17:50:41.369Z DEBUG Incrementing clean files scanned counter\
2023-05-09T17:50:41.369Z DEBUG Cleaning up \{"cleanupPolicy": "remove"\}
2023-05-09T17:50:41.369Z DEBUG Clean object, not removing \{"bucketName": "test-bucket", "objectKey": "..."\}
2023-05-09T17:50:41.369Z DEBUG Removing file from cache \{"cachePath": "..."\}
}

```

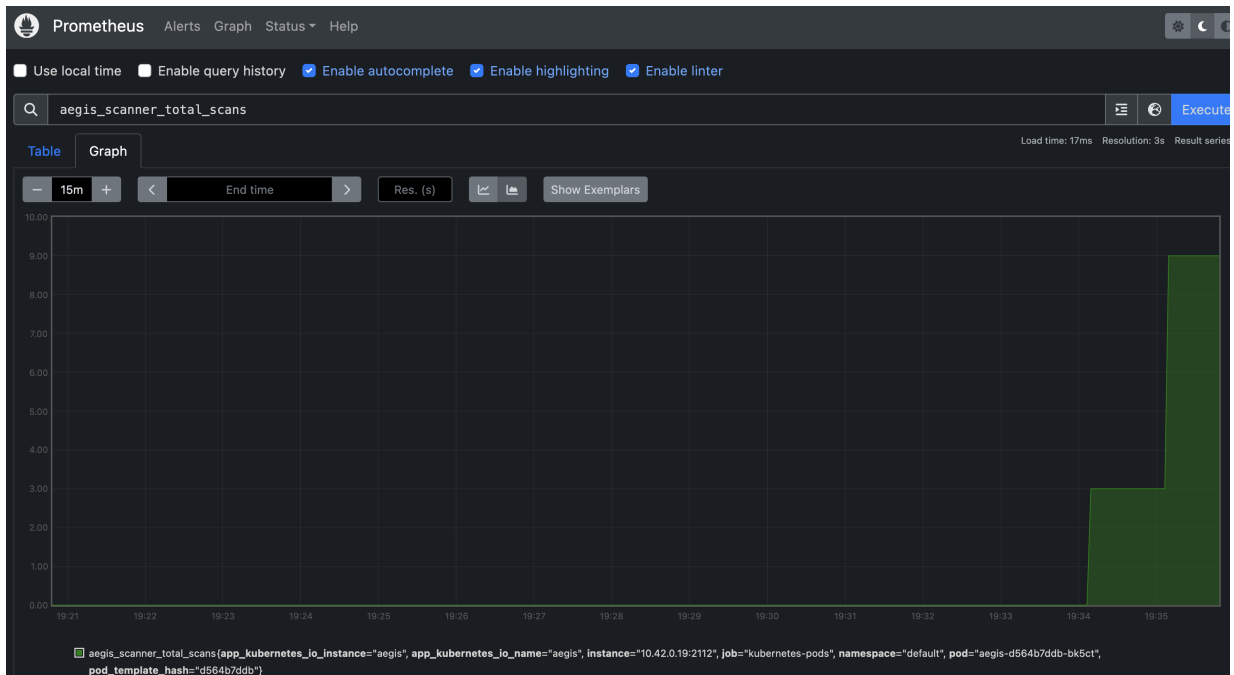



Figure 26: Exposed Prometheus Metrics

Listing 7: Example Audit Log

```
aegis_antivirus=# select * from aegis_audit_logs;
```

id	objectkey	bucketname	result	antivirus	timestamp	virustype
1	1cb3c3f91b2	test-bucket	infected	clamav	2023-05-10 10:06:09	Win. Trojan . Emotet -6396293-0
2	0e969221c2e	test-bucket	infected	clamav	2023-05-10 10:06:09	Win. Trojan . Agent -1816988
3	0b599447fdd	test-bucket	infected	clamav	2023-05-10 10:06:09	Win. Malware . Loki -6881381-0
4	2a299b9d8f0c	test-bucket	infected	clamav	2023-05-10 10:06:09	Win. Coinminer . Generic -7151253-0
5	sysclass.dll	test-bucket	clean	clamav	2023-05-10 10:06:18	
6	bidispl.dll	test-bucket	clean	clamav	2023-05-10 10:06:17	

(6 rows)

Listing 8: Output of Unit Tests

```
ok      aegis/internal/auditlog (cached)      coverage: 69.6% of statements
ok      aegis/internal/cleaner  (cached)      coverage: 62.3% of statements
ok      aegis/internal/dispatcher (cached)      coverage: 73.7% of statements
ok      aegis/internal/events   (cached)      coverage: 47.1% of statements
ok      aegis/internal/metrics  (cached)      coverage: 69.6% of statements
ok      aegis/internal/objectstore 0.273s      coverage: 58.0% of statements
ok      aegis/internal/scanner  (cached)      coverage: 68.5% of statements
```

Listing 9: Output of kubectl get all

```
>>> kubectl get all
```

NAME	READY	STATUS	RESTARTS	AGE
pod/aegis-prometheus-node-exporter-stdb4	1/1	Running	0	3h49m
pod/aegis-kube-state-metrics-776fb858c7-cvnc4	1/1	Running	0	3h49m
pod/aegis-prometheus-pushgateway-75d654897c-kssmh	1/1	Running	0	3h49m
pod/aegis-alertmanager-0	1/1	Running	0	3h49m
pod/aegis-prometheus-server-5cc5469468-bqztp	2/2	Running	0	3h49m
pod/aegis-minio-8588645fc6-fdrbj	1/1	Running	0	3h49m
pod/aegis-postgresql-0	1/1	Running	0	3h49m
pod/aegis-zookeeper-0	1/1	Running	0	3h49m
pod/aegis-kafka-0	1/1	Running	0	3h49m
pod/aegis-clamav-668f695bc-t7r66	1/1	Running	0	92m
pod/aegis-5d7698d4bf-45xq8	1/1	Running	1 (88m ago)	89m

pod/aegis-clamav-cronjob-28062065-m9sxs	0/1	Completed	0	6m29s
pod/aegis-clamav-cronjob-28062067-q9czx	0/1	Completed	0	4m14s
pod/aegis-clamav-cronjob-28062069-bjb48	1/1	Running	0	119s

NAME	TYPE	CLUSTER-IP	EXTERNAL-IP	PORT(S)	AGE
service/kubernetes	ClusterIP	10.43.0.1	<none>	443/TCP	3h52m
service/aegis-zookeeper-headless	ClusterIP	None	<none>	2181/TCP,2888/TCP,3888/TCP	3h49m
service/aegis-kafka-headless	ClusterIP	None	<none>	9092/TCP,9093/TCP	3h49m
service/aegis-postgresql-hl	ClusterIP	None	<none>	5432/TCP	3h49m
service/aegis-alertmanager-headless	ClusterIP	None	<none>	9093/TCP	3h49m
service/aegis	ClusterIP	10.43.6.8	<none>	80/TCP	3h49m
service/aegis-kube-state-metrics	ClusterIP	10.43.180.151	<none>	8080/TCP	3h49m
service/aegis-zookeeper	ClusterIP	10.43.181.148	<none>	2181/TCP,2888/TCP,3888/TCP	3h49m
service/aegis-postgresql	ClusterIP	10.43.90.131	<none>	5432/TCP	3h49m
service/aegis-minio	ClusterIP	10.43.69.101	<none>	9000/TCP,9001/TCP	3h49m
service/aegis-clamav	ClusterIP	10.43.20.200	<none>	3310/TCP	3h49m
service/minio	NodePort	10.43.234.39	<none>	9001:30001/TCP	3h49m
service/aegis-kafka	ClusterIP	10.43.208.56	<none>	9092/TCP	3h49m
service/postgresql	NodePort	10.43.231.175	<none>	5432:30080/TCP	3h49m
service/aegis-prometheus-pushgateway	ClusterIP	10.43.88.49	<none>	9091/TCP	3h49m
service/aegis-alertmanager	ClusterIP	10.43.78.103	<none>	9093/TCP	3h49m
service/aegis-prometheus-node-exporter	ClusterIP	10.43.213.77	<none>	9100/TCP	3h49m
service/aegis-prometheus-server	ClusterIP	10.43.195.143	<none>	80/TCP	3h49m
service/prometheus	NodePort	10.43.5.128	<none>	9090:30090/TCP	3h49m

NAME	DESIRED	CURRENT	READY	UP-TO-DATE	AVAILABLE	NODE SELECTOR	AGE
daemonset.apps/aegis-prometheus-node-exporter	1	1	1	1	1	<none>	3h49m

NAME	READY	UP-TO-DATE	AVAILABLE	AGE
deployment.apps/aegis-kube-state-metrics	1/1	1	1	3h49m
deployment.apps/aegis-prometheus-pushgateway	1/1	1	1	3h49m
deployment.apps/aegis-prometheus-server	1/1	1	1	3h49m
deployment.apps/aegis-minio	1/1	1	1	3h49m
deployment.apps/aegis-clamav	1/1	1	1	3h49m
deployment.apps/aegis	1/1	1	1	3h49m

NAME	DESIRED	CURRENT	READY	AGE
replicaset.apps/aegis-kube-state-metrics-776fb858c7	1	1	1	3h49m
replicaset.apps/aegis-prometheus-pushgateway-75d654897c	1	1	1	3h49m
replicaset.apps/aegis-prometheus-server-5cc5469468	1	1	1	3h49m
replicaset.apps/aegis-minio-8588645fc6	1	1	1	3h49m
replicaset.apps/aegis-clamav-659c5f8c69	0	0	0	3h49m
replicaset.apps/aegis-clamav-668f695bc	1	1	1	92m
replicaset.apps/aegis-d564b7ddb	0	0	0	3h49m
replicaset.apps/aegis-5d7698d4bf	1	1	1	89m

NAME	READY	AGE
statefulset.apps/aegis-alertmanager	1/1	3h49m
statefulset.apps/aegis-postgresql	1/1	3h49m
statefulset.apps/aegis-zookeeper	1/1	3h49m
statefulset.apps/aegis-kafka	1/1	3h49m

NAME	SCHEDULE	SUSPEND	ACTIVE	LAST SCHEDULE	AGE
cronjob.batch/aegis-clamav-cronjob	* * * * *	False	1	2m45s	3h49m

NAME	COMPLETIONS	DURATION	AGE
job.batch/aegis-clamav-cronjob-28062065	1/1	2m15s	6m29s
job.batch/aegis-clamav-cronjob-28062067	1/1	2m15s	4m14s
job.batch/aegis-clamav-cronjob-28062069	0/1	119s	119s

Listing 10: Shutdown Logs of Aegis

Normal scanning

```

...
2023-05-11T16:26:29.844Z   DEBUG   Scanning file with antiviruses {"bucketName": "bucket", "objectKey": "..."}
2023-05-11T16:26:30.343Z   INFO    Shutting down Aegis
2023-05-11T16:26:30.344Z   DEBUG   Non fatal error related to shutdown
2023-05-11T16:26:30.344Z   DEBUG   Stopping Kafka consumer
2023-05-11T16:26:30.344Z   DEBUG   Closing Kafka Reader
2023-05-11T16:26:33.631Z   DEBUG   clamscan output {"output": "..."}
2023-05-11T16:26:33.633Z   DEBUG   virus type output {"virusType": "Win.Trojan.PonyStealer-9831667-0"}
2023-05-11T16:26:33.633Z   DEBUG   Incrementing files scanned counter
2023-05-11T16:26:33.633Z   DEBUG   Adding audit log
2023-05-11T16:26:33.641Z   WARN    Infected file {"bucketName": "bucket", "objectKey": "..."}
2023-05-11T16:26:33.641Z   DEBUG   Incrementing infected files scanned counter
2023-05-11T16:26:33.641Z   DEBUG   Cleaning up {"cleanupPolicy": "remove"}
...

```

Finishing existing scans

```

...
2023-05-11T16:26:55.863Z   DEBUG   virus type output {"virusType": "Win.Trojan.Generic-7363"}
2023-05-11T16:26:55.863Z   DEBUG   Incrementing files scanned counter
2023-05-11T16:26:55.863Z   DEBUG   Adding audit log
2023-05-11T16:26:55.869Z   WARN    Infected file {"bucketName": "bucket", "objectKey": "..."}
2023-05-11T16:26:55.869Z   DEBUG   Incrementing infected files scanned counter
2023-05-11T16:26:55.869Z   DEBUG   Cleaning up {"cleanupPolicy": "remove"}

```

2023-05-11T16:26:55.869Z	DEBUG	Removing infected object	{ "bucketName": "bucket", "objectKey": "..." }
2023-05-11T16:26:55.869Z	DEBUG	Removing object	{ "bucketName": "bucket", "objectKey": "..." }
2023-05-11T16:26:55.880Z	DEBUG	Incrementing remove object counter	
2023-05-11T16:26:55.880Z	DEBUG	Successfully removed infected object	{ "bucketName": "bucket", "objectKey": "..." }
2023-05-11T16:26:55.880Z	DEBUG	Incrementing cleaner object removed counter	
2023-05-11T16:26:55.880Z	DEBUG	Removing file from cache	{ "cachePath": "..." }
2023-05-11T16:26:55.886Z	DEBUG	Dispatcher loop stopped	
2023-05-11T16:26:55.886Z	DEBUG	Stopping Metrics Manager	
2023-05-11T16:26:55.886Z	DEBUG	Stopping Metric Server	
2023-05-11T16:26:55.886Z	DEBUG	Prometheus server closed, exiting	

References

- Abdollahi, V. L., Aymen, S. M., Maria, T. and Ferhat, K. 2019. Kubernetes as an availability manager for microservice applications. *arXiv preprint arXiv:1901.04946* .
- Abdollahi Vayghan, L., Saied, M. A., Toeroe, M. and Khendek, F. 2018. Deploying microservice based applications with kubernetes: Experiments and lessons learned. In: *2018 IEEE 11th International Conference on Cloud Computing (CLOUD)*. pp. 970–973.
- Artifact Hub. 2022. Artifact hub, Available at: <https://artifacthub.io/>. [Accessed: 16 Apr 2023].
- Aslan, Aslan, O. and Refik, S. 2020. A comprehensive review on malware detection approaches. *IEEE Access* 8, pp. 6249–6271.
- Baresi, L., Quattrocchi, G. and Tamburri, D. A. 2022. *Microservice architecture practices and experience: a focused look on docker configuration files*, [Online].
- Bruce, M. 2001. *PostgreSQL: introduction and concepts*, vol. 192. Addison-Wesley New York.
- ClamAV. 2023a. Clamav, Available at: <https://www.clamav.net/>. [Accessed: 24 Mar 2023].
- ClamAV. 2023b. Clamav, Available at: <https://www.github.com/Cisco-Talos/clamav>. [Accessed: 24 Mar 2023].
- David, B., Csaba, S. and Markosz, M. 2020. Adaptive scaling of kubernetes pods. In: *NOMS 2020 - 2020 IEEE/IFIP Network Operations and Management Symposium*. pp. 1–5.
- Dictionary, L. O. 2023. Aegis definition in oxford dictionary, Available at: <https://web.archive.org/web/20200323141618/https://www.lexico.com/definition/aegis>. [Accessed: 15 Feb 2023].
- Dileepa, J. 2012. Towards structured log analysis. In: *2012 Ninth International Conference on Computer Science and Software Engineering (JCSSE)*. pp. 259–264.
- Doaa, A., Naglaa, G., Eman, E. and Lamiaa, D. 2022. The malware detection approach in the design of mobile applications. *Symmetry* 14(5). Available at: <https://www.mdpi.com/2073-8994/14/5/839>.
- Docker. 2022. Docker, Available at: <https://www.docker.com/>. [Accessed: 16 Apr 2023].
- Docker. 2023. Dockerfile documentation, Available at: <https://docs.docker.com/engine/reference/builder/>. [Accessed: 24 Apr 2023].
- Francia, S. 2023. Viper, Available at: <https://github.com/spf13/viper>. [Accessed: 25 Mar 2023].
- Gita, M., Wildan, S. and Ardiansyah, A. F. "2018". "personal extreme programming with moscow prioritization for developing library information system". *"IAES Indonesia Section"*

- "Vol 5: EECSI 2018". Available at: <http://journal.portalgaruda.org/index.php/EECSI/article/view/1701/1140>.
- GNU. 2023. Makefile, Available at: <https://www.gnu.org/software/make/manual/make.html>. [Accessed: 25 Mar 2023].
- Go. 2023. Effective go, Available at: https://go.dev/doc/effective_go. [Accessed: 2 May 2023].
- Go by Example. 2022a. Closing channels, Available at: <https://gobyexample.com/closing-channels>. [Accessed: 30 Mar 2023].
- Go by Example. 2022b. Ranging over channels, Available at: <https://gobyexample.com/range-over-channels>. [Accessed: 30 Mar 2023].
- Go by Example. 2022c. Waitgroups, Available at: <https://gobyexample.com/waitgroups>. [Accessed: 30 Mar 2023].
- Goverment, U. 2018. The data protection act 2018, Available at: <https://www.gov.uk/data-protection>. [Accessed: 28 Feb 2023].
- Helm. 2023. Helm documentation, Available at: <https://helm.min.io/>. [Accessed: 29 Apr 2023].
- John, G. and David, R. 2012. The digital universe in 2020: Big data, bigger digital shadows, and biggest growth in the far east. *IDC iView: IDC Analyze the future* 2007(2012), pp. 1–16.
- Joshua, D. and John, W. 2002. *Practical PostgreSQL*. " O'Reilly Media, Inc."
- K3d. 2023a. K3d config documentation, Available at: <https://k3d.io/v5.4.1/usage/configfile/>. [Accessed: 24 Apr 2023].
- K3d. 2023b. K3d documentation, Available at: <https://k3d.io/v5.4.9/>. [Accessed: 24 Mar 2023].
- Kil, C. S., Iulian, M., Jiyong, J., John, T., David, B. and G., A. D. 2011. Splitscreen: Enabling efficient, distributed malware detection. *Journal of Communications and Networks* 13(2).
- Kubernetes. 2023. Kubernetes documentation, Available at: <https://kubernetes.io/>. [Accessed: 16 Apr 2023].
- Levy, E. 2022. Kafka vs rabbitmq: Architecture, performance, and use cases, Available at: <https://www.upsolver.com/blog/kafka-versus-rabbitmq-architecture-performance-use-case>. [Accessed: 24 Mar 2023].
- Liao, H.-J., Richard Lin, C.-H., Lin, Y.-C. and Tung, K.-Y. 2013. Intrusion detection system: A comprehensive review. *Journal of Network and Computer Applications* 36(1), pp. 16–24. Available at: <https://www.sciencedirect.com/science/article/pii/S1084804512001944>.
- M, I. 2022. Installing apache kafka without zookeeper: Easy steps 101, Available at: <https://hevodata.com/learn/kafka-without-zookeeper/>. [Accessed: 24 Mar 2023].
- Martínez, J. 2022. Kubernetes services clusterip, nodeport and loadbalancer, Available at: <https://sysdig.com/blog/kubernetes-services-clusterip-nodeport-loadbalancer/>. [Accessed: 16 Apr 2023].

- McKusick, M. K., Neville-Neil, G. V. and Watson, R. N. M. 2014. *Process Management in the FreeBSD Operating System*, Addison-Wesley Professional, p. 928. 2nd ed., Available at: <https://www.informit.com/articles/article.aspx?p=2249436&seqNum=8>.
- Michael, F., Kalman, M., Dalit, N., Ohad, R. and Julian, S. 2005. Object storage: the future building block for storage systems. In: *2005 IEEE International Symposium on Mass Storage Systems and Technology*. pp. 119–123.
- Miguel, H. R. 2021. Analysis of software engineering automation tools for go., Available at: <https://repositorio.uniandes.edu.co/handle/1992/54945>. [Accessed: 15 Apr 2023].
- MinIO. 2023a. Minio go sdk repository, Available at: <https://github.com/minio/minio-go>. [Accessed: 15 Mar 2023].
- MinIO. 2023b. Minio object lambda, Available at: <https://min.io/docs/minio/linux/developers/transforms-with-object-lambda.html>. [Accessed: 11 May 2023].
- MinIO. 2023c. Minio object storage, Available at: <https://min.io/>. [Accessed: 15 Mar 2023].
- MinIO. 2023d. Minio pricing, Available at: <https://min.io/pricing/> [Accessed: 24 Mar 2023].
- MinIO Erasure Coding. 2023. Minio erasure coding, Available at: <https://min.io/docs/minio/linux/operations/concepts/erasure-coding.html>. [Accessed: 25 Apr 2023].
- Narūnas, K. 2020. Performance studies of kubernetes network solutions. In: *2020 IEEE Open Conference of Electrical, Electronic and Information Sciences (eStream)*. pp. 1–6.
- Nitin, N., Paul, J., Roger, C., Jonathan, G. and Yaochu, J. 2020. Evaluating automatically generated yara rules and enhancing their effectiveness. In: *2020 IEEE Symposium Series on Computational Intelligence (SSCI)*. pp. 1146–1153.
- Nitin, N., Paul, J., Savage, N. and Longzhi, Y. 2019. Cyberthreat hunting - part 1: Triaging ransomware using fuzzy hashing, import hashing and yara rules. In: *2019 IEEE International Conference on Fuzzy Systems (FUZZ-IEEE)*. pp. 1–6.
- Nuha, A., Nour, A. and Roger, E. 2016. A systematic mapping study in microservice architecture. In: *2016 IEEE 9th International Conference on Service-Oriented Computing and Applications (SOCA)*. pp. 44–51.
- Omer, A. 2017. Performance comparison of static malware analysis tools versus antivirus scanners to detect malware. In: *International Multidisciplinary Studies Congress (IMSC)*.
- Ormandy, T. 2011. Sophail: A critical analysis of sophos antivirus. *Proc. of Black Hat USA* .
- Ot, A. 2022. The object storage market, Available at: <https://www.enterprisestorageforum.com/cloud/cloud-object-storage-market/>. [Accessed: 17 Mar 2023].
- Po-ching, L., Zhi-xiang, L., Ying-dar, L., Yuan-cheng, L., C, L. F. *et al.* 2006. Profiling and accelerating string matching algorithms in three network content security applications. *IEEE Commun. Surv. Tutorials* 8(1-4), pp. 24–37.
- Prometheus. 2023. Prometheus documentation, Available at: <https://prometheus.io/>. [Accessed: 24 Mar 2023].

- Ryer, M. 2020. Why you shouldn't use func main in go, Available at: <https://pace.dev/blog/2020/02/12/why-you-shouldnt-use-func-main-in-golang-by-mat-ryer.html>. [Accessed: 30 Mar 2023].
- Samuel, G. 2021. *An A/B Testing Platform for Fastly's Compute@ Edge*. Ph.D. thesis, Worcester Polytechnic Institute.
- Scott, M., Johnston, S. J. and Cox, S. J. 2017. Metagit: Decentralised metadata management with git. *Information Systems* 65, pp. 78–92. Available at: <https://www.sciencedirect.com/science/article/pii/S0306437916303118>.
- Segmentio. 2022. Kafka go repository, Available at: <https://github.com/segmentio/kafka-go>. [Accessed: 24 Mar 2023].
- Srinivasan, G., Eidelman, A. and Casmer, E. 2022. Integrating amazon s3 malware scanning into your application workflow with cloud storage security, Available at: <https://aws.amazon.com/blogs/apn/integrating-amazon-s3-malware-scanning-into-your-application-workflow-with-cloud-storage-security/>. [Accessed: 21 Mar 2023].
- Svetoslav, Z. and Anna, R. 2019. Using microservices and event driven architecture for big data stream processing. *AIP Conference Proceedings* 2172(1). Available at: <https://doi.org/10.1063/1.5133587.090010>.
- Uber. 2023. Zap, Available at: <https://github.com/uber-go/zap>. [Accessed: 25 Mar 2023].
- vektra. 2023. A mock code autogenerator for golang, Available at: <https://github.com/vektra/mockery>. [Accessed: 11 May 2023].
- Vivek, S. 2022. Managing multi-cloud deployments on kubernetes with istio, prometheus and grafana. In: *2022 8th International Conference on Advanced Computing and Communication Systems (ICACCS)*. vol. 1, pp. 525–529.
- Vlad, B., Dehelean, C. and Liviu, M. 2018. Object storage in the cloud and multi-cloud: State of the art and the research challenges. In: *2018 IEEE International Conference on Automation, Quality and Testing, Robotics (AQTR)*. IEEE, pp. 1–6.
- Yang, J. 2009. Analyzing uml sequence diagrams with utp. *2010 Fifth International Conference on Frontier of Computer Science and Technology* pp. 417–423.