# Stateful FaaS

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## Abstract

Serverless Computing is an up and coming platform as a service offering where the cloud provider manages and allocates resources needed to keep the application running. This lets the developer focus on the application development and not on server maintenance. Alongside off loading the provisioning and maintenance of the server, Serverless computing also reduces resource waste by scaling up and down the allocation depending on the load and the configurations. The users only pay for the resources that were used by the application thereby saving huge operational cost on their infrastructure hosting.

Although Serverless might sounds like the holy grail of application hosting, the current state of art technology fall short in several places to meet the industrial requirements. Data intensive applications, streaming applications, and distributed computing are some of the fields that could be benefited heavily by implementation on Serverless platforms in terms of ease of development, efficiency and cost. But all the existing platforms offer very poor performance in these fields and works mostly via workarounds and n number of third party tools.

This thesis analyses the Serverless paradigm in depth, pointing out the reasons for this reduced adaptability. To solve these issues, we propose a lightweight extension to an existing Open Source Serverless platform, OpenFaaS, by provide flexibility, scalability and adaptability, while making sure not to violate the notion of functions. Our implementation tries to reduce the operational gap between the industrial applications and theoretical ideas produced by researches in the academia in the past few years. This thesis also offers a deep study of the full potential and limitations of Serverless thereby making it clear to the reader why more innovations are necessary in this field.

# Contents

# 1 Introduction

Serverless can easily be considered as the new generation of platform as a service. It can be thought of as an infrastructure where the programmer send their application as functions in a predefined format, in a supported programming language as documented by the provider. This function get hosted at a certain endpoint which can be triggered with certain events supported by the platform. In short, instead of having continuously running servers, functions operate as event handlers and when the functions execute, the equivalent CPU usage is paid for by the user. This has huge economical and architectural implications that is still waiting to be explored in its full power. While the developers worry about the logic of handling the requests/events, the infrastructure provider takes care of receiving the request, responding to them, capacity planning, task scheduling, and operational monitoring[**gotoconf**].

In the current industrial applications, data intensiveness of the applications are increasing day by day paving way to adopt several resource heavy tools to do stream processing, distributed processing etc. More than often CPU and memory loads in these machines tent to vary a lot and rather than having a dedicated server to accommodate the whole range of requirements, it makes perfect sense to convert it into a Serverless workload thereby saving up on operational cost, resource waste, and ease of development. Having said that, the current commercial offerings of Serverless do not work very great with such workloads.

This is mostly due to the sheer nature of the Serverless paradigm of being completely stateless, thereby forcing the developers to use external block storages for data store and communication. In this thesis, we try to extend Serverless to leverage its full potential by introducing an efficient form of state thereby providing flexibility, scalability and adaptibility at the same time not violating the notion of functions in these platforms. We will be extending an Open Source serverless platform called OpenFaaS considering its simplistic and expandable architecture.

Currently most of the commercial serverless offerings are closed source and vendor locked in to their respective platforms by cloud providers. But in the past couple of years the field has gotten a lot of traction in the academia and a lot of Open Source alternatives are being widely adopted. This being the case, a lot of these works hasn't been properly applied in the industry, some because of the absense of proper integrations with the industry standard tools, and some because of the operational gap between the theoretical ideas and the practicality or usability in the field. This thesis tries to reduce that gap by proposing a very secure and multi-tenant implementation of a state-ful Serverless setup which can be easily used for production quality applications. A focus on the possibility to monitor the application performance and usage provides a possibility to do fine grained billing of the resources and thereby contributing to the easy adaptability of our extension.

Using our proposed Serverless setup, we try to efficiently run a Extract-Transfer-Load(ETL) workload on streaming data. ETL basically is a pipeline that involves receiving data from source, cleaning and transforming it, and loading it to a sink. We will split the whole operation into multiple functions as per the Serverless notion and have them communicate data and state internally to complete the pipeline thereby reducing the latency and external bottlenecks.

This document describes more on Serverless paradigm, the shortcomings of it, the ones we are trying to solve, our solution and evaluation. It is split into several sections as follows:

In Section 2, we go a bit in depth to understand the history of cloud infrastructure and the technological innovations that led to Serverless paradigm. We also look in detail at the characteristics and nature of Serverless. We look at some commercial Serverless offerings and understand how in the programming world Serverless has influenced even in the way of developing. We will also see what limitations it holds at its current state of evolution and on solving which issue are we particularly interested in, in the scope of this thesis.

In Section 4, we look at the current state of research in the field of Serverless technologies and some related works.

In Section 3, We present the proposed solution for our Serverless setup going into detail about how certain unacceptable limitations can be overcome.

In Section 4, the implementation of the system including the architecture and the tools used is presented.

In Section 5, we go on with the evaluation of our system as opposed to standard Serverless workloads.

We move on to Section 6 to understand the limitations of our proposed system.

In Section 7, the future work that can be done in this direction is laid out before the reader.

# 2 Background and Motivation

The term serverless have been vaguely thrown around the domain of cloud infrastructure in the past decade as the breakthrough resource(and hence money) saving tool that lets the developers focus on application logic rather than the deployment and server maintenance. Having said that, it is often hard to define what exactly serverless is since the service offering tend to change based on the cloud provider and the interpretations of the users. It is fair to say that serverless is a huge leap in the direction of using computational power as a resource which can be paid for as per the usage. Although the terminology is irrelevant, we will be focusing on the serverless offering called Function-as-a-Service(FaaS) where the cloud providers offer a platform to which we can upload our application code to(complying to the API rules) and get uninterrupted service of the same at an endpoint irrespective of the traffic or data load. Paying only for what resources has been used adds to the attraction of the domain. In this section, we will understand more about this technology, the popular commercial offerings the same, and its limitations and the current state of research. We will also analyze the popular data processing and streaming pipelines in the industries these days and why serverless computing fall short in being the right tool of development and deployment here.

## 2.1 Evolution of cloud resource management

In the past 3 decades, software deployments and infrastructure management has seen a lot of innovation and evolution. Before diving into the current industrial standards, it is important to understand the evolutions in this field to get a better grasp on the technological innovations that bought this about.

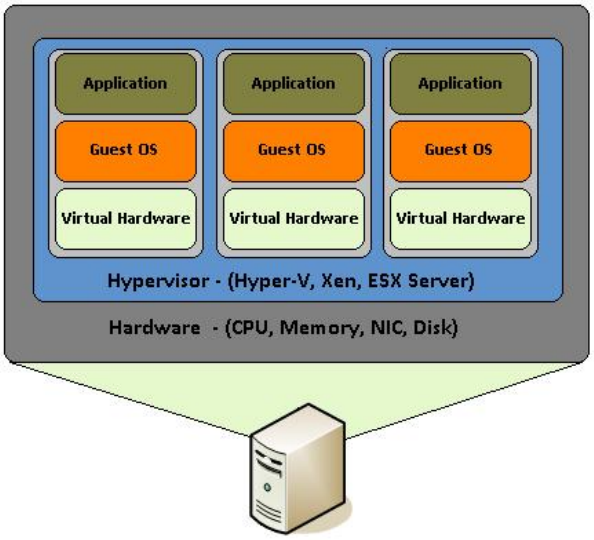
### 2.1.1 Dedicated servers

Even as recent as 15 years ago this was the industry standard for deployments. Dedicated servers are physical machines. The general practice was to have server racks on the premise of the company which are maintained by system administrators and all your software is hosted there. Although this method offers advanced security and high availability, it is often common that a lot of physical resources were underutilized and each resource was for single client. Not to mention the environmental impact of the reserved heavy hardware which leaves a heavy carbon footprint and e-wastes.

### 2.1.2 Dedicated virtual machines(BaaS)

Virtualization technology changed the face of software infrastructure by decoupling applications from the underlying hardware. Virtualized servers are not physical machines, they are a software construct. Virtual servers run on dedicated servers, the resources of which are divided between several virtual servers. To get slightly technical, virtualization usually involves installing a virtualization software(Hypervisor) on an existing operating system and then having multiple operating systems on it, sharing all the resources of the underlying operating system, yet providing great security and isolation.

Figure 1: Figure 1: Virtualization through hupervisors



Although applications in hosted on the virtual machine suffers from a heavy input/output and network overload because of the added layer of indirection, this technology reduces the resource waste to a great extend. The enterprises could share their hardware into multiple virtual machines and have different hosting and computation in each of the them. System administrators started splitting up their bare metal resources among multiple Virtual Private Servers(VPS) by the help of virtualization software. Each VPS would give you the feeling of having a real system although it is a virtualized system which is sharing the resources with other VPSs. This reduced a lot the amount of work and energy spent on maintaining server racks along with the terrible underutilization of resources.

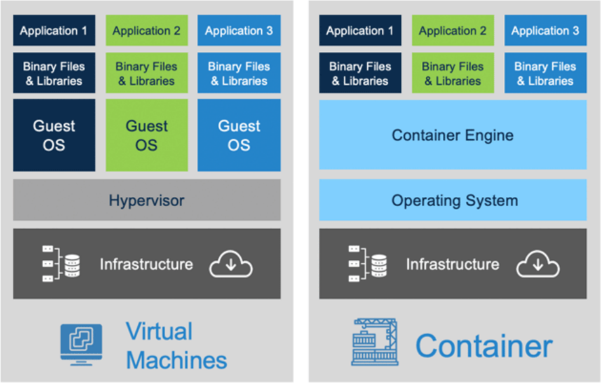
More and more companies started adapting this technology and in early 2006 Amazon Web Services(AWS) re-launched themselves as a platform that offers computing and storage space to developers and enterprises on an on-demand basis revolutionizing how companies were designing their system architecture. Soon after Google and Microsoft followed suit with their cloud infrastructure platforms offering similar services. All these providers function by maintaining huge, dedicated server farms across the globe to provide the necessary resources to the customers.

These kind of services, generally called as Infrastructure as a Service(IaaS) or Platform as a Service(PaaS), went through a series of changes during the past decade. On-demand compute instances to completely managed deployment services(eg: Google App Engine), Pay per use block storages(AWS S3) to fully managed dedicated relational databases(Google Cloud SQL, AWS RDS, etc.) a lot of really efficient and interesting services started to be available for the developers disposition. The billing scheme of these services also started to be quite flexible even allowing a per second billing plan in the past couple of years by Google.

It is also worth noting that with the advent of virtualization, the job profiles in several companies shifted from having a system administrator role to having profiles called DevOps(development and operations) who are application developers focusing on the provisioning of the virtual machines to deploy their applications. Although IaaS solved a lot of hassle around infrastructure provisioning, the systems and load of the applications still remained independent. Applications always had dedicated virtual machines even if the load/traffic to and fro the application is not constant. This meant that a lot of resources were still being wasted.

**Linux Containers** A game changer in the world of virtualization was containerization. Containers are yet another packaged computing environment that combine various IT components and isolate them from the rest of the system just like a virtual machine would. It was developed to solve a lot of problems with virtual machines. The purpose of the containers is to encapsulate an application and its dependencies within its own environment. This allows them to run in isolation while they are using the same system resources and the same operating system. Since the resources are not wasted on running separate operating systems tasks, containerization allows for a much quicker, lightweight deployment of applications. Each container image could be only a few megabytes in size, making it easier to share, migrate, and move. Figure 2 shows the difference in the isolation levels of containers and virtual machines. [containers]CITE Even though Linux Containers have existed for a very long time, in the past decade, containers were made a lot more approachable and adaptable as a technology by the advent of communities like Docker and rkt.

Figure 2: Figure 2: Virtual Machines Vs Containers



The light weight of the containers made it the ideal candidate for running applications. What makes container based deployments special as opposed to the ones deployed directly on the host is the consistency of the environment. The application execution environment can be recreated and ported from one system to another without affecting the functionality of the application or having to reinstall the whole binary dependencies on the new machine. Reproducability of the production environment even in the local exactly, meant that the development/testing cycle became much more efficient. The isolated package of the application, enveloped as a container image, is agnostic of the operating system it runs on opening new possibilities for the deployment. One could also limit and fine tune the resources used by a running containers giving a lot more control over the application.

**Autoscaling** The ease in which one can limit the resources and tweak the runtime parameters externally contributed heavily to the service offering called autoscaling which basically meant resources for an application runtime were added or removed as per the usage. All the commercial cloud providers started offering the aforementioned service in different flavors. Autoscaling on EC2 or Google Compute, AWS Fargate, etc. are some examples.

In the past two years, innovations have taken a leap in the field of isolation environments, introducing solutions like AWS Firecracker, Cloudflare workers, etc. to the community. These solutions aim at mitigating the shortcomings of Containers which we will discuss in Section 2.2.4

### 2.1.3 Serverless

Like mentioned earlier, in the past two years the terms Serverless and Function-as-a-Service are quite often used interchangeably. In terms of the resource reservation, Serverless can be considered as a platform as a service solution that scales. Your application will always have enough and only enough resources dedicated to it. It will scale up and down based on the load and traffic and the developer only pays for the usage. This paradigm of autoscaling has been hence applied even to database storage solutions by major cloud providers such that even the block storage is allocated based on usage and there will be a burst of reservation as soon as a certain limit is reached. The pioneers of this technology can be considered as the proprietary service Lambda by Amazon Web Services[CITE]. Several other cloud providers followed suit with similar platforms specific to their infrastructure. The nature of serverless makes it attractive for both developers and the cloud providers since in the case of former, it means paying much less and in case of the latter, it means they can easily provide shared tenant resource allocation units.

We will dive more into the properties and nature of the solution Function-as-a-Service(FaaS) in the following session.

## 2.2 FaaS

So far, we have covered the infrastructure management style of FaaS or Serverless in general. Let us get a bit in detail into the specifics of the hosting platform that provides the FaaS functionality.

Most FaaS platforms being closed source, provides the client API for developers to supply a package including their code and dependencies to. Most platforms supports a limited set of programming language runtime although it is usually possible to do workarounds to deploy custom runtime. Behind the screen, the platform containerizes the application and deploy it so as to get triggered via pre-defined hooks specified by the developer. The infrastructure also provides endpoints or interfaces to specify the maximum and minimum CPU and memory allocated for the application, the maximum timeout for the application(although there is a hard bound on this imposed by the infrastructure provider usually). To understand the flow of FaaS workloads, it is important to be aware of the following properties of the platform.

### 2.2.1 Properties of FaaS

**Statelessness** Statelessness in deployments is a conscious decision that was taken during the conception of the Serverless infrastructure model to make the management of the platform straight forward and less cumbersome. Statelessness simply means that the applications that are to be deployed on the said platform exists as independent functions that are pure in nature. As in, the same data input given to the function always produces the same output at any point in time. This can be considered as the side-effect less programming. The data source and sink of the function can be any supported platform or tool as per the requirement, but there won't be any intermediate state or cache for the function. This means that the function at any execution will have no information about the previous execution unless explicitly specified.

The main advantage with this method for the infrastructure manager is pretty obvious. The fact that there are no volumes necessary to store any internal state means that the function can be scaled up and down independently and the whole infrastructure can stay elastic. Along with this, the provider can schedule the function in any node in the cluster that they use to host the application, move it around as per the usage burst, have multi-tenant deployments in a single machine ensuring the proper isolation for maximum profitability, and the list goes on.

In short, the notion of function is of prime importance in a Function-as-a-Service workload like the name suggests.

**Triggers** The functions that are hosted on a FaaS solution need to get triggered on a timely basis or based on an event. Usually most cloud providers provide more than a few ways to trigger the functions which the developer can choose from. Some of the most common triggers for FaaS applications are

- HTTP requests: An endpoint will be provided by the platform for the function that was deployed.

This endpoint can be called as an REST API endpoint and the event handler of the function will get the payload from the call.

- Data arrival in a storage or data broker system: This is the most popular and heavily used triggering mechanism in FaaS. The idea

is that the function gets triggered as soon as a new data arrives in whatever format at a particular storage setup. This can be arrival of a file object in the S3 block storage, arrival of streamed data in Kafka message broker system, etc. This method is the most suited for big data and streaming data applications since the function can be activated as soon as the new data is detected in the source. Usually the FaaS infrastructure provide supports more than a bunch of source storage to be used as the sources for the trigger.

- Cron: Another very common way to trigger function is based on a schedule. The

programmer can choose how often the function should be triggered on what days of the week, month, year, etc.

**Parallelism**

**Billing**

### 2.2.2 How programming models are getting affected by this

**Faas + Microservices** In Software Systems Design, a very heavily discussed topic is if to design the application in a monolithic fashion or a microservices fashion. Monolith is the kind of design pattern where you have one big application doing multiple functions and maintained as one solid stack. On the contrary, when one designs their app in a microservices pattern, they will have split up their application into multiple smaller parts which can be independently built and deployed, and yet working together with inter app communications. Both of these methods has its advantages and challenges. When monoliths are easier to develop and maintain, it can be very hard to test and manage due to the size, and usually if one part is buggy, it tends to break the whole system. On the other hand, microservices, since they work as independent units don't usually affect each others working and can be very easily tested and maintained. It is although often a very tedious task developing a system that fragmented and maintaining it that way.

With the advent of FaaS, a very interesting pattern has been adapted in the industry. The pattern pushed microservices one step further. The idea is that instead of having microservices that are available and on at all time, the huge applications are split up into functions that can be deployed to a FaaS infrastructure and triggered with the help of HTTP endpoints to act as a part of web application setup. This method is very effective resource usage wise and much easier to deploy and manage compared to vanilla microservices which has to be built and deployed independently.

**Statelessness a.k.a Functional programming model** Like mentioned earlier, the notion of function is very important for the serverless platforms. It is intrinsically linked with functional programming. It is very interesting to note that Amazon named their FaaS solution Lambda which is a very basic concept of functional programming. Stateless clean functions that produce no side effect was objectively the perfect choice for an infrastructure solution of this scale.

What this change bought about is a thriving interest in functional programming languages. A lot of the functional programming languages belonging to the LISP family and some purely functional ones have seen a very increasing adaptation in the past few years in Serverless platforms. Since these languages are perfectly suited for stateless program it is only natural that they can be efficiently used to code for this environment.

### 2.2.3 Popular commercial offerings

#### AWS Lambda

#### Google cloud functions

#### Azure functions

### 2.2.4 Where Serverless computing fall short

Although serverless computing might sound like the silver bullet of the deployment solutions, it is a field that is still being rapidly grown and researched on. There are several staggering shortcomings for this technology that makes it unsuitable for certain applications. The current offering have the following noticeable limitations.

**Lack of state** As mentioned earlier, statelessness is a primary nature for serverless workloads making it easy to deploy and port agnostic of the environment and server. Hence serverless/auto-scaling paradigm generally push for a development style involving no state to make the infrastructure simple, encouraging a functional style of development. Although this can contribute to easily scalable and parallelisable applications, it often limits the technology from being adapted in applications that are data intensive and/or requires faster response times. The fact that serverless functions don't store any intermediate state requires the application developers to use a block storage to store the data and state after the execution. This basically means communication via slow storage and adds a lot to the latency. This discourages the use of serverless in distributed computing which is actually a domain that needs very fine grained communication between the functions and usually a lot of resources are wastefully dedicated to ensure high availability.

A function during execution has no clue of the previous executions and its results. Which is something that is usually very basic for data analysis operations. The developers in this case are forced to send the data after each execution to a block store and retrieve the data from the block store before the next execution. Other than the input output overhead and the network latency this adds, it is a violation of the elastic nature of the Serverless paradigm.

**I/O Latency** Like was mentioned earlier, FaaS have had a lot of influences in the system architecture and programming paradigms like would with any new infrastructure management system. It is quite unfortunate though that, even with a paradigm with such huge potential, FaaS is very conventional when it comes to its data engineering architecture. Functions are run in isolated units separate from the data or data store. This is actually a very huge system design anti-pattern because Input/Output have and will remain to be a bottle neck even with heavy memory and huge number of dedicated cores to a function. The pattern where the data is taken to code as opposed to code to data adds to the latency, cost, and inconvenience. For the clarity of the reader, an example of a code shipping architecture is procedures that you run in databases. The code is moved to the data than the other way around in this.

**Coordination issues among functions** As we saw in the previous sections, FaaS workloads are usually containerized by the cloud provider to deploy it easily in their node pool or cluster. By nature, docker containers are indiscoverable units that need to be opened up explicitly to the network of the host machine. Meaning that, we cannot explicitly address the docker container directly using an IP address or an endpoint. Cloud providers do not open up the container to the network consider the potential security issues this can cause and the necessity of state in this case. They provide handles to communicate with the function or trigger-able entry points, but no direct network addressability.

What this implies is that, if the developer has multiple functions that has to be composed together to form a pipeline, rather than triggering each other internally and directly, the developer will have to hack around by either triggering it via an HTTP endpoint if the provider allows that, or like was mentioned in the previous point via an external block storage, or other external queueing systems they provide, etc. In either of these scenarios, it is hard to avoid added latencies.

This makes FaaS particularly inefficient for applications like distributed computing when it depends on very fine grained communication between the functions. With FaaS we can only ensure very weak consistency across function storages making it a pretty bad candidate. What this also means is that there is no way we can actually have efficient parallelism even if we have many powerful cores installed over the current state of FaaS since the block storage will always be a bottleneck.

It goes without saying that most big data applications that need ephemeral storages between function executions suffers from the very similar kind of latencies as well. This includes function compositions like ETL on streaming and batch data alike.

CITE[onestepforward]

**Vendor lock-in** It is no secret that the most widely used FaaS/serverless offerings are the ones by proprietary cloud providers where they hand twist the developers into complying to their programming environment and runtime thereby forcing devs to use their technologies. What such practices contribute to is limited innovations and development around the paradigm of Function as a service itself and people re-inventing the wheel by creating custom made code and hack to fit each of these provider runtime.

In a system like FaaS, where you are basically out-sourcing the whole setup of your application to a vendor, the fact that the whole ecosystem is closed source and uses the tools developed by the vendor only means that the user has near to zero control over the infrastructure and the pipeline is not transparent at all for any kind of performance optimization or fine tuning.

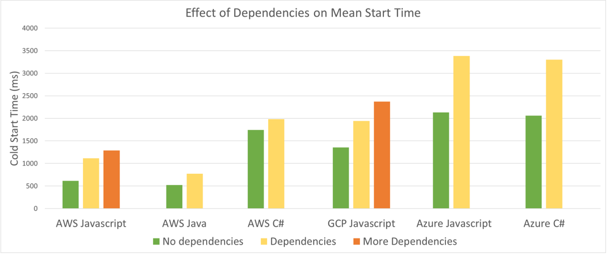
**Fixed timeouts** This is the one of the other bigger reasons that hinder the usage of FaaS in big data applications. In applications that involve heavy number crunching algorithms, there are chances that often the function needs to run for a longer period of time. Current commercial FaaS offerings has a fixed timeout, exceeding which the function execution is automatically terminated irrespective of the stage of the execution. The fact that the platform offer little to no control over this discourages the developers to use the tool.

Currently the maximum timeout for function execution in AWS and GCP platforms for the FaaS setups are 15 minutes and for Azure functions it is 10 minutes. These are all extremely bounding as conditions especially for functions that are composed and a function should wait for the other functions to finish executing.

**Cold Start** Cold start it the delay that the function incurs after the invocation or triggering of the function till the execution of the function. In the background, FaaS uses containers to encapsulate and execute the functions. When an user invokes a function, FaaS keeps the container running for a certain time period after the execution of the function (warm) and if another request comes in before the shutdown, the request is served instantaneously. Cold start is about the time it takes to bring up a new container instance when there are no warm containers available for the request CITE{Blog}. In most platforms serverless latency on average is measure to as 1-3 second CITE{BLOG}, which can have very dramatic impacts when it comes to certain workloads. According a 2018 survey, this is the third biggest concern developers have regarding the serverless platform CITE{BLog}.

The cold start time in-fact is overblown by several factors in the infrastructure. All the popular commercial FaaS offerings suffer from a cold start time. It can referred that irrespective of the language runtime used, the start time tend to be almost the same on a platform. The main deciding factor is the dependencies that were packaged for the application which obviously makes the container slower to start because of the heaviness. Figure 3 shows the cold start time differences across different commercial cloud providers under different runtime and different dependencies.

Figure 3: Figure 3: Cold start across cloud providers [[https://mikhail.io/2018/08/serverless-cold-start-war/][CITE]]



A solution for this problem, other than keeping the dependencies small, is to have a warm function up at all times so it can handle the request right away for time sensitive applications. The problem here though is that most commercial offerings do not offer this option. Instead the developers are forced to keep pinging the function to keep it warm for the next trigger. This is a very hacky solution and reduces the whole efficiency of the platform in general. Most of the cloud providers are although aware of this problem and are trying to be innovative and introduce lighter alternatives to Linux containers in the FaaS platform these days.

**Security issues in a multi-tenant environment** Like was previously mentioned, the whole FaaS infrastructure offering is economical for the cloud provider because they get to share their node pool among all their standard customers making the resource cost for them very low. The problem with this practice though is that this introduces safety issues for the data that is executed in the machines. Linux containers are not particularly secure as an isolation mechanism since they share a Kernel with the host operating system. This means that any bug or back door introduced to the Kernel get affected to all the containers as well exposing the customer data at a very high risk. This is an issue that is actively being worked on by companies. Till a while ago, the solution for this was to encapsulate the containers in a light weight VM which unfortunately contributed to the heavy cold start time. But recently the innovative new alternatives for Linux containers are also aimed at to fix these issues.

**Function caches** Along with the above mentioned issue with multi-tenancy across customers, a similar issue can occur under the same customer who runs an application across multiple of their client. The problem is that each function has an inaccessible cache that get cleaned up at an arbitrary time hidden from the user. There is a chance that somehow cache from the previous execution of the function somehow lingered and the data from one client got leaked on to another or got corrupted by the other. If the developers are not cautious enough while coding and usage of variables, there is a high chance for data corruption and leakage on the platform.

### Developer friendliness

- Dependency management
- Debugging and testing
- Deployment

- Logging and monitoring

## 2.3 Stream Processing/ETLs

## 2.4 Problem statement

From the above set of evaluations, there is no doubt that Serverless is the way of the future infrastructure maintenance and deployment. Even with the current state of art FaaS offerings, 21% of the entire workload is Data processing applications that include heavy batch and streaming Extract, Transform and Load operations CITE{SURVEY}. Having said that, the implementation usually involves numerous hacks in this setup, even after which the latency of the I/O, network and the platform itself slows from leveraging the full potential of the idea. All the existing commercial offerings being closed source and vendor locked in, implies that the limitations are set for you by the cloud provider and is often very difficult to fiddle with it or to extend the system so as to support an extra runtime, increase the running time, etc. Along with this, the way current FaaS offerings deal with function compositions and parallelism are extremely clumsy and almost always explicit. While this lets the providers have a very generic way of dealing with the platform and holds to the one way to code them all paradigm, the gateways often tend to be a bottleneck. Also the data transfer between functions always depend on a storage based off of Block IO which contribute to the latency immensely.

The focus of the thesis is mostly to propose a solution for the aforementioned issues. We are proposing a Open Source infrastructure, infrastructure that can be maintained by the companies which can offer a multi-tenant and completely elastic platform to deploy their data intensive and high throughput applications on. By nature, these data intensive applications can be a composition of multiple functions, that would pass along data between them. The setup would user ephemeral in memory storage to keep intermediate data. This infrastructure would comply perfectly with the notion of Serverless in the sense that, each element in the system would be independently elastic and scalable. Function composition based on conditionals and branching should be supported by the system along with independent scaling of the functions based on the load, so there wouldn't be any bottlenecks. An easily adaptable programmable API is required for defining this composition.

According to the aforementioned survey, the developer community is concerned about the monitoring and debugging of the functions during the development stage due to the lack of reproducability of the runtime. Our system should give a lot more flexibility and traceability when it comes to the development process. Along with that, we should aim at building a system that is easily adaptable and stable enough for production workloads, and easily integratable with the common development tools like Github, CI/CD pipelines etc.

# 3 Related work

Serverless has gained a lot of attention and traction from the scientific community in the past few years because of its massive implications in resource conservation and innovative programming when one doesn't have to worry about compute management anymore. The issues that were discussed in sessions above are being studied by various studies and the most significant ones are worth noting.

In a very recent Literature review CITE{PAPER}, 112 different academic papers and grey journals in and around the paradigm of FaaS were analyzed. The researchers found a staggering lack in the practicability of the work that were proposed by the scientific community. Along with the lack of reusability and reproducability, it was found that 88% of these proposals were worked in and around AWS lambda, which is not very universal as FaaS solution especially considering its vendor locked in and closed source attributes. The study also mentions how most of these works being done focus on unrealistic workloads that are not very common in the production setups in the industry. The paper also says how the current research lacks methods to chain and branch functions in a meaningful way.

In CITE{PAPER}, the authors interestingly look at the issues that the state of art isolation mechanisms in FaaS infrastructure bring forward as was mentioned earlier. These include the lack of security and the heavy cold start time. It introduces faaslets, an alternate isolation policy to be used instead of containers. With this, faaslets can share data across instances there by reducing data transfer costs. In a contemporary study CITE{PAPER}, an orchestration mechanism called TriggerFlow is introduced. It is a really interesting tool to manage the lifecycle of a cloud function. In this smart triggering system, function composition is allowed using Distributed Acyclic

Graphs(DAG) to define control flow and data flow in the pipeline. This has huge potential as an idea, although currently the usability of the platform is terrible and it can be quite bloated as a entry point to a FaaS system especially since it is not a very elastic platform.

**Serverless in the wild: characterizing and optimising the serverless workload at a large cloud provider** Published date: 6 Jun 2020

Here a way to reduce the cost of warm starts(practice of just keeping the resources idle to avoid cold start time) We depend on a learned histogram that charts the idle time of each application. For better results we can switch to ARIMA model. Use cases on both azure & openwhisk

**FaaSdom: A Benchmark Suite For Serverless Computing** Published date: 5 Jun 2020

It is a docker based platform that implements wrk2 This would be a really great tool to benchmark cross platform. Code

**Towards Fine-Grained Billing For Cloud Networking** Published: 24 Mar 2020

This is suggesting methods for the cloud provider to offer a fine grained billing by better usage of vswitched, network colocation, etc. This is an interesting read but beyond the scope of my research.

**Firecracker: lightweight virtualization for serverless applications** Published date: 25 Feb 2020

This is the isolation solution used by AWS based on KVM Although from the security pov firecracker is great, from the performance pov it is comparable to containers.

**INFINICACHE: Exploiting Ephemeral Serverless Functionsto Build a Cost-Effective Memory Cache** Published date: 20 Feb 2020

This is an in memory object cache. Super interesting. It uses erasure coding and data backup to ensure high availability. They implement it with AWS lambda. Lambda runtime is connected to a priority based queue. Could be useful to think of something like this for streaming data.

**Cloudburst: stateful functions-as-a-service** Published date: 14 Jan 2020

bring data to caches next to function runtimes a highly-scalable key-value store for persistent state, local caches co-located with function execution environments, and cache-consistency protocols to preserve developer sanity while data is moved in and out of those caches. It uses a DAGs for chaining functions. This is not yet wire speed though. The isolation is very weak, and it has a long way to come to be applied in production.

**Serverless Computing: A Survey Of Opportunities, Challenges and Applications** Published date: 23 Dec 2019

Doesn't introduce anything new. Issues like, function invocation latency, storage, state, security, are all mentioned. They suggest the use of a distributed queue for function composition. I could use inifinicache this way.

**Understanding Open Source Serverless Platforms:Design Considerations and Performance** Published Date: 13 Dec 2019

This compares openfaas kubeless knative The CPU usage is almost comparable in all the platform OpenFaas is said to have the most flexible architecture

**Formalizing Event-Driven Behavior of ServerlessApplications** Published on: 8 Dec 2019

Provides a detailed operational semantics for FaaS. It includes, object stores, key values etc. Could be useful to conceptualize control flows.

**Narrowing the Gap Between Serverless and its State withStorage Functions** Published date: 20 Nov 2019

Shredder is super interesting because it implements the function shipping approach. It uses v8 isolates to implement the sandboxes

**Formal foundations of serverless computing** Published date: 20 Nov 2019

Problems with misusing states in serverless a persistent store with transaction support necessary to manage shared state Introduces an operational semantics lambda SPL, a serverless composition language Function composition is being well done by this.

**Caching Techniques to Improve Latency inServerless Architectures** ( Published date: 17-Nov-2019

Vaguely mentions an in memory cache for aws lambda

**In Search of a Fast and Efficient Serverless DAG Engine** Published date: 14 Oct 2019

They introduce a system to do scheduling of jobs specified as DAGs. I think the memory footprint of this implementation is quite heavy. Trigger flow is an improvement.

**SERVERMIX: TRADEOFFS AND CHALLENGES OF SERVERLESS DATA ANALYTICS** Published date: 26 Jul 2019

A big date serverless piece. A lot of it sounded like mission statements.

**Fog Function: Serverless Fog Computing for DataIntensive IoT Services** Date: 18 Jul 2019

Out of scope. For edge devices.

**Cloud Programming Simplified: A Berkeley View onServerless Computing** Date: 10 Feb 2019

Mentions a lot of issues like need for ephemeral storage, coordination, security, hardware heterogeneity, etc.

**A framework and a performance assessment for serverless MapReduce on AWS Lambda** Date: 02 Feb 2019

This is a very practical paper. I used this to implement my first version of mapreduce on OpenFaaS. Code is on my github

**Serverless Computing: One Step Forward, Two Steps Back** Date: Jan 2019

A great read, I got the idea of function composition from this. Shows weak parallelism and hence distributed computing is terrible. Recommends a function shipping architecture.

**Serverless architecture efficiency: an exploratory study** Published date: 13 Jan 2019

Doesn't offer much. Weakly implements a serverless version of spark. Concludes that the lambda implementation is suboptimal after benchmarking. Costless: Optimizing Cost of Serverless Computing through Function Fusion and Placement (23 Nov 2018)

**Pocket: Elastic Ephemeral Storage for Serverless Analytics** Date: Oct 2018

This is a key value based storage specifically designed for serverless application. Implements dynamic block allocation based on kubernetes hueritics Project is not super active but I could deploy it and try it out

**Anna: A KVS For Any Scale** Published date: 8 Sep 2018

Another brilliant key value store that scales as well. It is distributed in nature and has local caches for better data locality. It is the basis for cloudburst

**SAND: Towards High-Performance Serverless Computing** Published Date: 11 July 2018

This is a similar idea to cloudburst and Faasm. A different sandboxing, function composition internally using a hierarchical message bus

**Serverless Computing: Current Trends and Open Problems** Published Date: 10 Jun 2017

This is a more practical approach on serverless and its issues. Talks about problems with deployment and the devops tools. It is yet again a bit outdated.

**Consistency analysis in Bloom: a CALM and collected approach**
Published Date: 9 Jan 2011

This is a distributed programming model with interesting state sharing ideas. This was mentioned in a paper as a potential alternative to the programming model for serverless since the traditional methods or way of thinking might not work for FaaS.

# 4 Proposed Solution

In this section we dig in deeper into the specifications of our proposal to build a production ready FaaS infrastructure stack that is completely elastic and not locked into any vendor. The idea is that, any party or enterprise should be able to reproduce this stack easily and developers should be able to deploy their application code from any git hosting service or command line to this platform without worrying about the server management. The platform we build also should be provider agnostic, in the sense that it should work with constant efficiency on any cloud provider the user may choose. The developer should be able to monitor the usage and performance of the application easily.

In the light of the above discussion we propose the following extensions to the existing Serverless platforms:

- Provision to compose functions by defining a computational graph
- Ephemeral in-memory storage to store intermediate data
- Multi-tenancy support by separating function instances using namespaces
- Fine grained tracing and monitoring of the functions and the compositions

To clarify how the above mentioned steps will help solve major limitations of Serverless paradigm, we will have a platform agnostic look at how the above steps change the current state of art FaaS systems. In the section 5, we will get into platform specific study by implementing these suggestions on a flexible open source FaaS solution for our proof of concept.

## 4.1 Function composition

As we have already seen, in the current industrial requirements, big data processing is pretty inevitable as an application scenario. The nature of these data can be very varied including streaming, semi-regular burst streams, etc. making it a very good space to apply Serverless paradigm to, to save up resources and have fine grained scaling of the resources based on requirement. The aforementioned complexity in the application logic suggests that it make a lot of sense to split the application into multiple functions and compose them efficiently. If applied to the Serverless logic, this means that each function can be scaled independently based on the load in that logic.

The above requirement exposes some issues that were discussed in the section 2.2.4 of FaaS. Function composition is not something that has been cleanly supported by popular commercial FaaS offerings. The popular infrastructure today do not have any information about the dependencies between multiple functions. It is up to the developer to programatically call functions from each other which are packaged and deployed separately. If there are any heavy data to be transferred among these functions, which we can refer to as intermediate data, the developers are expected to use a block storage of some sort(eg: S3, google data store, etc.) adding heavily to the Input/Output latency of the service, not to mention the network latency if the infrastructure is in a different VPC.

In a recent case study CITE{STUDY}, Autodesk claims their FaaS-ification of their whole platform. Unfortunately, their account creation platform, which was implemented as a composition of multiple small functions on AWS lambda incurred a round trip time of 10 minutes. This is horrendous especially considering the vitality of the task in discussion. Overhead of Lambda in task management and the state management is explained as the causes.

More products has been introduced by cloud providers, like AWS step functions CITE{Step functions}, instead of fixing the inherent architecture of FaaS solutions to help create data intensive workflows in FaaS. These systems work by introducing an event queue like AWS SQS to the equation. The problem with such solutions is that they violate the notion of Serverless in a way by introducing an element that is practically non scalable and can't be debugged easily. It becomes extremely difficult to develop and test the system locally. Not the mention, the fact that this introduces more lock in to the vendor.

Another approach can be found here CITE{LINK}, where the function composition is done by triggering the other functions by pushing intermediate data to s3, which the following function considers as the trigger. The example in question is a very simple map reduce which is not very intensive computationally even with a heavy load of data. Even with that the setup takes around 2 minutes to complete the task for a dataset of size 25GB. It can be seen that the majority of the running time was spent on pushing and pulling data and not on the compute.

It is quite clear that the ability of functions to call each other are rather important. There should be a way to define programatically the relationship between the functions in a FaaS infrastructure along with the data flow dependencies. If cloud provider exposes an API that would let the developer feed a computational graph for this function composition, this would not just improve the performance, but also would be useful for better function and data placement so the latency for data and control transfer would be minimum. This can be a very tricky thing conceptually since, containers are not directly addressable network wise.

Before getting into the technicalities of the platform itself, let us look at different approaches in which functions can be composed in a serverless workload.

### 4.1.1 Manual Compilation

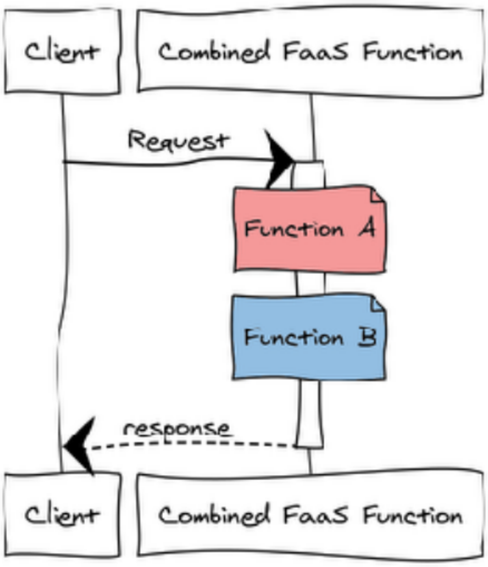
This the most basic and inefficient way of compiling the functions. This basically involves merging all the functions together to form a huge function. From FaaS executor's point of view, it is one big function.

```
def funcA():
  doStuff()

def funcB():
  doStuff()

def main():
  funcA()
  funcB()
```

Figure 4: Merged in the source code

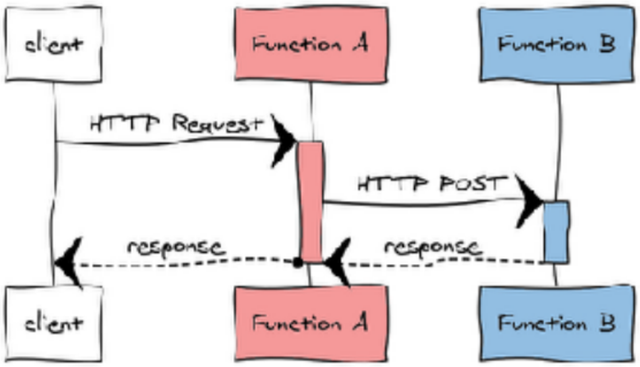


The above code block and Figure 4 explains how the control flow works in this kind of compilation scheme. As is pretty obvious, with this method one cannot scale individual functions independently and function can get really big. There is no necessity to store intermediate data or serialize and deserialize data between functions. But the problem is that this kind of violates the notion of serverless since each application is not an atomic functional unit. If the compute is complex, function might not even completely run because of the hardbound limit to the running time set on most FaaS platforms.

### 4.1.2 Direct function chaining

Like can be seen from Figure 5, here each task is a separate function. Each function directly call the succeeding function in a chain. Meaning the code is written so that the current knows the details of the next function, but not any further. Even here like before, there is no need for any serialization deserialization overhead since functions can directly send each other data. No external components are used either. Although the problem arises when the data load increases. The load on the network to transfer data via HTTP

Figure 5: Direct function chaining



rises. Along with that each function will have to wait for the next function. If a function fails then the logic to retry/fallback etc. will have to be coded into each function. The following pseudo code shows how the function design would be.

```
def funcA():
  doStuff()
```

```
def funcB():
  doStuff()
```

### 4.1.3 Composition via coordinator functions

In this method, a coordinator function will be used which manage the execution of all the functions by calling them directly. The individual functions will be unaware of each other.

The win over the previous method here is that, the house keeping code need not be present in each individual task. Also it is very flexible in the sense that, each function can be tested independently and then the user can properly write the control flow in one place, that being the coordinator function. This comes at a cost of adding an extra function which is the coordinator function. This function will continue running the whole time, costing more

Figure 6: Coordination functions

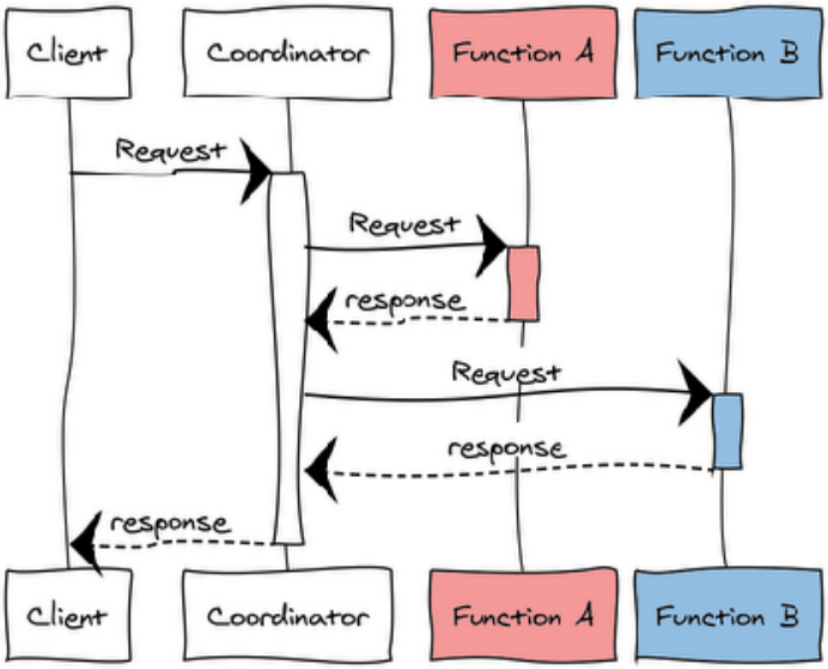
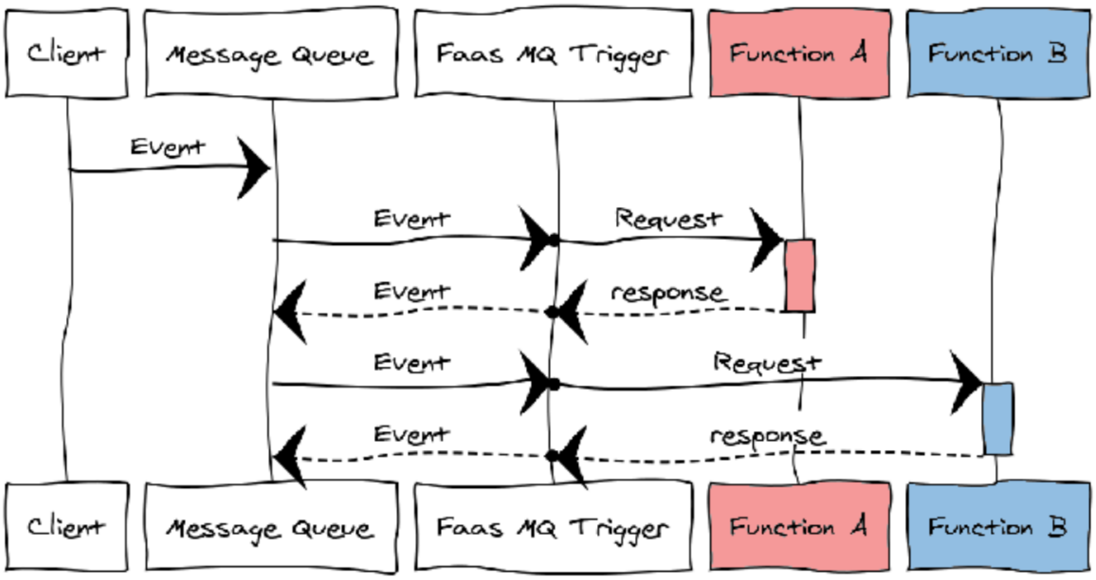


Figure 7: Event driven function composition



and violating the FaaS paradigm a bit. An example of this kind of coordination can be found here CITE {PAPER}

### 4.1.4 Event driven composition

This is a powerful design pattern that supports a lot more fault tolerance and involves changing or extending the infrastructure of the FaaS platform. In this method, one introduces message queues in the architecture as can be referred from Figure 7. Functions emit events to these message queues. Alongside, all the functions listen to the same queues. So on receiving certain events, they react in the programmed ways. Contrary to all the previous methods, it is very interesting to note that in this method, the stress is given to the data flow instead of the control flow among functions. The intermediate data between the functions has to be managed separately by using a storage.

This is a very commonly used and popular architecture. Message queues like Kafka or MQTT brokers like rabitMQ offer a lot of functionalities and features like fault tolerance, error handling, alerting, backup, etc. Functions can be completely decoupled. This is a very good solution for big data and streaming data applications.

The problem with this method is though the very heavy dependencies which are very hard to manage. The fact that message queues are not inherently serverless makes the platform less elastic and thereby billing and usage tracking can be troublesome of the infrastructure manager. Alongside, message queues usually only supports limited control flow structures. Probably just conditional and on-error handles. It will be terribly complicated to do dynamic branching, iterations, etc. Along with this, since functions are so tightly dependent on the message queues, it will be slightly challenging to upgrade or version them.

### 4.1.5 Workflows

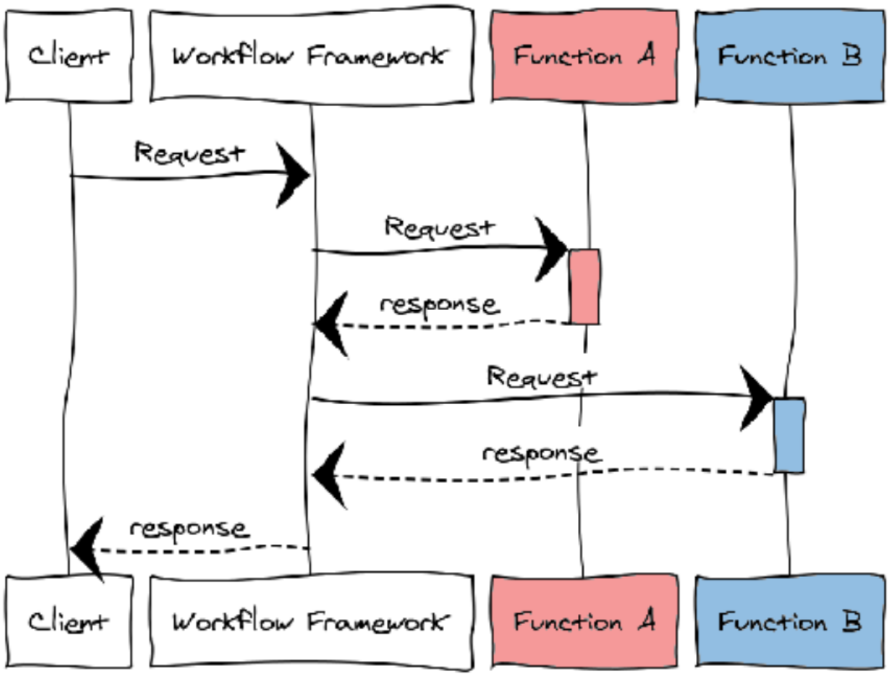
Workflows are a very interesting architectures pattern where the system supports the creation of a sort of flowchart of the functional interaction. Workflows are a very widely used pattern these days in a lot of big data processing tools.

An workflow is designed as a directed acyclic graph (DAG). This means that a new runtime has to be introduced in the FaaS system to manage the execution of the functions. When authoring a workflow, one should think how it could be divided into tasks which can be executed independently. The workflow runtime would let one to merge these tasks into a logical whole by combining them into a graph.

This definitely adds the overhead of writing a runtime for the FaaS platform, providing an API to define the DAG to the runtime and then managing and executing the workflow based on the DAGs. But once the platform is in place, it provides numerous flexibility. One can get done dynamic branching, iteration, etc. very easily on this platform along with individual upgrade of the functions. The fact that no external infrastructure tool has to be managed to work as a triggering mechanism maintains the elastic nature of the tool. The only thing is that there has to be a storage unit to manage the state of the DAG for the workflow framework. Similarly just the event driven composition, the intermediate data store has to be handled separately.

Logically, this method resembles the coordinate function setup, just that

Figure 8: Workflows

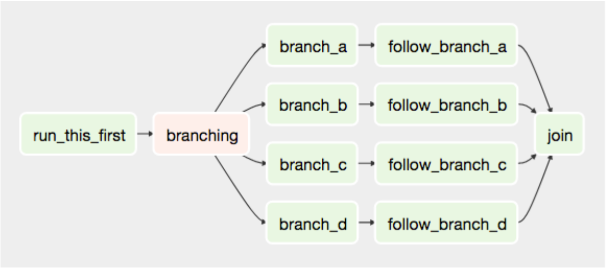


instead of a simple coordinator function, in this case we have a month more powerful framework that is added permanently to the infrastructure. This can be referred from Figure 8.

The shape of the graph decides the overall logic of the workflow. A DAG can include multiple branches and you can decide which of them to follow and which to skip at the time of workflow execution. This creates a very resilient design, because each task can be retried multiple times if an error occurs. To give the reader clarity on what a DAG looks like, the Figure 9 from the Airflow's operator might shed some light.

With this setup, we can get a lot more centralization to the compositional logic, making logging and visualization lot more easier. With this method the function scheduling and placement can also be improved. Meaning, functions that have compositions with each other can be scheduled in the same node, if we have a cluster or the intermediate data can be placed nearer, etc. One downside to this method is that the user will have to use the workflow

Figure 9: Branching example with DAGs



specific language or DSL and not just the programming language used for the function implementation.

It is arguably clear that workflows offer the most flexible and application independent solution as a composition pattern. Of course the concern of having a storage for the running state of the workflow framework remains along with the storage of the intermediate data. We will look into the solution to this in section 4.2.

## 4.2 Ephemeral Storage

In the previous section, we saw that flexible function composition can be achieved via workflow pattern. Although to make this efficient state storage is inevitable. The problem is that we have to not violate the notion of elasticity when it comes to Serverless. The resources involved in Serverless should be scalable up and down, only when we can have a per usage payment and resource conservation. Scaling up also affects the availability of the tool since one should be able to have all the requested served without much latency. Along with storing the state of the workflow or DAG, if function has to pass around data from one function to another, we should introduce some sort of intermediate storage since there is no direct communication between functions. The workflow framework take care of triggering each function based on its state and the data transferred between the functions will be via this intermediate storage as well.

In traditional analytics framework, long running process in nodes takes care of managing the intermediate data in local storages. On contrary to this conventional approach, Serverless workloads do not have any long running processes. Because of the network addressing problem of containers, direct transfer of data is also pretty impossible between functions.

In all the commercial service offerings of FaaS this intermediate storage is done via a block storage like S3. This is a very inefficient approach since a block storage adds a lot of I/O latency to the system. Along with that, it adds a non scalable entity to the equation. Conventional storage systems are not designed to meet the demands of serverless applications in terms of elasticity, performance, and cost. We are talking about data that has limited life span, which we can refer to as ephemeral data CITE{POCKET}.

Traditional storages like RDBMS, NoSQL, block storage, etc. are not made for short lived data because of the latency involved in writing to the disk. An in-memory key value store seem like the most obvious choice. But unfortunately the industry standard key value stores like Redis doesn't scale very easily. One has to take care of the scale of the storage cluster, network configuration, maintenance, etc. Per use billing can also be very tricky in this case.

We should be looking into innovative new ideas to use for serverless platforms when it comes to data storage because of the ephemeral and scalable nature of it. Since Serverless functions are deployed on clusters that exists across multiple nodes, a distributed key value cache that is scalable is the desirable option we are looking for.

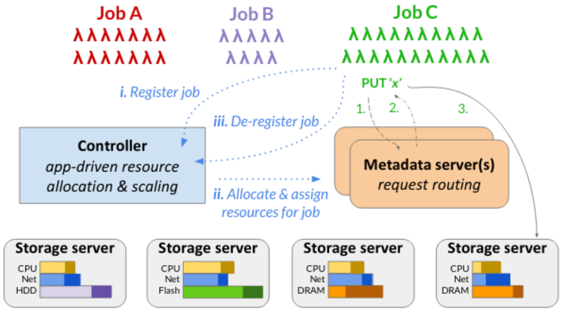
In our preferred storage medium, we should have automatic scaling, fine grained usage tracking & billing, low latency, high throughput, low cost, and unlimited availability. Key value stores like Redis and memcache offer low latency and high throughput but at the higher cost of DRAM. They also require users to manage their own storage instances and manually scale resources CITE{POCKET}. We look into two different storage solutions for the adaption to our FaaS extension: Pocket & Orlic

### 4.2.1 Pocket

Pocket CITE{POCKET} is an ephemeral storage build for the Serverless workflows. It is a key value store suited for storing and exchanging data between hundreds of fine-grained, short-lived tasks. Pocket is an elastic distributed storage service for ephemeral data that automatically and dynamically right sizes storage cluster resource allocations to provide high I/O performance while minimizing cost CITE. Pocket is not completely an in-memory storage infrastructure like expected. Instead, pocket has a smart data allocation system that leverages different storage media(DRAM, Flash, Disk) to store the data depending on the requirement of the application while minimizing the cost.

Pocket has a tiered architecture. It has three planes - A control plane, a meta data plane and the data plane. Like the name suggests data plane stores the data ultimately. Meta data plane tracks the presence of the data distributed across this data plane. Finally the control plane manages cluster scaling and data placement. This layer keeps the platform elastic, in that it scales the storage resources based on the usage. Each of the aforementioned layers can scale independently. The project claims to have a sub-millisecond latency for I/O operations.

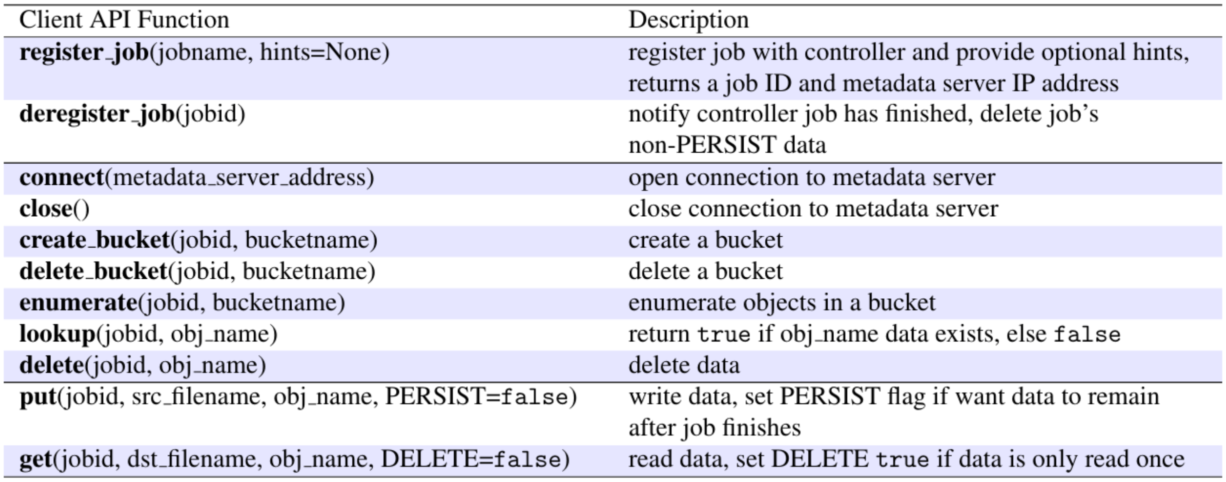
Figure 10: Pocket system architecture



**Architecture** Like Figure 10 represents, Pocket system has one centralized controller server, one or more meta data servers, and multiple data plane storage servers. The meta data plane according to us is the most interesting in the architecture, since it enforces coarse-grain data placement policies generated by the controller. It manages data at the granularity of blocks whose size is configurable, defaulted to 64KB. Objects larger than this size is divided into blocks and are distributed across storage servers by the meta data server. Client access data blocks directly from storage servers.

**Client API** Pocket provides an API to communicate with the system. There are system calls to each of the three planes. First of all it lets the client register and un-register of the jobs(control plane). The client gets to

Figure 11: Pocket Client API



| Client API Function | Description |
|---|---|
| **register_job**(jobname, hints=None) | register job with controller and provide optional hints, returns a job ID and metadata server IP address |
| **deregister_job**(jobid) | notify controller job has finished, delete job's non-PERSIST data |
| **connect**(metadata_server_address) | open connection to metadata server |
| **close**() | close connection to metadata server |
| **create_bucket**(jobid, bucketname) | create a bucket |
| **delete_bucket**(jobid, bucketname) | delete a bucket |
| **enumerate**(jobid, bucketname) | enumerate objects in a bucket |
| **lookup**(jobid, obj_name) | return `true` if obj_name data exists, else `false` |
| **delete**(jobid, obj_name) | delete data |
| **put**(jobid, src_filename, obj_name, PERSIST=`false`) | write data, set PERSIST flag if want data to remain after job finishes |
| **get**(jobid, dst_filename, obj_name, DELETE=`false`) | read data, set DELETE `true` if data is only read once |

communicate with the meta data server multiple times during its lifetime. The data in pocket is stored as objects that goes in buckets. They are identified using names. Meta data plane provides system calls to create and delete these buckets, look up objects and delete these objects.

Client put and get data directly to/from the object at a byte granularity. The put and get operations invoke the meta data layer with the Job ID of the client. This is to do the meta data look up operation to get the data placement of the object that is being looked up. When a put call is invoked, with a PERSIST flag to be true, the object will remain in the data even after the job terminates despite the ephemeral nature of the storage. It will remain until it is explicitly deleted or after a configurable timeout period. The get call with a DELETE flag set will get deleted right away after returning the value of the object. The nature of the ephemeral storage in discussion is assumed to be write and read once only. Figure 11, describes the system calls in detail.

### Implementation

1. Controller: Pocket is run on Kubernetes with each layer as separate

docker containers. A resource monitoring daemon is run on each node in the cluster sending resource utilization info to the controller. The controller right sizes the cluster by launching new nodes and sending the info of the existing meta data servers to it. The load is balanced using data steering new active job data to the newer server than balancing out existing data since this can add a heavy overhead especially since the data is short lived. The container also keeps the meta data server resource usage under the target limit by precalculating the load a job would put on the meta data server from its throughput and capacity allocation. Based on this estimate the controller select the meta data server.

2. Meta data and Storage tier: These are implemented on top of Apache Crail distributed data store CITE{CRAIL}. Crail is designed for low latency, high throughput storage of arbitrarily sized data with low durability requirements. Crail provides a unified namespace across a set of heterogeneous storage resources distributed in a cluster. Its modular architecture separates the data and meta data plane and supports pluggable storage tier and RPC library implementations. As of the storage tier, Pocket project implements it on DRAM, NVMe on top of ReFlex and then on generic block storage.

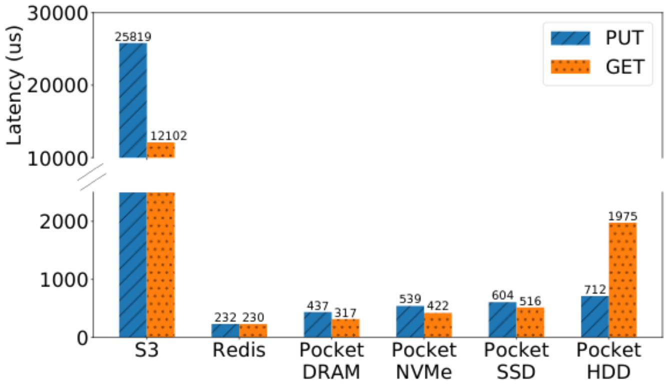
3. Client library: The API is written in Python to provide better adaptability of the tool. The core library although is in C++

**Analysis** Pocket is seen to have pretty good performance almost comparable to Redis but much better economically when set up on DRAM. It is seen to be almost 300% faster than S3 storage for the GET requests. It can be seen from Figure 12. So considering that DRAM will be used as the storage tier, it can be the right tool for the ephemeral storage in Serverless platforms.

### 4.2.2 Olric

Olric CITE{Olric} is a distributed in-memory key/value data store. The idea is that we can create a shared pool of RAM across a cluster of computers to store the data in, in a scalable manner.

Figure 12: Pocket Performance for get and put requests



## 4.3 Multi-tenant security and isolation

Namespacing in kubernetes Cloud Multi-tenancy

## 4.4 Monitoring and tracing

It is quite curious to note from the survey of 2018 done by serverless CITE{SURVEY} that the second most thing the devs are worried about the development process of a FaaS application is monitoring.

Tracing Logging Monitoring

# 5 Implementation

For implementing the aforementioned strategies and verifying its effectiveness in making the Servereless workflows efficient, it is important to trial it on a platform that calls for innovation. Extending platforms like AWS Lambda, which are closed in its source and vendor locked is practically impossible and stalling the growth of Serverless as a paradigm. Instead several Open Source FaaS infrastructure were analyzed for this thesis for the implementation of our ideas. Along with the platform, choosing the right orchestration and clustering tools, the workflow implementation tool, the right monitoring tools, etc. are also vital in the implementation. So before going in detail about the architectural specifics of the implementation, let us analyze the tools used in the process and the reasoning behind their choosing.

## 5.1 Tools

### 5.1.1 Container Orchestration

We are going to work with a containerized setup like was hinted at the beginning of the thesis description. Each function that is being written will be containerized and brought up and down, scaled up and down based on the configurations and usage requirement. We have to go with the right containerization platform and an clustering tool that would take care of managing, scheduling, scaling up and down, etc. of these containers across a cluster of nodes agnostic of the application specifics or the underlying systems specifics. We of course go with the industry standard here which are Docker and Kubernetes especially because all of the leading FaaS solutions these days work on both of these technologies. A gentle introduction to both tools before proceeding to FaaS specific solutions.

**Docker** Docker CITE{Docker} one of the leading Linux Containers solution that is being adopted very widely across all kinds of software infrastructure maintenance environments. According to the Docker Inc., over 3.5 million applications have been placed in containers using Docker technology and over 37 billion containerized apps have been downloads CITE{BLOG}. Advantages of using containers for application shipping was already seen in Section 2.1.2. Docker made the whole Linux Containerization landscape a lot more approachable as a packaging technology by the introduction of namespaces.

Without delving too much into the technicalities of containerization, we would like to quickly explain the life of a containerized application with Docker. Some terminologies that would help with understanding the concept:

**Docker image:** Like in any virtual machine environment, images can be thought of somewhat a snapshot of the current state of an execution environment(which is basically a stripped down operating system with applications installed on it, ready to run). What makes Docker images unique is its immutability. You cannot modify a docker container. You can create copies or delete and recreate but not change the state. This helps in guaranteeing that once your Docker image has reached a working stage, it will always continue working no matter what. You can try an add changing to the running instance of this image, but none of these changes are persistent from the point of view of the image. You can shut it down and start from the same image state as was created.

Sharing these images is an extremely easy process. There are container registries which are hosting services for docker images like Github is for git tracked code. Popular publicly available container registry is DockerHub CITE{DockerHub}. Developers can push their docker image to docker with a simple ‘docker push‘ command from their command like and share or make it publicly available for other developers or software tools.

To create a docker image, the most straightforward way is via a configuration file called Dockerfile. According to the reference from CITE{Docker ref},

> "Docker can build images automatically by reading the instructions from a Dockerfile. A Dockerfile is a text document that contains all the commands a user could call on the command line to assemble an image. Using docker build users can create an automated build that executes several command-line instructions in succession."

For example, the following code block shows a Dockerfile written to dockerize a simple Python app, that runs a simple flask HTTP server.

```
FROM python:3.6.1-alpine
WORKDIR /project
ADD . /project
RUN pip install -r requirements.txt
CMD ["python","app.py"]
```

**Docker Container:** If Docker image is a digital photograph, a docker container is like a printout of the photograph CITE{BLOG}. Containers can be thought of as a running instance of the image. Each container is run separately and unlike the images, you can change the running container. If you want to persist these changes though, you will have to commit the running container it its running state by committing it as a new image. Your host operating system isolated the running container from the others in the computer. Each container instance will have its process namespace, limits on the resource usage, allowed system calls, etc. Communication across containers can be setup explicitly. Most production applications, usually have multiple containers running together with communication internally so as to isolate each process environment, to avoid cascaded application damage, etc. A container is inherently not addressable directly from external network, although one can open it up by exposing corresponding service port to that of the host system, provided necessary security precautions are taken.

**Orchestration tools:** Docker by default ship a couple of orchestration tools that are specific to Docker. An significant one among this is a docker-compose. Docker-compose lets one tie up multiple docker containers, expose certain ports in each docker containers, pass environment variables, define the communication and storage usage rules, etc with the help of a configuration file by default to be name docker-compose.yml. This is a very simple tool to use that helps in most basic usages of the application deployment. One can connect multiple nodes together and deploy the containers across these nodes via docker-compose using a library called docker-swarm. Docker swarm takes care of very basic scaling up and down of containers etc.

**Kubernetes** Now that we have seen a popular containerization solution called Docker, it is time to see the most popular orchestration solution. Docker swarm was already mentioned but when it comes to modern applications, the requirement goes far beyond this. The application needs better scaling heuristics, version rollout policies, cluster management, better networking and application discoverability, better monitoring and alerting systems, etc. This takes up to a much more advanced container orchestration platform called Kubernetes. It is worth noting that Kubernetes is not just built for Docker but for multiple flavors of Linux Container technologies.

Kubernetes is an Open Source platform for managing containerized workloads and services, that facilitates both declarative configuration and automation CITE{DOCS}. Contrary to the traditional deployment setups where applications ran on physical servers, we have moved to an era where we deploy packaged applications and are deployed across clusters of virtual nodes provided by cloud providers. We require smarter tools for this to manage complexities in different levels starting from application packaging to cluster management. Kubernetes can be considered as the most popular solution that deals with these complexities.

Kubernetes provides the framework to run these applications along with the tools for the following purposes CITE{DOCS:

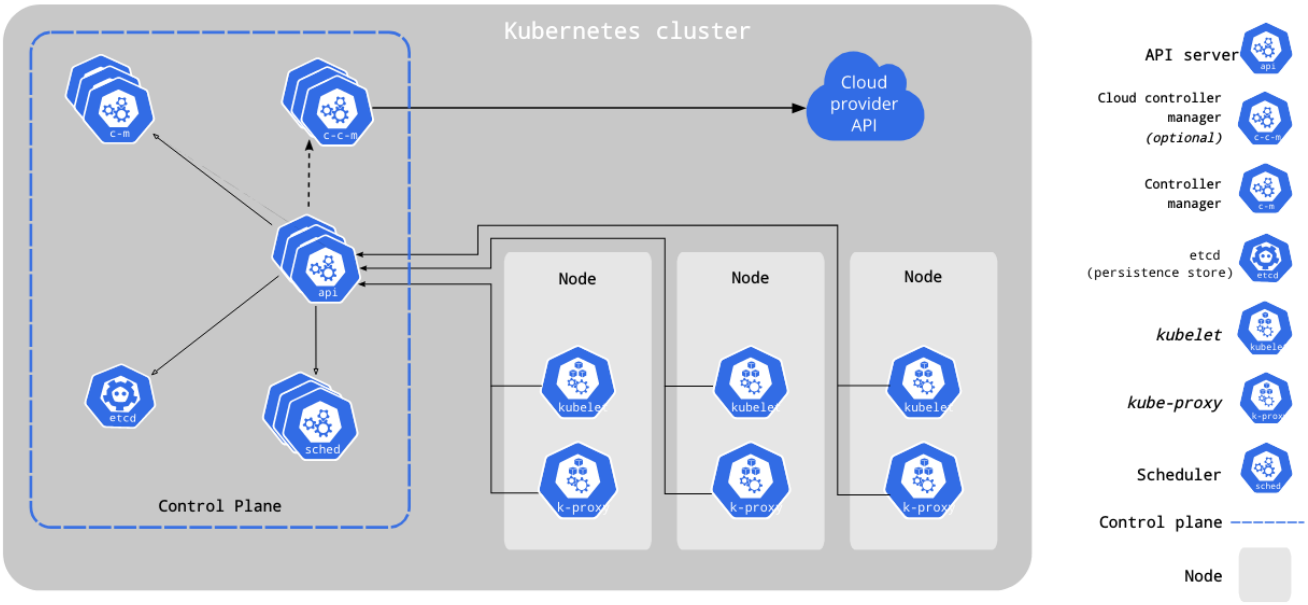
- Service discovery and load balancing
- Storage orchestration
- Automated rollouts and rollbacks
- Automatic bin packing to make sure optimal resource usage
- Secret and configuration management
- Monitoring the usage and load to the cluster and applications

A great thing about Kubernetes as project these days, is the community support. It has a very large and widely adopted community. Along with that most cloud providers now support out of the box kubernetes engines making the development of infrastructure agnostic applications very easy. This is the way to go to be away from a deployment cycle that is not completely vendor locked in.

Kubernetes is an immensely complex piece of software with numeral tools and add-ons. Figure 13 depicts the architecture of Kubernetes. The control plane is the core component of the setup. It consists of the API server to the platform, etcd to store the state of the cluster, scheduler to deploy the Pods(collections of containers that makes up an application) to the corresponding node in the cluster evaluating the usage requirements and availability, cloud controller manager that links the logic of the cluster to the API of the cloud provider, etc. At the risk of getting out of this scope of the thesis, we do not analyze more of the technicalities of kubernetes.

In our implementation, we will use the heuristics of scaling provided by kubernetes in multiple cases. Alongside, the web UI kubernetes provides lets us visualize the resource usage by the platform and applications to a great extending helping with the monitoring of the setup.

Figure 13: Kubernetes infrastructure



**Namespaces:** It is very useful to understand the concept of Namespaces in Kubernetes though. We can logically divide each cluster into multiple virtual clusters called namespaces. It is a way to divide the existing cluster into separate logical partitions. The implications of this provision is huge. We will be utilizing this feature of kubernetes to logically partition the function executors to support multi tenancy.

Namespaces provide a scope for names. Names of resources need to be unique within a namespace, but not across namespaces. Namespaces cannot be nested inside one another and each Kubernetes resource can only be in one namespace. CITE{DOC}

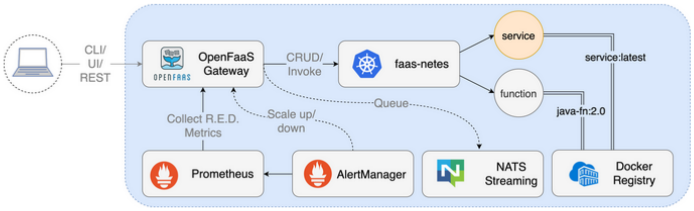
### 5.1.2 OpenFaaS

Now that we have seen an overview of the packaging and clustering management systems, it is time to look at the right platform to test out our state-ful FaaS idea on. Considering that one main aim of the thesis is to move away from vendor locked platforms, it all makes sense that we investigate the available open source FaaS solutions to extend on.

A survey was done comparing multiple open source FaaS offerings as explained in the section 2.2.3. From CITE{PAPER}, it is quite clear that one of the most simplistic approach to architecture and flexibility belongs to OpenFaaS. The ease of setup and the community support also is a huge add on for the OpenFaaS to be chosen as out tool of preference.

OpenFaaS was a one person project that was initially developed just to test out the power of vanilla docker orchestration tools to deploy event driven functions on demand and scale. The clean and scalable architecture soon put the project in spotlight. The best thing about OpenFaaS is that, the core modules of OpenFaaS are very light weight and all the other units can be added on to this core as necessary. The tool soon got to using Kubernetes as the default deployment platform due to the increased popularity and to make the best of Kubernetes heuristics for scaling.

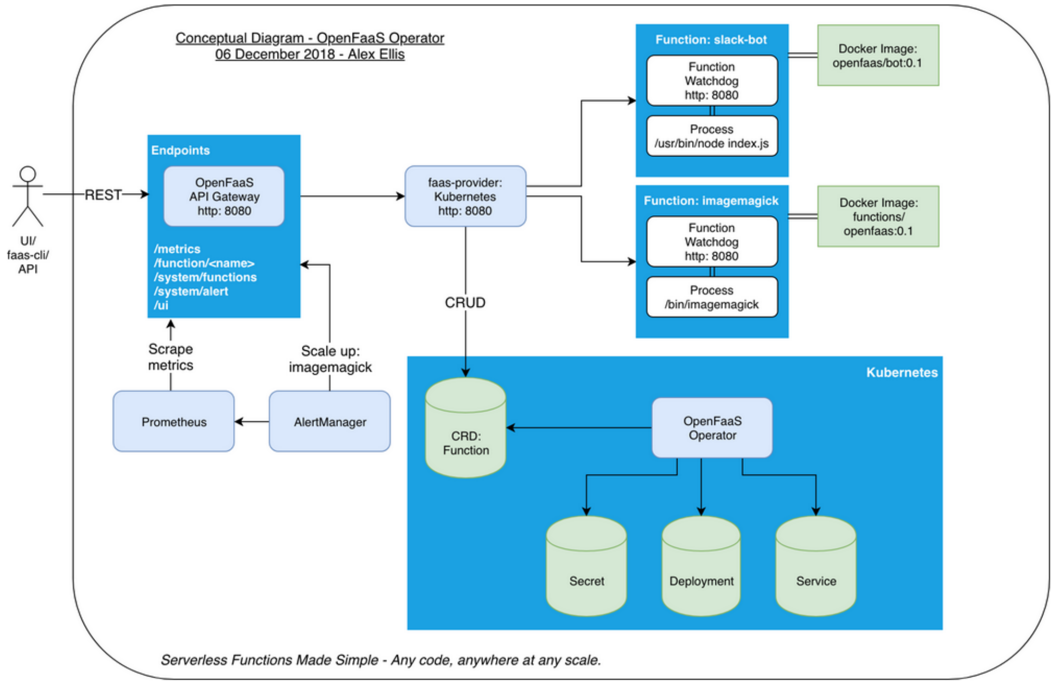
Figure 14: OpenFaaS workflow



The following are the main components on an OpenFaaS setup to give the user a bit more intuition on how functions are scheduled, executed and scaled in the platform. Figure 14 goes along with the following description.

**OpenFaaS Gateway** The gateway is the entrypoint to the FaaS infrastructure. It provides an API which opens an external route into the functions. The gateway does a lot of the main functions in the infrastructure. The gateway is basically responsible for collecting the metric information and scaling the functions accordingly. It has a built in UI portal for ease of deployment and invocations of functions for the user. When kubernetes is used as the orchestration platform, the conceptual design of OpenFaaS can be visualized as Figure 15.

Figure 15: OpenFaaS conceptual design with Kubernetes



As can be noted in the image, Prometheus and Alertmanager are connected to the OpenFaaS Gateway API.

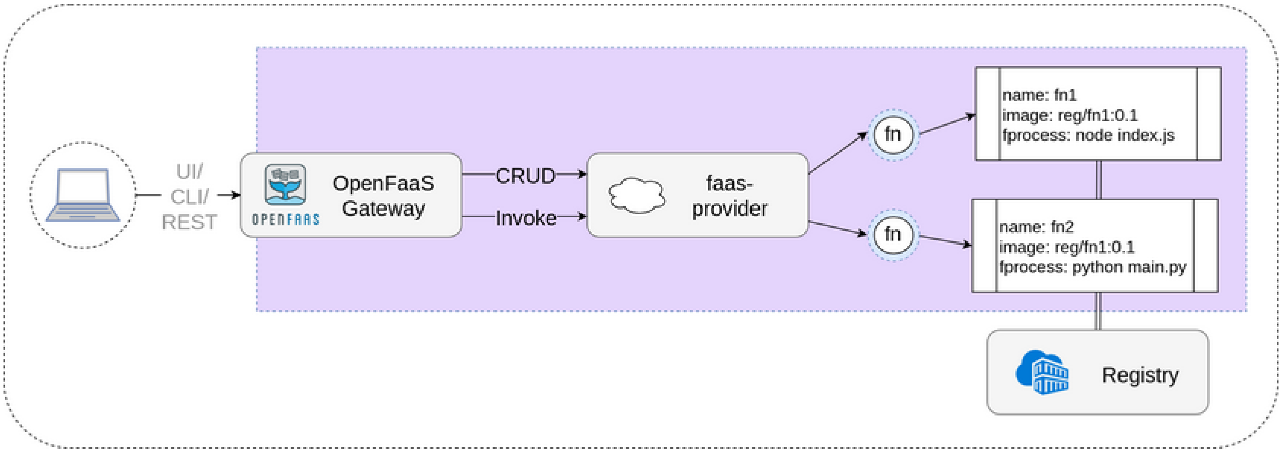
- Prometheus is a monitoring system and time series database. Prometheus is now the de-facto monitoring solution for Cloud Native projects. It combines a simple interface with a powerful query language to monitor and observe microservices and functions, which are the two primitives of any FaaS. Prometheus basically does two functions. It gets metrics from machines in your cluster. These machines can be actual nodes or virtual machines or containers. One can define custom rules to check on these metrics and if any of the rules are triggered, Prometheus will fire off alerts via AlertManager. OpenFaaS Gateway exposes a lot of these collected metrics via Prometheus for visualization and monitoring. We will be using these metrics for our monitoring.

**faas-provider** faas-provider is a very flexible interface that provides CRUD(create, read, update, delete) to functions and the invoke capability. The information about the function that need to be created/updated/invoked gets fed directly from the OpenFaaS gateway which is the endpoint to which external world communicates to.

The design of faas-provider makes OpenFaaS a unique platform. One can their own faas-provider and hence change the backend of the OpenFaaS infrastructure very easily. There are design guidelines available to develop your own faas-provider backend CITE {DOC}, which basically is defining how CRUD and invoke operations are handled by the backend. The most stable and popularly used faas-provider that is maintained by the community is faas-netes, which is the Kubernetes backend for OpenFaaS.

faas-provider takes care of scheduling the functions in the right node based on the availability and requirement. It also does the scaling up and down of the function instances based on the information from the gateway that it gathered via Prometheus. Figure 16 shows the conceptual view of just faas-provider stripping away the rest of the complexities.

Figure 16: faas-provider



**OpenFaaS watchdog** The OpenFaaS watchdog CITE {DOC} is responsible for starting and monitoring functions in OpenFaaS. Any binary can become a function through the use of watchdog.

The watchdog becomes an "init process" with an embedded HTTP server written in Golang, it can support concurrent requests, timeouts and healthchecks. The newer of-watchdog mentioned below is similar, but ideal for streaming use-cases or when an expensive resource needs to be maintained between requests such as a database connection, ML model or other data.

**Auto-scaling** OpenFaaS ships with a single auto-scaling rule defined in the mounted configuration file for AlertManager. AlertManager reads usage (requests per second) metrics from Prometheus in order to know when to fire an alert to the API Gateway.

The API Gateway handles AlertManager alerts through its /system/alert route.

The auto-scaling provided by this method can be disabled by either deleting the AlertManager deployment or by scaling the deployment to zero replicas.

One can specify the minimum number of replicas and the maximum replicas to be available. If minimum replicas is defined to be >0 then a warm copy of the function will always be idle-ing there by avoiding the cold start issue. Although this comes with an added cost of a docket container always up in the memory although the resource usage during the idle time is super low. We can also fine tune several other parameters like the factor by which the function should be scaled up or down when there is a burst or decline of the traffic, etc. This makes OpenFaaS extremely powerful and yet in the most simplistic way possible.

When Kubernetes is used as the backend, instead of AlertManager the built-in Horizontal Pod Autoscaler CITE{DOC}. This is a lot more matured as a scaler scheduler and we will be using that for the thesis implementation.

**NATS streaming** A curiously lightweight application that has been adapted into OpenFaaS is NATS. NATS provides simple and secure messaging functionality to the setup. It does event and data streaming in the cluster. OpenFaaS uses NATS Streaming which builds on top of the base NATS protocol to offer data streaming or a queue CITE {doc}. NATS streaming provides Queue worker in which the function invocation requests can be queued up by the API Gateway, and processed in parallel when the capacity becomes available. Asyncronous invocations can be very easily done since it is built in without making any changes to the gateway. Each function will have a separate endpoint that can be used to invoke it asynchronously.

NATS streaming is a Pub Sub protocol implementation like Kafka but with very high throughput compared to the latter. Publish-subscribe pattern corresponds to a mechanism where in producers publish messages that are grouped into categories and consumers subscribe to categories which they are interested CITE {PAPER}. NATS is extremely lightweight as a technology making it the right candidate for an elastic Serverless infrastructure, compared to a full blown message broker system like Kafka. Along side, considering the ephemeral nature of state in FaaS setup, an in-memory message delivery protocol like NAT could be extremely useful.

**Triggers** OpenFaaS functions can be triggered easily by any kind of event. A small piece of code will convert from the event-source and trigger the function using the OpenFaaS Gateway API. Some of the most used triggers are:

- HTTP: One can send POST requests to the function endpoint which follows the patter '`https://`<gateway URL>:<port>/function/<function name>'
- Cron
- NATS streaming/Async: You can execute a function or microservice asynchronously by replacing/function/ with *async-function* when accessing the endpoint via the OpenFaaS gateway.
- CLI: we can trigger user faas-cli which is a command line application to communicate with faas gateway
- Apache Kafka
- AWS SQS
- Redis
- Minio/S3
- RabbitMQ

**Runtime supports and templates** OpenFaaS is one of the unique engines that supports any and all programming languages to write functions in because of its architecture. The way OpenFaaS works, it dockerize the application by adding an of-watchdog to the application container and deploy it to the kubernetes cluster. To make the process easier, OpenFaaS doesn't expect you to write the Dockerfile. Instead, it provides already packaged versions of language bundles called templates. The developer can just pull the right template from the template store and just edit the entrypoint script to add their application logic.

Like was briefly hinted earlier, OpenFaaS provides a command line tool called faas-cli. This tool can be used to build, push and deploy the docker images from the code. With build, it build an image into the local Docker library. With push, it pushes that image to a remote container registry. With deploy, it deploys your function into a cluster.

As an example, to build a simple python function, the developer will follow the proceeding commands:

```
faas-cli template store pull python3
faas-cli new funcname --lang python3

faas-cli build -f funcname.yml
faas-cli push funcname
faas-cli deploy -f funcname.yml
```

### 5.1.3 FaaS-flow

### 5.1.4 Prometheus

### 5.1.5 Jauguer

### 5.1.6 Minio

## 5.2 Architecture

# 6 Evaluation

# 7 Future work

# 8 Conclusion

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