

# Serverless Computing: Current Trends and Open Problems

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**Abstract** Serverless computing has emerged as a new compelling paradigm for the deployment of applications and services. It represents an evolution of cloud programming models, abstractions, and platforms, and is a testament to the maturity and wide adoption of cloud technologies. In this chapter, we survey existing serverless platforms from industry, academia, and open-source projects, identify key characteristics and use cases, and describe technical challenges and open problems.

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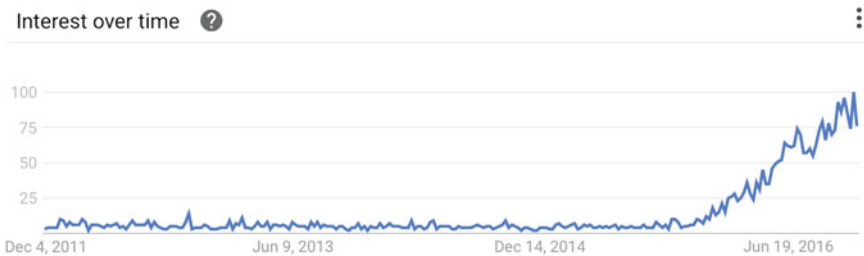
# 1 Introduction

Serverless computing (or simply serverless) is emerging as a new and compelling paradigm for the deployment of cloud applications, largely due to the recent shift of enterprise application architectures to containers and microservices [21]. Figure 1 shows the increasing popularity of the “serverless” search term over the last 5 years as reported by Google Trends. This is an indication of the increasing attention that serverless computing has garnered in industry trade shows, meetups, blogs, and the development community. By contrast, the attention of the academic community has been limited.

From the perspective of an Infrastructure-as-a-Service (IaaS) customer, this paradigm shift presents both an opportunity and a risk. On the one hand, it provides developers with a simplified programming model for creating cloud applications that abstracts away most, if not all, operational concerns; it lowers the cost of deploying cloud code by charging for execution time rather than resource allocation; and it is a platform for rapidly deploying small pieces of cloud-native code that responds to events, for instance, to coordinate microservice compositions that would otherwise run on the client or on dedicated middleware. On the other hand, deploying such applications in a serverless platform is challenging and requires relinquishing to the platform design decisions that concern, among other things, quality-of-service (QoS) monitoring, scaling, and fault tolerance properties.

From the perspective of a cloud provider, serverless computing provides an additional opportunity to control the entire development stack, reduce operational costs by efficient optimization and management of cloud resources, offer a platform that encourages the use of additional services in their ecosystem, and lower the effort required to author and manage cloud-scale applications.

Serverless computing is a term coined by industry to describe a programming model and architecture where small code snippets are executed in the cloud without any control over the resources on which the code runs. It is by no means an indication that there are no servers, simply that the developer should leave most operational concerns such as resource provisioning, monitoring, maintenance, scalability, and fault tolerance to the cloud provider.



**Fig. 1** Popularity of the term “serverless” as reported by Google Trends

The astute reader may ask how this differs from the Platform-as-a-Service (PaaS) model, which also abstracts away the management of servers. A serverless model provides a “stripped down” programming model based on stateless functions. Similar to PaaS, developers can write arbitrary code and are not limited to using a prepackaged application. The version of serverless that explicitly uses functions as the deployment unit is also called Function-as-a-Service (FaaS).

Serverless platforms promise new capabilities that make writing scalable microservices easier and cost-effective, positioning themselves as the next step in the evolution of cloud computing architectures. Most of the prominent cloud computing providers including Amazon [1], IBM [24], Microsoft [3], and Google [10] have recently released serverless computing capabilities. There are also several open-source efforts including the OpenLambda project [23].

Serverless computing is in its infancy and the research community has produced only a few citable publications at this time. OpenLambda [23] proposes a reference architecture for serverless platforms and describes challenges in this space (see Sect. 3.1.3) and we have previously published two of our use cases [5, 29] (see Sect. 5.1). There are also several books for practitioners that target developers interested in building applications using serverless platforms [12, 27].

1.1 Defining Serverless

Succinctly defining the term serverless can be difficult as the definition will overlap with other terms such as PaaS and Software-as-a-Service (SaaS). One way to explain serverless is to consider the varying levels of developer control over the cloud infrastructure, as illustrated in Fig. 2. The Infrastructure-as-a-Service (IaaS) model is where the developer has the most control over both the application code and operating infrastructure in the cloud. Here, the developer is responsible for provisioning the hardware or virtual machines, and can customize every aspect of how an application gets deployed and executed. On the opposite extreme are the PaaS and SaaS models, where the developer is unaware of any infrastructure, and consequently no longer has control over the infrastructure. Instead, the developer has

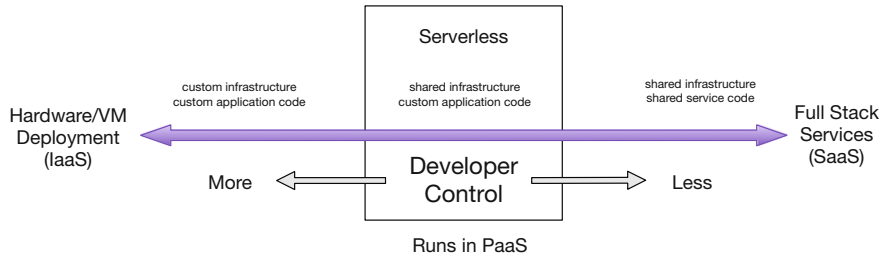


Fig. 2 Developer control and serverless computing

access to prepackaged components or full applications. The developer is allowed to host code here, though that code may be tightly coupled to the platform.

For this chapter, we will focus on the space in the middle of Fig. 2. Here, the developer has control over the code they deploy into the cloud, though that code has to be written in the form of stateless functions. (The reason for this will be explained in Sect. 3.) The developer does not worry about the operational aspects of deployment and maintenance of that code and expects it to be fault-tolerant and auto-scaling. In particular, the code may be scaled to zero where no servers are actually running when the user's function is not used, and there is no cost to the user. This is in contrast to PaaS solutions where the user is often charged even during idle periods.

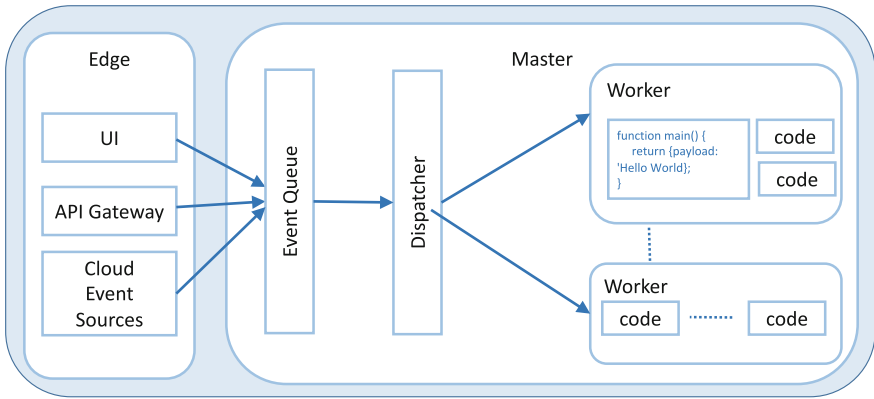
There are numerous serverless platforms that fall into the above definition. In this chapter, we present the architecture and other relevant features of serverless computing, such as the programming model. We also identify the types of application workloads that are suitable to run on serverless computing platforms. We then conclude with open research problems and future research challenges. Many of these challenges are a pressing need in industry and could benefit from contributions from academia.

## 2 Evolution

Serverless computing was popularized by Amazon in the re:Invent 2014 session “Getting Started with AWS Lambda” [2]. Other vendors followed in 2016 with the introduction of Google Cloud Functions [10], Microsoft Azure Functions [3], and IBM OpenWhisk [24]. However, the serverless approach to computing is not completely new. It has emerged following recent advancements and adoption of virtual machine (VM) and then container technologies. Each step up the abstraction layers led to more lightweight units of computation in terms of resource consumption, cost, and speed of development and deployment.

Among existing approaches, Mobile Backend as-a-Service (MBaaS) bears a close resemblance to serverless computing. Some of those services even provided “cloud functions”, that is, the ability to run some code server-side on behalf of a mobile app without the need to manage the servers. An example of such a service is Facebook's Parse Cloud Code [25]. Such code, however, was typically limited to mobile use cases.

Software-as-a-Service (SaaS) may support the server-side execution of user provided functions but they are executing in the context of an application and hence limited to the application domain. Some SaaS vendors allow the integration of arbitrary code hosted somewhere else and invoked via an API call. For example, this approach is used by the Google Apps Marketplace in Google Apps for Work [14].



**Fig. 3** Serverless platform architecture

### 3 Architecture

There are a lot of misconceptions surrounding serverless starting with the name. Servers are still needed, but developers need not concern themselves with managing those servers. Decisions such as the number of servers and their capacity are taken care of by the serverless platform, with server capacity automatically provisioned as needed by the workload. This provides an abstraction where computation (in the form of a stateless function) is disconnected from where it is going to run.

The core capability of a serverless platform is that of an event processing system, as depicted in Fig. 3. The service must manage a set of user-defined functions, take an event sent over HTTP or received from an event source, determine which function(s) to which to dispatch the event, find an existing instance of the function or create a new instance, send the event to the function instance, wait for a response, gather execution logs, make the response available to the user, and stop the function when it is no longer needed.

The challenge is to implement such functionality while considering metrics such as cost, scalability, and fault tolerance. The platform must quickly and efficiently start a function and process its input. The platform also needs to queue events, and based on the state of the queues and arrival rate of events, schedule the execution of functions, and manage stopping and deallocating resources for idle function instances. In addition, the platform needs to carefully consider how to scale and manage failures in a cloud environment.

### 3.1 Survey of Serverless Platforms

In this section, we will compare a number of serverless platform. We first list the dimensions which will be used to characterize the architectures of these platforms, followed by a brief description of each platform.

#### 3.1.1 Characteristics

There are a number of characteristics that help distinguish the various serverless platforms. Developers should be aware of these properties when choosing a platform.

- *Cost*: Typically, the usage is metered and users pay only for the time and resources used when serverless functions are running. This ability to scale to zero instances is one of the key differentiators of a serverless platform. The resources that are metered, such as memory or CPU, and the pricing model, such as off-peak discounts, vary among providers.
- *Performance and limits*: There are a variety of limits set on the runtime resource requirements of serverless code, including the number of concurrent requests, and the maximum memory and CPU resources available to a function invocation. Some limits may be increased when users' needs grow, such as the concurrent request threshold, while others are inherent to the platforms, such as the maximum memory size.
- *Programming languages*: Serverless services support a wide variety of programming languages including Javascript, Java, Python, Go, C#, and Swift. Most platforms support more than one programming language. Some of the platforms also support extensibility mechanisms for code written in any language as long as it is packaged in a Docker image that supports a well-defined API.
- *Programming model*: Currently, serverless platforms typically execute a single `main` function that takes a dictionary (such as a JSON object) as input and produces a dictionary as output.
- *Composability*: The platforms generally offer some way to invoke one serverless function from another, but some platforms provide higher level mechanisms for composing these functions and may make it easier to construct more complex serverless apps.
- *Deployment*: Platforms strive to make deployment as simple as possible. Typically, developers just need to provide a file with the function source code. Beyond that there are many options where code can be packaged as an archive with multiple files inside or as a Docker image with binary code. As well, facilities to version or group functions are useful but rare.
- *Security and accounting*: Serverless platforms are multi-tenant and must isolate the execution of functions between users and provide detailed accounting so users understand how much they need to pay.
- *Monitoring and debugging*: Every platform supports basic debugging by using print statements that are recorded in the execution logs. Additional capabilities may

be provided to help developers find bottlenecks, trace errors, and better understand the circumstances of function execution.

### 3.1.2 Commercial Platforms

Amazon's AWS Lambda [1] was the first serverless platform and it defined several key dimensions including cost, programming model, deployment, resource limits, security, and monitoring. Supported languages include Node.js, Java, Python, and C#. Initial versions had limited composability but this has been addressed recently. The platform takes advantage of a large AWS ecosystem of services and makes it easy to use Lambda functions as event handlers and to provide glue code when composing services.

Currently available as an Alpha release, Google Cloud Functions [10] provides basic FaaS functionality to run serverless functions written in Node.js in response to HTTP calls or events from some Google Cloud services. The functionality is currently limited but expected to grow in future versions.

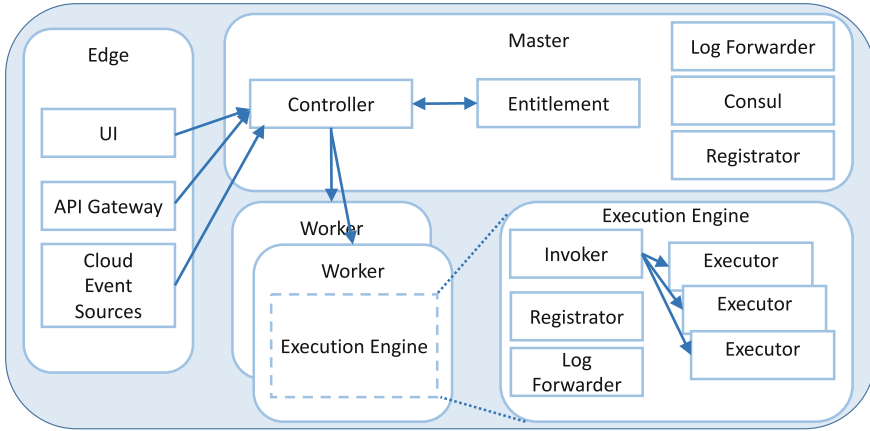
Microsoft Azure Functions [3] provides HTTP webhooks and integration with Azure services to run user provided functions. The platform supports C#, F#, Node.js, Python, PHP, bash, or any executable. The runtime code is open-source and available on GitHub under an MIT License. To ease debugging, the Azure Functions CLI provides a local development experience for creating, developing, testing, running, and debugging Azure Functions.

IBM OpenWhisk [24] provides event-based serverless programming with the ability to chain serverless functions to create composite functions. It supports Node.js, Java, Swift, Python, as well as arbitrary binaries embedded in a Docker container. OpenWhisk is available on GitHub under an Apache open-source license. The main architectural components of the OpenWhisk platform are shown in Fig. 4. Compared to the generic architectural diagram in Fig. 3, we can see there are additional components handling important requirements such as security, logging, and monitoring.

### 3.1.3 New and Upcoming Serverless Platforms

There are several serverless projects ranging from open-source projects to vendors that find serverless a natural fit for their business.

OpenLambda [23] is an open-source serverless computing platform. The source code is available in GitHub under an Apache License. The OpenLambda paper [15] outlines a number of challenges around performance such as supporting faster function startup time for heterogeneous language runtimes and across a load balanced pool of servers, deployment of large amounts of code, supporting stateful interactions (such as HTTP sessions) on top of stateless functions, using serverless functions with databases and data aggregators, legacy decomposition, and cost debugging. We have identified similar challenges in Sect. 6.



**Fig. 4** IBM openWhisk architecture

Some serverless systems are created by companies that see the need for serverless computing in the environments they operate. For example, Galactic Fog [13] added serverless computing to their Gestalt Framework running on top of Mesos D/C. The source code is available under an Apache 2 license. Auth0 has created webtasks [7] that execute serverless functions to support webhook endpoints used in complex security scenarios. This code is also available as open source. Iron.io had a serverless support for tasks since 2012 [28]. Recently, they announced Project Kratos [16] that allows developers to convert AWS Lambda functions into Docker images, and is available under an Apache 2 license. Additionally, they are working with Cloud Foundry to bring multi-cloud serverless support to Cloud Foundry users [9]. LeverOS is an open-source project that uses an RPC model to communicate between services. Computing resources in LeverOS can be tagged, so repeated function invocations can be targeted to a specific container to optimize runtime performance, such as taking advantage of warm caches in a container [20].

### 3.2 Benefits and Drawbacks

Compared to IaaS platforms, serverless architectures offer different tradeoffs in terms of control, cost, and flexibility. In particular, they force application developers to carefully think about the cost of their code when modularizing their applications, rather than latency, scalability, and elasticity, which is where significant development effort has traditionally been spent.

The serverless paradigm has advantages for both consumers and providers. From the consumer perspective, a cloud developer no longer needs to provision and manage servers, VMs, or containers as the basic computational building block for offering



distributed services. Instead the focus is on the business logic, by defining a set of functions whose composition enables the desired application behavior. The stateless programming model gives the provider more control over the software stack, allowing them to, among other things, more transparently deliver security patches and optimize the platform.

There are, however, drawbacks to both consumers and providers. For consumers, the FaaS model offered by the platform may be too constraining for some applications. For example, the platform may not support the latest Python version, or certain libraries may not be available. For the provider, there is now a need to manage issues such as the lifecycle of the user's functions, scalability, and fault tolerance in an application-agnostic manner. This also means that developers have to carefully understand how the platform behaves and design the application around these capabilities.

One property of serverless platforms that may not be evident at the outset is that the provider tends to offer an ecosystem of services that augment the user's functions. For example, there may be services to manage state, record and monitor logs, send alerts, trigger events, or perform authentication and authorization. Such rich ecosystems can be attractive to developers and present another revenue opportunity for the cloud provider. However, the use of such services brings with it a dependence on the provider's ecosystem and a risk of vendor lock-in.

### ***3.3 Current State of Serverless Platforms***

There are many commonalities between serverless platforms. They share similar pricing, deployment, and programming models. The main difference among them is the cloud ecosystem: current serverless platforms only make it easy to use the services in their own ecosystem and the choice of platform will likely force developers to use the services native to that platform. That may be changing as open-source solutions may work well across multiple cloud platforms.

## **4 Programming Model**

Serverless functions have limited expressiveness as they are built to scale. Their composition may be also limited and tailored to support cloud elasticity. To maximize scaling, serverless functions do not maintain state between executions. Instead, the developer can write code in the function to retrieve and update any needed state. The function is also able to access a context object that represents the environment in which the function is running (such as a security context). For example, a function written in JavaScript could take the input, as a JSON object, as the first parameter, and context as the second:

```
function main(params, context) {  
    return {payload: 'Hello,' + params.name  
            + ' from' + params.place};  
}
```

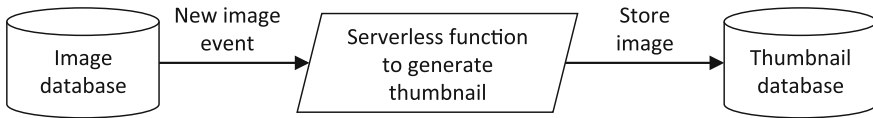
## 4.1 *Ecosystem*

Due to the limited and stateless nature of serverless functions, an ecosystem of scalable services that support the different functionalities a developer may require is essential to having a successfully deployed serverless application. For example, many applications will require the serverless function to retrieve state from permanent storage (such as a file server or database). There may be an existing ecosystem of functions that support API calls to various storage systems. While the functions themselves may scale due to the serverless guarantees, the underlying storage system itself must provide reliability and QoS guarantees to ensure smooth operation. Serverless functions can be used to coordinate any number of systems such as identity providers, messaging queues, and cloud-based storage. Dealing with the challenges of scaling of these systems on-demand is as critical but outside the control of the serverless platform. To increase the adoption of serverless computing, there is a need to provide such scalable services. Such an ecosystem enables ease of integration and fast deployment at the expense of vendor lock-in.

## 4.2 *Tools and Frameworks*

Creating and managing serverless functions requires several operations. Instead of managing each function independently, it is much more convenient to have a framework that can logically group functions together to deploy and update them as a unit. A framework may also make it easier to create functions that are not bound to one serverless service provider by providing abstractions that hide low-level details of each serverless provider. Other frameworks may take existing popular programming models and adapt them for serverless execution. For example, Zappa [30] and Chalice [8] use an `@app.route` decorator to make it possible to write python code that looks like a webserver but can be deployed as a serverless function:

```
@app.route("/{name}/{place}")  
def index():  
    return {"hello": name, "from": place}
```



**Fig. 5** Image processing

## 5 Use Cases and Workloads

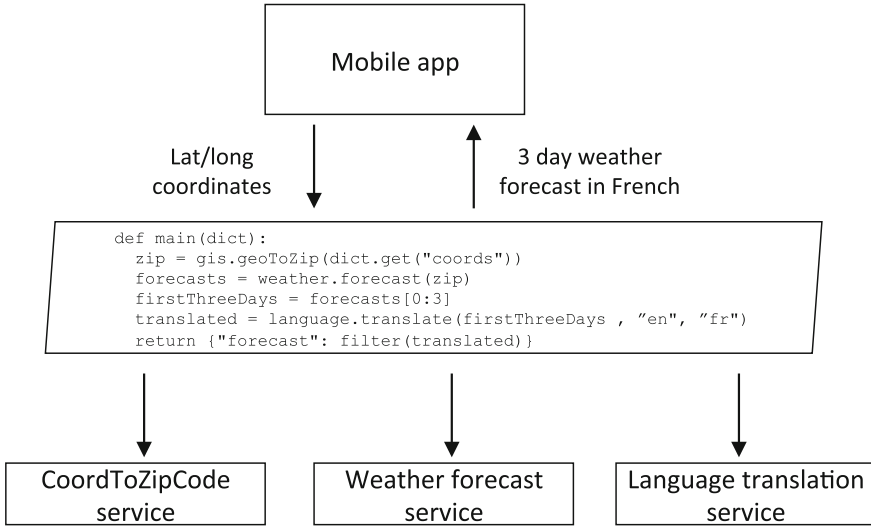
Serverless computing has been utilized to support a wide range of applications. From a functionality perspective, serverless and more traditional architectures may be used interchangeably. The determination of when to use serverless will likely be influenced by other non-functional requirements such as the amount of control over operations required, cost, as well as application workload characteristics.

From a cost perspective, the benefits of a serverless architecture are most apparent for *bursty, compute-intensive* workloads. Bursty workloads fare well because the developer offloads the elasticity of the function to the platform, and just as important, the function can scale to zero, so there is no cost to the consumer when the system is idle. Compute-intensive workloads are appropriate since in most platforms today, the price of a function invocation is proportional to the running time of the function. Hence, I/O bound functions are paying for compute resources that they are not fully taking advantage of. In this case, a multi-tenant server application that multiplexes requests may be cheaper to operate.

From a programming model perspective, the stateless nature of serverless functions lends themselves to application structure similar to those found in functional reactive programming [4]. This includes applications that exhibit event-driven and flow-like processing patterns.

### 5.1 Event Processing

One class of applications that are very much suitable for serverless computing is event-based programming [5, 29]. The most basic example, popularized by AWS Lambda, that has become the “Hello World” of serverless computing is a simple image processing event handler function. The function is connected to a data store, such as Amazon S3 [26], that emits change events. Each time a new image file is uploaded to a folder in S3, an event is generated and forwarded to the event handler function that generates a thumbnail image that is stored in another S3 folder. The flow is depicted in Fig. 5. This example works well for serverless demos as the function is completely stateless and idempotent which has the advantage that in the case of failure (such as network problems accessing the S3 folder), the function can be executed again with no side effects. It is also an exemplary use case of a bursty, compute-intensive workload as described above.



**Fig. 6** Offloading API calls and glue logic from mobile app to backend

## 5.2 API Composition

Another class of applications involves the composition of a number of APIs. In this case, the application logic consists of data filtering and transformation. For example, a mobile app may invoke geolocation, weather, and language translation APIs to render the weather forecast for a user's current location. The glue code to invoke these APIs can be written in a short serverless function, as illustrated by the Python function in Fig. 6. In this way, the mobile app avoids the cost of invoking the multiple APIs over a potentially resource constrained mobile network connection, and offloads the filtering and aggregation logic to the backend.

## 5.3 API Aggregation to Reduce API Calls

API aggregation can work not only as a composition mechanism, but also as a means to simplify the client-side code that interacts with the aggregated call. For example, consider a mobile application that allows you to administer an Open Stack instance. API calls in Open Stack [18] require the client to first obtain an API token, resolve the URL of the service you need to talk to, then invoke the required API call on that URL with the API token. Ideally, a mobile app would save energy by minimizing the number of required calls needed to issue a command to an Open Stack instance. Figure 7 illustrates an alternative approach where three functions implement the aforementioned flow to allow authenticated backups in an Open Stack instance. The

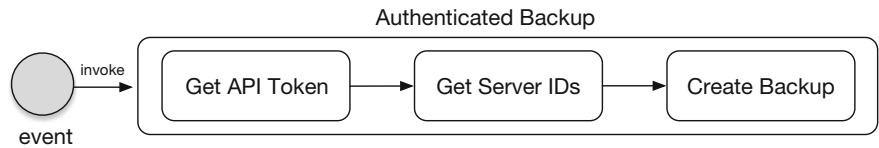


Fig. 7 Reducing the number of API calls required for a mobile client

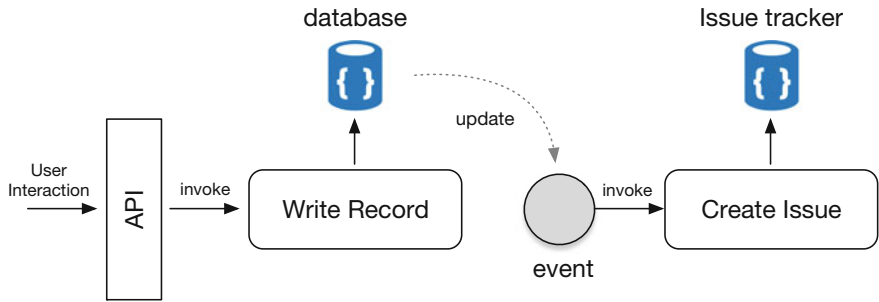


Fig. 8 Batched invocation for issue tracking

mobile client now makes a single call to invoke this aggregate function. The flow itself appears as a single API call. Note that authorization to invoke this call can be handled by an external authorization service, e.g., an API gateway.

5.4 Flow Control for Issue Tracking

Serverless function composition can be used to control the flow of data between two services. For example, imagine an application that allows users to submit feedback to the app developers in the form of annotated screenshots and text. In Fig. 8, the application submits this data to a backend consisting of a scalable database and an on-premise issue tracking system. The latter is mainly used by the development team and is not designed to accept high volume traffic. On the other hand, the former is capable of responding to high volume traffic. We design our system to stage all feedback records in the database using a serverless function which eliminates the need to standup a separate server to handle feedback requests but still allow us a level of indirection between the application and the backend database. Once we collect a sufficient number of updates, we can batch them together into a single update, which invokes a function to submit issues to the issue tracker in a controlled manner. This flow would work for a scalable database system [6] and an issue tracker system that accepts batched inputs [17].

## 5.5 Discussion

The workload and its relationship to cost can help determine if serverless is appropriate. Infrequent but bursty workloads may be better served by serverless, which provides horizontal scaling without the need for dedicated infrastructure that charges for idle time. For more steady workloads, the frequency at which a function is executed will influence how economical it can be for caching to occur which allows for faster execution on warm containers than executing from a cold container. These performance characteristics can help guide the developer when considering serverless.

Interestingly, the cost considerations may affect how a serverless application is structured. For example, an I/O bound serverless function can be decomposed into multiple compute bound ones. This may be more complex to develop and debug, but cheaper to operate.

## 6 Challenges and Open Problems

We will list challenges starting with those that are already known based on our experience of using serverless services and then describe open problems.

### 6.1 System-Level Challenges

Here is a list of challenges at the systems level.

- *Cost*: Cost is a fundamental challenge. This includes minimizing the resource usage of a serverless function, both when it is executing and when idle. Another aspect is the pricing model, including how it compares to other cloud computing approaches. For example, serverless functions are currently most economical for CPU-bound computations, whereas I/O bound functions may be cheaper on dedicated VMs or containers.
- *Cold start*: A key differentiator of serverless is the ability to scale to zero, or not charging customers for idle time. Scaling to zero, however, leads to the problem of cold starts, and paying the penalty of getting serverless code ready to run. Techniques to minimize the cold start problem while still scaling to zero are critical.
- *Resource limits*: Resource limits are needed to ensure that the platform can handle load spikes and manage attacks. Enforceable resource limits on a serverless function include memory, execution time, bandwidth, and CPU usage. In addition, there are aggregate resource limits that can be applied across a number of functions or across the entire platform.
- *Security*: Strong isolation of functions is critical since functions from many users are running on a shared platform.

- *Scaling*: The platform must ensure the scalability and elasticity of users' functions. This includes proactively provisioning resources in response to load, and in anticipation of future load. This is a more challenging problem in serverless because these predictions and provisioning decisions must be made with little or no application-level knowledge. For example, the system can use request queue lengths as an indication of the load, but is blind to the nature of these requests.
- *Hybrid cloud*: As serverless is gaining popularity, there may be more than one serverless platform and multiple serverless services that need to work together. It is unlikely one platform will have all functionality and work for all use cases.
- *Legacy systems*: It should be easy to access older cloud and non-cloud systems from serverless code running in serverless platforms.

## 6.2 Programming Model and DevOps Challenges

- *Tools*: Traditional tools that assumed access to servers to be able to monitor and debug applications are not applicable in serverless architectures, and new approaches are needed.
- *Deployment*: Developers should be able to use declarative approaches to control what is deployed and tools to support it.
- *Monitoring and debugging*: As developers no longer have servers that they can access, serverless services and tools need to focus on developer productivity. As serverless functions are running for shorter amounts of time, there will be many orders of magnitude more of them running making it harder to identify problems and bottlenecks. When the functions finish the only trace of their execution is what the serverless platform's monitoring infrastructure recorded.
- *IDEs*: Higher level developer capabilities, such as refactoring functions (e.g., splitting and merging functions) and reverting to an older version, etc. will be needed and should be fully integrated with serverless platforms.
- *Composability*: This includes being able to call one function from another, creating functions that call and coordinate a number of other functions, and higher level constructs such as parallel executions and graphs. Tools will be needed to facilitate creation of compositions and their maintenance.
- *Long running*: Currently, serverless functions are often limited in their execution time. There are scenarios that require long running (if intermittent) logic. Programming models and tools may decompose long running tasks into smaller units and provide necessary context to track them as one long running unit of work.
- *State*: Real applications often require state, and it is not clear how to manage state in stateless serverless functions—programming models, tools, and libraries will need to provide the necessary.
- *Concurrency*: Expressing concurrency semantics, such as atomicity (function executions need to be serialized), etc.
- *Recovery semantics*: Such as exactly once, at most once, and at least once semantics.

- *Code granularity*: Currently, serverless platforms encapsulate code at the granularity of functions. It is an open question whether coarser or finer grained modules would be useful.

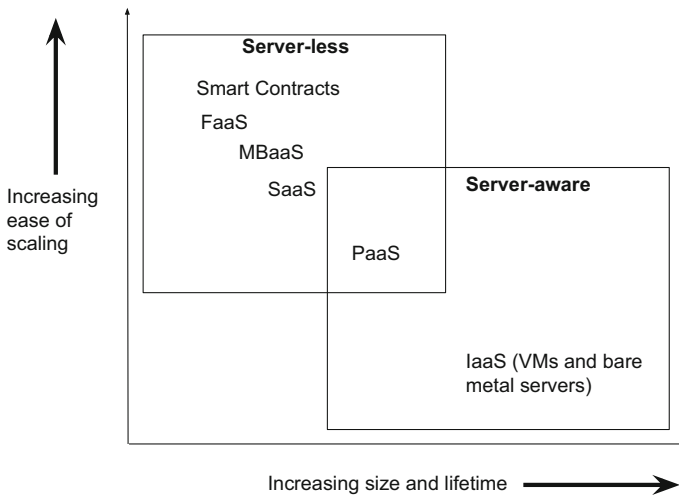
### 6.3 Open Research Problems

Now, we will describe a number of open problems. We frame them as questions to emphasize that they are largely unexplored research areas.

**What are the boundaries of serverless?** A fundamental question about serverless computing is of boundaries: is it restricted to FaaS or is broader in scope? How does it relate to other models such as SaaS and MBaaS?

As serverless is gaining popularity the boundaries between different types of “as-a-Service” may be disappearing (see Fig. 9). One could imagine that developers not only write code but also declare how they want the code to run—as FaaS or MBaaS or PaaS—and can change as needs change. In the future, the main distinction may be between caring about server (server-aware) and not caring about server details (serverless). PaaS is in the middle; it makes it very easy to deploy code but developers still need to know about servers and be aware of scaling strategies, such as how many instances to run.

Can different cloud computing service models be mixed? Can there be more choices for how much memory and CPU can be used by serverless functions? Does



**Fig. 9** The figure is showing relation between time to live (x-axis) and ease of scaling (y-axis). Server-aware compute (bare metal, VMs, IaaS) has long time to live and take longer to scale (time to provision new resources); serverless compute (FaaS, MBaaS, PaaS, SaaS) is optimized to work on multiple servers and hide server details



serverless need to have IaaS-like-based pricing? What about spot and dynamic pricing with dynamically changing granularity?

**Is tooling for serverless fundamentally different from existing solutions?** As the granularity of serverless is much smaller than traditional server-based tools, we may need new tools to deal well with more numerous but much shorter living artifacts. How can we make sure that the important “information needle” is not lost in a haystack? Monitoring and debugging serverless applications will be much more challenging as there are no servers directly accessible to see what went wrong. Instead, serverless platforms need to gather all data when code is running and make it available later. Similarly debugging is much different if instead of having one artifact (a microservice or traditional monolithic app) developers need to deal with a myriad of smaller pieces of code. New approaches may be needed to virtually assemble serverless pieces into larger units that are easier to understand and to reason about.

**Can legacy code be made to run serverless?** The amount of existing (“legacy”) code that must continue running is much larger than the new code created specifically to run in serverless environments. The economic value of existing code represents a huge investment of countless hours of developers coding and fixing software. Therefore, one of the most important problems may be to what degree existing legacy code can be automatically or semi-automatically decomposed into smaller-granularity pieces to take advantage of these new pricing models.

**Is serverless fundamentally stateless?** As current serverless platforms are stateless will there be stateful serverless services in future? Will there be simple ways to deal with state? More than that is serverless fundamentally stateless? Can there be serverless services that have stateful support built-in with different degrees of quality-of-service?

**Will there be patterns for building serverless solutions?** How do we combine low granularity “basic” building blocks of serverless into bigger solutions? How are we going to decompose apps into functions so that they optimize resource usage? For example, how do we identify CPU-bound parts of applications built to run in serverless services? Can we use well-defined patterns for composing functions and external APIs? What should be done on the server versus client (e.g., are thicker clients more appropriate here)? Are there lessons learned that can be applied from OOP design patterns, Enterprise Integration Patterns, etc.?

**Does serverless extend beyond traditional cloud platforms?** Serverless may need to support scenarios where code is executed outside of a traditionally defined data center. This may include efforts where the cloud is extended to include IoT, mobile devices, web browsers, and other computing at the edge. For example “fog” computing [22] has the goal of creating a system-level horizontal architecture that distributes resources and services of computing, storage, control, and networking anywhere along the continuum from Cloud to IoT. The code running in the “fog” and outside the Cloud may not just be embedded but virtualized to allow movement between devices and cloud. That may lead to specific requirements that redefine cost. For example, energy usage may be more important than speed.

Another example is running code that executes “smart contracts” orchestrating transactions in a blockchain. The code that defines the contract may be deployed

and running on a network of Hyperledger fabric peer nodes [19], or in Ethereum Virtual Machines [11] on any node of an Ethereum peer-to-peer network. As the system is decentralized, there is no Ethereum service or servers to run serverless code. Instead, to incentivize Ethereum users to run smart contracts they get paid for the “gas” consumed by the code, similar to fuel cost for an automobile but applied to computing.

## 7 Conclusions

In this chapter, we explored the genesis and history of serverless computing in detail. It is an evolution of the trend toward higher levels of abstractions in cloud programming models, and currently exemplified by the Function-as-a-Service (FaaS) model where developers write small stateless code snippets and allow the platform to manage the complexities of scalably executing the function in a fault-tolerant manner.

This seemingly restrictive model nevertheless lends itself well to a number of common distributed application patterns, including compute-intensive event processing pipelines. Most of the large cloud computing vendors have released their own serverless platforms, and there is a tremendous amount of investment and attention around this space in industry.

Unfortunately, there has not been a corresponding degree of interest in the research community. We feel strongly that there are a wide variety of technically challenging and intellectually deep problems in this space, ranging from infrastructure issues such as optimizations of the cold start to the design of a composable programming model. There are even philosophical questions such as the fundamental nature of state in a distributed application. Many of the open problems identified in this chapter are real problems faced by practitioners of serverless computing today and solutions have the potential for significant impact.

We leave the reader with some ostensibly simple questions that we hope will help stimulate their interest in this area. Why is serverless computing important? Will it change the economy of computing? As developers take advantage of smaller granularities of computational units and pay only for what is actually used will that change how developers think about building solutions? In what ways will serverless extend the original intent of cloud computing of making hardware fungible and shifting the cost of computing from capital to operational expenses?

The serverless paradigm may eventually lead to new kinds of programming models, languages, and platform architectures and that is certainly an exciting area for the research community to participate in and contribute to.

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