



Unifying serverless and microservice tasks with SigmaOS

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Abstract

Many cloud applications use both serverless functions, for bursts of stateless parallel computation, and container orchestration, for long-running microservices and tasks that need to interact. Ideally a single platform would offer the union of these systems' capabilities, but neither is sufficient to act as that single platform: serverless functions are lightweight but cannot act as servers with long-term state, while container orchestration offers general-purpose computation but instance start-up takes too long to support burst parallelism.

σ OS is a new multi-tenant cloud operating system that combines the best of container orchestration and serverless in one platform with one API. σ OS computations, called *procs*, can be long-running, stateful, and interact with each other, making them a good match for both serverless and microservice tasks. A key aspect of the σ OS design is its *cloud-centric* API, which provides flexible management of computation, a novel abstraction for communication endpoints, σ EPs—which allow *procs* of a tenant to communicate efficiently but prohibits *procs* from sending packets to other tenants—and a flexible naming system to name, for example, σ EPs.

Quick *proc* start-up is important for serverless uses. A key enabling observation is that both serverless and microservice applications rely on cloud services for much of the work traditionally done by the local OS (e.g., access to durable storage and additional compute resources). σ OS exploits this observation by providing only a small and generic local operating system image to each *proc*, which can be created much more quickly than a container orchestration instance since σ OS need not install application-specific filesystem content or (due to σ OS's σ EPs) configure an isolated overlay network.

Microbenchmarks show that σ OS can cold start a *proc* in 7.7 msec and can create 36,650 *procs* per second, distributing them over a 24-machine cluster. An evaluation of σ OS

with two microservice applications from DeathStarBench, a MapReduce application, and an image processing benchmark, shows that the σ OS API supports both microservices and lambda-style computations, and provides better performance than corresponding versions on AWS Lambda and Kubernetes.

1 Introduction

A typical cloud tenant executes a variety of tasks on many machines: long-running analytics, short background job queues, fleets of web and web API servers, sharded database servers, and more. An important axis on which these workloads vary is the rapidity with which tasks come and go. Some are long-running stateful services, most recently typified by microservices. A contrasting workload is serverless functions [4, 17, 22, 33, 52], which are often invoked in large parallel bursts and tend to be short-lived. For convenience, this paper will refer to these two workload classes as “microservices” and “serverless.”

Cloud applications require infrastructure to deploy software, manage execution and communication, and enforce isolation. For microservice-style workloads, container orchestration [10, 21, 34] works well: each instance provides the full facilities of a traditional operating system, and is thus quite general-purpose. These instances, however, are ill suited to serverless workloads. The core problem is that container orchestration instances start slowly. This is reasonable in static situations but a problem if instances come and go rapidly. One source of slowness is that each instance involves a user-level Linux installation: an isolated read/write file system populated from an application-specific Linux container image. Another is that, in order for cooperating instances to communicate, the start-up process must configure each with an IP address and a connection to an isolated overlay network. Isolation is important when a provider has many independent tenants. Finally, the mechanism for finding a machine with enough resources to execute a new instance is typically not fast enough for rapidly-initiated serverless functions.

An ideal platform would be able to initiate new work rapidly enough for serverless uses, but also provide enough flexibility to satisfy microservice applications. This would simplify applications that need both kinds of support, for example burst parallel functions that need to communicate [27, 28] or need to keep state [45, 61], or micro-services whose fleet size should vary with load. Such a platform would



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need fast instance start, powerful facilities for instances to interact, and isolation for both execution and communication.

σ OS is a provider-hosted multi-tenant distributed operating system that addresses the above challenges. A key enabling insight is that cloud applications depend chiefly on cloud infrastructure, such as access to networked services, which the trend towards “cloud-native” applications [30] illustrates. Such applications can be designed to require little from the local machine beyond CPU, memory, and network access to cloud services. This simplifying assumption allows σ OS to provide both the communication services that microservice workloads require and the creation speeds that serverless workloads need.

A unit of work in σ OS is called a *proc*. σ OS assumes that *procs* will use cloud storage, and so does not go to the expense of creating per-*proc* local read/write file systems, but instead shares generic read-only file systems among multiple *procs*. σ OS provides a network addressing scheme (σ EPs) for *procs* that is more efficient than per-instance IP addresses, but allows communication only among the *procs* of the same tenant. σ OS isolates each *proc* in a lightweight “ σ container,” preventing the *proc* from using system calls not needed by the σ OS API or runtime using Seccomp and AppArmor.

To help a tenant’s *procs* cooperate, σ OS provides a per-tenant naming service (*named*) inspired by *etcd* [25] and Plan 9 [60]. *procs* use *named* to register σ EPs as well as to store configuration information and small items of shared and/or fault-tolerant state. As an example, σ OS has a fast and scalable placement service that chooses a machine to execute each newly spawned *proc*; this service organizes itself via *named*.

Following Borg [71], σ OS asks developers to mark each *proc* as either latency-critical (LC), with reserved CPU time and RAM, or best effort (BE). σ OS schedules BE *procs* as CPU and memory become available, either on the completion of previous BE *procs*, or because LC *procs* are temporarily under-using their reserved resources. The two classes capture a common distinction in cloud tasks, between services that are some or all of long-running, stateful, and in need of performance guarantees (LC); and tasks that are some combination of short-running, non-latency-critical, and in need of burst parallelism (BE).

Because σ OS can create *procs* rapidly, it is suitable for serverless tasks. Because *procs* can communicate with each other, coordinate through the σ OS name system, and can be long running, σ OS is also suitable for stateful microservices, as well as offering this set of facilities to serverless tasks.

We have implemented a prototype of σ OS in Go [1] on Linux. A microbenchmark of start times, critical for serverless workloads, shows that σ OS has warm- and cold-start times lower than those of AWS Lambda, Docker, and Kubernetes; for cold-start 7.7 milliseconds vs 1.3 seconds, 2.7 seconds, and 1.1 seconds respectively. σ OS start times are slower than MitoSis’ 3.1 milliseconds [75], though σ OS re-

quires neither Linux kernel changes nor RDMA and is suitable for stateful long-running microservices with strong network isolation. A communication microbenchmark shows that σ OS’s σ EPs deliver 48% lower per-packet latency and 14% higher throughput than Docker and Kubernetes overlay networks at the cost of higher dial latency. To demonstrate generality and application-level performance, we have implemented *proc*-based versions of a MapReduce library, the Hotel and Social Network web sites from DeathStarBench [29], and an image-processing service. σ OS provides better throughput and latency for these applications than those provided by Docker and Kubernetes, while also delivering fairness among tenants and guaranteed resources for LC *procs* (§6).

The contributions of this paper are: (1) the design of σ OS, a new multi-tenant distributed operating system that supports both long-running stateful executions and short-lived serverless tasks; (2) σ EPs, a novel abstraction which provides low-overhead network communication between *procs* with strong security isolation; (3) a σ container implementation of *procs* that provides strong isolation with quick start; and (4) an evaluation showing that σ OS provides high throughput for both serverless and microservice workloads. The σ OS source code is open-source and available at <https://github.com/mit-pdos/sigmaos>.

2 Related work

Compared to prior work, σ OS’s main contribution is unifying support for serverless and microservices tasks in a single, cloud-centric platform with unique support for network isolation through σ EPs and for *proc* isolation through σ containers. This section discusses related work that σ OS builds upon along the dimensions below. §6 measures the start times of several prior systems and compares them with σ containers and σ EPs.

Faster containers. Many techniques have been explored for fast start, since it is critical for burst-parallelism and transparent scaling of tenants’ workloads. SAND [3] shares a single container among the serverless functions of a given application to ease local communication, and relies on process boundaries to isolate functions within the application. For many applications SAND’s isolation is too weak. Consider an application which processes end-users’ images with a serverless function invocation per image. In SAND, each image would be handled by a different Linux process in a shared container. If a malicious user could craft an image to exploit a bug in the application, they could take control of the Linux process handling the application’s function invocation and corrupt or steal images of other users being handled by other Linux processes in the application’s container. σ OS makes this attack more challenging, as each image processing *proc* would run in a separate σ container with strong isolation.

SOCK [55] introduces “lean” containers specialized for

serverless functions; they cannot communicate directly, which allows SOCK to avoid the cost of network isolation. σ OS's σ EPs allow `procs` to communicate directly with low overhead and strong isolation.

Particle [69] amortizes costs of configuring network namespaces and overlay networks when launching batches of containers on a single node. σ OS's σ EPs don't use network namespaces or overlay networks, and allow quick start on cold and warm nodes with strong network isolation between tenants.

Sidecar-less service meshes [16, 38] provide network isolation without per-container user-space proxies. However, they rely on overlay networks and network namespaces. σ OS applications use σ EPs, which provide networking isolation without these costs.

Isolation. AWS Lambda uses microVMs [2] to provide stronger isolation than containers with less overhead than a full VM; functions of the same tenant may share a microVM [73]. AWS Lambda targets serverless workloads and isn't suitable for microservice-style workloads, because Lambdas cannot communicate directly and cannot maintain long-term state (they may be terminated after 15 minutes).

Gvisor [32] reimplements much of Linux in user space while restricting the set of system calls made available by the underlying host. σ OS σ containers also restrict the set of system calls, to those needed to implement the σ OS API.

LightVM [49] can start a VM with a unikernel and devices in 4ms. However, LightVM's reported start time is not comparable to σ OS's 1.8ms, because while σ OS provides strong network isolation, LightVM's start time does not include the cost of establishing network isolation (i.e., creating and configuring veth devices, network namespaces, and overlays).

Faasm [65] runs functions from different tenants in a shared WASM runtime, which allows for quick start times, but may be unsuitable for providers who are uncomfortable with the isolation guarantees of a shared WASM runtime [31] or the performance cost of WASM [39].

Fast application start. Application initialization after creating an isolated execution context (e.g., container or VM) is often another major bottleneck in fast start. Catalyzer [24] introduce `sfork` to start an application from a previously-checkpointed application image. Faasm, and SEUSS [13] also speed up application-start by checkpointing, respectively a WASM runtime or a unikernel. REAP [70] records and replays the working sets of functions to make starting from a snapshot faster. AWS Lambda [9] and FaasNET [72] reduce image fetch time with caching and efficient distribution. Mitosis [75] improves on Catalyzer's `sfork` by introducing `rfork`, which provides fast application start using remote fork over RDMA, reducing the need for caching. The above systems target serverless applications and aren't suitable for microservice-style workloads because these systems don't provide direct communication or network isolation. Like

`rfork`, σ OS leverages demand paging (but without modifying Linux and RDMA) and fetches pages from other nodes that have run the `proc` recently to start both serverless and microservice-style `proc` quickly.

Single system image. σ OS's naming system inherits the idea of transparent access across a cluster from single-system image distributed systems [15, 20, 54, 57, 60, 68] but σ OS targets cloud computing and provides a single-system image per tenant. σ OS extends Plan9's 9P protocol [36], which is widely supported¹, and which allows σ OS to be administered from the Linux command-line. σ OS extends 9P with σ EPs, watches to wait for a file to be created or removed (inspired by Chubby [11], `etcd` [25], and ZooKeeper [37]), and RPCs for services that don't fit a file system interface. σ OS uses `etcd` to implement the root of a tenant's name space.

Schedulers. σ OS takes inspiration from prior work on schedulers to allow the σ OS scheduler to quickly schedule best-effort `procs` and guarantee resources to latency-critical `procs`. Like the Kubernetes scheduler [10, 64, 71], σ OS uses a centralized scheduler and resource requests to schedule long-running computations carefully. σ OS takes ideas from the distributed schedulers of Ray [74] and Sparrow [58] to schedule BE `procs` quickly and scalably. σ OS's two-scheduler design resembles Mercury's hybrid scheduler [44]. Like Apollo [8], σ OS uses real-time resource utilization to inform scheduling decisions.

Improving serverless. AWS Step Functions [5] and Azure Durable functions [6] simplify coordination and sharing among serverless functions. Recent research has eased restrictions on serverless functions by proxying communication [27, 28], by shuffling data efficiently [3, 42, 59, 61, 65], by resuming terminated functions [78], by allowing functions to communicate and maintain transient state [63], by providing exactly-once semantics despite re-execution [40, 43, 62, 77], by making function invocation fast [12, 17, 41, 53, 65], and by running functions close to the data and providing transactions [14, 46, 66].

σ OS is suitable for both serverless and microservice tasks, since it provides fast start, communication among `procs`, and support for stateful services. Like container orchestration systems, the σ OS scheduler allows `procs` to reserve resources for latency-critical microservice tasks, which serverless systems don't support. For example, although Faasm can run serverless functions from different tenants, developers cannot reserve resources for a faaslet that is long-running and latency critical and the Faasm scheduler runs all faaslets in round-robin, making it inappropriate for long-running, latency-critical microservices.

¹Linux, Windows Subsystem for Linux (WSL), QEMU, and Gvisor support or use 9P.

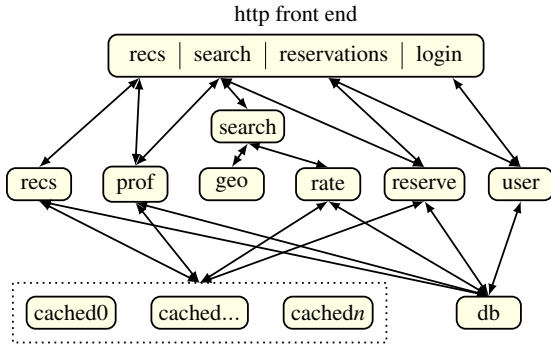


Figure 1: Each yellow box is a proc in the Hotel Web site. The cache service consists of one proc per shard.

3 σ OS: a cloud-centric OS

σ OS’s goal is to provide tenants with a single platform that supports both serverless and microservice tasks and to multiplex the workloads from different tenants on the provider’s servers. σ OS’s API caters to cloud applications’ need to launch computations, to communicate among those computations, and to share storage; it aims to provide interfaces well-enough tailored to the cloud that traditional local OS interfaces are not needed. This section describes σ OS and its interfaces from the perspective of the tenant, while the next section §4 describes how σ OS is implemented on the provider’s hardware.

3.1 procs: application execution units

Developers write their applications in terms of procs, which are executed by σ OS. To illustrate how developers use procs, consider the following two running examples in this paper: `mr`, a MapReduce library, and `hotel`, a microservice application from DeathStarBench [29]. Both `mr` and `hotel` combine tasks that are best implemented as microservices with tasks that fit the serverless model.

The `mr` library creates a long-lived proc that coordinates the job. This coordinator spawns a serverless-style mapper proc for each shard of the input files and a reducer proc for each reducer bin. Current cloud offerings require developers to either use two platforms, a microservice platform to run the coordinator and a serverless platform to run the mappers and reducers, or run a coordinator together with a cluster of long-lived worker processes, which fails to take advantage of the elastic structure of MapReduce.

The `hotel` application creates a proc for the web front-end, a proc for each microservice, and a proc for each cache service shard. Figure 1 illustrates the proc-level organization of the `hotel` application. Some of the `hotel` microservices, like the sharded cache service and compute-intensive reservation service, benefit from the elasticity of serverless. Additionally, the `hotel` application may run periodic background jobs, such as image resizing or data analytics, which are a good fit for the serverless model. A developer who wishes to implement `hotel` on current cloud offerings would have to

Methods	Description
<code>Spawn(descriptor)</code>	Queue proc, return <code>pid</code>
<code>Kill(pid)</code>	Kill proc <code>pid</code>
<code>WaitStart(pid)</code>	Wait until <code>pid</code> starts
<code>WaitExit(pid)</code>	Wait until <code>pid</code> exits
<code>Started(pid)</code>	<code>pid</code> marks itself started
<code>Exited(pid, status)</code>	<code>pid</code> marks itself exited
<code>WaitKill(pid)</code>	<code>pid</code> wait for kill signal
<code>NewSigmaEP() → (Listener, SigmaEP)</code>	Create σ EP
<code>Accept(Listener) → (Conn, SigmaEP)</code>	Accept connection
<code>Dial(SigmaEP) → Conn</code>	Connect σ EP
<code>CloseEP(SigmaEP) → nil</code>	Close σ EP
<code>Create(...), Open(...), Close(...), Remove(...), Rename(...), Stat(...), Read(...), Write(...), Lseek(...), Watch(...)</code>	Access files in realm
<code>AbsPath(path)</code>	Resolve <code>~local</code>
<code>OpenWatch(dir, func)</code>	Watch for changes in dir

Table 1: Summary of the σ OS interface.

compose several cloud platforms to implement the different application tasks, and would be unable to make microservice tasks as elastic as serverless tasks.

In σ OS, the tenant can use a single cloud platform and API to implement all tasks of `mr` and `hotel`. Long-lived microservices and short-running functions can both be implemented as procs. The tenant does not provision worker machines when implementing `mr` and `hotel`; σ OS is in charge of choosing which of the provider’s machines should run each proc.

Table 1 shows the interface with which σ OS applications create and control procs. An application creates a new proc using `Spawn`, which returns a process identifier. The descriptor argument describes the desired attributes of the proc:

- the σ OS name-system pathname of the binary to execute (§3.3).
- arguments to be passed to the proc.
- whether the proc is to be latency-critical (LC) or best-effort (BE), following Borg [71]. For example, a developer would likely specify BE for a map or reduce worker, and LC for a microservice proc.
- for LC procs, the amount of CPU power to reserve (typically chosen for peak expected load).
- for all procs, the amount of RAM to reserve.

```

func (c *Coord) runProc(p *Proc) {
    for {
        SigmaOS.Spawn(p)
        exitStatus := SigmaOS.WaitExit(p.GetPid())
        if exitStatus = SUCCESS {
            break
        } else if exitStatus = ERROR {
            // Need to retry, so continue in loop
        }
    }
    c.procDone(p)
}

func (c *Coord) runMR(procs []*Proc) {
    for _, p := range procs {
        go c.runProc(ch, p)
    }
}

```

Figure 2: Simplified version of the code a MapReduce coordinator might use to start map or reduce procs, wait for them, and re-start them on failure.

- optionally, a failure domain for situations where procs should execute on independently-failing machines.

Spawn adds the proc request to a queue managed by the σ OS scheduler (§4). This queue gives the scheduler a view of demand, allows it to limit active load by deferring the start of some procs, and allows it to make informed decisions about how to distribute procs over machines. The caller of Spawn can wait until the scheduler starts its child by calling WaitStart. For example, hotel spawns microservices as LC procs and waits until they are started before accepting client requests. A proc signals to a parent that is running using Started.

A parent proc can wait until its child finishes using WaitExit, which returns an exit status provided by the child's call to Exited. σ OS itself may also call Exited on behalf of a child proc if a machine crashes or a partition makes the proc unreachable; WaitExit returns an error in this case. For example, the mr coordinator waits for its mappers and reducers, as illustrated in Figure 2, and uses the returned exit status to decide whether any procs must be re-run due to failures.

3.2 Endpoints: proc communication

σ OS must provide procs with high-performance network communication and must prohibit different tenants' procs from interfering with each other. σ OS does so using a novel abstraction: σ EPs. The σ EP API, shown in Table 1, allows σ OS to mediate connection setup, so that it can ensure that communication only occurs within each tenant.

When a server proc wishes to create an endpoint for incoming network traffic from other procs it calls NewSigmaEP, which requests σ OS to create an σ EP and a Listener. The σ EP is an opaque shareable token identifying the new endpoint. The server proc calls Accept with the Listener to

```

lis, ep := SigmaOS.NewSigmaEP()
SigmaOS.Write("/s3/s3srv_3", ep.Marshal())
for true {
    conn := SigmaOS.Accept(lis)
    go HandleClientConn(conn)
}

```

Figure 3: Server code to create a σ EP and register it under a name that clients can connect to.

```

b := SigmaOS.Read("/s3/s3srv_3")
ep := UnmarshalSigmaEP(b)
conn := SigmaOS.Dial(ep)
SendMsgToServer(conn)

```

Figure 4: Client code to retrieve a σ EP given its name, and connect to the listening server.

wait for incoming connections. Any proc of the same tenant can use the σ EP to connect to the server by calling Dial. Dial returns an connection which can be used to exchange messages directly with the server proc.

An σ EP is useable by any proc in the same realm. σ EPs are assigned by σ OS, however, so server procs must use the facilities in §3.3 to publish σ EPs under well-known names.

3.3 Realms: per-tenant global name spaces

σ EPs provide procs a low-level mechanism to create servers and establish connections. However, procs need a naming system in order to exchange σ EPs, interact with each other, and share data. σ OS supports this interaction with a per-tenant name space called a *realm*. A proc uses the σ OS API to discover and access resources in a realm using pathnames (inspired by Plan 9 [60]). A proc in one realm cannot name or access σ OS resources in other realms.

The root of a realm's file system is hosted by a name server called named, implemented using etcd [25], a Raft-replicated [56] persistent key/value store. σ OS-provided services and procs extend the name space by hosting subtrees. As shown in Figure 3, a server which wishes to register a subtree creates a file in the name space containing its σ EP object. When a proc traverses the name space and reaches the σ EP link file, it will transparently connect to the hosting server using the σ EP API and continue its traversal by communicating directly with the host of the subtree.

In this way, the logically global realm name space enables transparent access to a distributed set of resources, including filesystem-like services, named RPC services, proxies to storage systems, and storage for small configuration files. The namespace acts as a rendezvous so that procs, which are not directly aware of where they or other procs are physically executing, can find each other when needed. Furthermore, since a given pathname has the same meaning to all of a realm's procs, procs can directly exchange pathnames.

An example is σ OS's s3 proxy service, which exposes a tenant's Amazon's S3 buckets and keys in the tenant's

name space. σ OS stores binaries for procs in the σ OS S3 bucket and reads/writes them using pathnames (e.g., `/s3/sigmaos/mr-mapper`).

To help applications spread load, a directory can list σ EP link files for multiple proxy servers: `/s3/` can contain `s3srv_0`, `s3srv_1`, etc. Then a pathname with `~local` asks σ OS to find a proxy on the same machine. Now, `mr` mappers can read input files (e.g., books from the S3 bucket `gutenberg`) using `/s3/~local/gutenberg/pg-being_ernest.txt` in parallel through local s3 proxies and avoid copying each input file twice over the network. The `~local` pathname component resolves a fundamental tension in the realm namespace between locality and location-obliviousness. `procs` which want to access local resources without having to know which machine they are physically running on can include `~local` in the pathnames they access.

As another example of the use of `~local`, σ OS exposes per-realm scratch space on individual machines' local file systems under the pathname `/ux/<machine-name>/`; a `proc` can read and write scratch files on both its own machine and other machines with such pathnames. A `proc` that wishes to share a file in its local scratch space (e.g., `/ux/~local/a.txt`) with other `procs` first resolves the pathname to an absolute realm-global pathname with the `AbsPath(pathname)` API call, which translates `/ux/~local/...` to a global `/ux/<machine-name>` name. This ability to transparently access remote storage helps some data-intensive applications such as MapReduce [45, 48, 61, 67]. Uniform access via pathnames makes it straightforward for developers to choose between local and remote (e.g., S3) storage.

3.4 procs and failures

Many virtual machine and container systems re-start instances after a failure, which requires time-consuming persisting of configuration information at creation time. σ OS does not restart `procs` in response to failure, and the σ OS scheduling layer does not persist `proc` descriptors, which helps decrease creation cost. If a σ OS scheduling component crashes while involved in spawning a `proc`, the spawn request may be lost. σ OS guarantees that if such a failure prevented a `proc` from being spawned, `WaitStart/WaitExit` will return an error; the requesting `proc` can then re-issue the `Spawn` if appropriate.

σ OS provides mechanisms to support fault-tolerant applications. A realm's `named` provides fault-tolerant storage, backed by `etcd`. `procs` can achieve fault-tolerance by storing critical state in `named`; if such a `proc` fails, another can be started (or already be waiting) to take over, and read the latest state from `named`. `named` uses `etcd`'s support for leader election to help fault-tolerant `procs` avoid split-brain (more than one `proc` thinking it is the active leader).

As an example, the `mr` library creates three coordinator

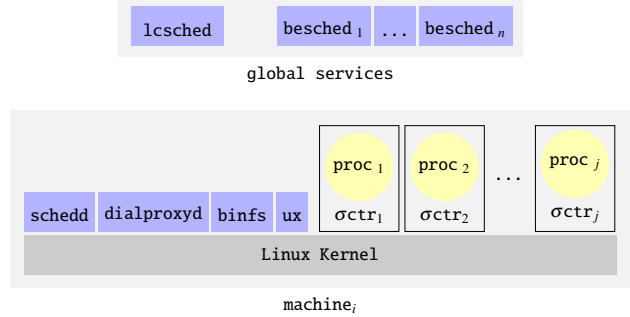


Figure 5: On each of a provider's machines, σ OS runs a `schedd` (for creating σ containers), `dialproxyd` (for mediating network connection setup), a `binfs` (for demand-paging `proc` binaries), and a `ux` (for exposing local storage). For distributed scheduling, each machine's `schedd` cooperates with one global `lcsched` for scheduling LC `procs` and several `bescheds` for scheduling BE `procs`. Not shown are provider `procs` that run in each realm (e.g., named, s3).

`procs`. One is elected as the leader, and the other two are standbys. The leader stores its progress (e.g., which mappers have completed) in the directory `/mr/coord/`. If the leader crashes, one of the standbys takes over and picks up from where the crashed coordinator left off.

To survive a system-wide failure (e.g., all machines crash), σ OS provides `initd`. An application can register a `proc` with `initd`; when σ OS reboots, it restarts registered `procs`. For example, the `mr` library registers the coordinator `proc` with `initd`. `initd` stores its state persistently in `named`.

4 Implementing the σ OS API

Implementing the σ OS API poses three challenges: how to both isolate `procs` strongly and start them quickly; how to communicate efficiently with σ EPs; and how to schedule BE and LC `procs`. σ OS addresses these challenges using the components shown in Figure 5. `lcsched` and `besched` are global schedulers which place `procs` on machines. Each machine runs a local scheduler agent (`schedd`), a network isolation agent (`dialproxyd`), a `proc` binary server (`binfs`), and a server providing temporary local storage (`ux`). This section describes how σ OS uses Linux primitives to implement these components.

4.1 Isolating `procs` with light-weight σ containers

Each `proc` must be isolated to prevent it from disturbing provider infrastructure, other realms' `procs`, and (except as allowed by the σ OS API) `procs` in the same realm. σ OS isolates each `proc` with a σ container: a dedicated computing environment with low initialization overhead. What allows σ containers to be light-weight is the fact that `procs` use only a small subset of the underlying operating system's facilities, relying instead on σ OS' cloud-centric API. This allows σ OS to avoid many expensive steps that traditional container systems must take to provide a full, private Linux environment. For example, σ OS does not set up a network namespace, which would take around a hundred milliseconds, nor does

it create an overlay file system, which would take around 5 milliseconds (plus the time to install files in the overlay file system). σ containers provide `procs` with isolation as good as traditional containers but with faster start times.

Creating `procs`. An executing `proc` consists of a Linux process within an isolating σ container started by `schedd` with the following steps:

- **Namespaces:** `schedd` gives the `proc` private Linux namespaces for UTS, IPC, and PIDs. Because a `proc` doesn't need its own IP address (it uses σ EPs and connections established via `dialproxyd`), the σ container doesn't include a network name space and overlay network. Further, because `procs` that need temporary local storage talk to the local `ux` server rather than making direct filesystem system calls, the σ container doesn't include an overlay file system.
- **Jail:** `schedd` jails the `proc`'s Linux process in a file system with just a few read-only configuration files and a few `/proc` pseudo-files. It mounts σ OS's `binfs` read-only on `/mnt/binfs`; `binfs` is a FUSE [7] server through which the Linux kernel demand-pages the `proc`'s binary.
- **Seccomp:** `schedd` uses a `seccomp` filter to allow only system calls that allocate memory, create and manage threads, handle a few signals, access randomness, and manage timers. These calls are needed by the Go and Rust runtimes. The filter forbids networking system calls such as `socket`, `connect`, `bind`, `accept`, and `listen`, since connection setup occurs via `dialproxyd`.
- **AppArmor:** `schedd` drops all Linux capabilities and further restricts file system access using an AppArmor profile. This profile denies many uses of signals, and forbids access to directories in `/proc` other than the `proc`'s own `/proc` directory.
- **cgroups:** `schedd` provides performance isolation by assigning the σ container to a `cgroup`. `schedd` pre-creates and manages a pool of `cgroups` to move `cgroup` creation off the `proc` start path. `schedd` uses one `cgroup` to isolate each realm's BE `procs`, and another for each realm's LC `procs`. §4.3 describes how σ OS configures `cgroups` to enforce resource reservations and utilize idle resources.

After this setup, the σ container calls `exec` with the path `/mnt/binfs/<binary-name>`. Linux demand-pages the binary via FUSE and `binfs`, allowing the `proc` to start quickly. The first time a `proc` binary runs in a σ OS cluster, `binfs` reads its pages from S3. `binfs` caches these pages on the local disk, to speed future invocations of the same binary. The former situation is “cold start”; the latter “warm start”. σ OS tracks where binaries have recently run so that `binfs` can take advantage of cached binaries on other machines in the σ OS cluster.

σ container isolation. σ OS restricts a `proc` to 67 system calls; the other 309 [47] are forbidden. For comparison, Docker's `seccomp` filter allows containers to use 352 system calls [23]; Kubernetes allows 340 [19]. Gvisor, which reimplements much of Linux in user space to reduce the number of host system calls a container requires, allows 55 system calls [76].

σ container startup time. An σ container is quicker to start than a traditional container because it doesn't unpack a container image, set up a network namespace (σ OS uses σ EPs), or create an overlay file system (`procs` cannot directly create files on the local host). Additionally, σ OS performs some expensive operations in advance of running any `proc` (e.g. creating a pool of `cgroups`). Finally, σ OS leverages Linux's demand paging via `binfs` to allow the `proc` to start without fetching the entire binary in advance.

4.2 σ OS endpoints

σ EPs allow σ OS to control the setup of network connections among `procs` without the expense of setting up a virtual IP namespace for each `proc`. `dialproxyd` mediates all connection setup, both server-side and client-side, and verifies that each leads to a `proc` in the same realm. Once `dialproxyd` establishes and verifies a connection, it passes it to the `proc` with UNIX-domain message passing, and the `proc` directly reads and writes bytes on the socket. A σ EP functions as a network address that `procs` can use without needing to know about host names, IP addresses, or port numbers.

Communication between `procs`. A typical scenario is that a `proc` offering a service creates a new σ EP by calling `NewSigmaEP`, writes that σ EP into a file in the named namespace, and waits for incoming connections with `Accept`. Clients find the relevant σ EP from `named` and call `Dial`.

Both `Accept` and `Dial` are IPCs to the local `dialproxyd`, which makes the required kernel TCP socket calls. Initially the new connection connects the two local `dialproxyds`, which interact to verify that the two `procs`' realms are the same, and then passes the connection file descriptors to the `procs` via UNIX-domain message passing. After that, the two `procs` can communicate directly over the TCP connection without further involvement by `dialproxyd`.

Outgoing communication with external services. `dialproxyd` allows `procs` to connect to entities outside of σ OS by creating and connecting to special *external* σ EPs.

A malicious `proc` may try to create an external σ EP that refers to a server `proc` in another realm. To prevent this, we expect the provider to deploy σ OS in a private network with a known range of IP addresses. `dialproxyd` inspects external σ EPs passed to it during connection setup to ensure that the IP addresses they contain lie outside its private range².

²An alternate design implemented in σ OS, which does not rely on IP address verification, has the client's and server's `dialproxyd` exchange a

Incoming communication from external services. `procs` may need to accept connections from entities outside of σ OS, such as HTTP clients. As is standard practice in Kubernetes and other container systems, we expect the client to configure a provider-managed IP endpoint and load-balancer to proxy connections to `procs`. The load-balancer would speak the `dialproxyd` identity verification protocol to ensure that external connections are delivered to the intended realm.

4.3 Scheduling `procs`

From the provider’s perspective, σ OS’s job is to decide the placement of spawned `procs` onto the provider’s machines, and, within each machine, to decide how to allocate CPU time and memory to running `procs`.

Placement. LC and BE `procs` have different placement requirements. LC `procs` must receive their guaranteed CPU and RAM, so σ OS must take care that the sum of LC reservations on each machine is less than capacity. BE `procs` should use unreserved CPU and RAM, as well as reserved LC CPU currently left idle, though BE `procs` cannot be allowed to use RAM reserved by LC `procs` even if currently idle. Realms that have BE work should get roughly equal shares of total unreserved provider CPU, though a real deployment would likely use a different policy (e.g., based on resource pricing).

σ OS places LC and BE `procs` with different mechanisms. When called for an LC `proc`, `Spawn` sends the descriptor to the provider’s `lcsched`, a single provider-wide service. `lcsched` tracks, for each of the provider’s machines, how much CPU power and RAM are currently reserved for existing LC `procs` on that machine. When a `Spawn` request arrives, `lcsched` chooses a machine with sufficient unreserved resources (if one exists) and forwards the request to the `schedd` on that machine; otherwise `lcsched` queues the `proc` request until a machine becomes available.

Because BE `procs` may be created at a high rate, σ OS shards the work of BE placement over a set of `besched` servers running on a subset of the provider’s machines. For a BE `proc`, `Spawn` sends the descriptor to a randomly selected `besched` server. That `besched` adds the descriptor to a private queue of `procs` waiting to run. Meanwhile, the `schedd` on each of the provider’s machines monitors the machine’s idle CPU time and idle RAM (less RAM reserved by LC `procs`), and if there are significant spare resources, sends a request to a randomly selected `besched`. That `besched` looks for a queued `proc` descriptor with a compatible memory request, giving each realm an equal chance. If the `besched` has nothing relevant queued, the machine’s `schedd` asks a different `besched`.

Enforcement. `schedd` uses Linux `cgroups` to reserve CPU and memory for LC `procs`, and a combination of the `cgroups` network classifier and Linux’s Traffic Control `tc`

cryptographically authenticated setup message to verify that connections internal to σ OS are initiated via `dialproxyd`.

	Component	LOC
Core	<code>proc/σcontainer</code>	3,889
	<code>lcsched procq schedd</code>	2,340
	<code>net/σEP</code>	1,244
	<code>file API</code>	5,694
	<code>realm: named realmd</code>	2,419
	<code>s3 ux db</code>	1,486
	<code>boot</code>	957
Libraries	<code>client</code>	4,059
	<code>server</code>	3,418
Applications	<code>hotel</code>	2,082
	<code>socialnet</code>	2,197
	<code>cache</code>	693
	<code>mr</code>	1,639
	<code>imgprocess</code>	447
	<code>kv</code>	1,931
Total		34,495

Table 2: Lines of Go code for σ OS’s components (excluding `etcd`, `etcd`’s Raft [26], and `protoc`-generated files for protocol buffers).

to prioritize LC `procs`’ network traffic. `schedd` configures `cgroups` so that BE `procs` receive equal fractions of CPU reservations left idle by LC `procs`.

4.4 σ OS prototype details

Most of σ OS is written in Go; Table 2 shows each component’s lines of code. To avoid the cost of `exec`-ing a Go binary, `schedd` uses a trampoline program when starting a new σ container, `exec-uproc`, written in Rust.

`proc` executables are statically-linked ELF files. Static linking results in larger binaries than dynamic linking, but allows the root file system to be generic, since it doesn’t have to provide `proc`-specific files such as application shared libraries.

σ OS supports interpreted languages like Python, which import modules at runtime dynamically, using the σ OS API. The developer provides a statically-linked version of the interpreter of their choice (e.g., CPython) as the `proc` binary, and σ OS provides a shim that intercepts the interpreter’s accesses to module files and loads them via the σ OS interface.

5 σ OS applications

Table 2 lists the lines of code for each application. `hotel` (the running microservice example) and `socialnet` are ports of the corresponding DeathStarBench applications originally written for Kubernetes. `cache` is a sharded in-memory cache, much like `memcached`, used in `hotel` and `socialnet`. `mr` is the running example of the MapReduce library. `imgprocess` is an image processing service that spawns an LC coordinator `proc` to manage resizing images; for each image, it spawns a

BE `proc` that stores its results in S3. The coordinator handles failures of `imgprocess` `procs`.

To demonstrate that σ OS is complete enough to build fault-tolerant microservices, we built `kv`; it implements a linearizable, sharded, fault-tolerant in-memory key-value service. `kv` has groups of three `procs`; each group replicates its shards using `etcd`'s Raft library [26]. `kv`'s balancer can add a new group in response to changes in load; it moves shards between groups by spawning a "mover" `proc` for each shard with keys that must be moved. The balancer uses a realm's named to store the configuration for each epoch so that client `procs` can look up which group they should contact for a given shard. Clients set a watch on this configuration file to be alerted of a new configuration. The balancer itself has two standby `procs`, which will elect one as the new balancer if the current balancer fails.

Porting applications to σ OS. σ OS does not provide out-of-the-box backwards compatibility for existing serverless or microservice applications. However, in our experience, porting an application to σ OS does not require major application rewriting; most σ OS ports involve switching some function calls in the existing codebase with analogous functions from the σ OS API. σ OS supports cloud APIs and access to databases like MongoDB well via proxies (e.g., `s3`, `db`) and σ EPs. Additionally, container- and serverless-structured applications are already broken up into execution units which map naturally onto `procs`.

σ OS and σ EP APIs (Table 1) provide replacements for most APIs that cloud applications use. σ OS applications Read/Write files in the realm instead of using the local file system or the S3 Get/Put API, spawn `procs` instead of forking Linux processes or Lambdas, and access the network using σ EP APIs like `NewSigmaEP` (analogous to `listen`) and `Dial`. The `NewSigmaEP` and `Dial` APIs are similar to those used to start servers and initiate network connections in Go and other high-level languages.

σ OS developers can port web server front-ends like Nginx to σ OS with σ EPs (§4.2). σ OS enables patterns similar to Kubernetes to in which web servers register public services with cloud provider load-balancers [35].

We ported `hotel` and `socialnet` from `DeathStarBench`, and most changes were "find-and-replace-all" operations. σ OS versions use the realm for service discovery instead of a service registry and call `NewSigmaEP` instead of `listen` to start a server and accept connections. σ OS's RPC library, implemented with σ EPs, replicates the core of `gRPC`.

Applications that use a wide range of Linux system calls (e.g., shared memory) are harder to port to σ OS. In our experience, most cloud applications don't do this. They rely on cloud APIs and are organized into containers and serverless functions.

Summary. There are two observations from the experience of implementing this set of applications. First, they can be

implemented using just the σ OS API. One reason is that the applications are cloud-centric and use few local OS services. Another is that σ OS allows a provider to export services that applications need through proxies (e.g., `ux`, `s3`, `db`, etc.), which can be accessed using the σ OS API. A final reason is that today's programming language like Go come with a large ecosystem of portable packages that allow application code to avoid much reliance on the local operating system.

The second observation is that σ OS can support both microservice and serverless-style applications in a single framework. Furthermore, some applications combine both LC and BE `procs`. For example, in `kv`, the caching `procs` are LC while the mover `procs`, which copy shards between groups, are BE.

6 Evaluation

The primary goal of σ OS is to provide a single API which seamlessly supports both serverless and microservice applications. To support short-running and burst-parallel serverless applications, σ OS must start `procs` with low latency and high scheduling throughput. To support microservices, σ OS must enable low-overhead communication between `procs` and allocate CPU to guarantee resource requests and achieve high utilization.

This section evaluates whether σ OS achieves this goal by answering the following questions:

1. Do σ containers allow fast `proc` start, and can σ OS schedule `procs` at high throughput? (§6.1)
2. Do σ EPs provide high-performance networking? (§6.2)
3. Do σ OS applications perform as well as their serverless and container-based counterparts? (§6.3)
4. Can the σ OS scheduler achieve good utilization with BE serverless tasks and LC microservice tasks, and provide fairness between tenants? (§6.4)

6.1 Fast `proc` start with σ containers

We measure the start latency of σ OS `procs` and compare it to several state-of-the-art platforms. For each platform, we time from the moment `spawn` is invoked until the first line of `main` executes. All but the AWS Lambda and Mitosis measurements use two AWS EC2 `m6i.4xlarge` VMs with 16 vCPUs backed by 2.9GHz Intel Ice Lake 8375C CPUs, 64 GiB of memory, up to 12.5Gbps network bandwidth, and up to 10 Gbps EBS burst bandwidth. The client invoking the function runs on one machine, and the platform runs on the other. We do not know what hardware AWS uses to run the Lambda functions. The Mitosis numbers are as reported in the Mitosis paper [75], which uses similar speed CPUs to the above configuration.

The `proc` being started is a simple BE Hello World program written in Rust to be able to measure σ container start times while excluding the 15 milliseconds that the Go runtime

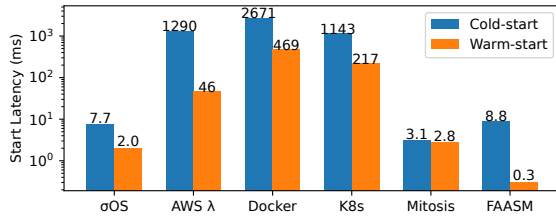


Figure 6: Start latency for a Hello World function on several platforms.

takes to start. Minimizing language runtime and application initialization time is an orthogonal problem, and existing techniques (like checkpoint-restore) are compatible with σ OS.

Start latencies. Figure 6 shows the results. First we consider cold- and warm-start times for AWS Lambda, Docker containers, and Kubernetes (K8s) pods. All three systems isolate execution units using containers, and AWS Lambda additionally isolates functions with a MicroVM. Cold-starts in these systems require downloading and unpacking the container image (and, in AWS Lambda, additionally involve starting a MicroVM), whereas warm-starts exclude these costs.

σ OS procs warm-start significantly faster than the other three systems’ containers, because the other three systems start full containers with overlay file systems [73]. σ OS’ σ containers (§4.1) avoid this cost because σ OS offers neither custom file system contents nor direct file system write access; instead, procs access remote or (via the ux server) local storage using the σ OS API. Additionally, σ OS’ dialproxyd (§4.2) design avoids expensive network isolation operations, and σ OS moves expensive cgroup creation off the critical path. σ OS’ cold-start latency benefits from binfs, which demand-pages proc binaries over the network.

Mitosis [75] is a platform that provides fast start of containers for serverless functions—its containers and scheduler are not suited to stateful, long-running microservices—using a new remote-fork primitive, implemented using RDMA and a modified Linux kernel [75]. Mitosis thus sets a high bar for how fast serverless functions can be started. To compare with Mitosis, we benchmark σ OS on an AWS EC2 instance with the same CPU clock rate as reported in the Mitosis paper³. Cold-starts in Mitosis involve remote-forking a running serverless function from a remote machine and creating a Mitosis “lean container” for the function. As expected, cold starts in σ OS are slower than Mitosis (7.7 ms vs. 3.1ms), because σ OS provides network isolation, σ OS’ proc binary demand-paging does not make use of specialized networking hardware (e.g., RDMA-capable NICs), and σ OS runs atop an unmodified Linux kernel, which adds latency as the paged proc binary data moves back and forth across the user-kernel boundary.

³We were unable to access the RDMA hardware and software setup required to run Mitosis and so report the Hello World benchmark numbers from the Mitosis paper.

		Time (ms)
Placement		0.42
σ container	Linux NS	0.28
	FS jail	0.42
	seccomp	0.46
	AppArmor	0.02
	exec	0.37
Total		1.97

Table 3: Breakdown of warm-start time for a Hello World BE proc written in Rust. Operations above the line are costs of proc placement, which includes time spent in the besched queue, whereas operations below the line are machine-local costs of σ container creation.

σ OS component	Max Throughput (procs/sec)
lcsched	50,144
besched shard	53,306
proc start (1 machine)	1,590
proc start (24 machines)	36,650

Table 4: Maximum throughput of some components of proc creation on Cloudlab c220g5 machines.

Faasm [65], a serverless platform for WASM programs, achieves low start time by relying on the WASM runtime for isolation and for restricting system calls. Faasm cold-starts include the cost of downloading the WASM program from a local Redis instance, whereas warm-starts exclude this cost. σ OS has slower warm-starts than Faaslets, because σ OS pays the cost for separate address spaces and other OS isolation techniques such as namespace isolation. σ OS has faster cold-starts than Faasm because binfs demand-pages proc binaries, whereas Faasm downloads the entire WASM program before executing the function. We took the Faasm measurements without network isolation enabled; with network isolation, the cost of starting Faasm functions would likely be much higher.

Breakdown of proc start latency. Table 3 breaks down BE procs’ warm-start latency, including the time required for Spawn to send the descriptor to besched, place the proc onto a schedd instance, create a σ container, and start the proc. The cost of a warm-start in σ OS is dominated by σ container setup time, which consumes nearly 80% of the total.

Cold-starts, which occur when a realm runs a given proc binary on a machine for the first time, include the additional time for binfs to page the proc binary’s first few pages over the network.

Spawn throughput. There are two main tasks that might limit the throughput at which σ OS can spawn new BE procs:

the sharded besched placement service (§4.3), and the time required to create the `proc` on the selected machine (§4.1). Both throughputs can be scaled up (by running more besched shard servers, and installing more machines, respectively). The following experiments examine quickly a single besched can process spawn requests, how quickly a single machine can create `procs`, and the end-to-end achievable `proc` start throughput on a cluster of 24 machines. Table 4 summarizes the results.

To find how many BE Spawns per second a single besched can handle, we run a σ OS cluster consisting of 24 CloudLab c220g5 machines, scheduled by a single besched. An open-loop client on a remote machine Spawns "dummy" BE `procs` at a fixed rate for 10 seconds. The BE `procs` never actually run, but they traverse the full BE `proc` scheduling path; they are spawned onto the besched, which places them onto a machine's `schedd`, which ignores them. The maximum client Spawn rate at which the single besched can keep up is 53,306 per second.

Once besched has placed a `proc` on a machine, that machine's `schedd` needs to create a σ container and start the `proc`. To evaluate the throughput limits of this task on a single machine, an open-loop client Spawns BE Rust Hello World `procs` at a set rate, regardless of how quickly σ OS responds. For this benchmark, a single besched, running on a dedicated machine, schedules the Hello World `procs` onto a single `schedd` running on a different machine.

`proc` start throughput saturates and queues begin to build up once the Spawn rate exceeds 1,590 `procs` per second. The bottleneck is Linux mount namespace creation which occurs every time a σ container is created and involves taking a global lock in Linux.

We evaluate the end-to-end sustainable `proc` start throughput on a cluster of 24 CloudLab c220g5 machines by running an open-loop client which Spawns BE Rust Hello World `procs` at a set rate, independently of how quickly σ OS starts them. A single besched places the `procs` across the cluster. σ OS is able to start up to 36,650 `procs` per second before the Spawn rate exceeds the start rate.

Even as the Spawn rate approaches the maximum start rate, σ OS' median and 90% scheduling latencies remain low. σ OS achieves 36,650 `proc` starts per second with p50 start latency of 5.8 ms and a 90% start latency of 11.6 ms. To put σ OS' `proc` start throughput in perspective, we compare to Mitosis, which can fork 10,000 containers across multiple machines in one second. Mitosis' container fork rate translates to 97 container starts per core per second, and σ OS' peak `proc` start rate translates to 76 `proc` starts per core second. σ OS achieves this performance without kernel changes or RDMA.

Summary: σ OS starts `procs` quickly and with high throughput. As a result σ OS is a good fit for applications structured as many short-running `procs`. Finer-grained `procs`

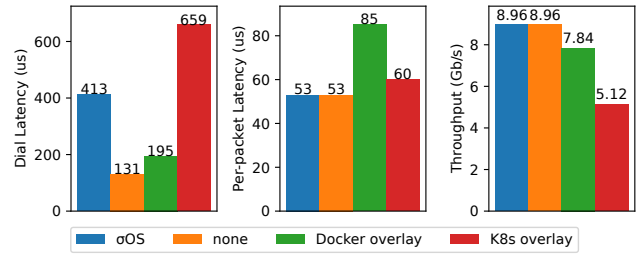


Figure 7: Different network isolation strategies' network latency and throughput between containers communicating across Cloudlab c220g5 machines. Measurements are taken from Go server and client programs which communicate via TCP. The implementations are identical across all isolation strategies, with the exception that the σ OS client and server communicate via the σ EP API.

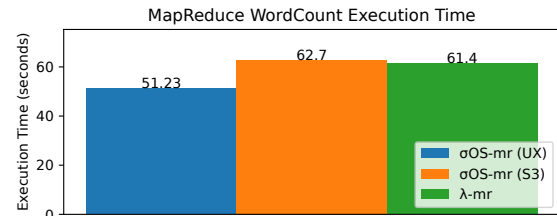


Figure 8: End-to-end execution time of MapReduce WordCount on σ OS and on λ -mr from a warm-start, with 10GB of input. Both σ OS-mr and λ -mr store input and output files in S3. σ OS (ux) stores intermediate output files in ux, σ OS's local file server.

give providers more frequent opportunities to rebalance resource allocations, and to smooth out short drops in resource utilization as realms' application load varies.

6.2 σ EP performance

To determine the performance of σ EPs, we benchmark network throughput and latency between two Cloudlab c220g5 nodes using different network isolation techniques. The measurements use a simple Go client and server that communicate with TCP; the σ OS version does this via the σ EP API. Dial latency is the time to establish a new TCP connection. Per-packet latency is half a TCP round trip. Throughput is the bit rate at which the client can write 1MB buffers to the server. All measurements are the average of 1000 trials.

Figure 7 compares σ OS' σ EP-isolated network performance to no network isolation, isolation using Docker overlays, and isolation using Kubernetes (K8s) overlays. The σ OS `dialproxyd`-mediated `Dial` protocol makes connecting more expensive than without network isolation. Once connected, σ EPs provide the same latency and throughput as no network isolation, since `dialproxyd` sends the TCP socket to the `proc`, which reads and writes directly. Docker and K8s, in contrast, forward all connection data through a local `proxy` process.

6.3 σ OS application performance

To evaluate application-level performance with σ OS, we compare σ OS-mr to Corral [18] (labeled λ -mr), a serverless

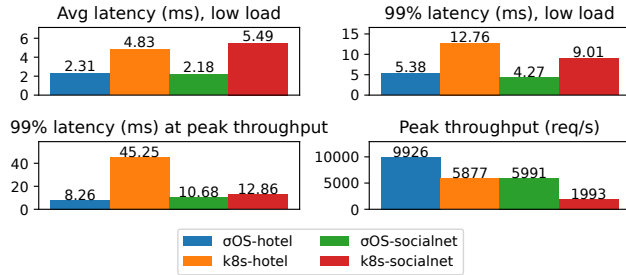


Figure 9: Latency and throughput of σ OS-hotel and K8s-hotel, and σ OS-socialnet and K8s-socialnet. The low-load 99% latency is measured at a request rate of 1000 Req/s. Peak throughput is the maximum request throughput with median request latency below 10ms.

MapReduce framework for AWS Lambda, σ OS-hotel to K8s-hotel, and σ OS-socialnet to K8s-socialnet.

σ OS-mr vs. λ -mr. We run σ OS-mr on an AWS Virtual Private Cloud (VPC) composed of 16 EC2 t3.xlarge VM instances. Each instance has 4 vCPUs, 16GiB of memory, and a 20GiB EBS volume. Each instance has up to 5Gbps network burst bandwidth, and 2,085Mbps EBS burst bandwidth. To make the comparison fair, we provision λ -mr’s lambdas with 1760MB of memory, which gives them the equivalent of 1 vCPU, and disable 2 vCPUs on each of σ OS’s 4-core VMs. Since λ -mr starts 32 lambdas in parallel for both the map and reduce phase, this gives λ -mr and σ OS-mr the same resources when σ OS-mr runs on 16 machines. Both σ OS-mr and λ -mr are written in Golang, and pay for the cost of the Go runtime (e.g., garbage collection). The input is 10GB from a snapshot of English HTML Wikipedia pages.

The input and final output files for both versions of MapReduce are stored in S3. For λ -mr, the intermediate files are also stored in S3. To evaluate the benefit of σ OS-mr’s transparent access to σ OS-exposed local storage, we run σ OS-mr in two configurations: σ OS (s3) and σ OS-mr (ux); the latter writes and then remotely reads intermediate files via ux, σ OS’ local file server.

Figure 8 shows the results. σ OS-mr performs comparably to λ -mr with intermediate files stored in S3, and 1.2 \times faster with intermediate files stored on local disk (really EBS) via ux. ux helps because it has higher throughput than S3. σ OS-mr can transparently take advantage of ux’s local scratch space exposed by just changing the application’s intermediate file pathnames.

σ OS-hotel vs. K8s-hotel and σ OS-socialnet vs. K8s-socialnet. We compare σ OS-hotel to K8s-hotel and σ OS-socialnet to K8s-socialnet on 8 Cloudlab c220g5 machines. Each machine has two Intel Xeon Silver 4114 10-core CPUs at 2.20 GHz, 192GB of memory, and a 10Gb Intel X520-DA2 NIC. To induce contention for resources and force σ OS and Kubernetes to place microservices on multiple hosts, all but 4 CPUs are disabled on each machine.

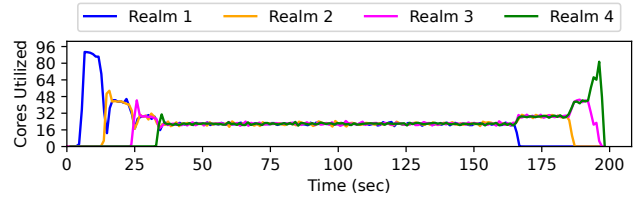


Figure 10: CPU utilization of 4 realms running BE `imgprocess` jobs starting at different times, on a 24 AWS t3.xlarge VM VPC scheduled by 2 besched shards. σ OS dynamically resizes each realm’s CPU allocation in response to load in order to give each realm an equal share of the cores. When one job’s load decreases, σ OS quickly reallocates its idle cores to the realms with remaining work.

Figure 9 shows the latency (average and 99%) and the peak throughput using the workload generator from Death-StarBench, running the search workload. Peak throughput is the maximum client request throughput for which median latency stays below 10ms. σ OS yields 42% lower 99% latency under low load for σ OS-hotel and 47% lower tail latency for σ OS-socialnet under low load. σ OS enables hotel and socialnet to achieve 1.68 \times and 3.01 \times higher peak throughput than Kubernetes.

The σ OS implementations of hotel and socialnet outperform the Kubernetes implementations because σ EP communication is more efficient than Kubernetes overlay networking, as shown in §6.2.

Summary: σ OS’s abstractions perform well and allow stateless- and microservices-style applications to achieve high performance.

6.4 Scheduling procs

σ OS’s scheduler goals include sharing resources fairly among realms with BE work and achieving high utilization by allowing BE procs to use resources reserved but left idle by LC procs (§4.3). This section evaluates whether σ OS meets its scheduling objectives through case studies in which σ OS multiplexes multiple realms’ BE workloads and realms with BE and LC workloads.

Fair sharing between realms with BE procs. We evaluate σ OS’ ability to divide resources equally between realms with BE work using `imgprocess`, a representative extract, transform, and load (ETL) application [50, 51]. `imgprocess` involves a short proc to process each 50KB input image. Of the 665ms average time for each `imgprocess` proc, 503ms are CPU-intensive work, and the remainder is I/O. `imgprocess` input and output images are stored in ux since ux provides high-throughput access to storage.

Figure 10 shows four realms, each running a job consisting of many `imgprocess` procs, and illustrates how σ OS shifts resources between them. The graph shows the CPU utilization of each realm as a function of time. There are 24 AWS t3.xlarge machines, each with four cores, and 2 besched shards which distribute BE procs among them. Realm 1’s

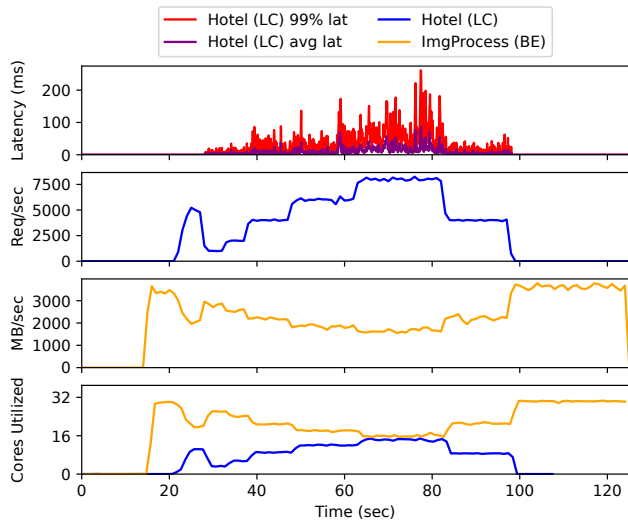


Figure 11: σ OS multiplexing two realms across a cluster of 8 Cloudlab c220g5 machines each with 4 cores available, under varying load. One realm runs σ OS-hotel, and the other runs *imgprocess*. As σ OS-hotel’s load increases, it regains its reserved CPU time from the BE *imgprocess* realm. When LC load drops, the BE realm is allowed to use the idle CPU time.

job starts at time zero, Realm 2 starts 10 seconds later, Realm 3 starts at 20 seconds, and Realm 4 starts at 30 seconds.

Each realm Spawns *imgprocess* procs at a fixed rate for 30 seconds, and then stops and waits for all its procs to complete. *imgprocess* procs are spawned with a 1.5GB memory request, and procs which cannot fit on any machine once spawned are queued at *besched*.

σ OS gives all 96 cores’ worth of CPU time to Realm 1. The graph shows that Realm 1 uses almost all of the CPU time, with the shortfall lost to I/O. As Realm 2 starts to enqueue procs, σ OS begins dequeuing procs from each realm in equal shares. The CPU utilizations of Realm 1 and Realm 2 quickly equalize because *imgprocess* procs are short-running, giving many resource rebalancing opportunities to the *besched* cluster-level scheduler. Together with the *cgroups* policies set up by *schedd*, this results in a rapid redistribution of cores between the realms as procs exit and release their memory requests.

Similarly, σ OS redistributes cluster CPU time when Realms 3 and 4 start, giving each an equal share. As each Realm’s work ends, σ OS gives more CPU time to the remaining realms.

Summary: σ OS automatically manages the allocation of compute resources to realms.

Guaranteeing LC reservations. Figure 11 shows a situation in which one realm runs a sequence of *imgprocess* procs while another runs the σ OS-hotel site. The σ OS-hotel procs are all LC, and the *imgprocess* procs are all BE. The x-axes show time; σ OS-hotel receives requests from time 20 until time 100, but receives a burst from times 60

to 80. The upper graph shows the latency with which the σ OS-hotel answers web requests; the second graph shows the σ OS-hotel request rate; the third shows *imgprocess* throughput; and the bottom graph shows how σ OS divides cores between the two realms.

When σ OS-hotel is under low load, *imgprocess* receives the majority of the cores in the cluster and can achieve high processing throughput. In fact, those cores are reserved for the σ OS-hotel procs (since they are LC), and merely borrowed for *imgprocess* when σ OS-hotel procs underutilize their reservations. When σ OS-hotel input load increases, σ OS’ *cgroups* configuration causes Linux to shift reserved CPU time back from *imgprocess* to σ OS-hotel. Although *cgroups* are able to preferentially give σ OS-hotel CPU time when it is under high load, the Linux *cgroup* API limits the degree to which one process can be prioritized over another. This causes σ OS-hotel to experience occasional latency spikes under periods of particularly high load.

Summary: σ OS’s resource management helps utilization: the σ OS-hotel application’s reserved resources are available when needed, without preventing other tasks from using those resources when the σ OS-hotel load is low.

7 Discussion and future work

The σ OS prototype lacks features that industrial orchestration systems have; for example, σ OS has limited support for authorization within a realm: AWS S3 tokens (e.g., to allow a proc to limit a child proc to specific S3 buckets) and the traditional ACLs that σ P inherits from \mathcal{P} . As another example, the prototype considers memory and CPU resources, but not other resources such as GPUs.

For some services, it will be too much work or infeasible to port them to the σ OS API, because, for example, their code base is large or they rely on specific system calls. Such services can be incorporated in σ OS through proxies such as *s3* and *db* or by running the service with its own container image and modifying the service to advertise itself using the σ OS libraries in a realm’s namespace.

8 Conclusion

This paper presented a multi-tenant cloud operating system, σ OS, that supports both microservices and serverless functions by combining the best features of container orchestration systems and serverless frameworks. σ OS provides developers with a cloud-centric API that allow developers to structure their applications using procs and that provides a shared namespace per realm, which hides machine boundaries and allows procs to easily communicate and coordinate. σ OS can efficiently multiplex the procs of different tenants on the provider’s hardware and responds automatically to shifts in load. Finally, by restricting procs to the σ OS interface,

σ OS can use σ containers to cold start procs rapidly (in 7.7 ms) with strong isolation.

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