Catalyzer: Sub-millisecond Startup for Serverless Computing with Initialization-less Booting

Dong Du[†‡], Tianyi Yu[†‡§], Yubin Xia[†‡], Binyu Zang[†‡], Guanglu Yan[§], Chenggang Qin[§], Qixuan Wu[§], Haibo Chen[†‡]

† Shanghai Key Laboratory of Scalable Computing and Systems, Shanghai Jiao Tong University
‡ Institute of Parallel and Distributed Systems, Shanghai Jiao Tong University
§ Ant Financial Services Group

Abstract

Serverless computing promises cost-efficiency and elasticity for high-productive software development. To achieve this, the serverless sandbox system must address two challenges: strong isolation between function instances, and low startup latency to ensure user experience. While strong isolation can be provided by virtualization-based sandboxes, the initialization of sandbox and application causes non-negligible startup overhead. Conventional sandbox systems fall short in low-latency startup due to their application-agnostic nature: they can only reduce the latency of sandbox initialization through hypervisor and guest kernel customization, which is inadequate and does not mitigate the majority of startup overhead.

This paper proposes Catalyzer, a serverless sandbox system design providing both strong isolation and extremely fast function startup. Instead of booting from scratch, Catalyzer *restores* a virtualization-based function instance from a well-formed checkpoint image and thereby skips the initialization on the critical path (init-less). Catalyzer boosts the restore performance by *on-demand recovering* both user-level memory state and system state. We also propose a new OS primitive, sfork (sandbox fork), to further reduce the startup latency by directly reusing the state of a running sandbox instance. Fundamentally, Catalyzer removes the initialization cost by reusing state, which enables general optimizations for diverse serverless functions. The evaluation shows that Catalyzer reduces startup latency by orders of magnitude, achieves <1ms latency in the best case, and significantly reduces the end-to-end latency for real-world workloads. Catalyzer has been adopted by Ant Financial, and we also present lessons learned from industrial development.

CCS Concepts • **Computer systems organization → Cloud computing**; • **Software and its engineering → Operating systems**.

Keywords serverless computing; startup latency; checkpoint and restore; operating system

ACM Reference Format:
Dong Du, Tianyi Yu, Yubin Xia, Binyu Zang, Guanglu Yan, Chenggang Qin, Qixuan Wu, Haibo Chen. 2020. Catalyzer: Sub-millisecond Startup for Serverless Computing with Initialization-less Booting. In *Proceedings of the Twenty-Fifth International Conference on Architectural Support for Programming Languages and Operating Systems (ASPLOS '20), March 16–20, 2020, Lausanne, Switzerland.* ACM, New York, NY, USA, 15 pages. https://doi.org/10.1145/3373376.3378512

1 Introduction

Serverless computing, the new trending paradigm in cloud computing, liberates developers from the distraction of managing servers and has already been supported by many platforms, including Amazon Lambda [2], IBM Cloud Function [1], Microsoft Azure Functions [3] and Google Cloud Functions [7]. In serverless computing, the unit of computation is a function. When a service request is received, the serverless platform allocates an ephemeral execution sandbox and instantiates a user-defined function to handle the request. This computing model shifts the responsibility of dynamically managing cloud resources to cloud providers, allowing the developers to focus purely on their application logic. Besides, cloud providers can manage their resources more efficiently.

The ephemeral execution sandboxes are typically containers [1], virtual machines [20, 44] or recently proposed lightweight virtualization designs [6, 8, 19, 35, 37, 41, 45]. However, container instances suffer from isolation issues since they share one kernel, which is error-prone. Virtual machines can achieve better isolation but are too heavy to run serverless functions. Lightweight virtualization designs like Google gVisor [8] and Amazon FireCracker [6] achieve high performance, easy resource management and strong isolation by customizing the host-guest interfaces, e.g., gVisor uses a process abstraction interface.

ASPLOS '20, March 16–20, 2020, Lausanne, Switzerland

ACM ISBN 978-1-4503-7102-5/20/03…$15.00
https://doi.org/10.1145/3373376.3378512

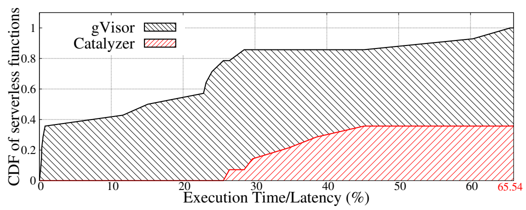


Figure 1. Distribution of Execution/Overall latency ratio in serverless computing. The ratio of all functions in gVisor can not even achieve 65.54%. The startup is cold boot.

Executing serverless functions with low latency is critical for user experience [21, 24, 28, 32, 38], and is still a significant challenge for virtualization-based sandbox design. To explain the severity, we conduct an end-to-end evaluation on three benchmarks, DeathStar [22], E-business microservices, and image processing functions, and divide the latency into "execution" part and "boot" part (§6.4). We calculate the "Execution/Overall" ratio of the tested 14 serverless functions, and present the CDF in Figure 1. The ratio of 12 functions (out of 14) in gVisor can not even achieve 30%, indicating that the startup dominates the overall latency. Long startup latency, especially for virtualization-based sandbox, has become a significant challenge for serverless platforms.

Existing VM-based sandboxes [6, 8, 37] reduce the startup latency through hypervisor customization, e.g., FireCracker can boot a virtual machine (microVM) and a minimized Linux kernel in 100ms. However, none of them can reduce the application initialization latency like JVM or Python interpreter setup time. Our studies on serverless functions (written by five programming languages) show that *most of the startup latency comes from application initialization* (**Insight I**).

This paper proposes Catalyzer, a general design to boost startup for serverless computing. The key idea of Catalyzer is to restore an instance from a well-formed checkpoint image and thereby skip the initialization on the critical path. The design is based on two additional insights: First, *a serverless function in execution stage typically accesses only a small fraction of memory and files used in the initialization stage* (**Insight II**), thus we can **on-demand recover** both application state (e.g., data in memory) and system state (e.g., file handles/descriptors). Second, *sandbox instances of the same function possess almost the same initialized state* (**Insight III**), thus it is possible to **reuse** most of the state of running sandboxes to spawn new ones. Specifically, Catalyzer adopts on-demand recovery of both user-level and system state. And it proposes a new OS primitive, sfork (sandbox fork), to further reduce the startup latency by directly reusing state of a running sandbox instance. Fundamentally, Catalyzer eliminates the initialization cost by reusing state, which enables general optimizations on diverse serverless functions.

We have implemented Catalyzer based on gVisor. We measure the performance with both micro-benchmarks and real-world applications developed in five programming languages. The result shows the Catalyzer can achieve <1ms startup latency on C-hello (best case), and <2ms to boot Java SPECjbb, 1000x speedup over baseline gVisor. We also present evaluations on server machines and share our lessons learned from industrial development at Ant Financial.

The main contributions of this paper are as follows:

- A detailed analysis of latency overhead on serverless computing (§2).
- A general design of Init-less booting that boosts startup of diverse serverless applications (§3 and §4).
- An implementation of Catalyzer on a state-of-the-art serverless sandbox system, Google gVisor (§5).
- An evaluation with micro-benchmarks and real-world serverless applications proving the efficiency and practicability of Catalyzer (§6).
- The experience of deploying Catalyzer on real platforms (§6.9).

2 Serverless Function Startup Breakdown

In this section, we evaluate and analyze the startup latency of serverless platforms with different system sandboxes (i.e., gVisor, FireCracker, Hyper Container, and Docker) and different language runtimes. Based on evaluation and analysis, we present our motivation that serverless functions should be executed with an initialization-less approach.

2.1 Background

Serverless Platform. In serverless computing, the developer sends a function to the serverless platform to execute. We use the term *handler function* to represent the target function, which could be written in different languages. The handler function is compiled offline together with a *wrapper*, which does initialization and invokes the handler function. Wrapped programs (consist of the wrapper and handler function) execute safely within sandboxes, which can be containers [5, 40] or virtual machines (VM) [6, 8, 10]. There is a *gateway program* running on each server as a daemon, which accepts "invoke function" requests, and starts a sandbox with two arguments: a configuration file and a rootfs containing both the wrapped program and runtime libraries. The arguments are based on OCI specification [12] and compatible with most of the existing serverless platforms.

gVisor Case Study. In this paper, we propose a general optimization to achieve sub-millisecond startup even for VM-based sandboxes like gVisor. In the following text, we will take gVisor as an example for analysis, implementation, and evaluation. For evaluation, we use server machines (§6.1) to reveal performance improvement in the industrial environment.

On a serverless platform, the first step of invoking a function is to prepare a sandbox. In the case of gVisor, the sandbox preparation includes four operations: configuration parsing, virtualization resource allocation (e.g., VCPUs and guest

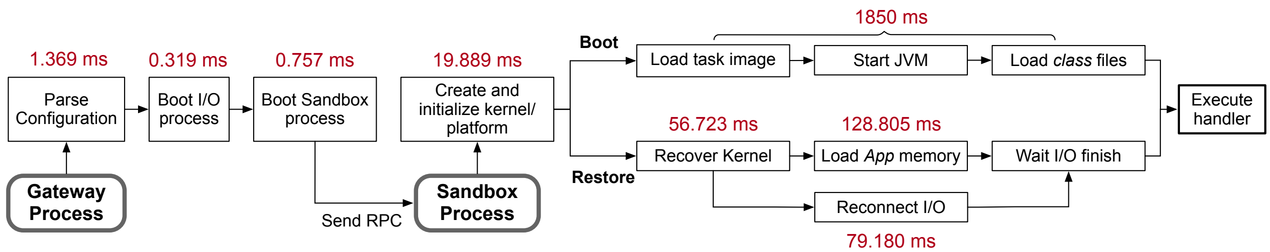


Figure 2. Boot process of gVisor. The numbers are the latency of each step of Java SPECjbb. The *Restore* path is the process of restoring a sandbox from a checkpoint image in gVisor (gVisor-restore).

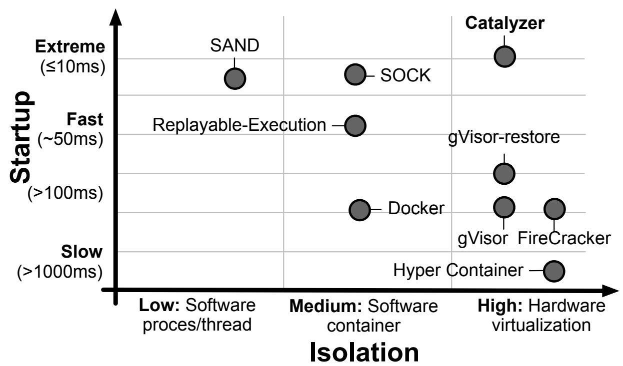


Figure 3. Serverless sandbox design. Catalyzer is the only system that achieves both high isolation and low startup latency.

memory regions), root file system mounting and guest kernel initialization (Figure 2). The guest kernel consists of two user processes: a *sandbox process* and an *I/O process*. The *sandbox process* sets up the virtualized resource, e.g., the extended page table (EPT)[1], and prepares the guest kernel. The *I/O process* mounts the root file system according to the configuration file. Figure 2 shows that sandbox initialization takes non-negligible time (22.3ms) in gVisor. Since sandbox initialization depends on function-specific configurations, it is hard to use techniques like caching [31, 40] to reduce sandbox initialization overhead. The critical path of startup refers to the period from when the "Gateway process" got a request until the handler executed. We use the term *offline* to represent the non-critical path operations (e.g., caching).

After sandbox initialization, the sandbox runs the wrapped program specified in the configuration file. Taking Java as an example, the wrapped program first starts a JVM to initialize Java runtime (e.g., loading class files), then executes the user-provided handler function. We define the application initialization latency as the period from when then wrapped program starts until the handler function is ready to run. As the following evaluation shows, the application initialization latency dominates the total startup latency.

[1]A hardware virtualization technique in Intel. The term is NPT (nested page table) in AMD, we use EPT to represent both in this paper.

2.2 A Quantitative Analysis on Startup Optimizations

The design space of serverless sandboxes is shown in Figure 3.

Cache-based Optimizations. Many systems adopt the idea of caching for serverless function startup [17, 39, 40]. For example, Zygote is a cache-based design for optimizing latency, which has been used in Android [14] to instantiate new Java applications. SOCK [40] leverages the Zygote idea for serverless computing. By creating a cache of pre-warmed Python interpreters, functions can be launched with an interpreter that has already loaded the necessary libraries, thus achieve high startup performance. SAND [17] allows instances of the same application function to share the sandbox which contains the function codes and its libraries. However, there are two reasons that caching is far from ideal. First, a single machine is capable of running thousands of serverless functions, so caching all the functions in memory will introduce high resource overhead. Caching policies are also hard to be determined in the real-world. Second, caching does not help with the tail latency, which is dominated by the "cold boot" in most cases.

Optimizations on Sandbox Initialization. Besides caching, sandbox systems also optimize their initialization through customization. For example, SOCK [40] proposes a *lean container*, which is a customized container design for serverless computing, to mitigate the overhead of sandbox initialization. Compared with container-based approaches, VM-based sandboxes [6, 8, 10] provide stronger isolation and also introduce more costs to sandbox initialization. Researchers have proposed numerous lightweight virtualization techniques [6, 19, 26, 36, 37] to solve performance and resource utilization issues [18, 23, 25, 29] in traditional heavy-weight virtualization systems. These proposals have already stimulated significant interest in serverless computing industry (e.g., Google's gVisor [8] and Amazon's FireCracker [6]).

Further, the lightweight virtualization techniques adopt various ways to optimize startup latency: by customizing guest kernels [26, 36], customizing hypervisors [19, 37] or a combination of the two [6, 8]. For instance, FireCracker [6] can boot a virtual machine (microVM) and a minimized Linux

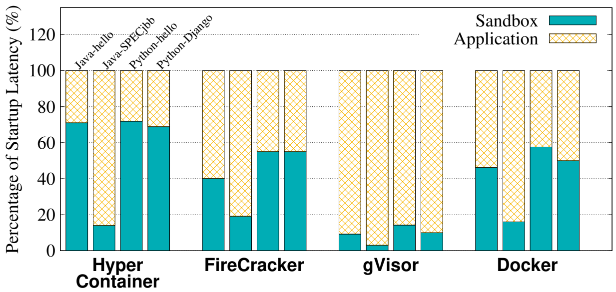


Figure 4. Startup latency distribution. Application initialization costs dominate in complex applications like Java SPECjbb, while sandbox initialization costs are significant for lightweight applications like Python Hello.

kernel in 100ms. Although different in design and implementation, today's virtualization-based sandboxes have one common limitation: they can not mitigate the application initialization latency like JVM or Python interpreter.

To understand the latency overhead (including sandbox and application initialization), we evaluate the startup latency of four widely used sandboxes (i.e., gVisor, FireCracker, Hyper Container, and Docker) with different workloads, and present the latency distribution in Figure 4. The evaluation uses the sandbox runtime directly and does not count the cost of container management. The settings are the same as described in §6.1.

We highlight several interesting findings from the evaluation. First, much of the latency overhead comes from application initialization. Second, compared with C language (142ms startup latency in gVisor), the startup latency is much higher for high-level languages like Java and Python. The main reason is that high-level languages usually need to initialize a language runtime (e.g., JVM) before loading application codes. Third, sandbox initialization is stable for different workloads and dominates the latency overhead for simple functions like Python Hello.

The evaluation shows that much of the startup latency comes from application initialization instead of sandbox. However, none of the existing virtualization-based sandboxes can reduce the application initialization latency caused by JVM or Python interpreter.

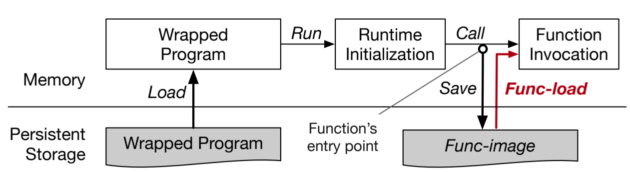


Figure 5. Init-less booting.

Checkpoint/Restore-based Optimizations. Checkpoint/restore (C/R) is a technique to save state of a running sandbox into a checkpoint image. The saved state includes both application state (in the sandbox) and sandbox state (e.g., the

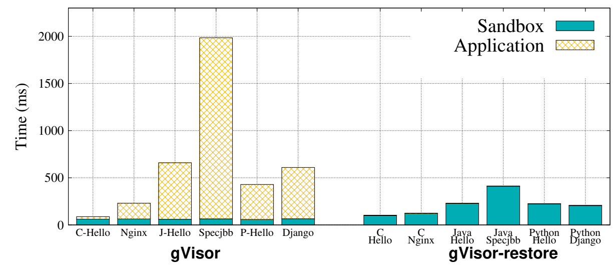


Figure 6. Startup latency of gVisor and gVisor-restore. gVisor-restore adopts C/R to eliminate the application initialization cost, but still has high startup (restore) latency.

hypervisor). Then, the sandbox can be restored from the image and run seamlessly. Replayable Execution [43] leverages C/R techniques to mitigate the application initialization cost, but only apply to container-based systems. Compared with other C/R systems, Replayable optimizes memory loading using an on-demand approach for boosting startup latency. However, our evaluation shows virtualization-based sandboxes incur high overhead to recover system state during the restore, which is omitted by the prior art.

The major benefit of C/R is that it can transform the application initialization costs into the sandbox restore costs (init-less). We generalize the idea as **Init-less booting**, shown in Figure 5. First, a *func-image* (short for function image) is generated offline, which saves initialized state of a serverless function (*Offline initialization*). The func-image could be saved to both local or remote storage, and a serverless platform needs to fetch a func-image first. After that, the platform can re-use the state saved in the func-image to boost the function startup (*func-load*).

Challenges. C/R (checkpoint/restore) techniques re-use serialized state (mostly application state) of a process to diminish application initialization cost, but rely on *re-do operations* to recover system state (i.e., in-kernel state like the opened files). A re-do operation recovers the state of a checkpointed instance and is necessary for correctness and compatibility. For example, a C/R system will re-do "open()" operations to re-open files that are opened in a checkpointed process. However, re-do operations introduce performance overhead, especially for virtualization-based sandboxes.

To analyze the performance effect, we implement a C/R-based init-less booting system on gVisor, called gVisor-restore, using gVisor-provided checkpoint and restore [4] mechanism. We add a new syscall in gVisor to trap at the entry point of serverless functions. We use the term, *func-entry point*, to indicate the entry point of a serverless function, which is either specified by developers or at the default location: the point right before the wrapped program invoking the handler function. The syscall is invoked by the func-entry point annotation and will block until checkpoint operation begins.

We evaluate the startup latency of gVisor-restore using different applications, and compare with unmodified gVisor. We use the sandbox runtime directly (i.e., *runsc* for gVisor) to exclude container management cost. As the result (Figure 6) shows, gVisor-restore successfully eliminates the application initialization overhead and achieves 2x–5x speedup over gVisor. However, the startup latency is still high (400ms for a Java SPECjbb application and >100ms in other cases). Figure 2 suggests that gVisor-restore spends 135.9ms on guest kernel recovery, which can be classified into "Recover Kernel" and "Reconnect I/O" in the figure. The "Recover Kernel" means recovering non-I/O system state, e.g., thread information, while I/O reconnection is for recovering I/O system state, e.g., re-*open* a "suppose opened" file. For reusable state ("App memory" in the figure), gVisor C/R mechanism compresses the saved data to reduce the storage overhead, and needs to decompress, deserialize, and load the data into memory on the restore critical path, costing 128.8ms for a SPECjbb application. During the restore process in SPECjbb case, gVisor recovers more than 37,838 objects (e.g., threads/tasks, mounts, sessionLists, timers, and etc.) in guest kernel and loads 200MB memory data.

Prior container-based C/R systems [43] have exploited on-demand paging to boost application state recovery, but still recover all the system state in the critical path.

2.3 Overview

Our evaluation and analysis motivate us to propose Catalyzer, an init-less booting design for virtualization-based sandboxes, which is equipped with novel techniques to overcome the high latency on the restore process.

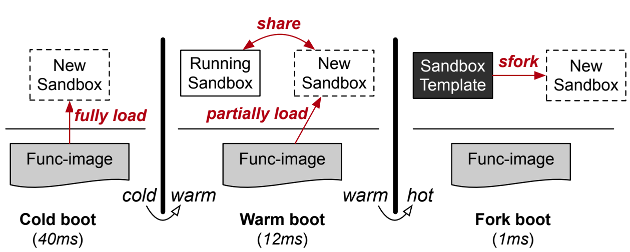


Figure 7. Overview of Catalyzer. Catalyzer combines C/R and *sandbox fork* to boost both cold boot and hot boot.

As shown in Figure 7, Catalyzer defines three kinds of booting: *cold boot*, *warm boot*, and *fork boot*. Precisely, cold boot means that the platform must create a sandbox instance from func-image through *restore*. Warm boot means there are running instances for the requested function; thus, Catalyzer can boost the restore by sharing in-memory state of running instances. Fork boot in Catalyzer needs a dedicated *sandbox template*, a sandbox contains the initialized state, to skip the initialization. Fork boot is a hot-boot mechanism [11, 40]—a platform that knows a function may be invoked soon and prepares the running environment for the function. The significant contribution is that fork boot is scalable to boot any number of instances from a single template, while prior hot boot can only serve limited instances (depending on the cache size).

Catalyzer adopts a hybrid approach combining C/R-based init-less booting and a new OS primitive to implement the *cold, warm, and fork boot*. Since a serverless function in the execution stage typically accesses only a small fraction of both memory and files used in the initialization stage, Catalyzer introduces *on-demand restore* for *cold and warm boot* to optimize the recovery of both application and system state (§3). In addition, Catalyzer proposes a new OS primitive, sfork (sandbox fork), to reduce the startup latency in *fork boot* by directly reusing the state of a template sandbox (§4). Fork boot can achieve faster startup than the warm boot, but also introduces more memory overhead; thus, fork boot is more suitable for frequently invoked (hot) functions.

3 On-demand Restore

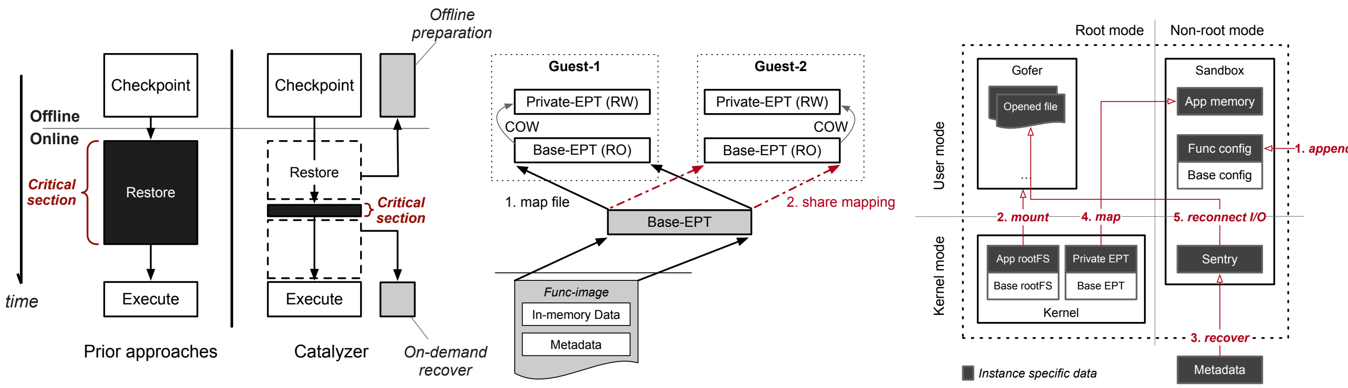
The performance overhead of restore comes from two parts. First, the application and system state need to be uncompressed, deserialized (only metadata) and loaded into memory. Second, *re-do operations* are necessary to recover system state, including multi-threaded contexts, virtualization sandbox and I/O connections.

As shown in Figure 8-a, Catalyzer accelerates restore by splitting the process into three parts: offline preparation, critical path restore, and on-demand recovery. The preparation work, like uncompression and deserialization, is mostly performed offline in the checkpoint stage. The loading of application state and recovering of I/O-related system state are delayed with on-demand paging and I/O re-connection. Thus, Catalyzer only performs minimized work on the critical path, i.e., recovering non-I/O system state.

Specifically, Catalyzer proposes four techniques. First, *overlay memory* is a new memory abstraction that allows Catalyzer to directly map a func-image into memory, boosting application state loading (for *cold boot*). Sandboxes running the same function can *share* a "base memory mapping", further omitting file mapping cost (for *warm boot*). Second, *separated state recovery* decouples deserialization from system state recovery on the critical path. Third, *on-demand I/O reconnection* delays I/O state recovery. Last, *virtualization sandbox Zygote* provides generalized virtualization sandboxes that are function-independent and can be used to reduce sandbox construction overhead.

3.1 Overlay Memory

The overlay memory is a design for on-demand application state loading through copy-on-write of file-based mmap. As shown in Figure 8-b, the design allows a "base memory mapping" to be shared among sandboxes running the same



(a) Comparison. **(b) Overlay memory.** **(c) Operational flow.**

Figure 8. On-demand restore. (a) Compared with prior approaches, Catalyzer leverages offline preparation and on-demand recovery to eliminate most of the work on the critical path. (b) Overlay memory allows a func-image to be directly mapped into memory to construct the *Base-EPT*, and the *Base-EPT* can also be shared among different instances through copy-on-write. (c) The operational flow shows how a gVisor sandbox is instantiated using on-demand restore.

function, and relies on memory copy-on-write to ensure privacy.

Overlay memory uses a well-formed func-image for direct mapping, which contains uncompressed and page-aligned application state. During a *cold boot*, Catalyzer loads application state by directly mapping the func-image into memory (*map-file* operation). Catalyzer maintains two layered EPTs for each sandbox. The upper one is called *Private-EPT*, and the lower one is *Base-EPT*. *Private-EPT* is private to each sandbox, while *Base-EPT* is shared and read-only. During a *warm boot*, Catalyzer directly maps the *Base-EPT* for the new sandbox with the *share-mapping* operation. The main benefit comes from the avoidance of costly file loading.

The platform constructs the hardware EPT by merging entries from the *Private-EPT* with the *Base-EPT*, i.e., using the entries of *Private-EPT* if the entries are valid, otherwise using the entries of *Base-EPT*. The construction is efficient and triggerd by hardware. *Base-EPT* is read-only thus can be inherited by new sandboxes through mmap, while the *Private-EPT* is established using copy-on-write when an EPT violation happens on the *Base-EPT*.

3.2 Separated State Recovery

C/R relies on metadata of system state (represented by objects in the sandbox) for *re-do operation*, which is serialized before saving into checkpoint images and deserialized during the restore. The system state includes all guest OS internal state, e.g., the thread list and timers. However, such process is non-trivial for sandboxes implemented by high-level languages (e.g., Golang for gVisor), as the language abstraction hides the arrangement of state data. Even with the help of serialization tools such as Protobuf [16], metadata objects have to be processed *one-by-one* to recover, which can cause huge overhead when the number of objects is large (e.g., 37,838 objects are recovered for SPECjbb application in gVisor-restore, consuming >50ms).

Catalyzer proposes *separated state recovery* to overcome the challenge, by decoupling deserialization from state recovery. During offline preparation, Catalyzer saves partially deserialized metadata objects into func-images. Specifically, Catalyzer first re-organizes the discrete in-memory objects into continuous memory; thus they can be mapped back to memory through mmap operation instead of *one-by-one* deserialization. Then, Catalyzer zeros pointers in objects with placeholders, and records all (pointer) reference relationships in a *relation table*, which stores a map from offsets of pointers to offsets of pointer values. The metadata objects and the *relation table* together constitute the partially deserialized objects. The *partially* means that Catalyzer needs to deserialize pointers during runtime using the relation table.

With the func-image, Catalyzer accomplishes state recovery in two stages: loading the partially deserialized objects from a func-image (**stage-1**), reconstructing the object relationships (e.g., pointer relation) and recovering system state in parallel (**stage-2**). First, objects as well as the saved *relation table* will be mapped to the sandbox's memory with overlay memory. Second, the object reference relationships are re-established by replacing all placeholders with real pointers through the *relation table*, and non-I/O system state are established on the critical path. Since each update is independent, this stage can be carried out in parallel. The design does not depend on a specific memory layout, which is better for portability so that a func-image can run on different machines.

3.3 On-demand I/O Reconnection

The numerous I/O operations performed in restore (e.g., opening files) add high latency on the critical path. Inspired by our insight that many of the I/O-related state (e.g., files) will not be used after restore, Catalyzer adopts an on-demand I/O reconnection design. For example, a previously opened file "/home/user/hello.txt" may only be accessed for specific requests. Those unused I/O connections can not be eliminated even with a proper point in the checkpoint, because existing serverless functions are usually running with language runtime (e.g., JVM) and third-party libraries, in which the developers have no idea whether they will access some rarely used connections.

Thus, we can re-establish the connections *lazily*—only re-establish when the connections are used. To achieve this, I/O reconnection is performed asynchronously on the restore critical path, and the sandbox guest kernel maintains the I/O connection status, i.e., a file descriptor will be passed to functions but tagged as *not re-opened* yet in the guest kernel.

We observe that for a specific function, the I/O connections that are immediately used after booting are mostly deterministic. Thus, we introduce an *I/O cache* mechanism to further mitigate the latency of I/O reconnection. The I/O connection operations performed during *cold boot* are saved in cache, which are used by Catalyzer to guide a sandbox (in *warm boot*) to establish these connections on the critical path. Specifically, the cache stores the file paths and the operations on the path, so Catalyzer can use the information as a hint to re-connect these I/O first. For I/O connections missed in the cache (i.e., the non-deterministic connections), Catalyzer will use the on-demand strategy to establish the needed I/O connections.

3.4 Virtualization Sandbox Zygote

On the restore critical path, a sandbox is constructed before application state loading and system state recovery. Challenges of reducing sandbox construction latency lie in two factors: first, sandbox construction depends on function-specific information (e.g., the path of *rootfs*), thus techniques like caching do not help; second, a sandbox is tightly coupled with system resources that are not directly re-usable (e.g., namespace and hardware virtualization resources).

Catalyzer proposes a *Virtualization Sandbox Zygote* design that separates the function-dependent configuration from a general sandbox (Sandbox Zygote) and leverages a cache of Zygotes to mitigate sandbox construction overhead. A Zygote is a generalized virtualization sandbox used to generate a function-specific sandbox during the restore. As described in Figure 2, a sandbox is constructed with a *configuration file* and a *rootfs*. Catalyzer proposes a *base configuration* and a *base rootfs*, which separate out function-specific details. Catalyzer caches a Zygote by parsing the *base configuration* file, allocating virtualization resources (e.g., VCPU) and mounting the *base rootfs*. Upon function invocation, Catalyzer specializes a sandbox from a Zygote by importing function-specific binaries/libraries, and appending the function-specific configuration in the Zygote. Virtualization Zygotes can be used in both *cold boot* and *warm boot* in Catalyzer.

3.5 Putting All Together

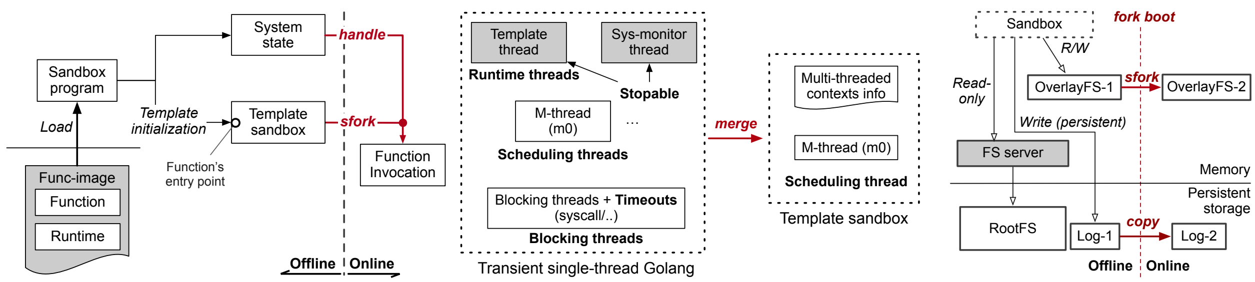
The three elements, overlay memory, separated state, and I/O connections, are all included in the func-image. The workflow of *cold boot* and *warm boot* is shown in Figure 8-c. First, function-specific configuration and its func-image (in "App rootFS") is passed to a Zygote to specialize a sandbox. Second, the function-specific rootfs indicated by the configuration is mounted for the sandbox. Then, the sandbox recovers system state using separated state recovery. After that, Catalyzer maps the *Base-EPT*'s memory to the gVisor process as read-only for *warm boot*, in which copy-on-write is used to preserve the privacy of the sandbox's memory. For *cold boot*, Catalyzer needs to establish the *Base-EPT* first by mapping the func-image into memory. At last, the guest kernel asynchronously recovers I/O connections, and I/O cache assists the process for *warm boot*.

4 sfork: Sandbox fork

Based on our Insight III, Catalyzer proposes a new OS primitive, sfork (sandbox fork), to further reduce the startup latency by reusing the state of a running "template sandbox" directly. The term, "template sandbox", means a special sandbox for a specific function that has no information about user requests; thus, it can be leveraged to instantiate sandboxes to serve requests. The basic workflow is shown in Figure 9-a. First, a template sandbox is generated through *template initialization*, containing clean system state at the *func-entry point*; then, when a request of the function arrives, the template sandbox will sfork itself to reuse the initialized state directly. The state here includes both user state (application and runtime) and guest kernel state.

Challenges. An intuitive choice is to use the traditional fork to implement sfork. However, it is challenging to keep system state consistent by using fork only. First, most OS kernels (e.g., Linux) can only support single-thread fork, which means the information of multi-threading will be lost after forking. Second, fork is not suitable for sandbox creation, during which a child process will inherit its parent's shared memory mappings, file descriptors and other system state that are not supposed to be shared between sandboxes. Third, fork will clone all the user state in memory, some of which may depend on system state that have been changed. For example, given a common case where the template sandbox issues getpid syscall and uses the return value to name a variable during initialization, the PID is changed in the forked sandbox, but the variable is not, leading to undefined behavior.

The clone syscall provides more flexibility with many options, but is still not sufficient. One major limitation is the



(a) Overview of *sandbox fork*. **(b) Transient single-thread for Golang.** **(c) Stateless overlayFS.**

Figure 9. Catalyzer with *sandbox fork*. (a) Catalyzer can sfork a new instance from a template sandbox generated offline. (b) The transient single-thread mechanism can support multi-threading fork by temporarily merge a multi-threaded program into a single thread. (c) Stateless overlay rootfs achieves efficient handling for file descriptors and files.

handling of shared memory (mapped with MAP_SHARED flag). If a child sandbox inherits the shared memory, it will violate the isolation between parent and child sandboxes; if not, it may change the semantics of MAP_SHARED.

Template Initialization. To overcome the challenges, Catalyzer relies on user-space handling of most inconsistent state and only introduces minimal kernel modifications. We classify syscalls into three groups, *denied*, *handled* and *allowed*. The allowed and handled syscalls are listed in Table 1. The handled syscalls require user-space logic to fix related system state after sfork for consistency explicitly. For example, clone creates a new thread context for a sandbox, and the multi-threaded contexts should be recovered after sfork (Challenge-1). The denied syscalls are removed from the sandbox since they may lead to non-deterministic system state modification. We illustrate how Catalyzer keeps the multi-threaded contexts and reuses inherited file descriptors (Challenge-2) after sfork with two novel techniques, *transient single-thread* and *stateless overlay rootFS*. The only modification to the kernel is adding a new flag, CoW flag, for shared memory mapping. We take advantage of Linux container technologies (USER and PID namespaces) to maintain system state like *user id* and *process id* consistent after sfork (Challenge-3).

4.1 Multi-threading Fork

Sandboxes implemented using Golang (e.g., gVisor) are naturally multi-threaded, because the Golang runtime uses multiple threads for garbage collection and other background works. Specifically, threads in Golang can be classified into three categories: runtime threads, scheduling threads, and blocking threads (Figure 9-b). The runtime threads are responsible for providing runtime functionalities like garbage collection and preemption. They are long-running and transparent to the developers. The scheduling threads (M-threads in Figure 9-b) implement the co-routine mechanism in Golang (i.e., Go routine). When a Go routine switches to the blocked state (e.g., executing blocking system calls like accept), Golang runtime will dedicate an OS thread to the Go routine.

Catalyzer proposes a *transient single-thread* mechanism to support multi-threaded sandbox fork. With the mechanism, a multi-threaded program can *temporarily* merge all the threads into a single thread (i.e., the transient single-thread), which can be *expanded* to a multi-threaded one after sfork. The process is shown in Figure 9-b. First, we modify the Golang runtime in Catalyzer to support stoppable runtime threads. When the runtime threads are notified to enter the transient single-thread state, they will save the thread contexts in the memory and terminate themselves. Then, the number of scheduling threads can be configured to one through Golang runtime. In addition, we add a time-out in all blocking threads, and the threads will check whether they should terminate for entering the transient single-thread state when the time-out is triggered. Finally, the Golang program will only keep the *m0* thread in the transient single-thread state, and expand to multiple threads again after sfork. Our modification is only used for template sandbox generation, and will not affect program behaviors after sfork.

4.2 Stateless Overlay RootFS

A sforked sandbox will inherit file descriptors and file systems of the template sandbox, which should be handled after sfork. Inspired by existing overlayFS design [13] and the ephemeral nature of serverless functions [27, 28], Catalyzer employs *stateless overlay rootFS* technique to achieve zero-cost handling for file descriptors and the rootFS. The idea is to put all the modification on the rootFS into the memory, which can be automatically cloned during sfork using copy-on-write (Figure 9-c).

Specifically, each sandbox uses two layers of file systems. The upper layer is the in-memory *overlayFS*, which is private to a sandbox and allows both read and write operations. The *overlayFS* is backed by an FS server (per-function) which manages the real rootFS. A sandbox cannot directly access the persistent storage for security reasons; thus, it relies on the (read-only) file descriptors received from the FS server to access the rootFS. During sfork, besides the cloned overlayFS, the file descriptors owned by the template sandbox are still

Categories	Handlers	Syscalls (in gVisor)
Proc	Transient single-thread, Namespace	**capget**, **clone**, **getpid**, **gettid**, arch_prctl, prctl, rt_sigaction, rt_sigprocmask, rt_sigreturn, seccomp, sigaltstack, sched_getaffinity
VFS (FS/Net)	Read-only FD	**poll**, **ioctl**, **memfd_create**, **ftruncate**, **mount, pivot_root, umount**, **epoll_create1, epoll_ctl, epoll_pwait, eventfd2, fcntl**, chdir, close, dup, dup2, lseek, openat
File (Storage)	Stateless overlayFS	**newfstat, newfstatat, mkdirat, write**, read, readlinkat, pread64
Network	Reconnect	**sendmsg**, **shutdown**, **recvmsg**, **getsockopt**, **listen**, **accept**
Mem	Handled by sfork	mmap, munmap
Misc	Namespace	**setgid, setuid, get(e)gid, get(e)uid**, getrandom, nanosleep, futex, getgroups, clock_gettime, getrlimit, setsid

Table 1. Syscall classification used in Catalyzer for sfork. Non-bold font means *allowed* but not *handled* syscalls, while bold font is for *handled* syscalls. The allowed syscalls can run as normal syscalls. Handlers are only used for handled syscalls.

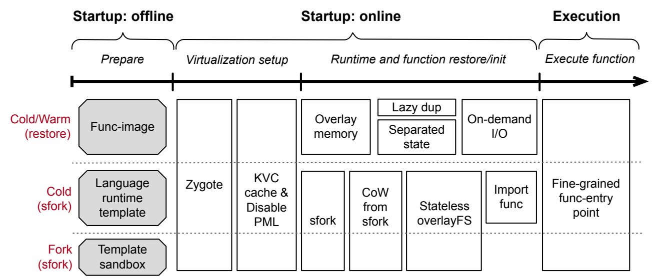


Figure 10. Techniques/Optimizations used in Catalyzer for different kinds of boot. Besides techniques introduced in §3 and §4, Catalyzer has other optimizations like the fine-grained func-entry point to further reduce startup latency.

valid in the child sandbox since they are read-only and will not violate the isolation guarantee.

Our industrial development lessons show that persistent storage is still required for serverless functions in some cases, e.g., writing logs. Catalyzer allows the FS server to grant some file descriptors of the log files (with the read/write permission) to sandboxes. Overall, the majority of files are sforked with low latency, and only a small number of persistent files are copied for functionalities.

4.3 Language Runtime Template for Cold Boot

Although the on-demand restore can provide promising cold boot performance, it relies on a well-formed func-image containing uncompressed data (larger image size). Thus, we propose another choice for the cold boot, using sfork with *language runtime template*, which is a template sandbox for functions written by the same language. A language runtime template initializes the environment of the wrapped program (e.g., JVM in Java), and will load a real function to serve requests on demand. Such a sandbox should be instantiated differently in different languages, e.g., loading libraries in C or loading Class files in Java. For instance, a single *Java runtime template* is sufficient to boost our internal functions as most of the functions are written in Java.

5 Implementation

Catalyzer is implemented based on gVisor, with 2017 LoC modification in gVisor and 732 LoC modification in Golang runtime for sfork, and 5000 lines of Golang modification to support the Init-less booting and optimizations. In addition, we extend our platform with a kernel module (about 300 lines of C) and a user-level manager program (500 lines of Golang).

Besides the techniques proposed in the design, Catalyzer leverages other optimizations to further reduce startup latency, e.g., the fine-grained func-entry point (§6.7). We present an overall view on how these techniques and optimizations are used in Catalyzer for different boots, as shown in Figure 10. The details will be explained in §6.7.

Func-image Compilation. The offline *func-image* compilation is performed by the following steps: 1) The *func-entry point* provided by the user is inserted into the wrapper program as an annotation; 2) The *func-entry point* annotation is transferred to a system call invocation (*Gen-Func-Image* in Catalyzer) in the wrapper program. For example, in C, the annotation is replaced by a call to “syscall()” of libC; in Java, the wrapper program uses JNI codes to invoke the syscall. Any invocation of the syscall is taken as “the program reaches the *func-entry point*”, and triggers Catalyzer to save the state; 3) The wrapper program starts to run, and traps into the gVisor kernel when it reaches the *func-entry point*; 4) The current program state, including in-memory data, system metadata and the I/O information is saved into the generated *func-image*. Most of the image compilation process is automated. Catalyzer uses the *func-image* for cold boot, and re-uses in-memory state of existing running instances for warm and fork boot.

Generality. Although we choose to implement Catalyzer on gVisor/Golang, the design is general, and most of the techniques are also applicable to other lightweight virtualization systems. For example, FireCracker [6] needs more than 100ms to boot a guest kernel, which can be optimized safely with the on-demand restore. The four techniques in on-demand restore (e.g., overlay memory) only depend on hardware virtualization extensions like Intel EPT or AMD NPT. Moreover, the transient single-thread of sfork is also general and can be used in other Golang-based virtualization systems (e.g., Google novm [9]).

6 Evaluation

In the evaluation, we try to answer the following questions:

- *Question-1*: How does Catalyzer improve the startup performance of diverse applications? (§6.2)
- *Question-2*: How does each technique in Catalyzer improve the startup performance individually? (§6.3)
- *Question-3*: How does Catalyzer reduce the latency of end-to-end serverless functions? (§6.4)
- *Question-4*: How does Catalyzer reduce memory usage of a serverless platform? (§6.5)
- *Question-5*: How is the scalability of Catalyzer when there are 1000 running instances? (§6.6)
- *Question-6*: How does Catalyzer achieve near 1ms latency through optimizations? (§6.7)
- *Question-7*: Will Catalyzer introduce new security issues? (§6.8)
- *Question-8*: What can we learn from industrial development? (§6.9)

6.1 Evaluation Environment

We use an x86-64 machine (the experimental machine) with an 8-core Intel i7-7700 CPU, 32GB memory and Samsung 512GB SSD, to evaluate microbenchmarks and performance breakdown. The OS is Ubuntu 16.04 with Linux kernel 4.17.3. In addition, we use a server machine from Ant Financial, with 96 cores (@2.50GHz) and 256GB memory for end-to-end latency and scalability evaluation. We compare several serverless platforms, including gVisor (commit #56fa562), FireCracker (commit #28f44b3) using the official minimized kernel, Docker runc (commit #bbb17ef) and Hyper Container (commit #565496c).

6.2 Application Startup Latency

We evaluate the startup latency of Catalyzer with diverse applications written by different programming languages to answer the first question.

Methodology. We compare *cold boot* (Catalyzer-restore), *warm boot* (Catalyzer-Zygote) and *fork boot* (Catalyzer-sfork) with Docker container, Hyper container, gVisor, gVisor-restore, and FireCracker. We chose applications written by five languages: C, Java, Python, Ruby, and Node.js, which are widely supported in existing serverless platforms. For each language, we test two workloads. One is "helloworld" which represents the minimal application, and the other is a real application. We do not evaluate Ruby on FireCracker since the official kernel provided by FireCracker does not support Ruby yet.

Table 2. Cold boot with Java runtime templates.

Systems	Native	gVisor	Java template
Cold boot (ms)	89.4	659.1	29.3

The C application is a widely used web server, Nginx (version 1.11.3). The latency is evaluated as the time from the "nginx" command to the start of its main function. SPECjbb2015 is a widely used benchmark to evaluate the Java server business scenarios. We evaluate the time between the "java" command and the entry of BackendAgent. Django is used for Python application and Sinatra for Ruby applications, which are both web frameworks/libraries for applications. For Node.js, we use a web server as the tested application.

Results. Figure 11 shows the result. Catalyzer achieves the best performance in all the applications. Specifically, Catalyzer-sfork can boost startup latency of a serverless function to even less than 1ms (0.97ms in C-hello). Catalyzer-Zygote can boot a serverless function using 5ms for C, 14ms for Java, 9ms for Python, 12ms for Ruby, and 9ms for Node.js applications. Catalyzer-restore usually needs extra 30ms over Catalyzer-Zygote to initialize the sandbox and map func-image into memory. The results also reveal the improvement of Catalyzer is general for diverse applications, from the simple C-hello to Java-SPECjbb.

Language Runtime Templates. The sfork primitive is proposed for hot boot in most cases. However, with the language runtime templates design (§4.3), sfork can provide a general template for diverse functions written by the same language (to achieve fast cold boot for lightweight functions). As shown in Table 2, we evaluate the latency of booting a lightweight Java-based function, using a JVM runtime template. The latency is about 20ms longer than Catalyzer-sfork, but still 30x faster than baseline gVisor. Moreover, Java template sandbox can even boost the startup latency better than the native (3.0x and 3.7x faster). The major overhead of Catalyzer-sfork is caused by loading Java class files of requested functions.

6.3 Improvement Breakdown

We evaluate the optimization of the three techniques used in Catalyzer (*cold boot*). The baseline is the gVisor-restore. We evaluate the startup latency of two applications, Python Django and Java SPECjbb with four configurations, the baseline (gVisor-restore), Catalyzer without separated loading and lazy reconnection, Catalyzer without lazy reconnection, and Catalyzer.

As shown in Figure 12, overlay memory can reduce 261ms of latency for Java SPECjbb compared with the gVisor-restore. Separated object loading reduces the kernel loading latency by 6.3x for Python Django, and 7.0x for Java SPECjbb, Lazy

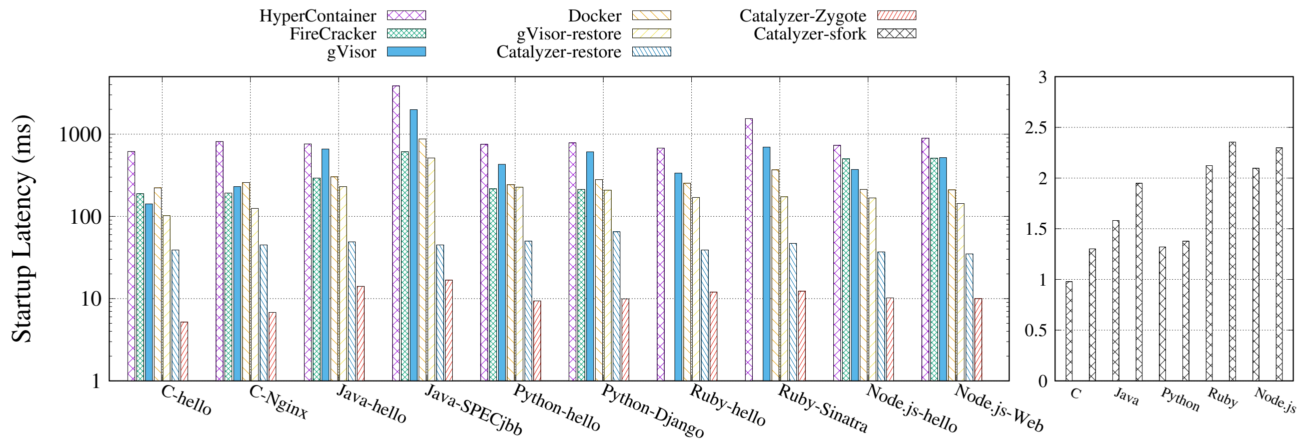


Figure 11. Startup latency of Catalyzer compared with other systems. The test cases for Catalyzer-sfork (right part) are the same.

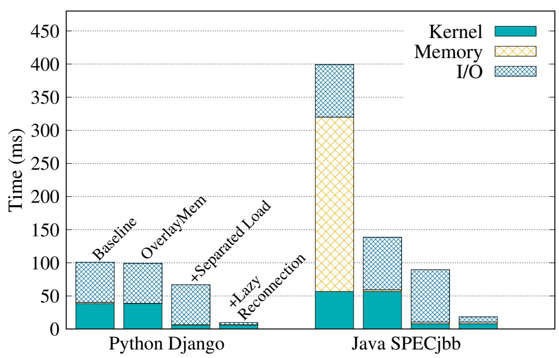


Figure 12. Breakdown of Catalyzer (*cold boot*) on gVisor.

I/O reconnection reduces >57ms of latency on I/O reconnection in both two applications, namely, 18x improvement. The result shows that applications with small memory footprint can benefit more from separated object loading and lazy I/O reconnection, while overlay memory contributes most of the optimization for applications with large memory footprint.

6.4 End-to-End Evaluation

We present three end-to-end tests to show how Catalyzer can reduce latency for real-world serverless functions. In each case, we present the startup latency (*Boot*) and the execution latency (*Execution*). We compare three systems, gVisor, Catalyzer-sfork (*fork boot*) and Catalyzer-restore (*cold boot*).

DeathStar Social Network Microservices. DeathStar [22] is an open-source microservice benchmark. We port five microservices in DeathStar social network benchmark to our serverless platform. Specifically, all *microservice invocations* in selected microservices are replaced by stub functions to be compatible with the platform.

The results are shown in Figure 13-a. DeathStar represents real-world lightweight serverless functions. All the selected functions are written in C++, and have <2.5ms execution time in all the cases, as shown in the figure. For these functions, Catalyzer can significantly reduce the overall latency by boosting startup (35x–67x using sfork).

Image Processing Application. Image processing can be implemented as serverless functions and has been deployed in existing platforms [17]. We use Python Pillow [15], a Python imaging library to implement five major tasks for image processing. Specifically, the Pillow applications receive images, process them (i.e., enhance/filter/roll/splitmerge/-transpose the images), and then return the processed results.

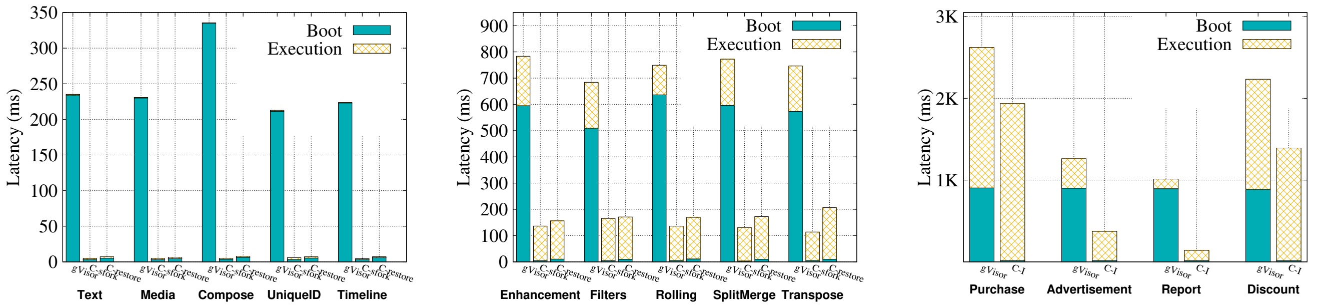
As shown in Figure 13-b, the execution time of the five functions are 100–200ms. The major cost is from reading the input images. Although the execution time is much longer than DeathStar, the startup latency still dominates the overall latency (>500ms). Overall, Catalyzer can reduce the end-to-end latency by 4.1x–6.5x in *fork boot*, and 3.6x–4.3x in *cold boot*, compared with the baseline.

E-commerce Functions. We evaluate four E-commerce serverless functions written in Java: purchase, advertising, report generation, and discount applying. The execution time of these services varies from hundreds of milliseconds (report generation) to more than one second (purchase). We compare the *Boot* and *Execution* latency of them running in gVisor and Catalyzer.

The results are shown in Figure 13-c. In baseline gVisor, booting of the four Java applications contributes to 34%–88% of their end-to-end latency. In Catalyzer, the number drops below 5%, which is a significant improvement over existing systems and is acceptable in most server service scenarios.

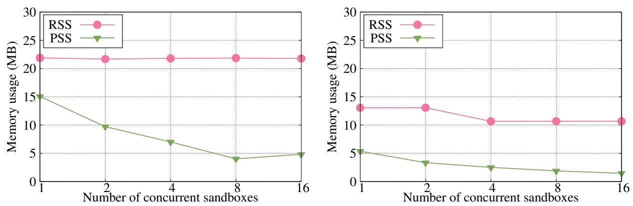
6.5 Memory Usage Evaluation

On-demand Paging. Figure 14 compares memory usages of the DeathStar composePost function in gVisor and Catalyzer (with sfork) under concurrent running sandboxes (from 1



(a) **Deathstar microservices.** (b) **Pillow image processing.** (c) **E-commerce functions.**

Figure 13. End-to-end evaluation. C-sfork means *fork boot* of Catalyzer, C-restore means *cold boot* of Catalyzer, and C-I means Catalyzer on the server machine.



(a) gVisor baseline. **(b) Catalyzer.**

Figure 14. Memory usages in the DeathStar.

Table 3. Memory costs in Catalyzer for *warm boot*.

Applications	Metadata Objects	I/O Cache	All
C-Nginx	165.5KB	370B	165.9KB
Java-SPECjbb	680.6KB	2.4KB	683.0KB
Python-Django	289.3KB	1.2KB	290.5KB
Ruby-Sinatra	349.2KB	1.5KB	350.8KB
NodeJS-Web	302.1KB	472B	302.6KB

instance to 16). We use resident set size (RSS) and the proportional set size (PSS) to represent the memory usage. RSS is the total memory used by a process, while PSS is composed by the private memory of that process plus the proportion of shared memory with other processes. Each point in the figure shows the average value of memory usages over all running sandboxes. A comparison of the two figures shows that Catalyzer achieves lower RSS and private memory usages (indicated by PSS) comparing to gVisor.

Memory Costs of Catalyzer. Memory costs of *warm boot* in Catalyzer are acceptable. We have observed that many metadata objects will be copied into *Private-EPT*, which incurs memory overhead. We present the costs of metadata objects and I/O caches in Table 3, which are negligible. For most applications, Catalyzer needs ≤2.4KB for I/O caches, 165–680KB for metadata objects. Notably, the overhead is per serverless function (not per serverless instance), making the cost (≤683KB overall) acceptable for most cases. sfork will introduce more memory overheads, e.g., a SPECjbb template sandbox can cost >200MB memory.

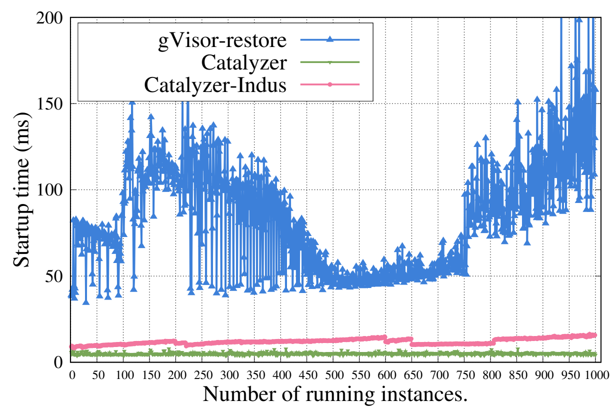


Figure 15. Startup latency as the instance number increases. Catalyzer-Indus means results from the server machine.

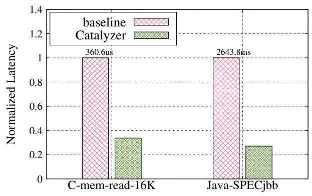
6.6 Concurrent Running

One appealing feature of serverless computing is auto-scaling. Hence, having many serverless instances running simultaneously in a machine is a common case. We evaluate the startup time of Catalyzer when there are concurrently running instances.

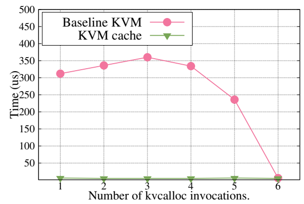
We use the DeathStar text service as the test function, which handles a request and hangs a while before exit, for evaluation. As shown in Figure 15, we evaluate the booting latency with n (0–1000) running instances. We compared Catalyzer with gVisor-restore and only considered the restore latency of gVisor-restore (without "create" sandbox latency). Overall, the startup latency in Catalyzer is less than 10ms on both the experimental machine and the server machine.

6.7 Optimizations

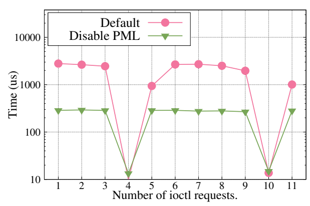
***Customized* func-entry point.** Carefully choosing the *func-entry point* location, e.g., moving it after the in-function preparation logic, can further improve the performance of serverless functions. Using the optimization, the developers should put the func-entry point in their function code. The developers should be careful to ensure privacy and security. Further, a platform can even warm up some dependencies of a



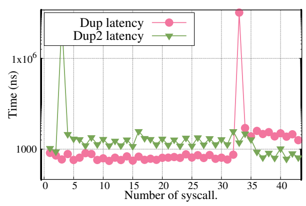
(a) Fine-grained func-entry point.



(b) KVM allocation cache.



(c) Latency of set_memory_region.



(d) Latency of dup/dup2 syscall.

Figure 16. Optimizations in Catalyzer. Figure (a) shows fine-grained func-entry point can reduce the execution latency by 3x. From Figure (b), adding a cache in KVM can reduce the latency of kvcalloc. Figure (c) shows the latency of *set_memory_region* ioctl in KVM and disabling PML achieves 10x shorter latency. Figure (d) shows the latency of dup syscall during boot. The burst one takes about 30 ms for the syscall.

function with user-provided requests as training and use the warmed state as func-image (*user-guided pre-initialization*). Thus, the time of application-dependent preparation work can be mitigated.

We use a case in Java SPECjbb and a memory reading C program (as microbenchmark) for evaluation. The C program will allocate a memory region to read and write. We move the *func-entry point* after memory allocation. For SPECjbb, we move the *func-entry point* after its initialization logic. As shown in Figure 16-a, the execution latency is reduced by 3x for both cases.

Optimizing KVM. Page modification logging (PML), which is a virtualization feature to monitor changes made to guest physical pages, is enabled by default in current KVM. If the guest does not need the feature, it has to be disabled, or it will introduce high latency when adding a new memory region, as shown in Figure 16-c. A trick we employed is to disable PML by default for both the baseline and our systems, which reduces 5–8ms of latency for setting KVM memory regions.

In addition, KVM uses *kvcalloc* to allocate memory resource for VM management, which can incur 1.6ms overhead, as shown in Figure 16-b. To mitigate the cost, we add a dedicated cache in KVM to boost the allocations, which can reduce the overhead to <50us in most cases.

High Tail Latency System Calls. System call invocation on the host kernel can incur high latency. For example, *dup* and *dup2* take ≤1ms to 30ms to finish (Figure 16-d). The burst latency comes from rare cases in the kernel. For example, the kernel may expand the fdtable when the table size is not enough, which causes long latency. Thus, we use a *lazy dup*, in which the Gofer process first returns an available fd and duplicate a new one for itself, to mitigate the overhead. This optimization is implemented in the Gofer process for on-demand I/O reconnection, which contributes to 10–20ms improvement.

6.8 Security Analysis

Catalyzer shares a "base mapping" among instances. Since the "base mapping" only contains user requests independent state, the sharing will not leak data or create new cache side channels. A possible issue is the violation of ASLR (Address Space Layout Randomization), which can be mitigated by periodically updating func-images and template sandboxes or adopting previous techniques [33, 34] to re-randomize the layout of address space during *sfork*.

6.9 Lessons Learned from Industrial Development

Heavyweight-functions. Prior work focuses on lightweight languages for serverless functions, e.g., Python. However, a trend is that more functions are directly ported from well-tested service code written in Java. Thus, a system to boost the startup latency of functions wrapped with a heavyweight language runtime is necessary. Recent work [43] on boosting Java-based serverless functions also confirms the necessity.

Sustainable Hot Boot. Most of existing serverless platforms use function caches to provide "hot boot". However, the benefits of caching depend on its policies and caching can not help reduce tail latency, which is dominated by the "cache miss boot" in most cases. Our *fork boot* using sfork guarantees a sustainable hot boot for functions.

The usage of sfork still depends on workloads and platforms. For private serverless platforms, it is reasonable to assign different priorities to different functions; therefore, the platform can use sfork to boot high priority functions. For a public platform, some hints from the developers are necessary to improve the boot switching policies to better leverage the efficiency of fork boot.

7 Related Work

Besides the systems mentioned in Section 2, there are other systems [30, 42, 43] that have tried to leverage the checkpoint/restore mechanism for instantiation. Flash cloning [42] uses a reference image which contains the memory snapshot of a pre-initialized OS and application environment. SnowFlock [30] provides a fast VM instantiation scheme using VM fork, allowing a virtual machine to fork a new instance to handle requests. The two systems target traditional virtual machines, and thus still have high latency, e.g., VM cloning operation in SnowFlock introduces near second latency. Replayable Execution [43] identifies two execution phases of FaaS applications and extends the checkpoint/restore mechanism with on-demand paging to achieve 54ms JVM boot. Catalyzer has two key distinctions. First, on-demand paging is not sufficient in virtualization-based sandboxes, as system state recovery occupies prominent overheads. Thus, Catalyzer adopts the on-demand recovery also for system state. Second, Catalyzer further proposes sfork primitive and achieves 1.5ms–2ms latency for Java functions.

Unikernels like Mirage [36] and OSv [26] can achieve faster startup than traditional VM by minimizing and customizing the guest OS for applications and removing the isolation between kernel and applications. LightVM [37] can achieve <10ms Unikernel booting by optimizing Xen and minimizing the guest environment. Catalyzer uses a different idea to boost startup by skipping the initialization, which is much more efficient and suitable for serverless. Besides, we believe that Catalyzer can also be applied to Unikernels.

8 Conclusion

This paper presents Catalyzer, a general design for serverless to boost the function startup by eliminating the initialization phase with on-demand restore and sfork. We implement the design based on gVisor, and the evaluation shows that Catalyzer can significantly reduce the latency overhead of diverse serverless applications.

Acknowledgments

We thank our shepherd Mike Swift and the anonymous reviewers for their insightful comments. This work is supported in part by the National Key Research & Development Program (No. 2016YFB1000104), and the National Natural Science Foundation of China (No. 61972244, 61925206), the HighTech Support Program from Shanghai Committee of Science and Technology (No. 19511121100), and the Program of Shanghai Academic/Technology Research Leader (No.19XD1401700). Yubin Xia (xiayubin@sjtu.edu.cn) is the corresponding author.

References

[1] [n.d.]. Apache OpenWhisk is a serverless, open source cloud platform. http://openwhisk.apache.org/. Referenced December 2018.

[2] [n.d.]. AWS Lambda - Serverless Compute. https://aws.amazon.com/lambda/. Referenced December 2018.

[3] [n.d.]. Azure Functions Serverless Architecture. https://azure.microsoft.com/en-us/services/functions/. Referenced December 2018.

[4] [n.d.]. Checkpoint/Restore in gVisor. https://gvisor.dev/docs/user_guide/checkpoint_restore/. Referenced July 2019.

[5] [n.d.]. The Docker Containerization Platform. https://www.docker.com/. Referenced December 2018.

[6] [n.d.]. Firecracker. https://firecracker-microvm.github.io/. Referenced December 2018.

[7] [n.d.]. Google Cloud Function. https://cloud.google.com/functions/. Referenced December 2018.

[8] [n.d.]. Google gVisor: Container Runtime Sandbox. https://github.com/google/gvisor. Referenced December 2018.

[9] [n.d.]. google/novm: Experimental KVM-based VMM for containers, written in Go. https://github.com/google/novm. Referenced Jan 2020.

[10] [n.d.]. Hyper - Make VM run like Container. https://hypercontainer.io/. Referenced December 2018.

[11] [n.d.]. Keeping Functions Warm - How To Fix AWS Lambda Cold Start Issue. https://serverless.com/blog/keep-your-lambdas-warm/. Referenced July 2019.

[12] [n.d.]. OCI Runtime Specification. https://github.com/opencontainers/runtime-spec. Referenced December 2018.

[13] [n.d.]. Overlay Filesystem. https://www.kernel.org/doc/Documentation/filesystems/overlayfs.txt. Referenced July 2019.

[14] [n.d.]. Overview of memory management | Android Developers. https://developer.android.com/topic/performance/memory-overview. Referenced December 2018.

[15] [n.d.]. Pillow: the friendly PIL fork. https://python-pillow.org/. Referenced December 2018.

[16] [n.d.]. Protocol Buffers Google Developers. https://developers.google.com/protocol-buffers/. Referenced July 2019.

[17] Istemi Ekin Akkus, Ruichuan Chen, Ivica Rimac, Manuel Stein, Klaus Satzke, Andre Beck, Paarijaat Aditya, and Volker Hilt. 2018. {SAND}: Towards High-Performance Serverless Computing. In *2018 {USENIX} Annual Technical Conference ({USENIX}{ATC} 18)*. 923–935.

[18] Nadav Amit and Michael Wei. 2018. The Design and Implementation of Hyperupcalls. In *2018 USENIX Annual Technical Conference (USENIX ATC 18)*. USENIX Association, Boston, MA, 97–112. https://www.usenix.org/conference/atc18/presentation/amit

[19] Adam Belay, Andrea Bittau, Ali José Mashtizadeh, David Terei, David Mazières, and Christos Kozyrakis. 2012. Dune: Safe User-level Access to Privileged CPU Features.. In *Osdi*, Vol. 12. 335–348.

[20] Fabrice Bellard. 2005. QEMU, a fast and portable dynamic translator.. In *USENIX Annual Technical Conference, FREENIX Track*, Vol. 41. 46.

[21] Sol Boucher, Anuj Kalia, David G. Andersen, and Michael Kaminsky. 2018. Putting the "Micro" Back in Microservice. In *2018 USENIX Annual Technical Conference (USENIX ATC 18)*. USENIX Association, Boston, MA, 645–650. https://www.usenix.org/conference/atc18/presentation/boucher

[22] Yu Gan, Yanqi Zhang, Dailun Cheng, Ankitha Shetty, Priyal Rathi, Nayan Katarki, Ariana Bruno, Justin Hu, Brian Ritchken, Brendon Jackson, et al. 2019. An Open-Source Benchmark Suite for Microservices and Their Hardware-Software Implications for Cloud & Edge Systems. In *Proceedings of the Twenty-Fourth International Conference on Architectural Support for Programming Languages and Operating Systems*. ACM, 3–18.

[23] Abel Gordon, Nadav Amit, Nadav Har'El, Muli Ben-Yehuda, Alex Landau, Assaf Schuster, and Dan Tsafrir. 2012. ELI: Bare-metal Performance for I/O Virtualization. In *Proceedings of the Seventeenth International Conference on Architectural Support for Programming Languages and Operating Systems (ASPLOS XVII)*. ACM, New York, NY, USA, 411–422. https://doi.org/10.1145/2150976.2151020

[24] Joseph M Hellerstein, Jose Faleiro, Joseph E Gonzalez, Johann Schleier-Smith, Vikram Sreekanti, Alexey Tumanov, and Chenggang Wu. 2018. Serverless Computing: One Step Forward, Two Steps Back. *arXiv preprint arXiv:1812.03651* (2018).

[25] Sanidhya Kashyap, Changwoo Min, and Taesoo Kim. 2018. Scaling Guest OS Critical Sections with eCS. In *2018 USENIX Annual Technical Conference (USENIX ATC 18)*. USENIX Association, Boston, MA, 159–172. https://www.usenix.org/conference/atc18/presentation/kashyap

[26] Avi Kivity, Dor Laor Glauber Costa, and Pekka Enberg. 2014. OS v—Optimizing the Operating System for Virtual Machines. In *Proceedings of USENIX ATC'14: 2014 USENIX Annual Technical Conference*. 61.

[27] Ana Klimovic, Yawen Wang, Christos Kozyrakis, Patrick Stuedi, Jonas Pfefferle, and Animesh Trivedi. 2018. Understanding Ephemeral Storage for Serverless Analytics. In *2018 USENIX Annual Technical*

Conference (USENIX ATC 18). USENIX Association, Boston, MA, 789–794. https://www.usenix.org/conference/atc18/presentation/klimovic-serverless

[28] Ana Klimovic, Yawen Wang, Patrick Stuedi, Animesh Trivedi, Jonas Pfefferle, and Christos Kozyrakis. 2018. Pocket: Elastic Ephemeral Storage for Serverless Analytics. In *13th USENIX Symposium on Operating Systems Design and Implementation (OSDI 18)*. USENIX Association, Carlsbad, CA, 427–444. https://www.usenix.org/conference/osdi18/presentation/klimovic

[29] Yossi Kuperman, Eyal Moscovici, Joel Nider, Razya Ladelsky, Abel Gordon, and Dan Tsafrir. 2016. Paravirtual Remote I/O. In *Proceedings of the Twenty-First International Conference on Architectural Support for Programming Languages and Operating Systems (ASPLOS '16)*. ACM, New York, NY, USA, 49–65. https://doi.org/10.1145/2872362.2872378

[30] Horacio Andrés Lagar-Cavilla, Joseph Andrew Whitney, Adin Matthew Scannell, Philip Patchin, Stephen M Rumble, Eyal De Lara, Michael Brudno, and Mahadev Satyanarayanan. 2009. SnowFlock: rapid virtual machine cloning for cloud computing. In *Proceedings of the 4th ACM European conference on Computer systems*. ACM, 1–12.

[31] David Lion, Adrian Chiu, Hailong Sun, Xin Zhuang, Nikola Grcevski, and Ding Yuan. 2016. Don't Get Caught in the Cold, Warm-up Your JVM: Understand and Eliminate JVM Warm-up Overhead in Data-Parallel Systems. In *12th USENIX Symposium on Operating Systems Design and Implementation (OSDI 16)*. USENIX Association, Savannah, GA, 383–400. https://www.usenix.org/conference/osdi16/technical-sessions/presentation/lion

[32] Ming Liu, Simon Peter, Arvind Krishnamurthy, and Phitchaya Mangpo Phothilimthana. 2019. E3: Energy-Efficient Microservices on SmartNIC-Accelerated Servers. In *2019 USENIX Annual Technical Conference (USENIX ATC 19)*. USENIX Association, Renton, WA, 363–378. https://www.usenix.org/conference/atc19/presentation/liu-ming

[33] Kangjie Lu, Wenke Lee, Stefan Nürnberger, and Michael Backes. 2016. How to Make ASLR Win the Clone Wars: Runtime Re-Randomization.. In *NDSS*.

[34] Kangjie Lu, Chengyu Song, Byoungyoung Lee, Simon P Chung, Taesoo Kim, and Wenke Lee. 2015. ASLR-Guard: Stopping address space leakage for code reuse attacks. In *Proceedings of the 22nd ACM SIGSAC Conference on Computer and Communications Security*. ACM, 280–291.

[35] Anil Madhavapeddy, Thomas Leonard, Magnus Skjegstad, Thomas Gazagnaire, David Sheets, David J Scott, Richard Mortier, Amir Chaudhry, Balraj Singh, Jon Ludlam, et al. 2015. Jitsu: Just-In-Time Summoning of Unikernels.. In *NSDI*. 559–573.

[36] Anil Madhavapeddy, Richard Mortier, Charalampos Rotsos, David Scott, Balraj Singh, Thomas Gazagnaire, Steven Smith, Steven Hand, and Jon Crowcroft. 2013. Unikernels: Library operating systems for the cloud. In *Acm Sigplan Notices*, Vol. 48. ACM, 461–472.

[37] Filipe Manco, Costin Lupu, Florian Schmidt, Jose Mendes, Simon Kuenzer, Sumit Sati, Kenichi Yasukata, Costin Raiciu, and Felipe Huici. 2017. My VM is Lighter (and Safer) than your Container. In *Proceedings of the 26th Symposium on Operating Systems Principles*. ACM, 218–233.

[38] Garrett McGrath, Jared Short, Stephen Ennis, Brenden Judson, and Paul Brenner. 2016. Cloud event programming paradigms: Applications and analysis. In *2016 IEEE 9th International Conference on Cloud Computing (CLOUD)*. IEEE, 400–406.

[39] Edward Oakes, Leon Yang, Kevin Houck, Tyler Harter, Andrea C Arpaci-Dusseau, and Remzi H Arpaci-Dusseau. 2017. Pipsqueak: Lean Lambdas with large libraries. In *2017 IEEE 37th International Conference on Distributed Computing Systems Workshops (ICDCSW)*. IEEE, 395–400.

[40] Edward Oakes, Leon Yang, Dennis Zhou, Kevin Houck, Tyler Harter, Andrea Arpaci-Dusseau, and Remzi Arpaci-Dusseau. 2018. {SOCK}: Rapid Task Provisioning with Serverless-Optimized Containers. In *2018 {USENIX} Annual Technical Conference ({USENIX}{ATC} 18)*.

[41] Zhiming Shen, Zhen Sun, Gur-Eyal Sela, Eugene Bagdasaryan, Christina Delimitrou, Robbert Van Renesse, and Hakim Weatherspoon. 2019. X-containers: Breaking down barriers to improve performance and isolation of cloud-native containers. In *Proceedings of the Twenty-Fourth International Conference on Architectural Support for Programming Languages and Operating Systems*. ACM, 121–135.

[42] Michael Vrable, Justin Ma, Jay Chen, David Moore, Erik Vandekieft, Alex C Snoeren, Geoffrey M Voelker, and Stefan Savage. 2005. Scalability, fidelity, and containment in the potemkin virtual honeyfarm. In *ACM SIGOPS Operating Systems Review*, Vol. 39. ACM, 148–162.

[43] Kai-Ting Amy Wang, Rayson Ho, and Peng Wu. 2019. Replayable Execution Optimized for Page Sharing for a Managed Runtime Environment. In *Proceedings of the Fourteenth EuroSys Conference 2019*. ACM, 39.

[44] Liang Wang, Mengyuan Li, Yinqian Zhang, Thomas Ristenpart, and Michael Swift. 2018. Peeking behind the curtains of serverless platforms. In *2018 {USENIX} Annual Technical Conference ({USENIX}{ATC} 18)*. 133–146.

[45] Liang Zhang, James Litton, Frank Cangialosi, Theophilus Benson, Dave Levin, and Alan Mislove. 2016. Picocenter: Supporting Long-lived, Mostly-idle Applications in Cloud Environments. In *Proceedings of the Eleventh European Conference on Computer Systems (EuroSys '16)*. ACM, New York, NY, USA, Article 37, 16 pages. https://doi.org/10.1145/2901318.2901345