Abstract

We present MITOSIS, an OS primitive to support fast remote fork with minimal resource provisioning for serverless computing. MITOSIS is the first to fork over 10,000 new containers from only one instance across multiple machines within a second. It also allows transparent and efficient intermediate data sharing between producer and consumer serverless functions even across machines. The key enabler for this high speed is an RDMA-OS co-design, which imitates local fork with RDMA’s remote memory read capability bypassing extra software overhead for starting and running containers. We also introduce techniques for lightweight connection and memory management based on advanced RDMA transport and fast containerization in a distributed setting. We have implemented MITOSIS on Linux and integrated it to FN, a popular serverless computing framework. Under load spikes in real serverless workloads, MITOSIS reduces the FN tail latency by 95.2% with orders of magnitude smaller memory usage.

1 Introduction

Serverless computing is a popular cloud computing paradigm widely supported by major cloud providers such as AWS Lambda [12], Azure Function [52], Google Serverless [26], just to name a few. One of its key promises is auto-scaling—the user only provides the function code, and the platform automatically provisions computing resources (e.g., containers) to execute them. On-demand resource provisioning also makes serverless computing economical: the platforms only bill when the function executes with no charge for idle time.

However, the cost of cold start, i.e., starting a container from scratch, becomes a key obstacle for fast of auto-scaling, because the cold start time can be orders of magnitude higher than the ephemeral serverless function execution time [20, 53]. Nevertheless, auto-scale functions to multiple machines are required in real-world serverless workloads. As shown in the upper part of Figure 1, the invocation frequency of real-world serverless functions can spike to 33,000X within one minute. To avoid stalling the execution of new invocations, we need sufficient concurrency that starts containers across multiple machines (see the bottom part of Figure 1).

Reducing the cold start cost for serverless computing has become a hot research topic [22, 69, 53, 8, 57, 20]. However, most of them target at a single-machine setting and require non-trivial resources to provide warm-start invocations in a distributed setting (§2.3). Specifically, caching containers [22, 69, 53, 8, 57] allows functions to reuse cached instances without starting them from scratch. Yet, each machine must cache sufficient instances to handle unpredictable high function invocations. Sandbox-fork [20, 8] leverages the OS fork to start new containers but each machine still has to deploy dedicated instances as forking seeds. There is “no free lunch” for these resources: existing platforms require users to pre-prepare and pay for the provisioned resources (e.g., AWS Lambda Provisioned Concurrency [6]) to achieve better performance (i.e., lower response time).

The approach of checkpoint and restore (C/R)—checkpoint a container to a well-formed file image and restore it from the image accordingly [4, 65]—is currently the only way to remote warm-start containers without provisioning resources on each machine, since the images can be sent through network or stored in a distributed file system (DFS). Unfortunately, remote start of C/R can be orders of magnitude slower than local start (§2.4). First, copying the entire image can be costly and unnecessary since serverless functions typically runs on a small portion of the checkpointed states [68, 20]. Storing the image in a DFS enables on-demand restore, yet DFS incurs non-negligible software overhead and thus fails to fully utilize the high performance of modern interconnects (i.e., RDMA) when recovering the memory states. Finally, checkpointing is typically slow and thus is inefficient for dynamically checkpointing serverless functions.

We propose MITOSIS, a new OS primitive to provide remote fork for accelerating container boot in a distributed setting with minimal required resources, based on the following observations. First, fork has been shown efficient in both
performance and resource usage for single-machine settings: one running container is sufficient to warm start any subsequent functions with a similar performance as caching [8, 20]. When generalizing fork to remote efficiently, one container is sufficient to warm start any functions across different machines. Second, (remote) fork provides transparent intermediate results sharing between dependent functions—since the children can reuse the parent’s in-memory states. Otherwise, developers must explicitly communicate with external storages (e.g., Amazon S3), which is shown to be slow [32].

The key for MITOSIS to achieve fast remote fork is co-designing OS with fast interconnect (RDMA) that has been widely deployed in cloud platforms. In particular, an OS can directly access a remote machine’s physical memory with RDMA-capable NIC (RNIC) [63], bypassing the remote OS and CPU and thus is extremely fast. The insight is that we can map a child container’s virtual memory to its remote parent’s physical memory and read the memory data with RDMA on demand in a read-on-access way, bypassing any extra software overhead (e.g., filesystem) compared to C/R.

Using RDMA for remote fork, however, poses a significant challenge for OS to manage its physical memory because RNIC can read it in an OS-bypassing way. Though infrequent, OS may reclaim the physical memory mapped by remote peers, e.g., swap. Traditionally, OS adopts an active control model that changes the mapping of all processes referencing the page before reclaiming it. Unfortunately, the active model is impractical in the context of remote fork because a container can be forked to thousands of children across machines (e.g., Figure 2). Instead, we propose a passive model for OS to manage the memory. Specifically, the parent OS can reclaim physical pages mapped by remote children without synchronizing with them. It relies on RNIC to reject future accesses to these pages. Thus, children OSs can passively detect the reclamation and execute a fallback path for correctness. A straightforward way of realizing this model is to leverage RDMA’s memory registration. However, we found it far-from-optimal for remote fork due to non-trivial registration overhead and incompatible issues in the kernel (§3.1). To this end, we further propose a novel mechanism that leverages dynamic connection authentication feature of advanced RDMA transport (DCT) [1], to design a registration-free memory control for remote fork. Finally, RDMA alone is insufficient for efficient forking all the states of a container. MITOSIS also introduces techniques including generalizing single-machine lean container [53] to a distributed setting for efficient forked process containerization.

We implemented MITOSIS on Linux, which can remote fork 10,000 containers on 18 machines in 0.86 second. It is fully compatible with mainstream container platforms, e.g., Docker. Therefore, it can seamlessly integrate to existing container-based serverless computing frameworks to achieve an efficient auto-scale with minimal resource usage. To demonstrate its effectiveness, we integrated MITOSIS to Fn [70], a popular open-source serverless computing framework. Under load spikes in real-world serverless workloads, MITOSIS reduces the 50th (median) and 99th percentile latency of spike function by 44.55% and 95.24%, respectively, with orders of magnitude smaller memory usage.

Contributions. We make the following contributions:

• Problem: A detailed analysis of the requirement of auto-scaling containers to multiple machines in serverless computing and the performance-resource provision trade-off of existing approaches when doing so (§2).

• MITOSIS: An RDMA-accelerated OS remote fork primitive to quickly fork containers to remote machine with minimal resource provisioning (§4).

• Implementation & evaluations: An implementation on Linux and an integrations to Fn [70] (§5) with evaluations on micro-benchmarks and real serverless applications demonstrates the efficacy of MITOSIS (§6).

2 Background and Motivation

2.1 Serverless computing and containers

Serverless computing is an emerging cloud programming paradigm that allows developers to construct applications efficiently without explicit resource management. Specifically, developers can focus on the core logic of applications, write the code in managed language runtime like Python and upload their code as functions to serverless platforms. The platform automatically runs the functions in response to events like invocation requests, which offers automatic computing resource provision usually by running functions in containers [33, 70, 34, 53, 11, 17, 52, 26, 11] and scales them up or down according to increased or decreased demands. Hence, serverless computing relieves developers from tedious tasks including provisioning, scheduling, and scaling. It is also more economical than traditional virtual machine-based solutions because the serverless providers typically charge in a pay-as-you-go way.

Serverless computing frameworks widely use containers to execute functions because they embrace the features of ease-of-deployment, high performance and lightweight resource isolation with cgroup and namespace. We focus on container-based serverless computing in this paper.

2.2 The case for auto-scaling in serverless computing

“...for a service to be considered serverless, it must scale automatically with no need for explicit provisioning.”

Cloud Programming Simplified: A Berkeley View on Serverless Computing [38]

Auto-scaling—the ability to automatically boot functions on demand but does not require explicit resource provisioning—is promised by all serverless computing providers, including AWS Lambda [12], Azure Function [52], Google Serverless [26], and Alibaba Serverless Application Engine [17].
Table 1: Techniques to warm start serverless functions. Resource is the per-machine resource to warm start n invocations of a particular function. The warm start time is measured by TC0 in Figure 2. TCO’s cold start time is 783ms with Docker. When the resource is not on the machine, the warm start time becomes remote warm start. MITOSIS and C/R only need one resource to fast start others at M machines, so the amortized per-machine resource is 1/M.

| Technique     | Resource for warm start | Remote warm start |
|---------------|-------------------------|-------------------|
| Caching       | n * container           | <1ms              |
| Fork-based    | 1 * container           | 1ms               |
| C/R [68, 20, 65] | (1/M) * image file      | 14.8ms            |
| MITOSIS       | (1/M) * container       | 11ms              |

It is beneficial in various scenarios. From the perspective of programmers, auto-scaling removes their burden on provisioning containers to handle variant workloads. Meanwhile, burst-parallel serverless applications such as video processing [10, 23] and data analytic [54, 62] require scaling to thousands of short-lived functions for complex jobs. More importantly, load spikes—instance many instances of a particular function—exist in production serverless workloads [67, 57]. The top part of Figure 1 presents our analysis of two typical functions that undergo spikes in Azure Function’s serverless traces [57]. Under spikes, the invocation frequencies can fluctuate to 33,000X within one minute. To improve the application performance under such workloads, serverless frameworks must spawn enough containers to run these functions.

Key requirement: booting containers at multiple machines. One machine typically cannot handle the unpredictable spike workloads without sacrificing the performance. The bottom half of Figure 1 quantifies the least machines required to handle each function’s workload without stalling their execution, e.g., waiting for the previous to finish and then start the next. The number is estimated by the function execution time and the hardware configurations (e.g., number of CPUs). Function 660323 and 9a3e4e require up to 31 and 10 machines to handle load spikes, respectively.

2.3 Auto-scale containers! But at what cost?

Cold start cost. Booting a container from scratch (cold start) is notoriously slow for handling ephemeral serverless workloads [53, 8, 20, 57, 62, 24, 67, 72, 60]: the serverless framework needs to not only create a new container but also initialize the managed runtime of a high-level language. For example, the cold start of container may introduce delays of a few seconds in AWS Lambda [8] while initializing the Java runtime for SPECjbb takes around 1.8 seconds [20].

Resource usage cost. To alleviate the booting overhead, various techniques aim to transform cold start to warm start [22, 69, 53, 8, 57, 20] by pre-allocating computing resources, as summarized in Table 1. Caching-based techniques [22, 69, 53, 8, 57], reuse launched containers for handling subsequent invocations to the same functions. To warm start n containers it needs to cache n running instances, which inevitably face the trade-off between cold start costs and high resource overhead since the cached containers should match the number of unpredictable invocations for possibly many functions. Some other work leverages the mechanism of fork to achieve low-latency function start [8, 20] similar as caching, which reduces the pre-allocated resource for a particular function n to 1 per-machine. However, fork cannot generalize to remote machines and has scale poorly on a single machine [13]. Thus, caching and fork require deploying container instances on all the involved machines.

Checkpoint/Restore (C/R) is the only known solution that supports remote warm start without pre-deploying resource on the remote machine. However, it is still has an unsatisfactory performance for auto-scaling (demonstrated in §2.4).

2.4 Checkpoint/Restore is inefficient

Figure 3 (a) shows using C/R to warm start a container from one machine (M0) to another (M1). The system first selects a previously started container and checkpoints its execution state to image files. It can be skipped if the M0 already has checkpointed the image. M1 can then copy these files to itself and restore the execution accordingly. Current CRIU implementation loads all memory pages from the files upon restore, which is often unnecessary for serverless workloads [68, 20]. Hence, we further optimize it with the on-demand restore technique [68] such that only restore the touched pages. As illustrated in Figure 2 (d) and (e), on-demand restore improves the vanilla CRIU by 22% and 24% when restoring from tmpfs for TC0 and TC1—two representative functions from ServerlessBench [72], respectively. Note that we also optimize its isolation restore (e.g., cgroup) with SOCK [53], otherwise it will dominate the restore (restore isolation in Figure 2 (d), e.g., >190ms).

Though C/R generalizes to a remote setting, it is orders of magnitude slower than caching or fork (see Table 1) even with careful optimizations due to the following issues:

Issue#1. File copy cost. Figure 2 (a) and (b) breakdown the overhead of restoring a container from one machine to another. For TC0, copying files takes 73% and 77% of the total restore and execution time and for TC1, it consumes 45% and 52%, respectively. Note that we carefully optimized the copy phase: first, the files are stored tmpfs (i.e., in DRAM) bypassing the slow storage (e.g., SSD); Second, we copy the file through RDMA. Yet, the copy still takes much time. The copy overhead increases linearly with the image size, and transferring the whole image is usually unneeded due to the on-demand execution nature of typical serverless functions.

Issue#2. Resource usage cost. A naive way to avoid copying files is to pre-deploy these files on all the machines. As illustrated in Figure 3 (d) and (e), restoring from pre-deployed image on demand (+OnDemand tmpfs) is relative fast: it re-
duces the restore time by 59% and 65% (compared with file copy) for TC0 and TC1, respectively. However, this approach fallbacks to the existing caching technique (e.g., §2.3) which faces the trade-off of cold start overhead (i.e., copy file) and high resource overhead.

**Issue#3. Access distributed file system cost.** To reduce resource usage, we can store image files in a distributed file system (DFS), as illustrated in Figure 3 (b). Consequently, each machine can restore from the shared file with minimal local resource usage. However, DFS introduces higher overhead during container restore (Θ and Ω in Figure 3 (b)) compared to local filesystem due to the abstractions of remote files. As illustrated in Figure 2 (d) and (e), using a DFS not only makes the restore process 1.2X and 1.15X slower (+OnDemand tmpfs vs. +OnDemand DFS), but also causes 840% and 81% slowdowns on the execution for TC0 and TC1, respectively. DFS also affects the execution because the memory pages are pulled from it in an on-demand way. Note that we have deployed a state-of-the-art DFS (Ceph [3]) backed by fast network (i.e., RDMA) and stores all files in the DRAM.

**Issue#4. Slow checkpointing.** Finally, checkpointing a container is slow because it stores all the container’s states to files. As shown in Figure 2 (c), the cost is proportional to the container size (TC0 and TC1 uses 10.2MB and 38MB files, respectively) and is dominated by memory checkpointing. Since checkpointing typically takes tens of milliseconds (e.g., checkpoint TC1 to tmpfs takes 30ms in Figure 2 (c)), implementing dynamic checkpointing is inefficient for serverless frameworks. However, fast dynamic checkpoint is crucial to implement the remote fork primitive [61] that suits serverless well. We describe it in more details next (§3).

## 3 Overview and Challenges

**Goal: ultra-fast remote fork for serverless computing.** Remote fork is promising for serverless computing because first, it can incur minimal latency and resource provisioning when booting a function to multiple machines. Second, it enables efficient and transparent data sharing between the parent and child containers (i.e., through global variables), which is slow in the traditional approach that leverages an external database [32]. However, existing systems uses a (defective) remote fork with C/R [61], which are inefficient for auto-scaling containers in serverless computing, as we have analyzed in §2.3. MITOSIS seeks to provide an ultra-fast remote fork by co-designing OS with modern interconnect technologies.

**Opportunity: hardware-accelerated, globally addressable memory with RDMA.** Remote Direct Memory Access (RDMA) is a fast and low CPU cost networking feature widely deployed in modern data-centers [63, 28, 25]. RDMA-capable network cards (RNICs) can directly read the memory of remote machines bypassing the host CPUs (i.e., one-sided RDMA READ), with both low latency (e.g., 2µs) and high bandwidth (400Gbps [51]). We observe that RDMA enables efficient global addressable memory: given the (physical) address of the remote machine, reading its content can be completely offloaded to the RNIC in the OS [63]. For remote fork, the child machine can directly read the parent’s mapped page with RDMA bypassing DFS (see §2.4).

**Our approach: imitate local fork with RDMA.** MITOSIS is a new OS primitive that supports forking a container from anywhere. The core idea is to imitate the execution of a local OS fork with RDMA. The key observation is that if each machine’s physical address is globally addressable, minimal data structures copies, e.g., registers and page table—is sufficient to recover a serverless container capable of executing user functions with RDMA. For example, we can first map the children’s VM to remote parent’s physical memory with the copied page table. Afterward, the child OS can leverage RDMA to read from the parent in a read-on-access fashion, similar to the copy-on-write in local fork.

A remarkable difference compared to C/R techniques is that MITOSIS only uses RDMA to restore the children’s execution state during runtime, bypasses any software overhead (e.g., interfacing with DFS) and avoids storing extra local resources (e.g., a local file). Hence, it fundamentally avoids the resource provisioning for fast container startup and achieve an extremely low-latency boot and execution for serverless computing.
3.1 Challenges and approaches

Challenge#1. Efficient and scalable RDMA connection creation. Though RDMA is fast (e.g., 2\(\mu\)s), establishing connections between different machines is orders of magnitude slower (e.g., 4ms), which may significantly increase the startup time of the distributed container. Caching connections to all other machines is impractical as cloud providers have built RDMA-capable clusters with more than 10,000 nodes [25]. To address this issue, MITOSIS leverages RDMA dynamic connected transport (DCT) [1], an underutilized but widely supported RDMA feature for fast and scalable connection setup between machines (§4.2).

Challenge#2. Efficient and safe parent memory control. Kernel can directly use RDMA to access the remote physical memory, which is the most efficient for remote fork. However, the OS may change the parent’s virtual–physical memory mappings in multiple page management mechanisms, e.g., kernel samepage merging [43], transparent huge page [46], swap [44], and others [45]. If directly exposing the physical memory with RDMA, the parent OS must coordinate with all the remote children to prevent them from reading a wrong page upon mapping changes in the active control model of traditional OSes.

A more viable approach is to leverage RNIC’s memory registration (MR) to manage the exposed memory via virtual addresses. Specifically, OS first registers the parent’s virtual memory to the RNIC before the fork. It can then de-register the MR related to the changed page on the fly to reject future access to the page. However, the overhead of memory registration is non-trivial, which increases linearly with the container’s memory and may take several microseconds even for a small container (e.g., 64MB). Further, kernel-space RDMA has a limited support for memory registration, i.e., incompatible with DCT.

MITOSIS proposes a registration-free memory access control method (§4.3) that provides a similar abstraction as MR, yet the RNIC accesses the physical memory. The method is based on the observation that we can replace the RNIC’s memory permission check with network connection permission check by logically assigning different connections to different VM ranges. To reclaim access to the physical memory of a VM range, we only need to shutdown the corresponding network connections. Assigning multiple connections per-container is practical with DCT thanks to its dynamic connecting feature.

3.2 Architecture and execution flow

Architecture. MITOSIS follows a decentralized architecture—each machine can fork from others and vice versa. We extend the kernel with four components shown in Figure 4. The fork orchestrator (§4.1) rehearsals the remote fork and provides interfaces to applications (e.g., serverless frameworks). MITOSIS uses a network daemon to manage RDMA-capable connections in a scalable manner (§4.2). Virtual memory (VM) extends the vanilla OS VM subsystems—including page tables and fault handlers (§4.3) to support read-on-access remote paging with RDMA. Since RDMA alone is insufficient to recover all children’s memory states, MITOSIS leverages RPC to restore them with a fallback daemon hosted on the parent’s OS.

Execution flow. As presented in Figure 3 (c), MITOSIS divides the remote fork into two phases. First, MITOSIS copies the parent container’s metadata (e.g., isolation information and page tables) to a condensed descriptor (§4.1) (1). Second, the child’s OS fetches the descriptor with one-sided RDMA and restores from it, similar as the procedure of process copying in a local fork (2). Note that the restore is more lightweight than C/R because MITOSIS can directly recover from the parent’s in-memory data structures instead of serialized file content. During runtime, MITOSIS transparently read the page from parent via one-sided RDMA in an on-demand way (3) since it has mapped the child’s memory to the remote parent’s physical address.
4 Design and Implementation of MITOSIS

4.1 Fork orchestrator

Serverless frameworks can use orchestrators to fork containers from remote machines. For simplicity, we assume one-hop fork (a container can only fork once, i.e., non-cascading) throughout §4.1–§4.3 and describe multi-hops fork in §4.4.

Interface. MITOSIS adopts a two-phases fork (see the execution flow in §3.2) for serverless workloads and provides a corresponding system call respectively (see Figure 5). The first phase (fork_prepare) generates a local in-memory data structure (container descriptor) that captures the execution states of the parent. The descriptor is globally identified by the parent machine’s RDMA address, a handler ID, and an authentication key (fork meta). MITOSIS will lookup the descriptor at the address’s machine using the handler ID, and the key is used for authentication. With these metadata, the second phase (fork_resume) can fork a child from the parent. We hide the descriptor content from the platform to simplify application’s burden on descriptor management, i.e., the platform only needs to store and pass the fork meta (a few bytes) between machines to fork containers.

A two-phase fork suits serverless computing well. For example, serverless platforms only needs to invoke fork_resume to start containers if it has pre-prepared the descriptors and cached their fork meta at the platform (§5), saving additional network roundtrip for calling fork_prepare.

Container descriptors and shadow container. The descriptor is a condensed in-memory image storing minimal metadata of the parent. It is similar to file images in C/R in functionality but is several orders of magnitude smaller (KB vs. MB), because it does not contain the memory pages. MITOSIS recovers these pages on-demand from the parent machine with RDMA (§4.3). In particular, the descriptor contains: (1) computing resource (e.g., memory) limits and namespace flags—for reconstructing the container isolation boundaries, (2) registers—for recovering execution states, (3) virtual memory related structures, i.e., a list of virtual memory areas and page tables—for virtual memory subsystems, and (4) file descriptors—for I/O recovering.

Similar to the local fork, MITOSIS copies the parent’s process data structures to generate the descriptor. The parent is also marked as copy-on-write to concurrently run with remote children. To achieve so, we first locally fork a shadow container—a local child that never executes and generate the descriptor from the shadow container.

After generating the descriptor, we internally assign a handler ID and an authentication key to it descriptor. We also record a mapping between the fork meta and shadow container and its descriptor so that each machine can handle future descriptor fetches and fallback page requests (§4.3).

Fast RDMA-based container descriptor fetch. Since descriptors are stored at the remote, MITOSIS first fetches the requested descriptor upon fork_resume. A straightforward approach is sending an RPC to the remote machine to copy the descriptor. However, RPC incurs non-trivial overhead due to extra memory copies, especially when descriptors may take several KBs.

For fast descriptor fetch, MITOSIS organizes the descriptor in a compact format and uses one-sided RDMA to read them at remote peers in a zero-copy way. The fetch is two-phase. It first sends an RPC with the fork meta to query the descriptor address and size at the remote machine. MITOSIS returns the results if the ID and the key are valid. We use FaSST RPC [39] that is based on RDMA’s unreliable datagram to achieve connection-less communication between peers to further reduce network handshake costs. With the returned address and size, MITOSIS can thereby issue one-sided RDMA to read the descriptor from the parent machine. Note that it’s safe to pass addresses between machines because they are invisible to the applications.

Fast containerization with generalized lean containers. MITOSIS starts a local container that inherits from the parent after fetching the descriptor. Unlike local fork, MITOSIS should re-construct several process data structures (e.g., cgroup) during startup. MITOSIS categorizes these data structures into two categories and initializes them respectively: (1) impose the isolation boundaries (containerization) and (2) construct process execution data structures, including re-opening files, restoring virtual memory areas and page table and CPU registers.

(2) is fast (e.g., takes sub-millisecond) in MITOSIS because first, we preserve a near-identical VM mapping between parents and children thanks to RDMA’s remote memory feature. Thus, few transformations are required to recover the child’s VM-related structure from the descriptor. Second, serverless containers rarely interact with files since their default execution model is stateless. Stateful serverless functions [73, 36] typically leverage an external storage (e.g., Amazon S3) through the network where the network descriptors are efficient to restore (e.g., 4ms for a connected socket[18]). We follow CRUI [4] to restore file descriptors.

However, containerization (1) is slow due to the overhead including creating cgroups, which may cost more than a hundred of milliseconds. Luckily, fast containerization has been well-studied [53, 8, 15] for single-machine serverless systems. For instance, SOCK [53] introduces lean container that equips with techniques such as creating a pool of cgroups to minimize the containerization overhead. MITOSIS further generalizes SOCK’s lean container to a distributed setting for fast remote fork across machines. Specifically, we
first use SOCK’s lightweight isolation primitives to create an empty container for fast containerization. We then switch the container’s other data structures to the ones recovered from the descriptor. Hence, the resulting container can simultaneously achieves the isolation and execution states of the parent. As such, containerizing takes less than 10 milliseconds for common serverless workloads.

### 4.2 Network daemon

**MITOSIS** deploys a network daemon at each machine to manage RDMA-capable connections. Traditionally, RDMA is only supported in reliable connected (RC) transport, which we found non-optimal for remote fork because it has a huge connection overhead. As shown in Figure 6, RC requires a dedicated connection to each remote node and uses a slow handshake to connect two peers, whose latency is orders of magnitude larger than RDMA requests (4ms vs. 2μs). Further, each machine has a limited throughput creating RCQPs (up to 700 QPs/sec), which significantly limits the fork throughput considering our goal of launching over 10,000 containers within a second. A naive solution would be caching connections to all other nodes in the OS. However, caching is impractical when modern RDMA-capable datacenters have more than 10,000 nodes [25].

**Use advanced RDMA transport.** Dynamic connected transport (DCT) is a less-studied but widely supported advanced RDMA transport. It preserves the functionality and reliability of RC and is connection-less. As illustrated in Figure 6, one DC connection (DCQP) can simultaneously communicate to different nodes. RNIC can reconnect DCQP to different nodes with an extreme low latency (<1μs). To identify which target to use, the sender only needs to pack the handshake to connect two peers, whose latency is orders of magnitude larger than RDMA requests (4ms vs. 2μs). Further, each machine has a limited throughput creating RCQPs (up to 700 QPs/sec), which significantly limits the fork throughput considering our goal of launching over 10,000 containers within a second. A naive solution would be caching connections to all other nodes in the OS. However, caching is impractical when modern RDMA-capable datacenters have more than 10,000 nodes [25].

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We observe that the connection-less nature of DCT is well-suited for remote fork that requires fast startup. After caching a small number of DCQPs at the network daemon, we no-longer pay the RC connection cost when issuing RDMA requests during remote fork. **MITOSIS** further piggybacks the DCT key with the RPC reply of descriptor address (§4.1) to reduce avoid additional network roundtrip to query it.

**Discussion of using DCT.** DCT is slower than RC due to larger request headers and higher processing costs. These overheads is prohibitive for transferring small payloads (e.g., <64B) but has little impacts to **MITOSIS** since **MITOSIS** reads remote pages in large payloads (i.e., page granularity (4KB), see §4.3). For large payloads, transferring the payload dominates the processing time and we confirm that DCT has a similar performance as RC in **MITOSIS**.

### 4.3 On-demand restore via extended VM subsystems

For fast boot, **MITOSIS** initializes minimal container data structures (e.g., page table) when child starts (§4.1). Its physical memory pages are restored during execution via the extended VM subsystems. To fully leverage RDMA, we map the children’s VM to the parent’s physical memory (e.g., stack or file) is also stored in the children’s physical address (PA) is stored in the page table.

**Table 2:** The restore methods of child VM based on whether the virtual address (VA) is mapped to remote and whether the request physical address (PA) is stored in the page table.

| Example      | VA mapped | Parent PA in PTE | Method  |
|--------------|-----------|------------------|---------|
| Code in .text| ✓         | ✓                | RDMA    |
| Mapped file  | ✓         | ✗                | RPC     |
| Stack grows  | ✗         | -                | Local   |

2**DCT Key** is actually composed by a NIC-generated number (4B) and a user-passed key (8B). We treat them as a whole without losing generality.

3A virtual memory area can be partially mapped to the remote, e.g., stack.
a new local page and reads the remote page via one-sided RDMA. Note that the remote physical page may be swapped out or moved. MITOSIS detects such a case with connection-based access control (describe below) and fallbacks to RPC for correctness. If the page is not mapped, e.g., when the stack grows, MITOSIS locally maps and restores them based on its VMA type via the vanilla OS policy.

**Fallback daemon.** MITOSIS restores most of children’s in-memory states with RDMA because they typically touch a subset of its parent’s memory [68, 20]. More specifically, the shared library that a child is typically loaded by the parent to its memory. However, in corner cases the child may touch parent’s unloaded memory. MITOSIS will issue RPCs to read them. In particular, the RPC request includes the requested VA and the fork metas of the descriptor (§4.1), which is handled by a fallback daemon deployed on each machine. After checking the access permissions, the daemon will read the physical page of the shadow container corresponding to the VA, load the page from a secondary storage if necessary, and return to the child. The fallback path is much slower than normal remote page faults but rarely executes.

**Connection-based passive memory access control.** To avoid the registration overhead and incompatible issues of MR (§3.1), MITOSIS directly exposes the parent’s physical memory to the children. Though efficient, this approach means that the OS would lack the access control to the physical pages because remote machines may access them in a CPU-bypassing way with RDMA. To this end, MITOSIS adopts a passive access control model and relies on RNIC to reject requests to the pages reclaimed by the OS. Specifically, the OS first tells RNICs to reclaim certain pages. The remote peer would then passively detect the reclamation with a network request error. They will thereby fallback to RPC and utilize the fallback daemon to read the new physical page corresponding to the fault VA.

Interestingly, RDMA originally provides access checks to host memory with MR, but how to achieve the same functionality without it? The insight is that we can replace RNIC’s memory checks with connection checks. Specifically, we can logically use different connections to access different areas of parent’s VM. If the parent OS reclaims one physical page within one VM area, MITOSIS can close the corresponding connection so that the RNIC will reject future accesses to the page (the area).

MITOSIS assigns one connection to the parent’s each VMA for the fine-grained access control. However, this approach requires many extra connections for each forked container. Thus, it is crucial to minimize the overheads of creating and storing these connections. Luckily, DCT adopted by MITOSIS (§4.2) is well-suited to our connection-based memory access control since it is orders of magnitude smaller in storage and faster than other RDMA connections (i.e., RC). For creation, RC takes several microseconds while DCQP only uses 200

![Fig. 8. An illustration of sharing data between functions in a serverless function chain with remote fork.](image)

μs at the parent and no cost at the children—they can use the cached DCQP (§4.2). Since connections are only logically related to containers’ VMAs, we further cache DC targets at a pool to amortize the cost for creating them. Note that DC targets and DCQPs are compact in storage: the connection at the parent (target) only consumes 144B while child needs 12B key for each connection4. Thus, 1MB of memory can store more than 7,000 DC targets, which is sufficient for forking containers since one container typically has tens of VMAs. In comparison, a single RCQP would require several KBs of storage since it must allocated dedicated queues.

Figure 7 shows how we apply DCT-based access control. Upon fork preparation, MITOSIS assigns one DC target to each parent VMA. These targets are selected from a DC target pool to prevent creation overhead. The keys of these targets are encoded in the parent’s descriptor and are recorded at children’s VMA upon their startup. When reading a parent’s page with RDMA, MITOSIS first finds the VMA of the VA and uses its key to send the request. If one physical page belonging to a parent VMA changes, MITOSIS will destroy VMA’s associated target. Consequently, future requests to the page will be rejected by the RNIC, and children read from parents via RPC with fallback daemon under such a scenario.

**Optimization: remote page sharing.** Reading remote pages from parents may consume non-negligible network bandwidth even with RDMA, which is prohibitive when multiple children concurrently read from the parent machine. Further, they consume extra memory for read-only pages (e.g., shared libraries). Observing that each machine typically fork many children of the same function during auto-scaling, MITOSIS shares the fetched remote page between them to reduce network transfer and memory usage. To achieve so, we track the running instance of the children of a particular parent, mark their fetched pages as copy-on-write and locally restore from these pages whenever possible.

### 4.4 Multi-hops remote fork

Serverless applications can composite individual functions together to build complex applications e.g., using function chain to implement a image processing pipeline [72]. Each function typically depends on previous function’s results, as illustrated in Figure 8. When composite more than two func-

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4Note that we don’t count the network queues of DCT since one queue can be shared by all others: the amortized storage is negligible.
functions sequentially, we need multi-hops fork to fully leverage remote fork for share data between dependent functions, i.e., fork func2 from func1, which itself is forked from func0. Forking func2 from func0 would drop the results of func1, abandoning the transparent data (e.g., data[1]) sharing capability of fork.

Supporting multi-hops fork is similar to one-hop fork in MITOSIS. The main difference is that the grandchildren’s physical pages may spread across multiple elders machines. As shown in Figure 8, data[1] of func2 may reside at func1’s machine while data[0] resides at func0. As such, MITOSIS should track the owner of each remote page. A naive approach would be maintaining an index to track the mapping between virtual page and its owner. However, it would consume non-trivial storage overhead.

To reduce memory usage, MITOSIS encodes the owner in the PTE’s redundant bits. Specifically, each child maintains a copy of predecessor lists whose element is the elder container’s RDMA address and DCT keys for remote memory accesses (see §4.3). Thus, the owner can be compactly represented by the index to the predecessor lists. We dedicate 4bit in PTE to encode these indexes—supporting a maximum of 15-hops remote fork, which is typically sufficient for many serverless workloads.

5 Bring MITOSIS to Serverless Computing

To demonstrate the effectiveness of MITOSIS, we integrate it to FN [70], a popular open-source serverless framework. Though we focus on FN in this paper, MITOSIS is also expected to benefit other container-based serverless computing frameworks (e.g., OpenWhisk [69]).

Basic FN. Figure 9 shows the architecture of FN and our extensions. Developers typically code FN functions with vanilla functions in a high-level programming language (e.g., Python function). The function is linked to a (hidden) function development kit (FDK) that executes an event loop to call the function according to specific events (e.g., user invocations). MITOSIS leverages Docker to run functions. When registering a function to FN, it will generate a Docker image encapsulating the code with the FDK.

FN handles invocations at a load balancer that dispatches them to invokers for function execution. After receiving a function request, the invoker will start the corresponding container with Docker. To avoid cold start, the invoker may execute them with warm start via caching (§2.3).

Seed function. To apply MITOSIS, we first introduce seed function: the seed is a dedicated function container cached at only one invoker for each registered function, which can be forked by others using MITOSIS. Since one seed is sufficient to start all the others, the seed can be cached much longer than FN’s cached function (e.g., 1 hour vs. 1 minute). The seed is chosen by the platform based on the invoker’s available memory and system loads. To balance the memory pressures of machines, we may migrate the seeds between invokers via CRIU [4] in the background. We currently places the seed functions randomly.

Since each function should explicitly call MITOSIS interfaces (§4.1), we extend FN invoker and FDK to generate and handle fork calls, respectively. Specifically, after a running function becomes the seed, its invoker will generate a fork event to our extended FDK. The FDK then calls fork_prepare to create the container descriptor. The descriptor metadata (e.g., handler ID) is returned to the load balancer so that later invocations can leverage MITOSIS to start. The invoker will call fork_resume to start a function if the load balancer sends the fork meta (e.g., handler ID).

Seed store. We cache the fork meta of seed functions at the load balancer to reduce extra network roundtrip to query them. A problem of caching is that the cached seed descriptors could become stale because the physical memory belonging to it may be continuously changing (§4.3). Fortunately, these changes are rare so we periodically renew the seed’s container descriptor (e.g., 10 minutes) to address this issue.

Scheduler. Finally, we extend load balancer to support complex serverless applications that are commonly expressed as Directed acyclic graphs [16, 2] (DAG), where each node corresponds to a function and each edge specifics data dependencies. To accelerate data sharing between nodes, we further use MITOSIS to fork a target node function from the source if it is only pointed by one source.

Since the source may not be a seed function, the scheduler will issue a special execution request such that after the source finish execution, it will call fork_prepare to generate a descriptor and return its fork meta to the scheduler. The scheduler can then fork the target. We only temporarily keep these additional non-seed descriptors and they will be garbage collected after the DAG finishes.

6 Evaluation

Experimental setup. We conduct all our experiments on a local cluster with 24 machines spread over two racks. Each machine has two 12-core Intel Xeon E5-2650 v4 processors and 128GB of DRAM. 18 machines are further equipped with two ConnectX-4 MCX455A 100Gbps Infiniband RNIC with PCIe 3.0 x16 connected to two Mellanox SB7890 100Gbps Switch. We use these 18 machines as FN invokers to execute serverless functions and leave others that do not have RDMA as the load balancers to issue function requests (§5).
We start evaluating MITOSIS with microbenchmarks aiming to answer the following questions:

• **The throughput of remote fork?** To show how fast can MITOSIS fork, we use a container start benchmark to measure how MITOSIS scales with the increasing number of invokers in Figure 10 (a). The functions are invoked by the load balancers that start Python hello-world container in Serverlessbench [72]. We evaluate more complex real serverless functions in §6.4.

From the figure, we can see that MITOSIS can fork more than 10,000 containers with 17 machines (11,002 with total of 18 machines). It’s throughput is 2.1X and 14.1X faster than CRIU-tmpfs and CRIU-remote, respectively. CRIU-tmpfs is bottlenecked by interacting and parsing images from the tmpfs while CRIU-remote has the costs of distributed filesystem. MITOSIS also scales linearly with the increasing of invoker machines because it has not saturated the bandwidth of RDMA. The load-balancer can further start 10,000 function containers within 0.86 second, as shown in Figure 11 (a).

• **The latency of remote fork?** We use the same benchmark but varies the number of load balancer machines, thread and coroutine configuration to measure the latency of function invocation of each method in Figure 10 (b). All invokers are involved in this experiment. MITOSIS can fork 10,000 containers in 858 milliseconds dominated by initializing the sandbox environment, but it’s still 1.9–26.4X faster than variants of CRIU. Note that CRIU has a longer invocation latency than the results in Figure 2 due to the extra create and destroy overhead when integrating to FN.

Note that MITOSIS achieves 46.4% peak throughput as Caching(Ideal), which is bottlenecked by pausing and unpauing running containers. This is because MITOSIS has extra containerization and remote interaction overheads. Nevertheless, it consumes orders of magnitude smaller memory (described below).

• **Memory saving.** MITOSIS not only saves the memory for resource provision but also is more cost-effective during runtime. As shown in Figure 11 (b), caching needs sufficient running instances (48 Python hello-world containers) to achieve the ideal performance: <1ms startup time and 1,300 throughput-per-invoker before running any functions. The cost is 261MB memory consumption for this simple function. In comparison, CRIU-tmpfs needs to provision a 16MB image while others don’t need. During runtime, MITOSIS also consumes 29.8–46.2% less memory compared to CRIU because it doesn’t need to link the CRIU binary. Finally, CRIU-remote may take more runtime memory than CRIU-tmpfs due to extra data stored during file transfer process.

### 6.2 Performance under load spikes

This section evaluates the performance of MITOSIS under load-spikes in real-world serverless workloads (see Figure 1). Since Azure function only provides the function invocation traces not the detailed function invoked [57], we evaluate the spikes with two representative functions from ServerlessBench [72]: TC0 is a simple Python hello-world function while TC1 is a complex image processing function. The request is generated by triggering the requests according to the number of invokers.
Fig. 12. The average latency (a) and memory consumption (b) of TC0 under the spikes of Func 660323 shown in Figure 1.

Fig. 13. The CDF of latency of TC0 and TC1 (see Figure 2) under the spikes of Func 660323 shown in Figure 1, respectively.

Latency reduction. Figure 12 (a) presents the TC0 invocation latencies during load spikes period while Figure 13 (a) summarizes the latency CDF. The geometric mean of 50th (median) and 99th percentile latency of FN+MITOSIS is just 69.2ms and 172.32ms, and is 44.55 and 95.24% smaller than FN, respectively. Though FN achieves a 65.07% cache hit rate during this time period, it still suffers from significant latency increase due to the queuing effect of previous stalled function requests, since the cold start time of TC0 is 1,566X higher than warm start. Meanwhile, MITOSIS also achieves 59.67 and 87.44% smaller median latency than CRIU-tmpfs and CRIU-remote, respectively. MITOSIS is even faster than CRIU-tmpfs because few RDMA is issued for this simple function.

Figure 13 (b) further present the latency CDF on TC1, which is similar to TC0. Note that we omit the latency variations with time of TC1 due to space limitations. The only difference compared to TC0 is that MITOSIS has a similar performance as CRIU-tmpfs on TC1 because it reads more memory pages through RDMA. Nevertheless, we still have 76.35% shorter function invocation time than CRIU-remote.

Memory saving. MITOSIS achieves better performance with less memory consumption thanks to the powerful abstraction of remote fork. As illustrated in Figure 12, at 1.6min, MITOSIS consumes 96% smaller memory than FN (41M vs. 562M) on TC0. TC1 has a similar result so we omit it. The caching dominates the extra memory usage of FN and it decreases slowly even under low loads. This is because a cached instance is only evicted by FN after 30 seconds. Reducing the cache time would significantly decrease the hit ratio of FN. MITOSIS also reduces considerable memory compared to variants of CRIU. At the same time (1.6min), MITOSIS uses 86% and 83% smaller memory than CRIU-tmpfs and CRIU-remote due to less running instances, respectively. These results are aligned with our memory analysis (see Figure 11 (b)) in microbenchmarks (§6.1).

6.3 Data sharing and multi-hops fork

A powerful feature provided by remote fork is transparent data sharing between functions—we pack different functions in the same container and thus they can share data via global variable (see Figure 8). Note that the images and descriptors of CRIU and MITOSIS are not prepared throughout the evaluations in this section.

Data share performance. Figure 14 (a) presents the communication latency for receiving various-sized data using the data transfer benchmark from ServerlessBench [72]. Basic FN uses flow [5] to pass data between different containers, which are warmed for FN. With MITOSIS and CRIU-remote, the sender can store the data in a global variable, and the receiver only needs to read from it. We use rcopy-based CRIU (see Figure 3 (a)) as CRIU-remote in this section since coordinating with Ceph introduces extra communications and is not optimal for evaluations in this section. From the figure we can see MITOSIS is 26.17–66.34% faster than vanilla FN for payloads larger than 100KB, thanks to efficient data sharing with between via RDMA-based remote fork. For smaller payloads, flow piggybacks them in the function requests. MITOSIS is also 37.89-80.10% faster than CRIU-remote. CRIU-remote requires checkpointing the entire image while MITOSIS only dumps a minimal container descriptor in the sender’s DRAM (17.24ms vs. 2.8ms).

Multi-hops fork performance. We evaluate the performance of multi-hops fork by forking a TC0 container sequentially across machines. Figure 14 (b) shows the results. The latency of fork increases linearly with the number of hops for MITOSIS and CRIU-remote as expected. MITOSIS is 87.74% faster to finish one hop since it doesn’t physically checkpoint the image and bypass the overhead of DFS.

6.4 End-to-end serverless applications performance

MITOSIS may introduce extra runtime overhead due to additional latency incurred by RDMA, especially in complex
serverless functions. To quantify these overheads, this section conducts an end-to-end evaluation using real applications from FunctionBench [40]. We compare the startup latency of different approaches in Figure 15 (a) where the latency is normalized to CRIU-tmpfs. Note that we evaluate two variants of MITOSIS: MITOSIS-remote reads all pages from parent via RDMA while MITOSIS-shared uses locally read page to avoid sending extra network requests (§4.3).

From the figure we can see that MITOSIS-remote only incurs up to 1.2X longer execution time than chameleon, while others only take 1.01–1.05X more time. The increases are mainly due to extra latency of remote fetches, since CRIU-tmpfs restores from local DRAM and RDMA’s latency is still orders of magnitude high than DRAM [19]. For example, chameleon that renders an HTML page requires reading 2,303 pages from remote. Note that CRIU-tmpfs has to pre-prepare function images on each machine while MITOSIS only need to prepare one across the cluster. Meanwhile, MITOSIS-remote reduces the startup latency of CRIU-remote by 25–82% where both systems have the same resource provisioned. Finally, MITOSIS-shared has 4–29% latency reduction compared to CRIU-tmpfs thanks to the more lightweight restore, i.e., bypass the local filesystem. Sharing pages is common when auto-scaling multiple containers of the same function (e.g., in load spikes of §6.2).

6.5 Factor analysis

As illustrated in Figure 15 (b), the base MITOSIS, which creates RCQP upon child start can only achieve a peak throughput of 700 containers per second, bottlenecked by creating RDMA connections. Adding DCT (+DCT) fundamentally addresses this issue. Finally, sharing pages between containers further improves the peak throughput by 1.1X.

7 Related Work

Optimizing serverless computing frameworks. MITOSIS continues the line of research of reducing startup time for serverless computing frameworks [53, 8, 60, 20, 65], and we particularly focus on booting containers at remote machines. FAASM [60] uses language-based sandbox instead of containers for executing serverless functions. For other, container-based solution we have extensively compared with them (e.g., SOCK [53]) in §2.

Although the implementation of Linux fork may not be optimal in some scenarios [71, 14, 75], it can be suitable for accelerating the booting of serverless functions [8, 20]. Inspired by them, MITOSIS is an efficient fork primitive that targets forking serverless functions among physical machines.

Besides boosting the startup speed of serverless functions, existing work also investigates how to achieve fault tolerance [73], fast communication [36], realizing transactional causal consistency for serverless functions [48], and cost-efficiency [74] in serverless computing, which is orthogonal to MITOSIS.

Finally, recent works also consider better scheduling policy to reduce resource provisioning for caching [24, 56, 42, 55]. We believe MITOSIS can provide better flexibility for these works since minimal resource provisioning (one cached seed function) is sufficient to warm boot other instances.

Checkpoint and restore. The mechanisms of checkpoint and restore (C/R) has been investigated by OSes for a long time [21, 47]. For examples, KeyKOS [30], EROS [59], and Aurora [64] embrace the abstraction of single level store and make the whole-system checkpoint periodically for crash consistency; many researches on Linux [31, 41, 4, 76, 66] can dynamically generate applications’ checkpoints which can be restored after crashes or on other machines. VAS-CRIU [66] also notices the inefficient of C/R brought by the file abstraction. They leverage multiple independent address spaces (MVAS) [29] to reduce these overhead but MVAS is only support in a single machine. MITOSIS builds fast remote fork in a C/R-like way but leveraging the distributed addressable memory feature of RDMA, and targets efficient auto-scaling for serverless computing.

Remote paging with RDMA. Reading pages from remote hosts via RDMA is a common technique in modern OSes [9, 27, 7, 49, 58]. Infiniswap [9] allows swapping out pages to free memory on remote machines to support larger application capacity. Remote region [7] is an abstraction to expose a process’s memory to remote peers via RDMA. MITOSIS further considers fast RDMA-based remote fork via extended paging systems.
8 Conclusion
This paper presents MITOSIS, a new OS primitive for fast remote fork for serverless computing to improve function startup with minimal resource provision. The key insight is to co-design OS with fast datacenter interconnects with remote memory access capability. We address challenges including efficient global memory control when designing MITOSIS. Implementation on Linux and integration to FN demonstrate that MITOSIS can provide better response time on real-world serverless workloads with orders-of-magnitude smaller memory usage.

9 Acknowledgment
We thank WenTai Li, QingYuan Liu, Zhiyuan Dong and Dong Du for their valuable feedbacks. This work was supported in part by a research grant from Huawei Technologies.

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