Benchmarking, Analysis, and Optimization of Serverless Function Snapshots

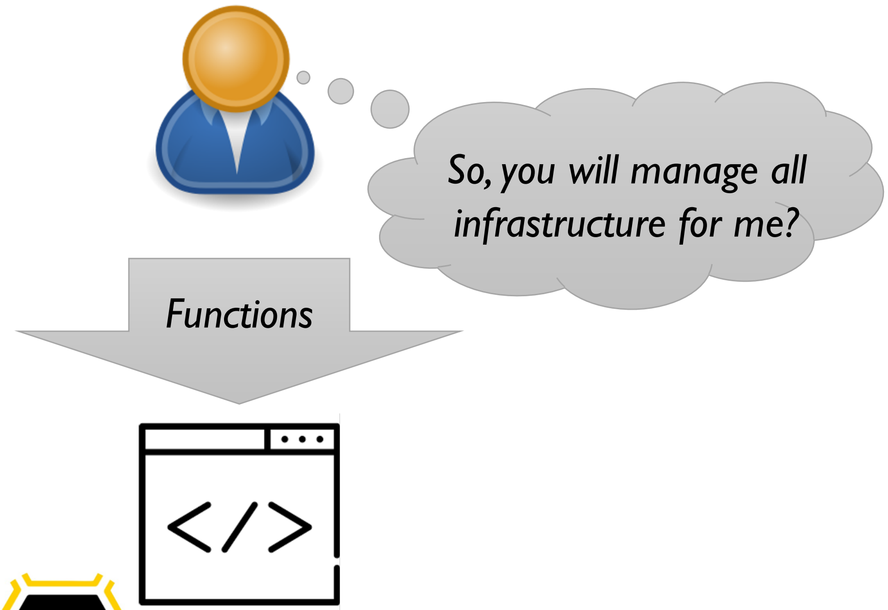
Dmitrii Ustiugov,

Plamen Petrov, Marios Kogias, Edouard Bugnion, Boris Grot

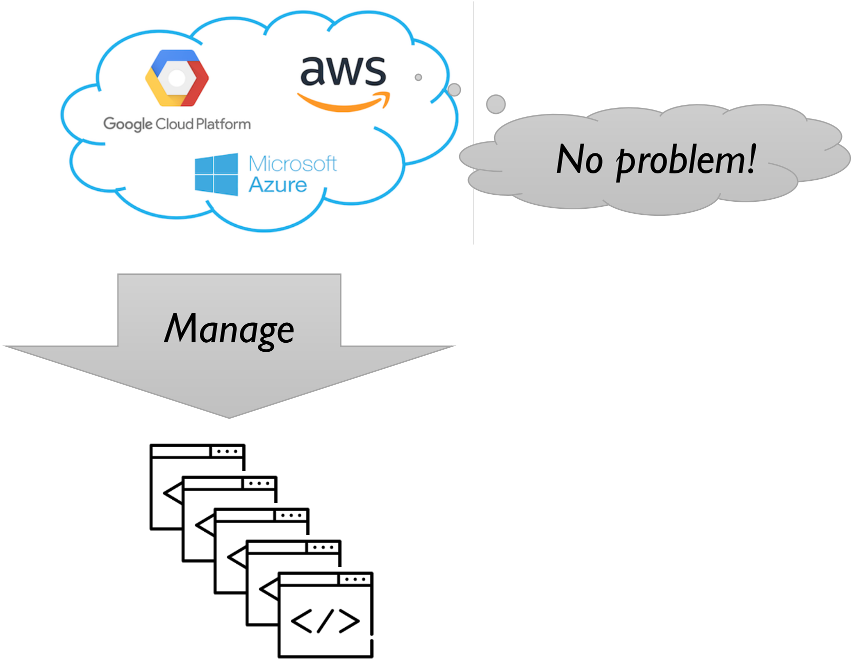
Why Users Love Serverless

THE UNIVERSITY of EDINBURGH informatics

Happy serverless user



Serverless providers



How to study serverless systems?

Studying Serverless: State-of-the-Art Frameworks

THE UNIVERSITY of EDINBURGH informatics

Bleeding-edge but **proprietary** systems
- Complex distributed software stack

Incomplete or **non-representative**
- Single component, e.g., hypervisor
- Container isolation only (e.g., OpenWhisk, OpenLambda)
  - but >70% of providers (AWS, Azure, Google) rely on VMs

vHive

Need for a complete open-source framework for serverless research

Serverless in the Age of Open Source

THE UNIVERSITY of EDINBURGH informatics

Kubernetes + Knative

Cluster scheduler & Function-as-a-Service API (Google & CNCF)

containerd

Host management (CNCF)

Firecracker

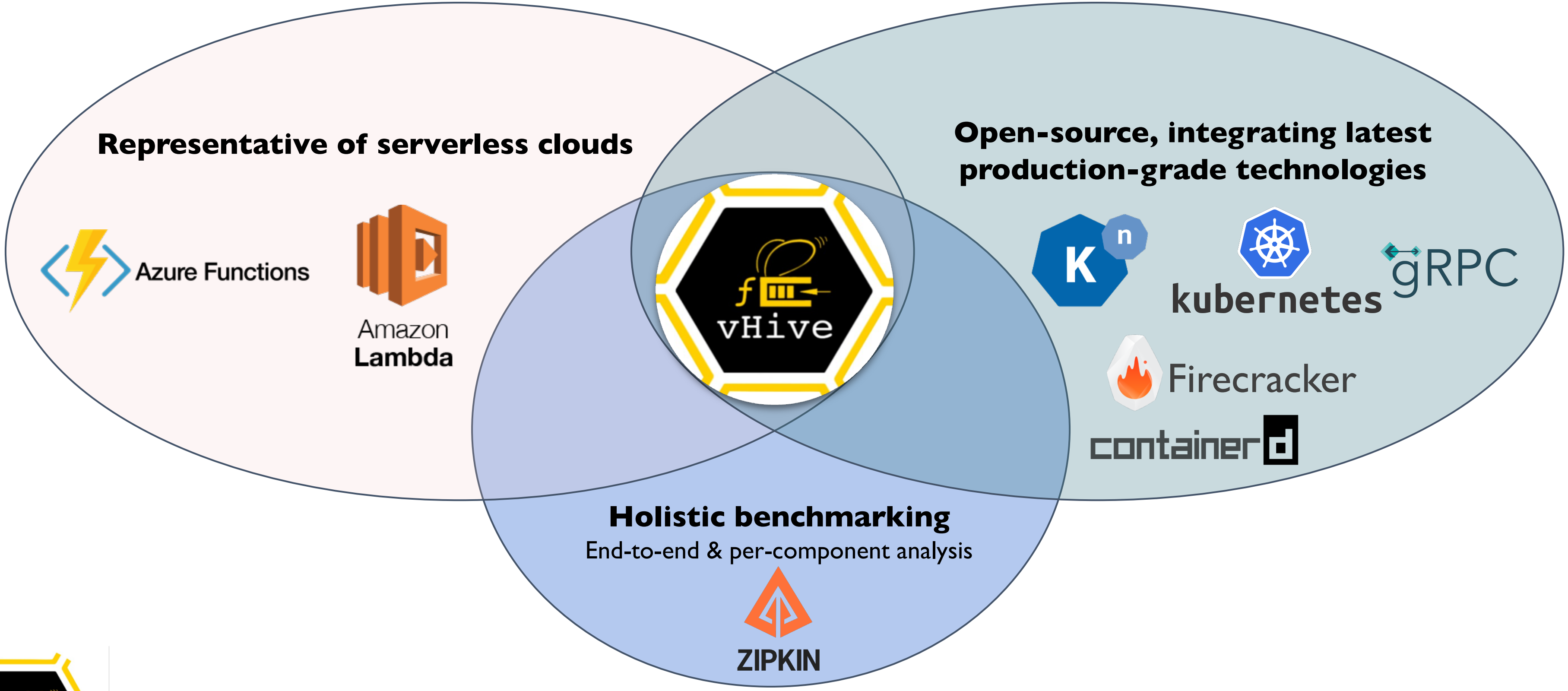
MicroVM (AWS Lambda)

gRPC

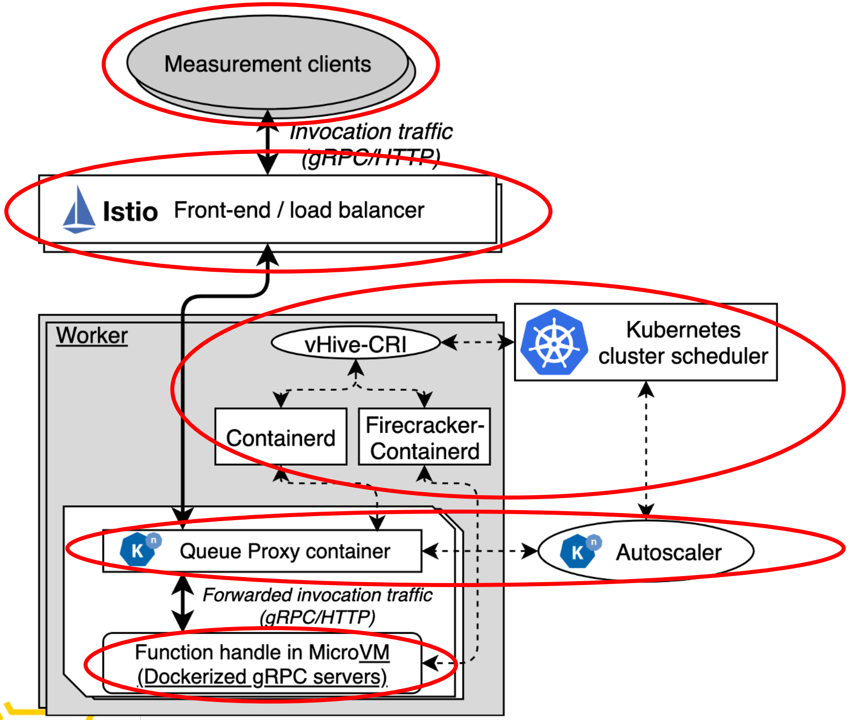
Communication fabric (Google)

vHive

vHive: Framework for Serverless Experimentation



vHive-CRI Integration



Load and **latency** measurement clients

Istio as load balancer

Kubernetes cluster scheduler

A function instance deployed as a Kubernetes pod, including

- **Queue-proxy** container (per function instance)
  - Monitors per-instance queue depth
  - Drives function autoscaling
- Firecracker **MicroVM** with a function handle

First to support snapshotting at scale

vHive integrates all serverless components in an open-source research framework

Characterizing Cold Starts with vHive

Why Providers… Struggle with Serverless

Happy serverless user

*Can I invoke my functions **once per hour**?*

*and… they run for **1 second***

*and… they should be **fast** & **cheap**!*

Serverless providers

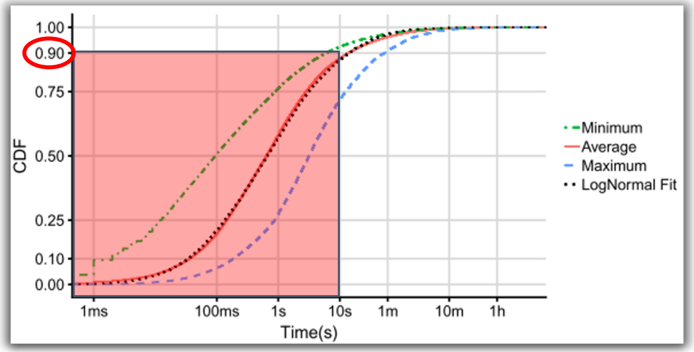
How common are rare and short function invocations in serverless?

FaaS Characteristics [Azure Functions, ATC'20]

Functions are **short** (user code)

- 670ms on average
- 90% execute for <10 seconds

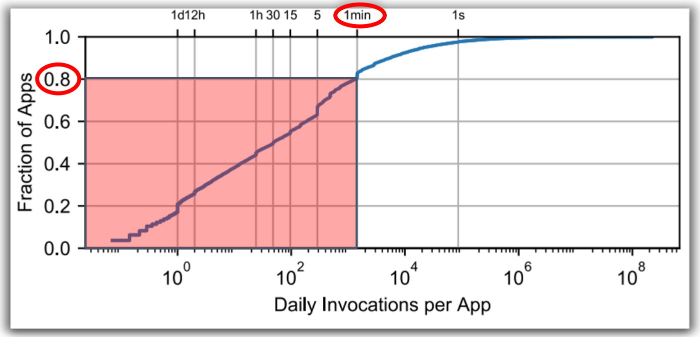
Function execution time (user code)



The majority of functions are rare ("**cold**")

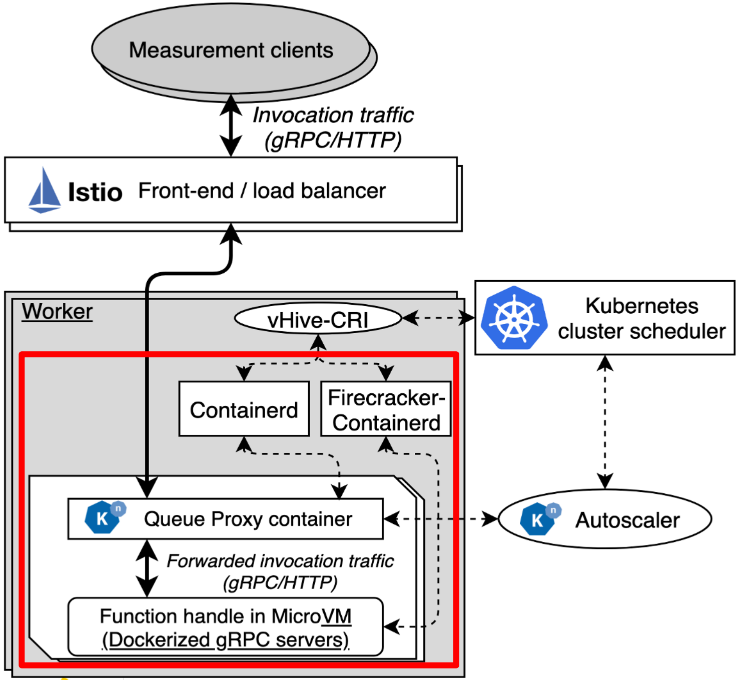
- 80% invoked less than once per minute

Average interval between function invocations



Short and cold functions are dominant

Why Cold Starts are Slow?



Cluster delays are low (<20ms)

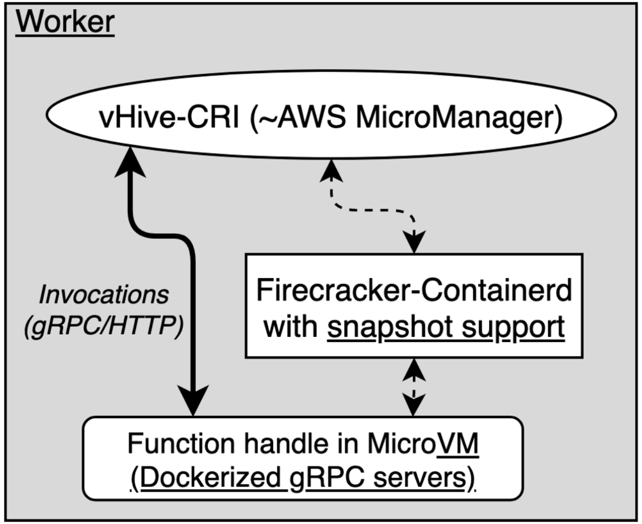
- Corroborating [Firecracker, NSDI'20]

Worker-internal delays dominate (helloworld, Python)

- Boot-based cold start: >2 seconds
- Firecracker snapshots: 100s of milliseconds

Cold start delays dominated by internal worker delays

Evaluating Worker-Internal Delays



Goal: Careful modelling of a single worker, similar to AWS Lambda

- MicroManager terminates connections to MicroVMs & Front-end

vHive single-node configuration

- MicroManager injects the invocation traffic to function instances

Extended Firecracker-Containerd to support VM snapshots

Firecracker Snapshotting Support

Function instance is snapshotted **after** function server initialization

Firecracker snapshots implementation follows Catalyzer [ASPLOS'20]

The procedure of loading a VM from a snapshot includes:

1. **Loads** the state of the VM monitor (VMM), virtual NICs and disks
2. **Mmaps** the guest memory file **without** populating its contents
3. **Resumes** function execution from the point of snapshotting
4. **Restores the connection** between the function server and the MicroManager

How fast is Firecracker snapshotting for cold functions?

Methodology: Serverless Characterization with vHive

THE UNIVERSITY *of* EDINBURGH informatics

Host specs

- 48-core Haswell Xeon, Linux v4.15 (Ubuntu 18)
- Snapshots stored on a local SSD (SATA3 850MB/sec)
- Large inputs (e.g., videos) stored in a MinIO object store

MicroVM specs

- Linux v4.14 (Alpine), 1 vCPU, 256MB RAM

Functions adopted from FunctionBench [SoCC'19]

- Wide range of single-function serverless workloads

Emulating cold invocations

- **Assumption**: guest memory pages evicted from memory
- **Modelling**: flush the host-OS' page cache after invocation

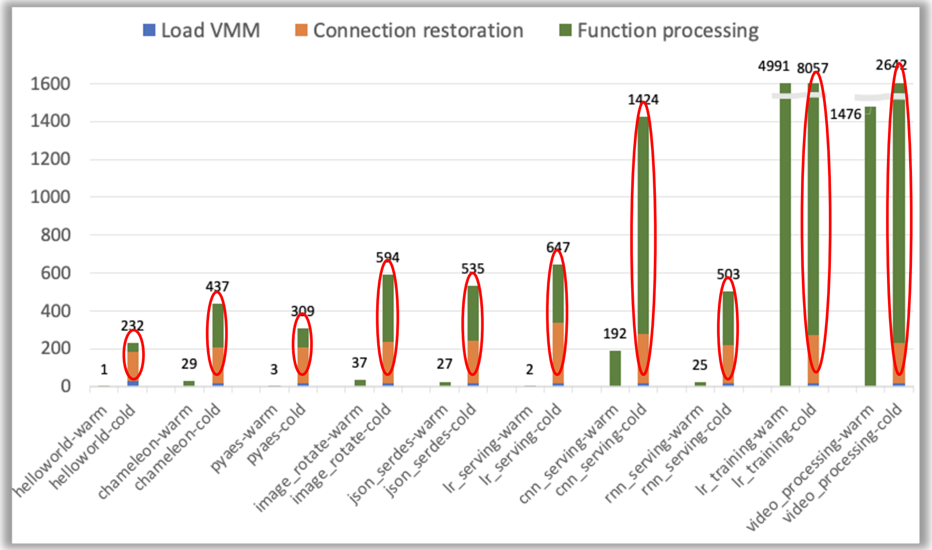
Evaluated functions from FunctionBench [SoCC'19]

Name	Description
helloworld	Minimal function
chameleon	HTML table rendering
pyaes	Text encryption with an AES block-cipher
image_rotate	JPEG image rotation
json_serdes	JSON serialization and de-serialization
lr_serving	Review analysis, serving (logistic regr., Scikit)
cnn_serving	Image classification (CNN, TensorFlow)
rnn_serving	Names sequence generation (RNN, PyTorch)
lr_training	Review analysis, training (logistic regr., Scikit)
video_processing	Applies gray-scale effect (OpenCV)

vHive

Cold Invocation Delay with Snapshots

Warm-start (left bars) and cold-start latencies (right bars), ms



Cold start delays dominated by:

- Connection restoration
- Useful function processing

Key: cold invocations are **~20x** slower than warm

What slows function processing down?

Function Memory Usage Characterization

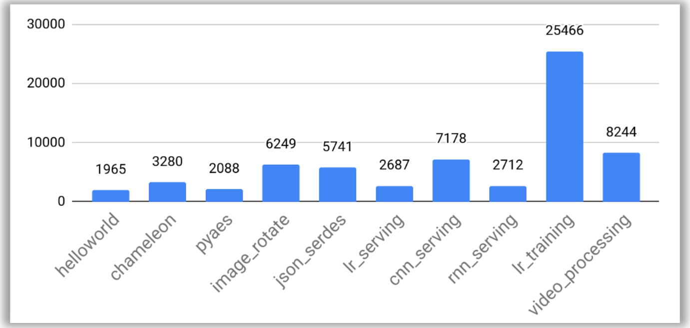
Functions have a **non-negligible** memory footprint

- High-level languages: Libraries and modules
- High infrastructure tax: gRPC fabric, kernel code, …

Recall: Snapshots rely on **lazy paging**

- Guest memory (file) is mapped but not populated with contents
- Page faults result in **20x slowdown** (avg)
  - **Serial**: Page faults occur one at a time
  - **No spatial locality**: Pages are scattered across the guest memory

Number of page faults during a single invocation



Observation: Serial & sparse disk accesses slow down function execution

- Linux run-ahead prefetching is inefficient due to the lack of locality

Page faults dominate snapshot-based cold invocation latency

Key Insight: Function Working Sets are Stable

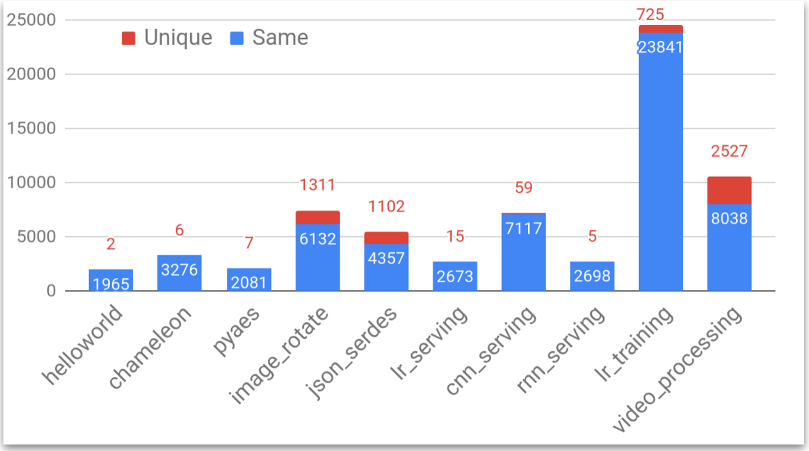
THE UNIVERSITY of EDINBURGH informatics

Study: Trace page faults with `userfaultfd`
(stock Linux user-level page fault handling mechanism)

Memory footprint is **non-trivial**
- Functions touch **8-99MB** upon each invocation

Key: Function working sets are **stable** across invocations
- Same language runtime, libraries, guest networking stack, …
- **76-99%** of pages are the same, even with different inputs!

Memory footprint, number of pages



vHive

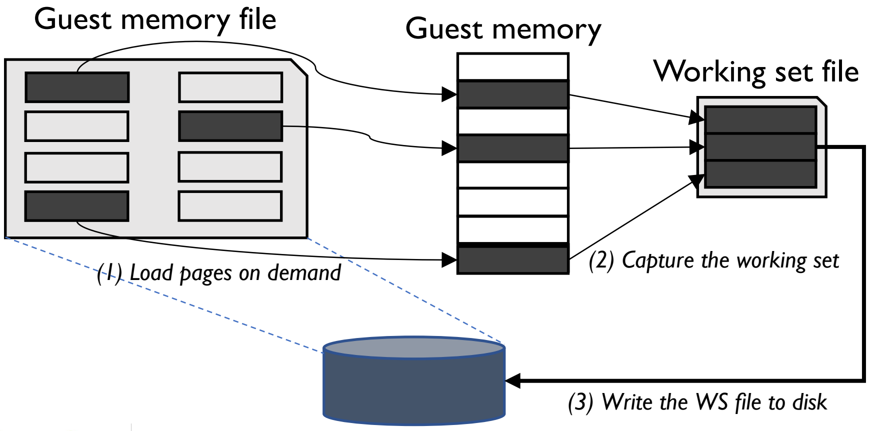
Idea: Record and prefetch the working set pages

REcord-And-Prefetch (REAP) Snapshots

THE UNIVERSITY of EDINBURGH informatics

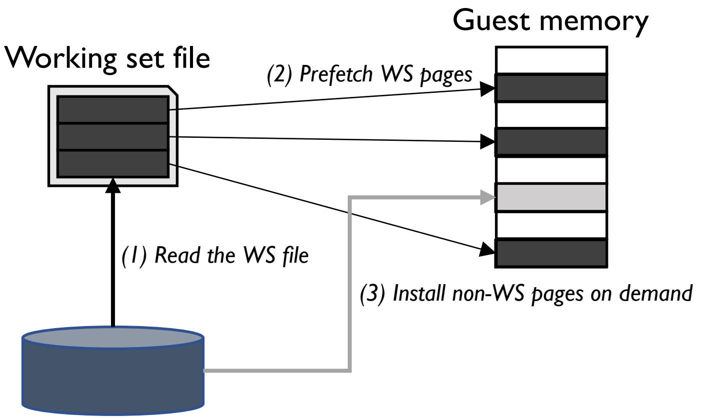
Record phase (1st invocation)

1. Intercept page faults with Linux `userfaultfd`
2. Capture working set (WS) pages in a compact file
3. Write the WS file to disk (SSD, HDD, AWS S3, …)



Prefetch phase (2nd and future invocations)

1. Read the WS file from the disk
2. Prefetch **all** WS pages into the guest memory
   - Also, install the page mappings into the host page tables
3. Install **missing,** non-WS, pages **on demand**



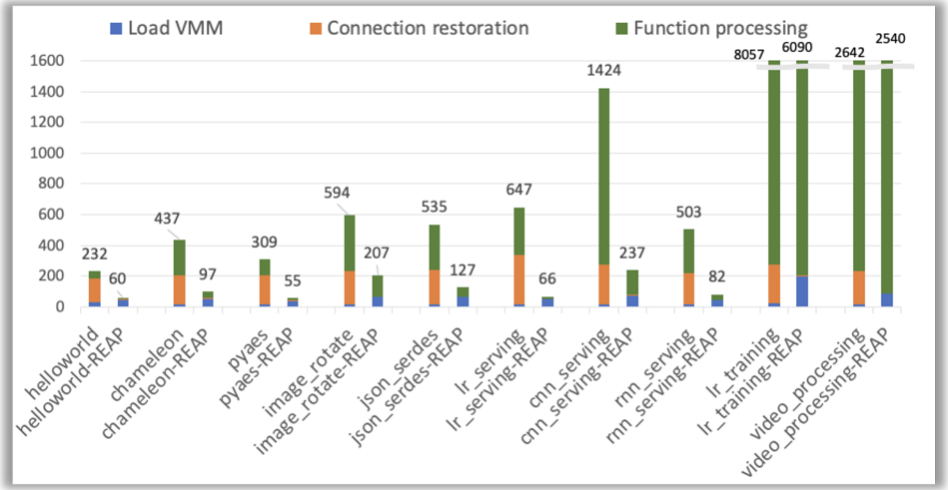
vHive

REAP trades off a little extra storage for faster cold starts

Evaluation: FunctionBench [SOCC'19]

THE UNIVERSITY of EDINBURGH informatics

Single function cold start latency, ms
(left bars: Firecracker snapshots, right bars: REAP)



REAP slashes connection restoration by **45x**

- Efficient prefetching of gRPC & network stack

Function processing reduced by **4.5x** (avg)

- Exception: video_processing, likely due to OpenCV's memory allocation depending on video aspect ratio

3.7x faster cold invocations, on average

vHive

Takeaways

We introduce the open-source **vHive** framework for serverless experimentation

Key insight: A function uses the **same** guest memory pages **across** invocations

We introduce **RE**cord-**A**nd-**P**refetch **(REAP)** technique

- Record working set (WS) pages upon 1st invocation, prefetch upon future invocations
  - Reduces the cold-start latency by **3.7x** (avg), by eliminating **97%** of page faults
- **Seamless** integration with Firecracker and Containerd (<250LoC)
  - Entirely in user space and infrastructure agnostic

Join the vHive Open-Source Community

https://github.com/ease-lab/vhive

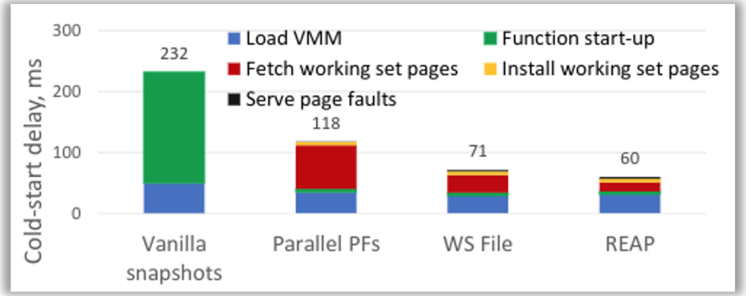
Slack: firecracker-microvm.slack.com, channel: #firecracker-vhive-research

Academic contributors:

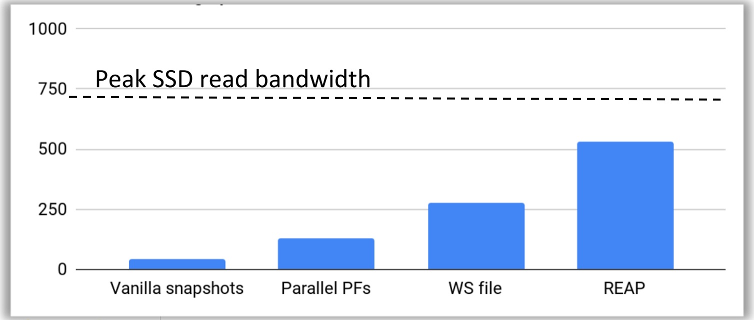
Industrial collaborators:

Evaluation: Optimization Steps (helloworld)

Single cold function invocation latency (prefetch phase)



SSD read throughput, MB/s



Vanilla snapshots: Load VMM and serial page fault processing

- Serial major page faults are slow

Parallel page faults: Fetch WS pages from large guest memory file

- Many SSD accesses to scattered locations in SSD

WS file: Fetch WS pages from a compact WS file

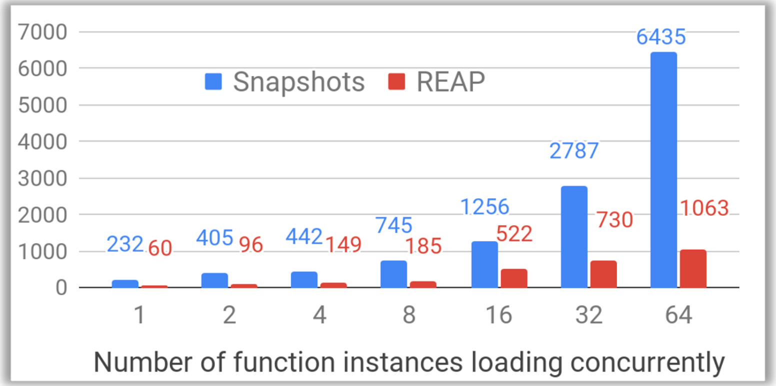
- Host filesystem limits SSD read bandwidth

REAP: Fetch from a WS file & bypass host OS page cache

Evaluation: Concurrent Cold Invocations

THE UNIVERSITY of EDINBURGH informatics

Cold-start latency if concurrently loading (all helloworld, avg)



REAP cold-start delays grow **sub-linearly** with concurrency

REAP extracts **4-6x** higher read SSD throughput

REAP becomes **SSD-bandwidth bound** with >16 instances

vHive

REAP shows better scalability **and** lower latency