Towards Virtual Machine Image Management for Persistent Memory

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Parallel and Distributed Software Technology Lab

Nankai - Baidu Joint Laboratory

Agenda

- Background & Motivation
- Design & Optimization
- Performance Evaluation

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Background | Motivation | Overview

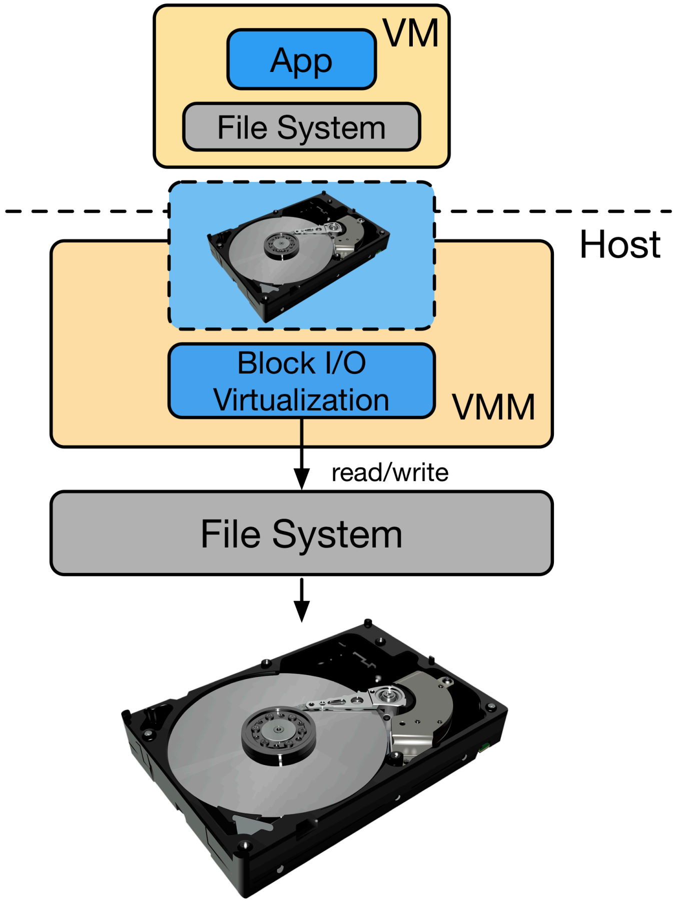
What is Persistent Memory (PM)?

- DIMM form device based Non-Volatile Memory (NVM) technologies.
- Also known as Storage Class Memory (SCM).
- Compared with DRAM :
  - Higher capacity
  - Non-volatile data storage
- Compared with external block storage:
  - Byte-addressable
  - Ultra-low latency (<1 us)

Intel’s DIMM form persistent memory

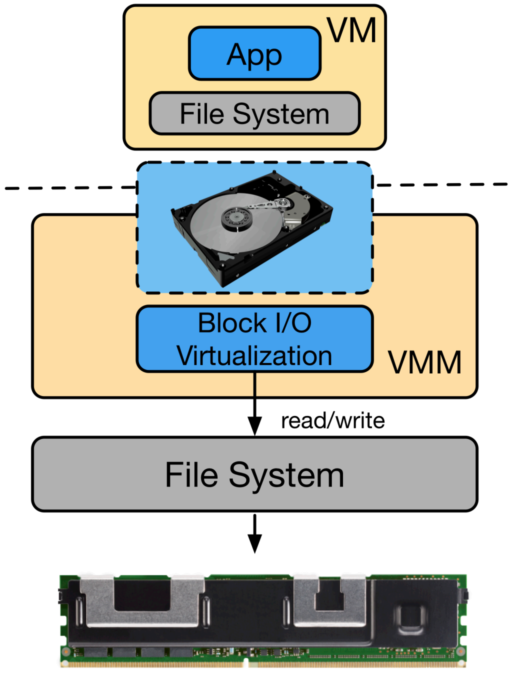
Block Storage Virtualization

- Virtual Machine Monitor (VMM) emulate a virtual disk inside the virtual machine.
- Virtual disk is backed by an image file created on the host file system.
- Virtual disk emulation and image file management are handled by VMM's block I/O virtualization mechanism.

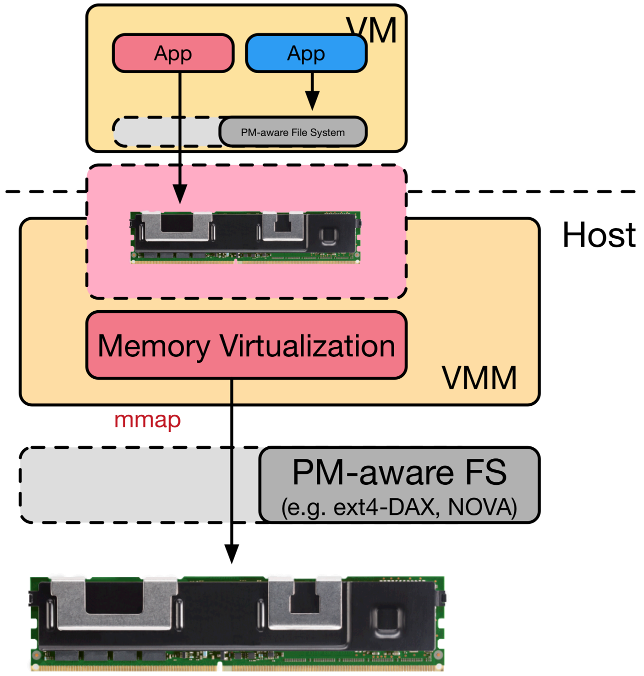


Background | Motivation | Overview

PM Device Virtualization



I/O virtualization

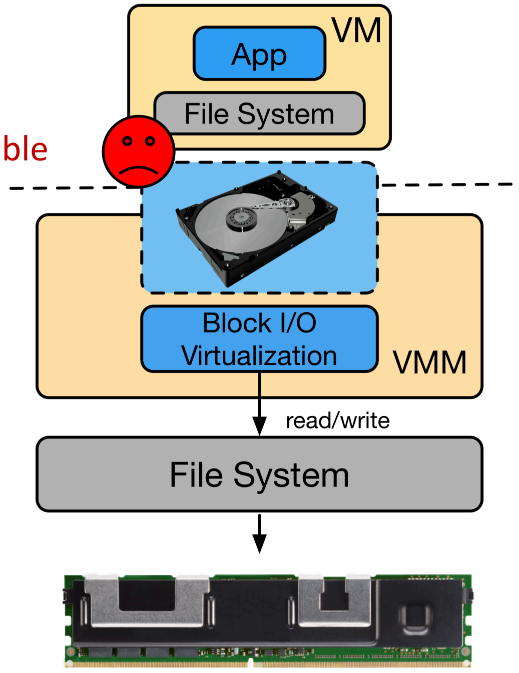


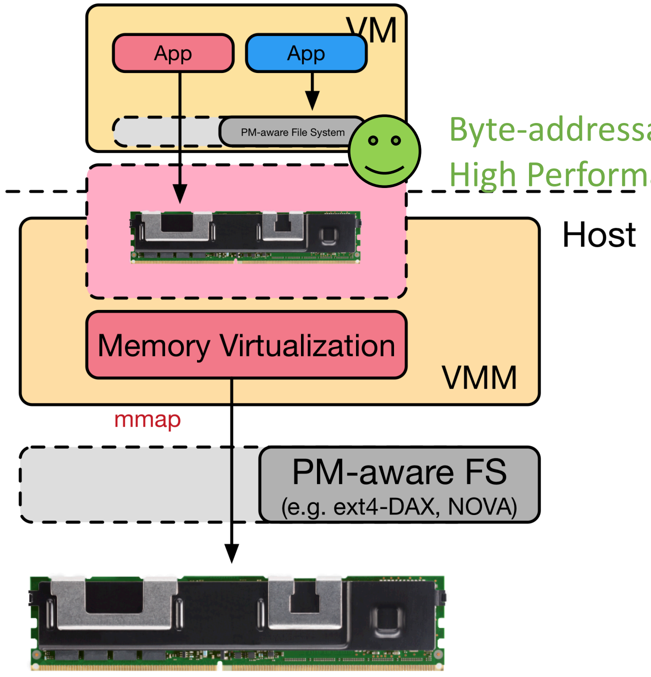
Memory virtualization

Background | Motivation | Overview

PM Device Virtualization

Not byte-addressable
512 B granularity





Byte-addressable &
High Performance

I/O virtualization

Memory virtualization

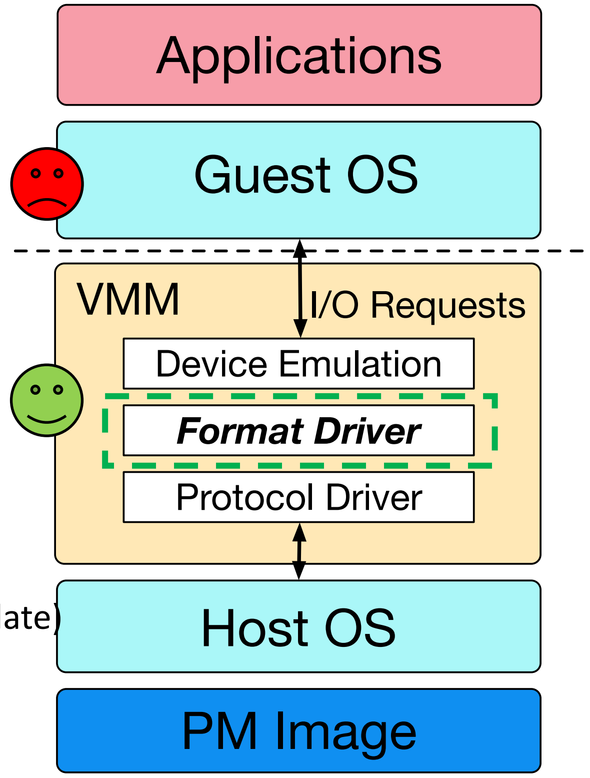
Which one should we choose?

Data Access Path of the Two Mechanisms

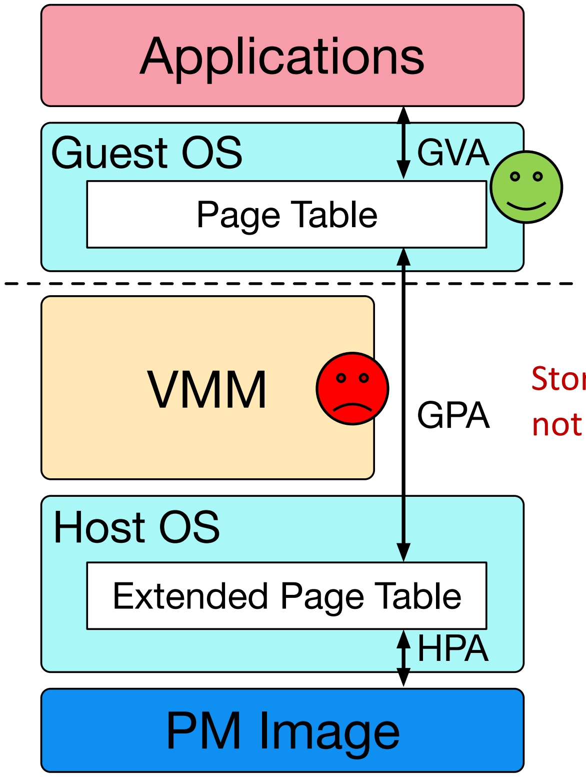
Not byte-addressable

Storage virtualization features:
(e.g. qcow2)

- thin-provision
- snapshot
- Base image (template)



QEMU's Block IO Virtualization



QEMU's Memory Virtualization

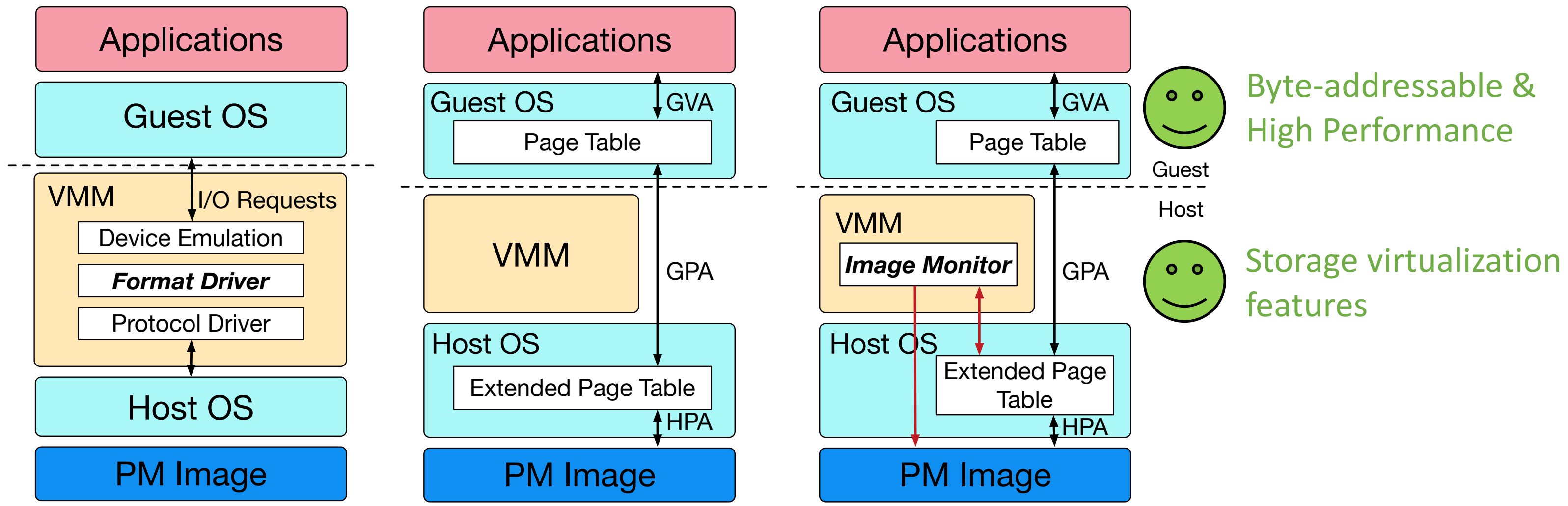
Byte-addressable & High Performance

Storage virtualization not implemented!

Storage Virtualization Features

- **Thin-provision** tends to promise users a large storage space while allocating much smaller space at the beginning.
- **Snapshot** protects the data as read-only after a snapshot is taken. It provides user the option to roll-back the image to any snapshot point.
- **Base image** is also called template, it provides the opportunity to build a new image based on images created before.

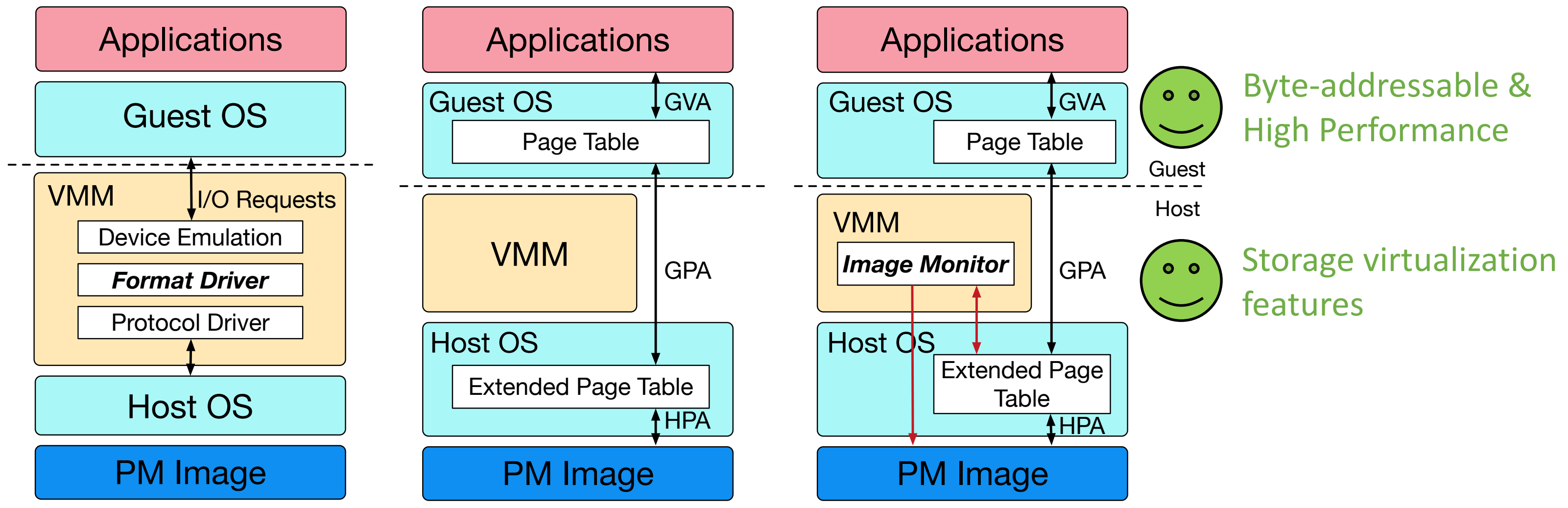
Motivation



(a) I/O virtualization (b) Memory virtualization (c) Our enhanced memory virtualization

	I/O Virtualization	Memory Virtualization	Our Scheme
Byte-addressability (PM form in Guest)	✗		
Storage Virtualization (Image management in host)		✗	

Motivation



(a) I/O virtualization (b) Memory virtualization (c) Our enhanced memory virtualization

Challenge:

Data access by-pass the VMM when using memory virtualization.

Opportunity:

PM can take advantage of hardware-assisted address translation designed for memory virtualization (nPT or EPT) to perform the translation between virtual PM address and image file offset.

Overview

Enhance QEMU's memory virtualization mechanism by an ***Image Monitor.***

Design a VM image format called ***Pcow*** (short for PM Copy-On-Write).

Three storage virtualization features implemented with help of ***Image Monitor*** and the ***Pcow*** format:

- Thin-provision
- Snapshot
- Base image (templete)

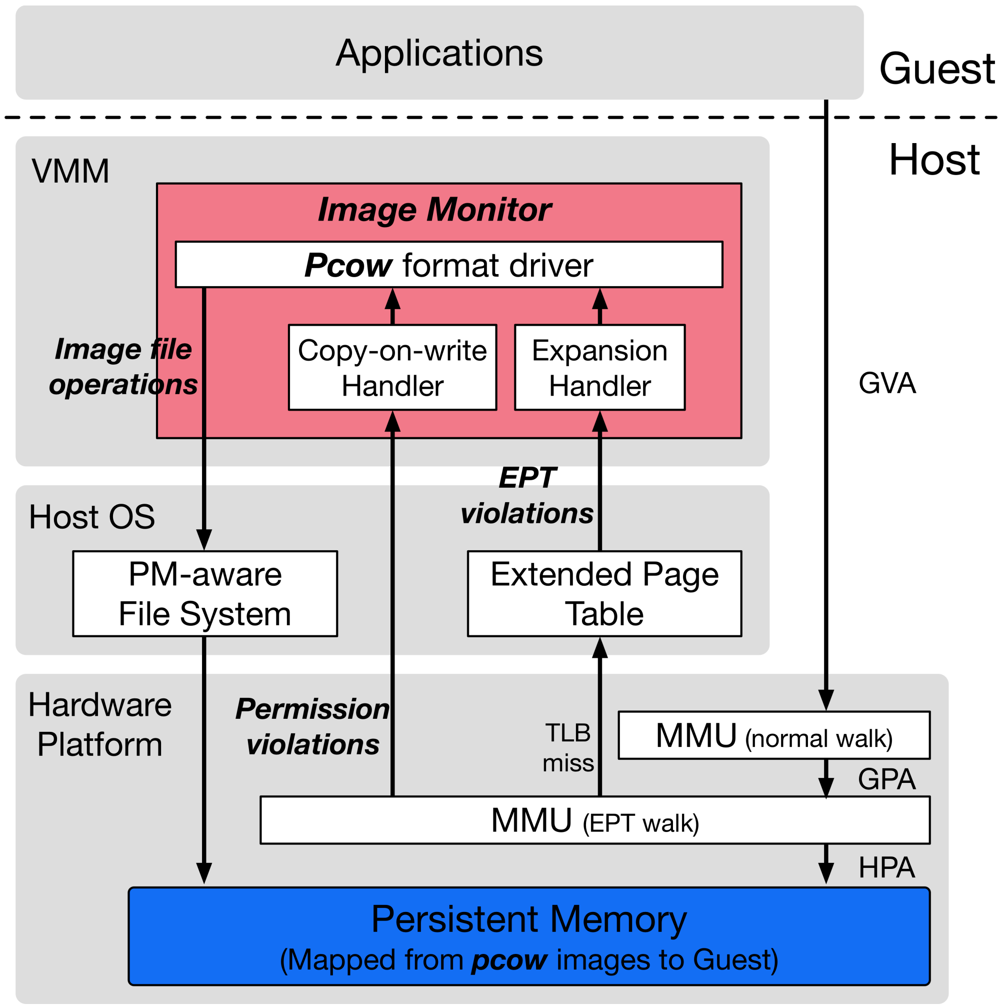


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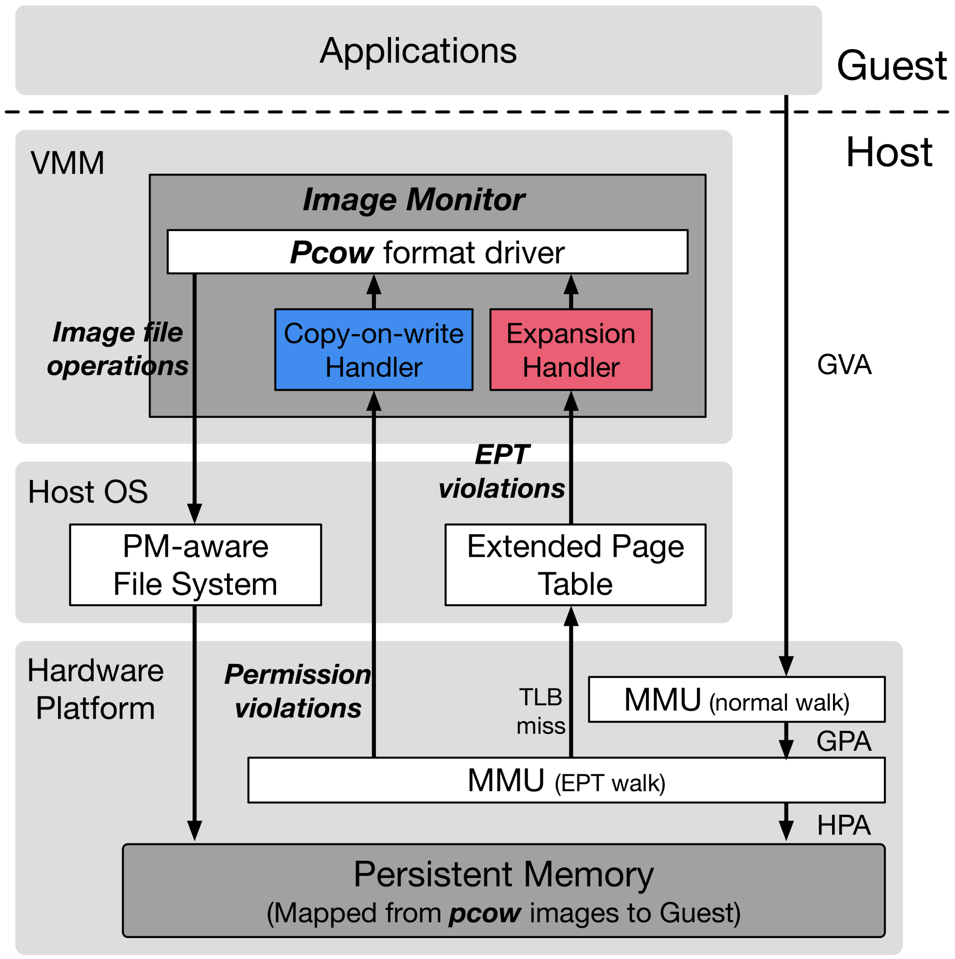
Image Monitor | Pcow Format | Details | Optimization

Expansion handler

- Expands the image file on demand.
- The basis of thin-provison, snapshot and base image features.
- An user-space page fault handler (Linux's new userfaultfd feature).

Copy-on-write handler

- Protects read-only data from being written using copy-on-write.
- The basis of snapshot and base image features.
- An SIGSEGV signal handler. (Raised when writing to a write-protection area)



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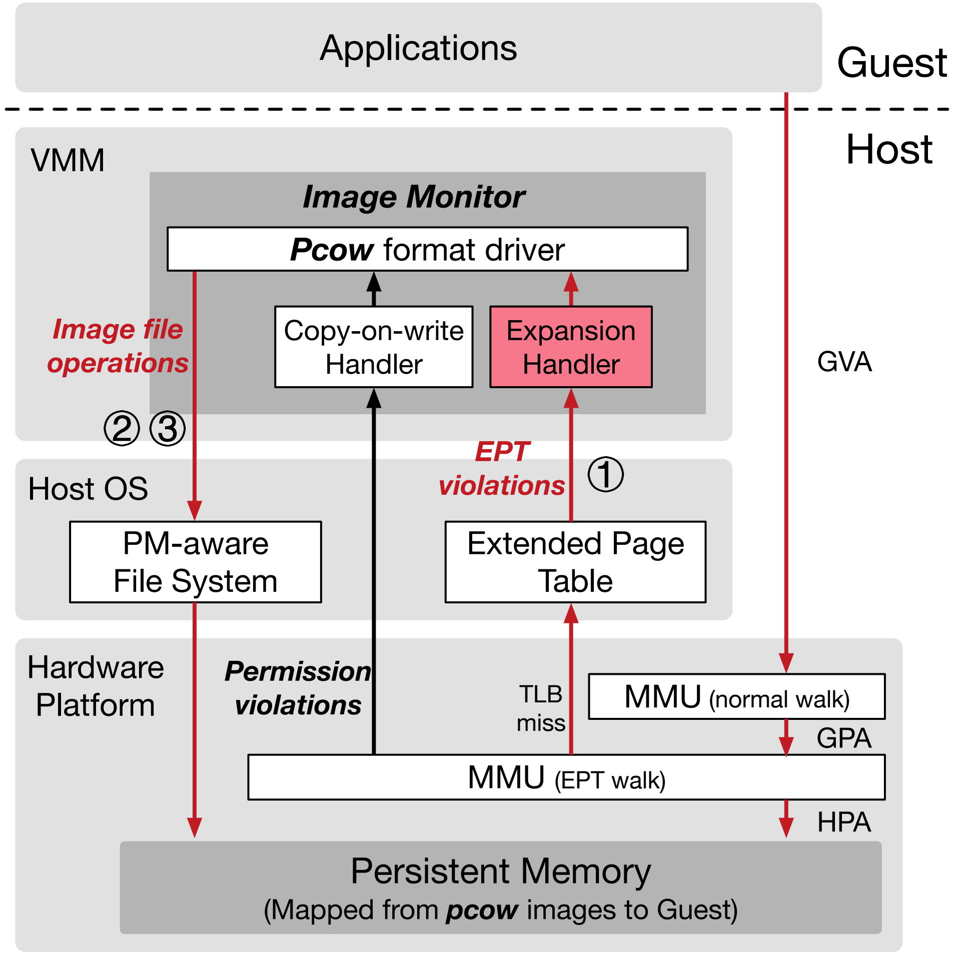
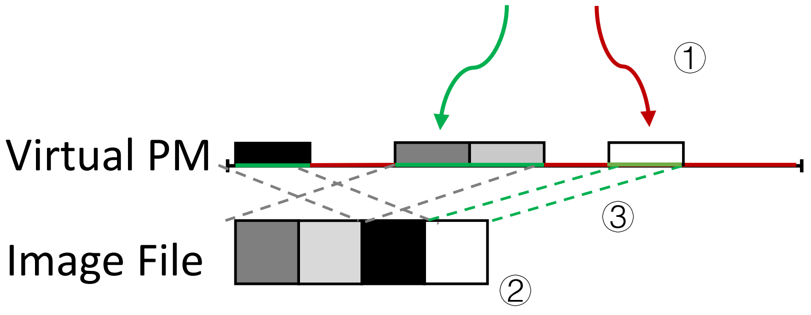
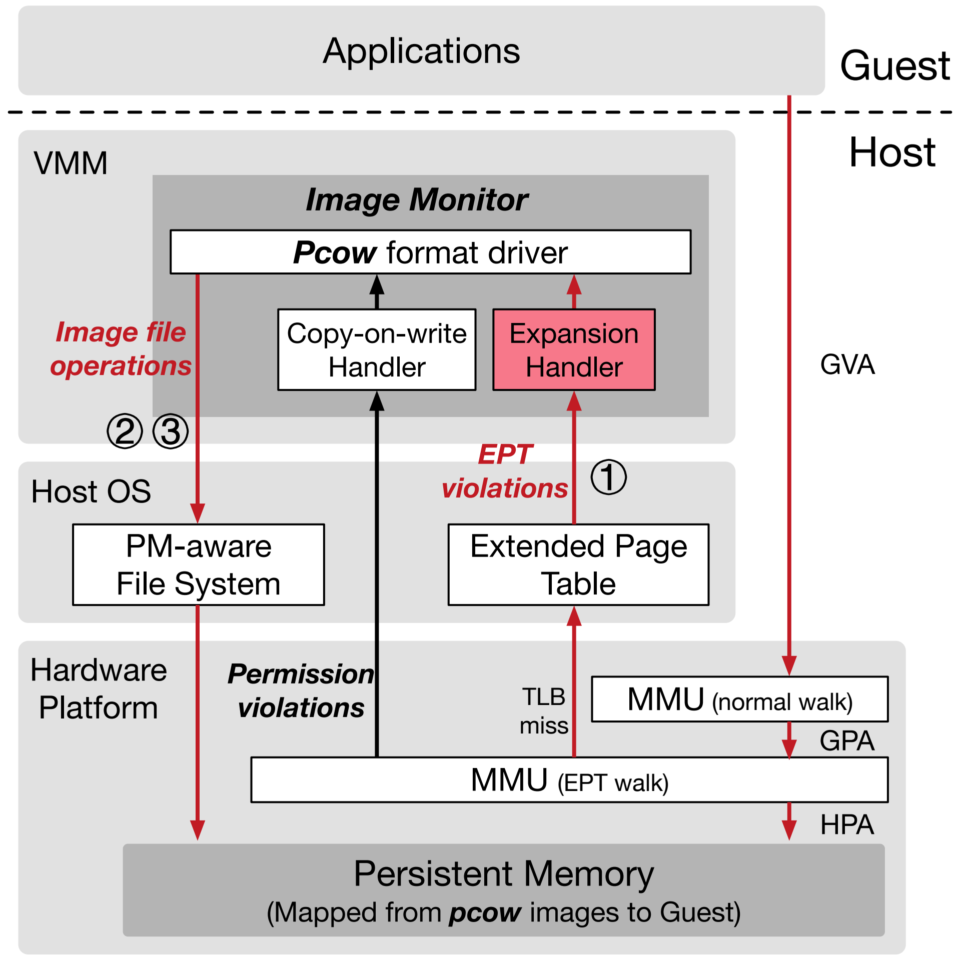


Image Monitor | Pcow Format | Details | Optimization

Expansion handler





① Guest Apps touch a page with no PM image file backed, the Expansion Handler is invoked.

② Pcow format driver allocates a new block at the end of the pcow image file.

③ Expansion Handler maps the newly allocated block to the fault address.

Image Monitor | Pcow Format | Details | Optimization

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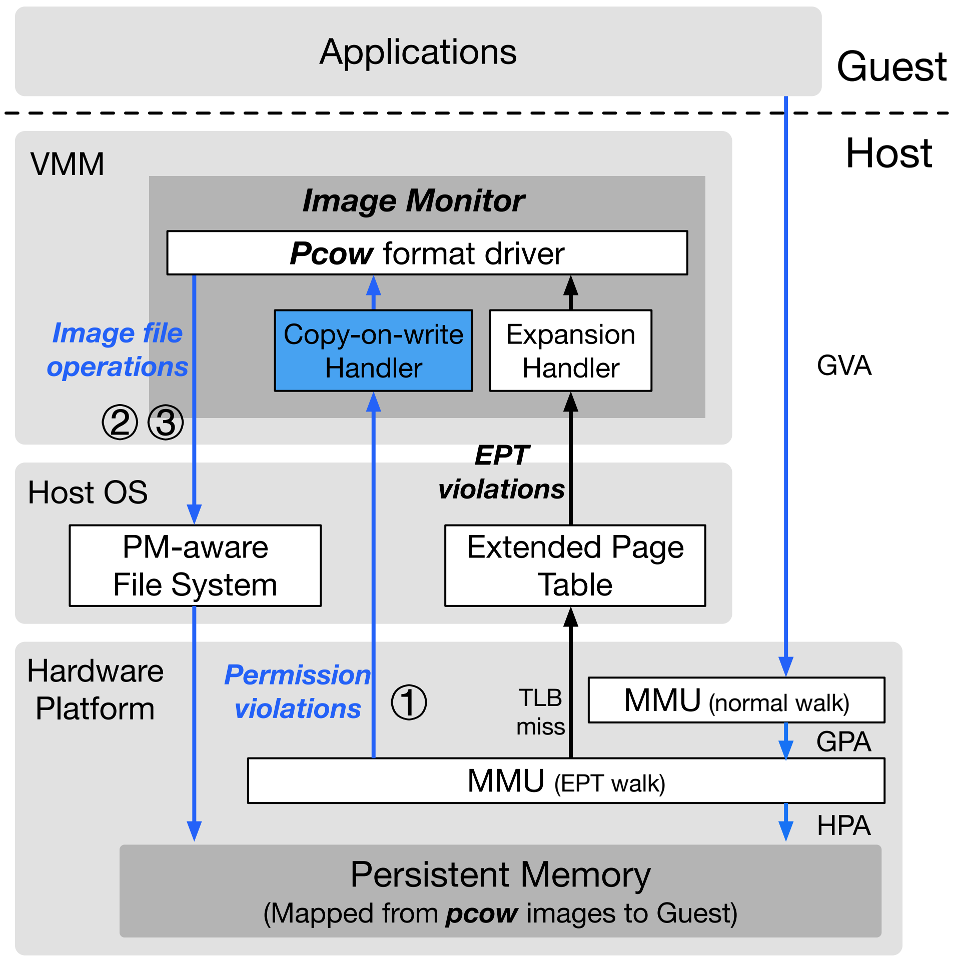
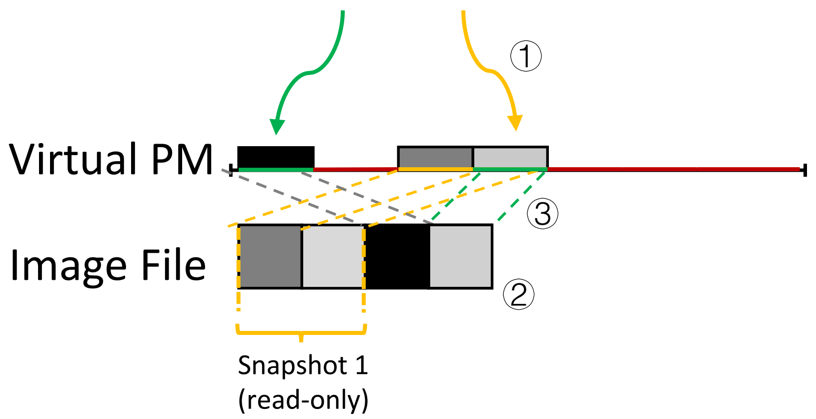
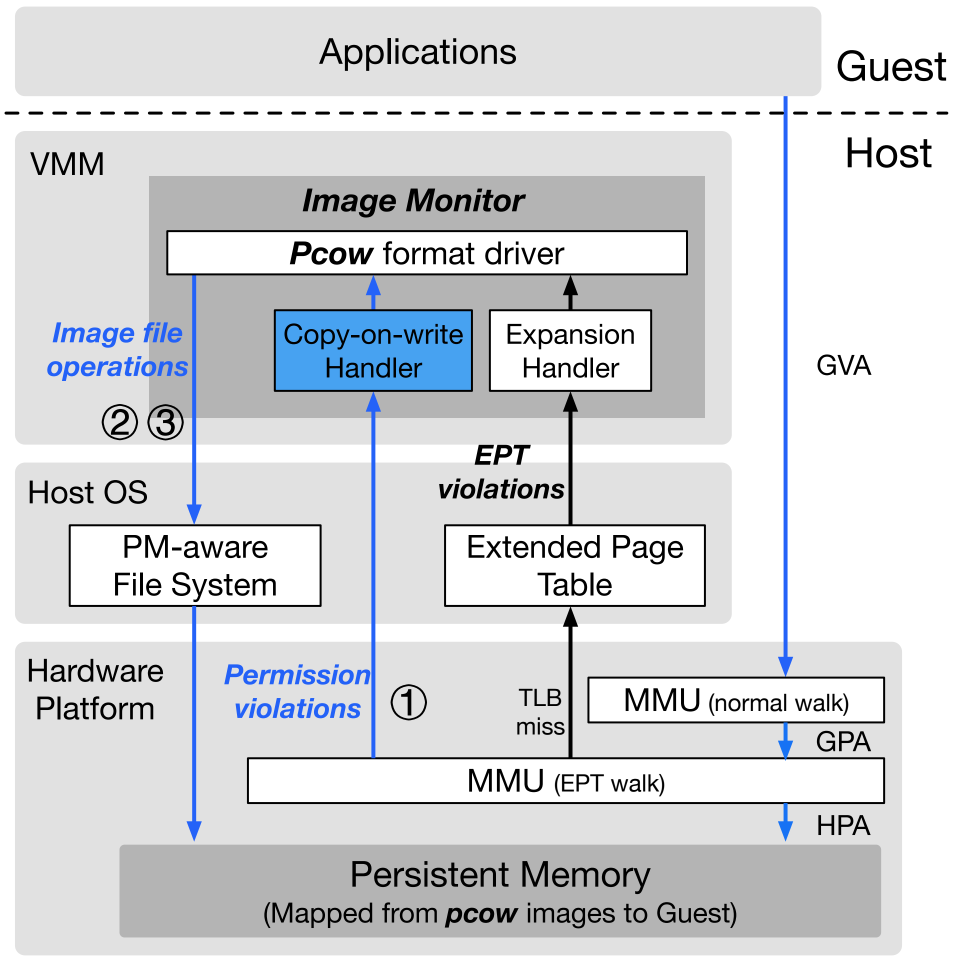


Image Monitor | Pcow Format | Details | Optimization

Copy-on-write Handler





① Guest Apps access an read-only page, the Copy-on-write Handler is invoked.

② Pcow format driver allocates a new block at the end of the image file and do COW.

③ Copy-on-write Handler maps the COWed block to the write permission violation address.

Pcow Image File Layout

- Data and meta-data is organized in fixed-size clusters.
- New clusters are created in an appending manner.
- Much more concise compared with IO virtualization formats like qcow2.

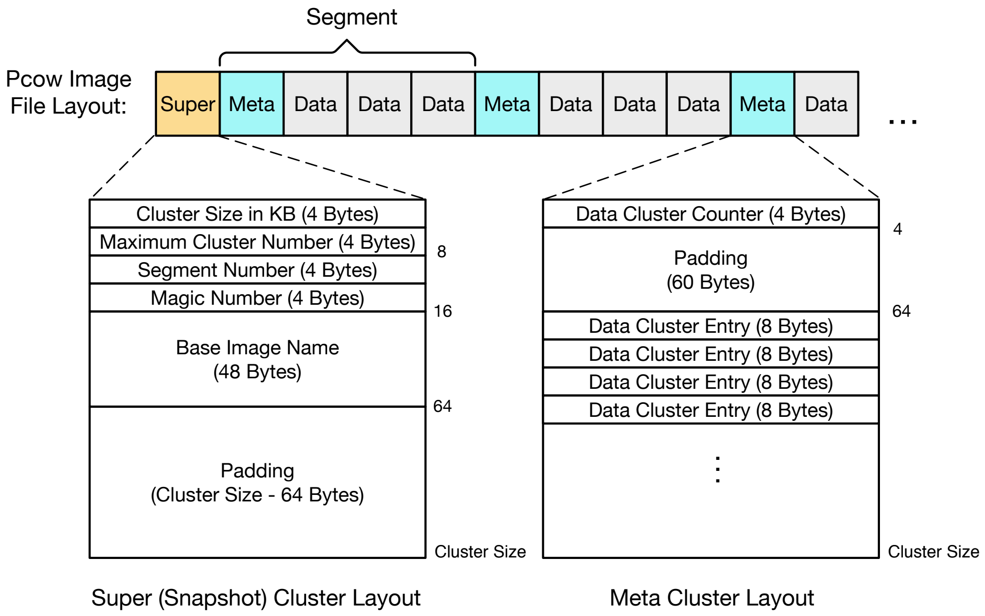
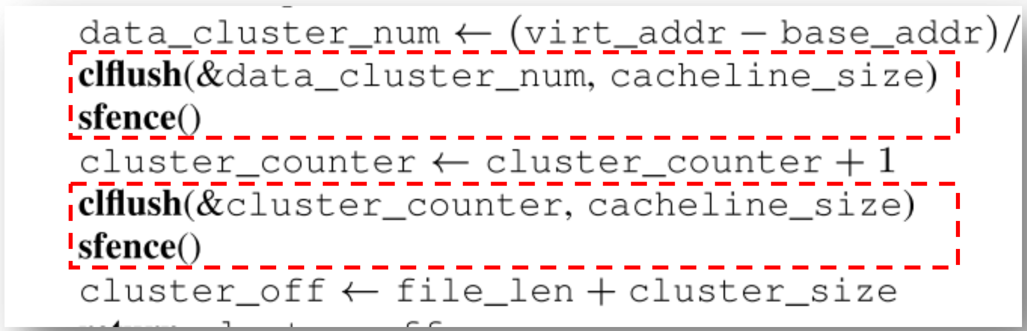

Segment
Pcow Image File Layout:
Super
Meta
Data
Data
Data
Meta
Data
Data
Data
Meta
Data
...
Cluster Size in KB (4 Bytes)
Maximum Cluster Number (4 Bytes)
Segment Number (4 Bytes)
Magic Number (4 Bytes)
Base Image Name (48 Bytes)
Padding (Cluster Size - 64 Bytes)
8
16
64
Cluster Size
Super (Snapshot) Cluster Layout
Data Cluster Counter (4 Bytes)
Padding (60 Bytes)
Data Cluster Entry (8 Bytes)
Data Cluster Entry (8 Bytes)
Data Cluster Entry (8 Bytes)
Data Cluster Entry (8 Bytes)
⋮
4
64
Cluster Size
Meta Cluster Layout

Image Monitor | Pcow Format | Details | Optimization

- Necessary clflush and sfence instructions are used to maintain for the crash consistency of meta-data.

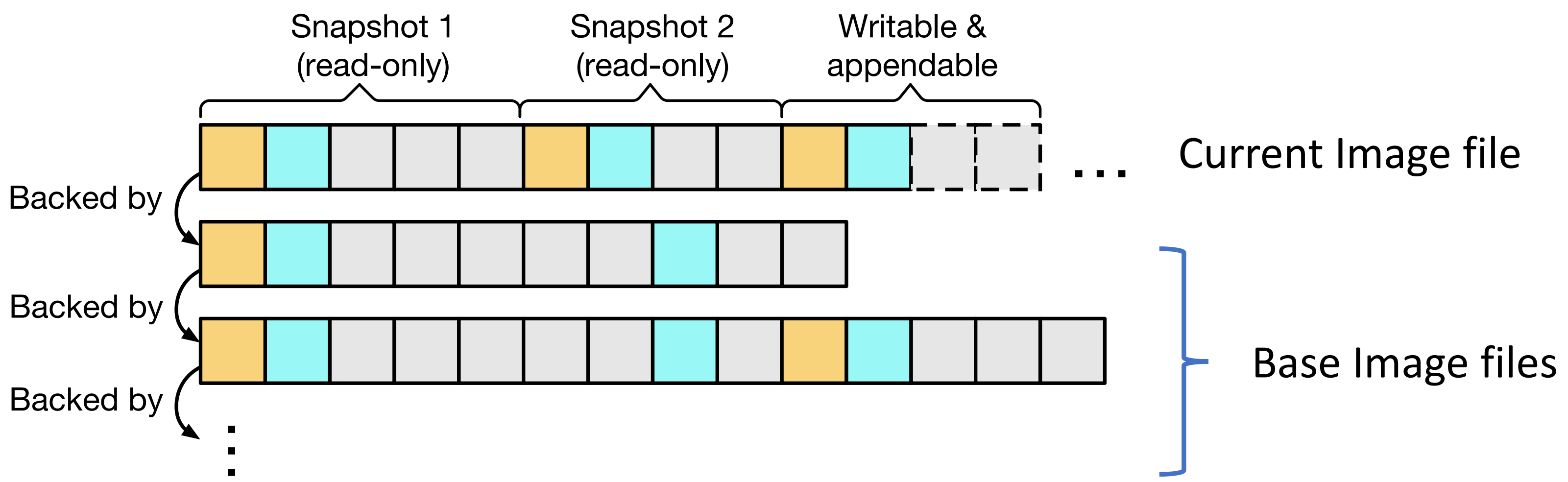


```
data_cluster_num ← (virt_addr − base_addr)/
clflush(&data_cluster_num, cacheline_size)
sfence()
cluster_counter ← cluster_counter + 1
clflush(&cluster_counter, cacheline_size)
sfence()
cluster_off ← file_len + cluster_size
```

- Some meta-data that needs to be updated frequently is stored in one cacheline size.

A Pcow Image Example

- **Thin-provision:** The image file is very small when created.
- **Base image:** A current image file is created based on the 2 base image file.
- **Snapshot:** The current image file consists of 2 snapshot part a writable part



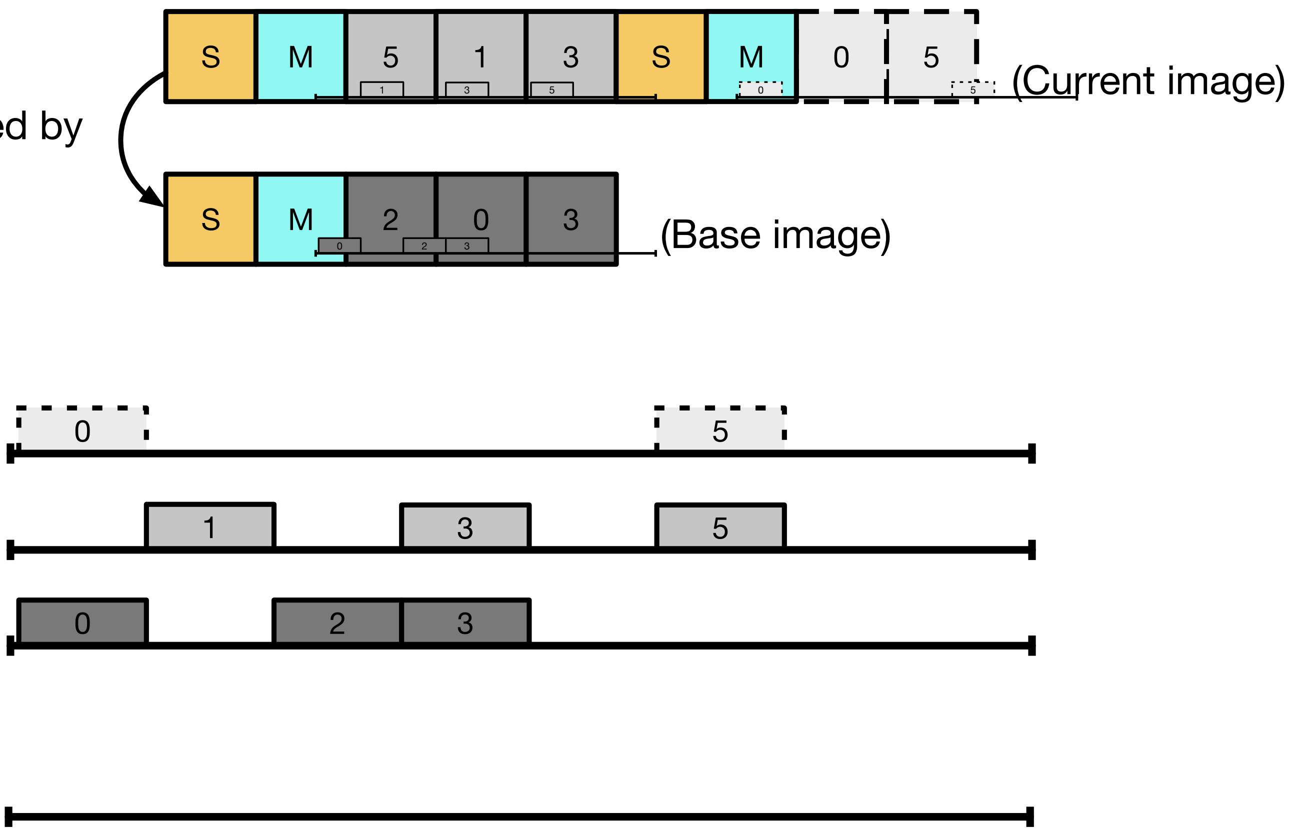
🟨 Super (snapshot) cluster
🟦 Meta cluster
⬜ Data cluster (read-only)
⬚ Data cluster (writable)

Pcow Mapping at Startup

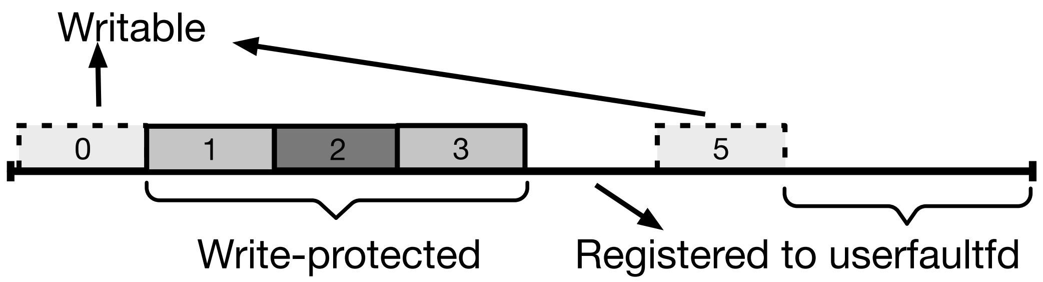
Pcow Image FIles

Logical Address Spaces

Virtual PM Address Space



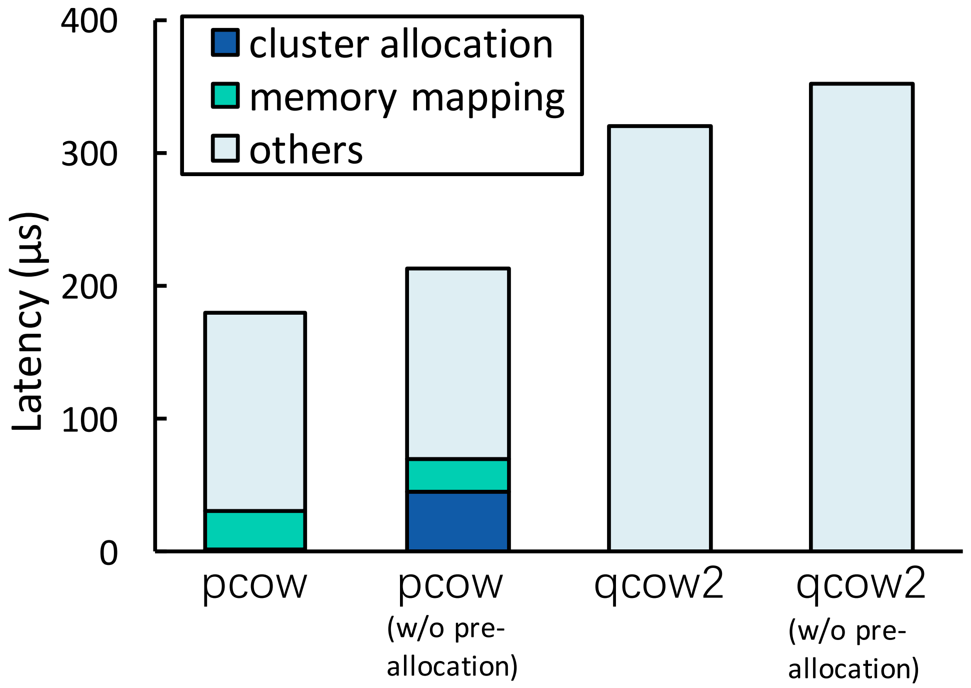
Pcow Updating at Runtime



- Writeable area can be read or write by the Guest Apps.
- Write to the write-protected area will invoke the Copy-on-write Handler.
- Read / write the userfaultfd area will invoke the Expansion Handler.
- Copy-on-write Handler and Expansion Handler do image file operations and update the EPT page table.

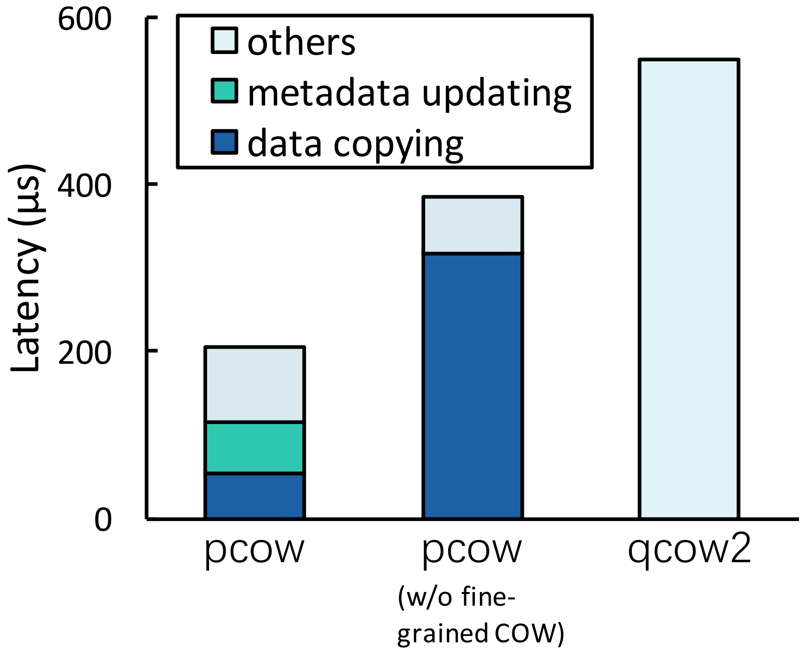
Pre-allocation

- Dedicated cluster allocation thread is use for cluster pre-allocation.
- Decreases the image expansion latency by 45 us.



Fine-grained Copy-on-write

- Copy 4KB instead of 64KB cluster size for lower COW latency.
- Decreases the copy-on-write latency by about 200 us.



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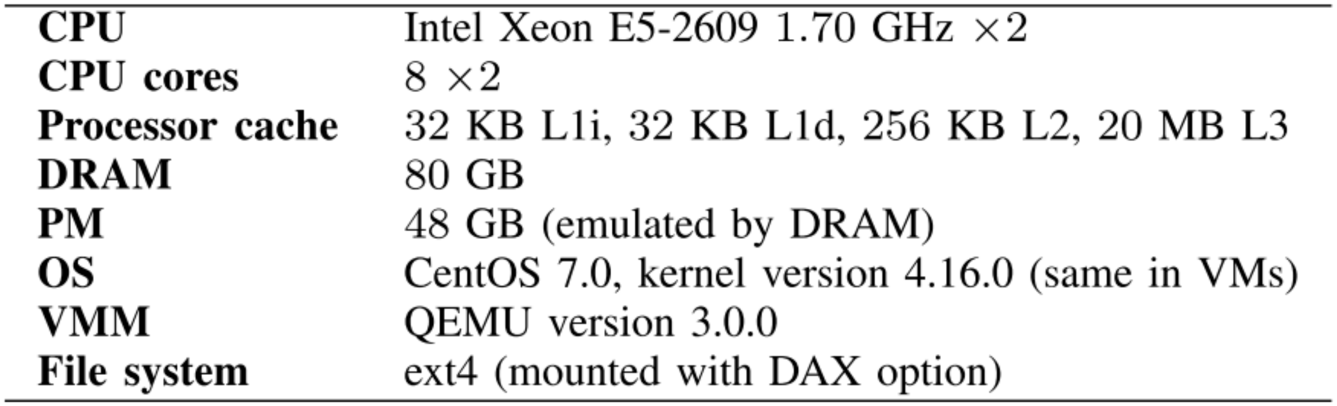
Configuration | Micro-benchmark | Copy-on-write | Redis-PMDK

Prototype implemented based on QEMU 3.0.

Our physical PM device is emulated by a DRAM partition.

Comparisons between:

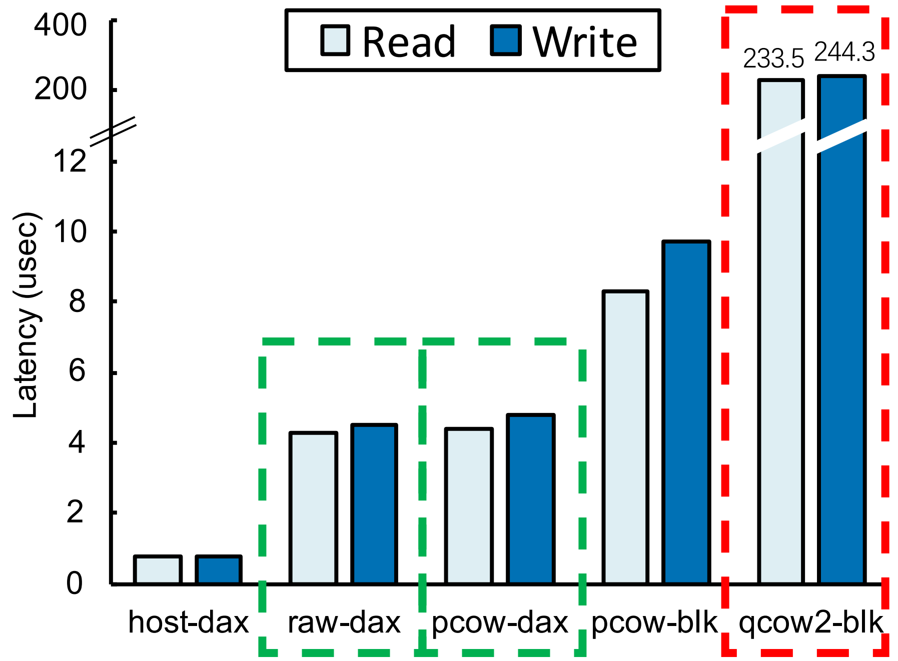
- Our prototype (pcow)
- Native memory virtualization (raw)
- I/O virtualization image format (qcow2)



CPU	Intel Xeon E5-2609 1.70 GHz $\times 2$
CPU cores	8 $\times 2$
Processor cache	32 KB L1i, 32 KB L1d, 256 KB L2, 20 MB L3
DRAM	80 GB
PM	48 GB (emulated by DRAM)
OS	CentOS 7.0, kernel version 4.16.0 (same in VMs)
VMM	QEMU version 3.0.0
File system	ext4 (mounted with DAX option)

Pcow-dax:

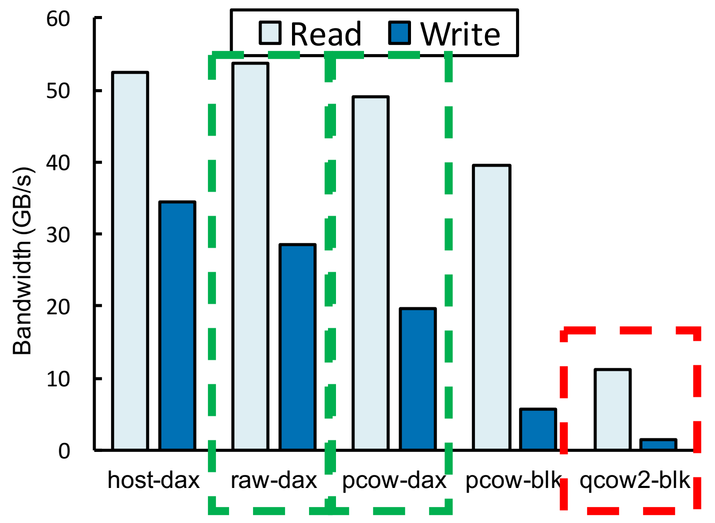
- No overhead compared with native memory virtualization (raw-dax).
- About 50x better than qcow2-blk.

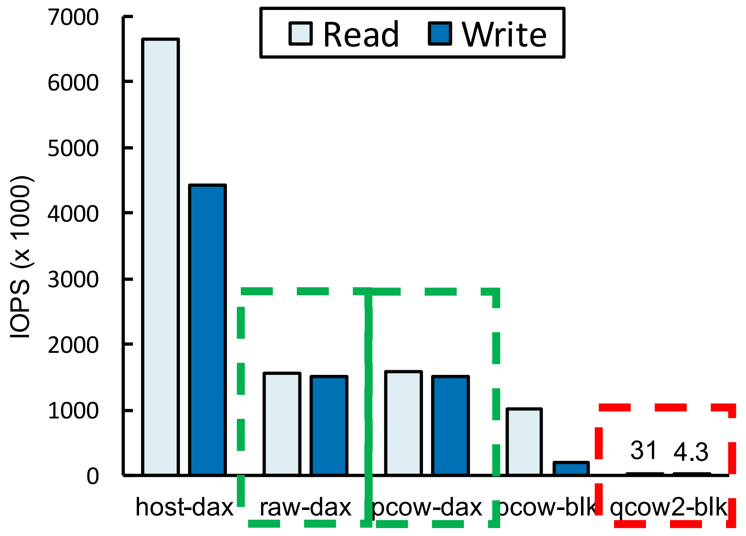


- Fio 4KB single thread
- -dax: mmap interface
- -blk: read / write interface

Pcow-dax:

- No overhead compared with native memory virtualization (raw-dax).
- Bandwidth 4x better than qcow2, IOPS hundreds of times better than qcow2.

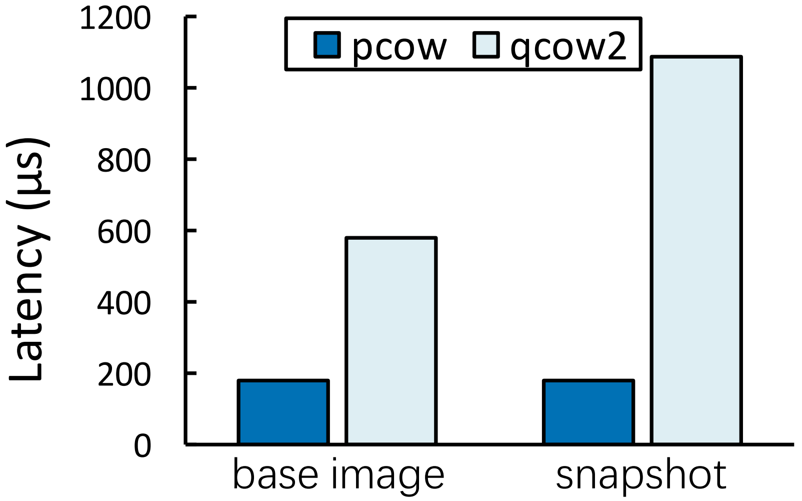


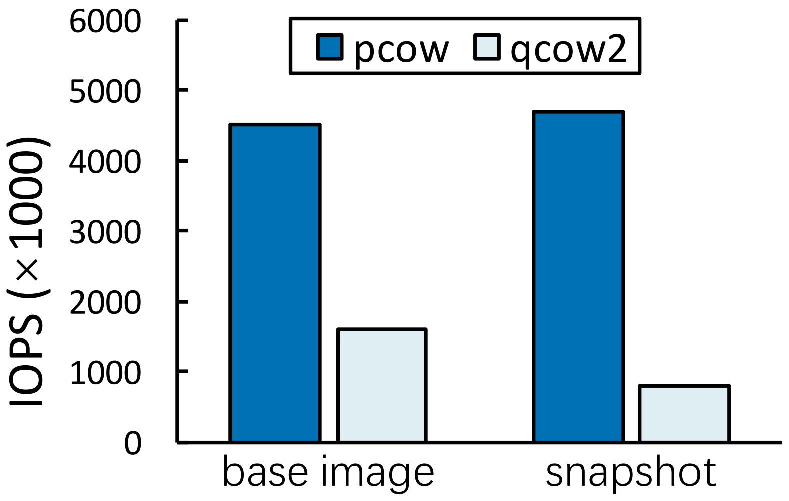


- Bandwidth: Fio 1MB 16threads
- IOPS: Fio 4KB 16threads
- -dax: mmap interface
- -blk: read / write interface

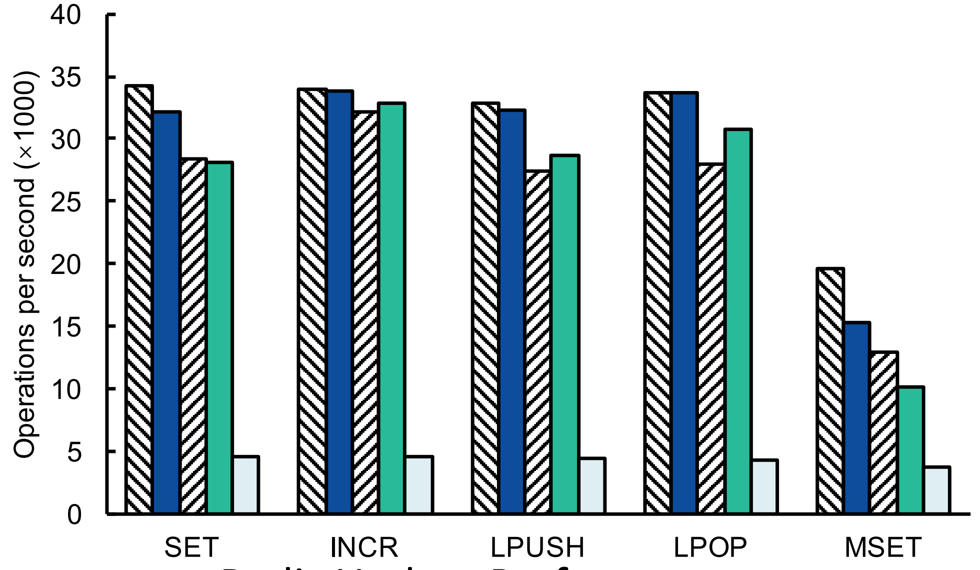
Copy-on-write

- Pcow's copy-on-write performance is about 3x better than qcow2.

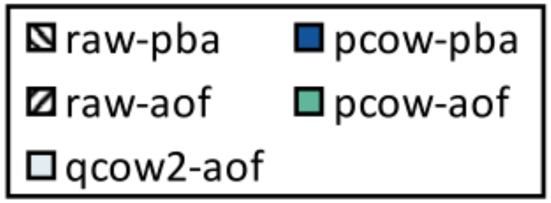




Redis-PMDK



Redis Update Performance



- Native memory virtualization (raw-)
- Our scheme (pcow-)
- I/O virtualization image format (qcow2-)

- Redis (-aof)
- Redis-PMDK (-pba)

- Redis-PMDK (pcow-pba) still have better performance than Redis (pcow-aof) when using our scheme.
- Our scheme is still compatible with the real-world application's optimization for PM in virtual machines.

Summary

- We achieve both virtual PM byte-addressability and image management.
- We implement 3 storage virtualization features for virtual PM.
- We take advantages of EPT for address translation between virtual PM and pcow image file offset.
- Our scheme is up to 50x faster than I/O virtualization image format qcow2. Almost no overhead compared with the native memory virtualization.

Source Code Released:

https://github.com/zhangjaycee/qemu-pcow

Usage:

Pcow manage tool “pcow-img”:

```
pcow-img   create   64    128    my_pcow_file.img
                   (KB)   (GB)
```

QEMU parameters:

```
qemu-sysmte-x86_64 … \
-object memory-backend-file,id=pm,mem-path=my_pcow_file.img,format=pcow,share=on,discard-data=off,merge=off \
-device nvdimm,id=pm,memdev=pm \
…
```

Thanks!   Questions?