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White Paper

SSD Virtualization: Expanding the Role of SSDs in Modern System Architectures

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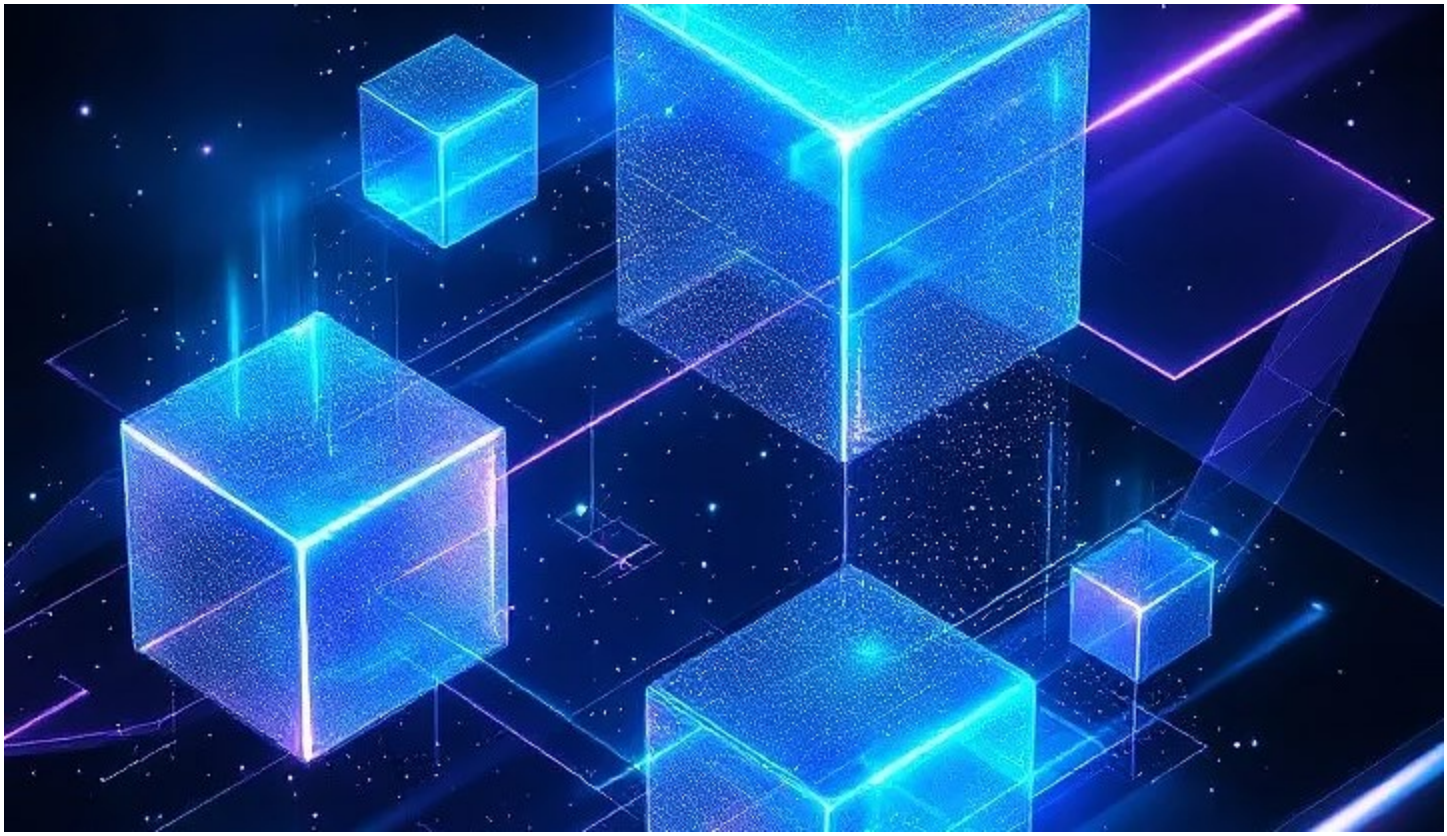

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Introduction

When striving to maximize the exploitation of big data, storage virtualization is highly effective in optimizing the underlying infrastructure through differentiated data access. Virtualization is critical to enabling differentiated access to stored data, and its importance is increasing as the data availability needs for artificial intelligence (AI) and machine learning (ML) grow. Even though training large language models (LLMs) is putting the spotlight on the thirst for data in AI processing, the need for differentiated data access has existed for quite some time.

This article discusses the advances in storage virtualization for NVMe® SSDs, focusing on recent extensions to the NVM Express® specification that enhance data access differentiation. Tracking LBA Allocation and Live Migration (LM) assist a virtual machine manager (VMM) or hypervisor (HV) in moving virtual machines (VMs) from a source enclosure to a target enclosure. LM includes Virtualized Reporting, which allows each VM to perceive a unique VMM-controlled version of the storage environment and also standardizes virtualized component creation. Flexible Data Placement (FDP) allows the host to optimize data writes to avoid efficiency-draining garbage collections — reducing the impact of a noisy neighbor. Both virtualized reporting and FDP are features with broad enough flexibility to allow their deployment toward multiple different virtualization goals. Finally, Quality of Service (QoS) in the context of an SSD relates to sharing available bandwidth in a predictable way among users.

Motivation

Storage virtualization is the abstraction and presentation of access to stored data with attributes that differ from conventional access to a drive dedicated to a single user. Because virtualization enables an altered view into the access of the stored data, its toolset offers a diversity of potential uses by its very nature. For example:

- When seeking to improve distributed access, virtualization might be used to present a large capacity SSD as several smaller SSDs for improved divisibility to the host.
- If emphasizing security concerns, a parent (e.g., a VMM) may wish to limit command availability to an unprivileged child (e.g., a VM).
- A host concerned with performance may prefer that a new SSD mimic the performance of an old SSD.
- Yet another implementation might need to share SSD performance among several different host tenants.

Many aspects of the storage control environment can be virtualized. For example:

- PCI Express® (PCIe®) layer attributes can be virtualized in single root I/O virtualization (SR-IOV) with physical and virtual functions.
- NVMe controllers can be virtualized using primary and secondary controllers. The administration of the NVMe SSD may be allocated to the primary controller and limited or emulated to the secondary controller.
- Performance virtualization — letting users perceive performance characteristics as if each were the sole user — is achieved through data separation or resource partitioning.
- A necessary component of transferring a VM from source to destination is the ability to provide a virtualized value overlay to attributes such as NVM subsystem, controller, namespace identifiers, and key management.

All of these virtualization aspects require defined and consistent mechanisms for effective utilization and adoption.

Background

Virtualized access to stored data has existed for decades. Examples of building blocks for virtualization that have come into existence over the years are plentiful.

Virtualization Building Blocks. For the SSD virtualization described here, PCIe transport is assumed and is using an NVMe protocol layer.

- PCIe layer attributes can be virtualized with SR-IOV, which presents a virtual function (VF) as if it were a physical function (PF). The VF can emulate the PF capabilities without replicating the full PF, conserving controller gate area and power. VFs can also be used to limit the ability of a child host entity to change the settings of the PCIe device.
- The later introduction of NVMe resource management of primary and secondary controllers was needed to distribute the limited ASIC features to the child controllers associated with each VF.
- Dual port access and namespace (NS) reservations have been enabled in HDDs for decades and carry forward into NVMe SSDs. They have been key contributors to ease of differentiated access to stored data and provide useful tools for the virtualization toolset.
- Many NVMe over Fabric (NVMe-oF™) instantiations are at the forefront of virtualization due to the broad deployment environments, large amount of stored data accessible through these interfaces, flexibility of the software (SW) implementation for new features, and the varying levels of integration to the SW layers consuming the stored data.

NVMe SSDs are beginning to use the building blocks of HDD virtualization and NVMe-oF. However, it is only recently that usage models for several of the virtualized attributes have solidified to the point where the virtualization techniques can be committed to hardware.

Tenants. Virtualization can be thought of as enabling a limited or replaced view of storage access provided to a tenant. A tenant may take many forms, each of which is composed of SW and/or hardware (HW) components.

- Software — A SW process may be a tenant. For example, a file system (FS) can be separated into SW processes that manage end user reads, end user writes, FS reads, FS writes, etc. Applications, containers, or VMs may also each be identified as a tenant.
- Hardware — Some tenants may be composed of or identified by HW components. Groupings such as a CPU processor, CPU core(s), CPU thread(s), an FPGA, a GPU, or a GPU partition (warp or wavefront) can all be considered as tenants.

A tenant may comprise a mixture of the HW and SW components. The definition of a tenant is necessarily broad because the deployment options for virtualization are nearly infinite.

Yesterday: Software-Based Virtualization Approaches

The longstanding need for virtualization has, up until recently, been implemented primarily in host software. Fast host processors, slow storage access, and drive sharing among a limited number of tenants have allowed software implementation of virtualization to be sufficient for many years.

A virtualization example is shown in Figure 1, with the VMM overlaying and controlling the entire system from the host. The VMM administers and sets up the SSD with a different namespace for each VM, and implements SW boundaries between the VMs.

From the NVMe point of view, the accesses to the storage by a VM might allow some minimal inspection or manipulation of the submission queue entries (SQEs) by the VMM. Additionally, doorbells are commonly intercepted by the VMM prior to triggering the doorbell on the SSD. The VMM fully controls the administrative path. In the event of the VM attempting to submit an admin command, the VMM may locally respond (e.g., Command not Supported), pass the command through to the SSD (e.g., Create NS), or manipulate the command to the SSD (e.g., Identify Controller and Identify Namespace).

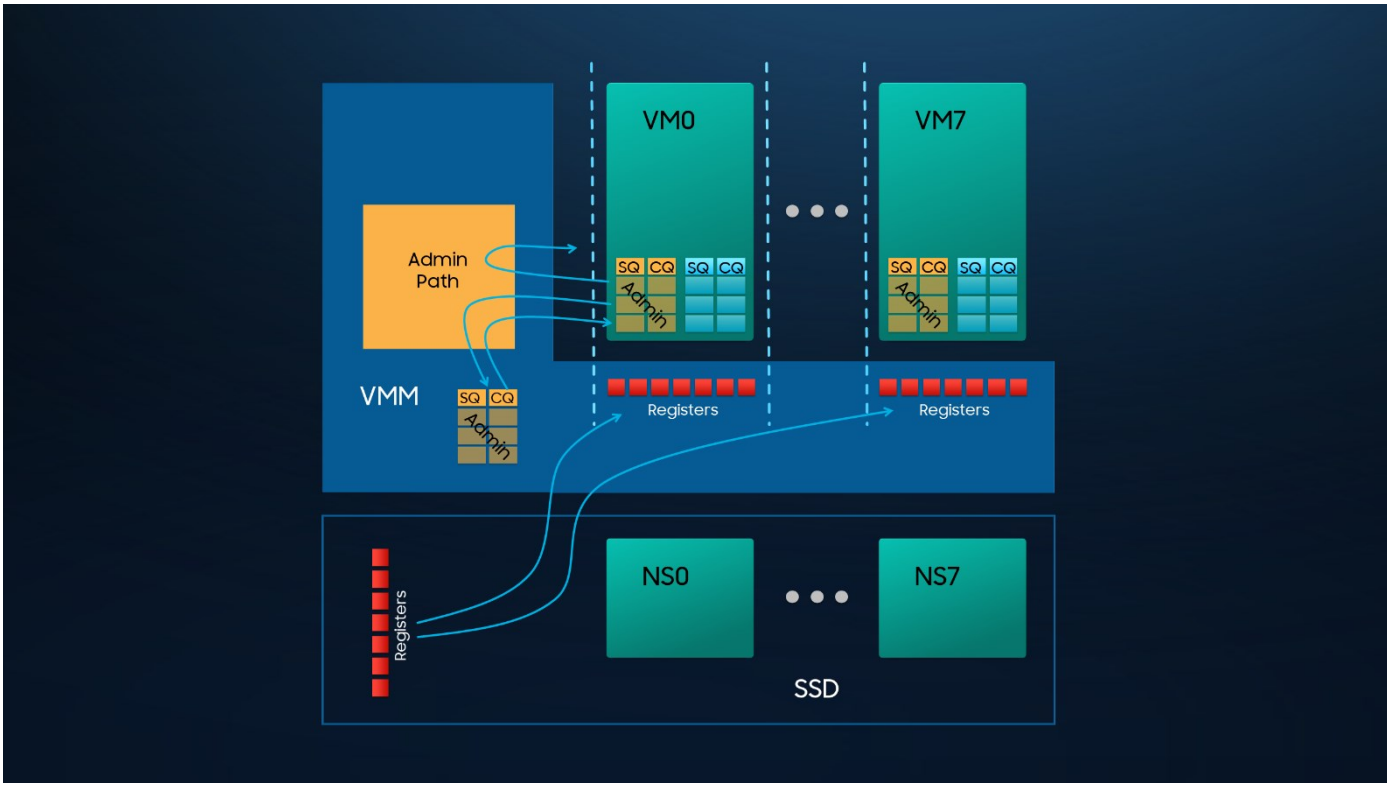

Figure 1. VMM overlaying and controlling the entire system from the host

Using software to implement virtualized access to storage brought real advantages:

- Virtualization was achieved quite effectively, as demonstrated by the longstanding success of this method.
- During a time when virtualization was immature and developing a very dynamic set of needs, updating the virtualization techniques was very easy within the SW.
- This rapid update capability also enabled deploying and testing of exotic or advanced features.

However, the advantages started to become outweighed by the challenges:

- Host CPU cycles and DRAM access time taken by the VMM deprived the VM of those cycles. Since every interaction with the VMM takes time, delays to the VM became quite measurable as the speed of storage increased. VMM resource efficiency suffered as well.
- As security became more of a concern, the software-enacted VMM was seen more and more as a potential attack vector for bad actors.
- Finally, there was a practical limit to the amount of differentiation among tenants within the SSD. A good example is the noisy neighbor problem: A conventional SSD receives all traffic from the host mixed together; therefore, it must route all incoming write data to the same append point. In this scenario, multiple sequential (WAF=1) tenants can appear to write randomly to the SSD due to the intermingling of the data, so a write by one tenant can trigger garbage collection (GC) involving another tenant's data — effecting a clear loss of differentiation.

As a result, the need to move virtualization to the SSD hardware became critical.

Today: Hardware Virtualization for SSDs

Moving the virtualization to the SSD facilitates an improved experience:

- For end customers, tighter performance and latency needs (commonly breaking under 100µs) can better be met with bare metal access to the SSD.
- The stability of the virtualization needs over the past few years reduces the advantages of deploying test features.
- With security requirements increasing, virtualization in the SSD moves the security into HW where the attack surface is reduced.
- An SSD that is given the tenant information is able to propagate desired behaviors all the way through to the storage medium.

In consideration of the functionality needed to move a software-based virtualization approach onto bare metal, new hardware-specified features have been added to the virtualization toolbox.

The following virtualization features are central to the discussions in this blog:

- Flexible data placement (TP4146 Flexible Data Placement)
- Tracking LBA allocation (TP4165 Tracking LBA Allocation)
- Live migration of a namespace (TP4159 PCIe Infrastructure for Live Migration)
- Live migration of a controller (TP4193 PCIe Exported NVM Subsystems Migration[1]

Virtualization through Data Placement

The theory of data placement is that the host manages the logical blocks written to a given superblock in the SSD, such that it can efficiently "place" updated blocks and invalidate old ones in a way that reduces or eliminates the need for the SSD controller to waste cycles on GC. The mechanism implemented through TP4146 Flexible Data Placement provides the host the ability to control the write amplification factor (WAF) in the SSD, achieving even a WAF of 1 in some cases.

The flexible data placement (FDP) mechanism allows the host to control which logical blocks are written into a set of NAND blocks, called a reclaim unit (RU), that is managed by the SSD. The host is able to select among multiple RUs, allowing it to isolate data written to a given RU per application (or even within an application) in order to separate data written with different life cycles ("hot" vs. "cold" data temperature: data that changes frequently or data that rarely requires updates).

Data placement is considered a key technique in virtualization because the separation of data enables separation of WAF. FDP can be set up toward this goal as shown in Figure 2, which is showing multiple VMs managed by a VMM. The FDP-enabled SSD has one reclaim group (RG), and the RU size is striping the data across all of the NAND available. Furthermore, the reclaim unit handle (RUH) types supported by this example SSD are all persistently isolated (PI) — that is, they will be unaffected by garbage collection in other RUHs.

1 NVMe Interoperable Migration of PCIe virtual SSDs, https://nvmexpress.org/enabling-ssd-virtualization-and-live-migration-with-nvme-pcie-exported-nvm-subsystems/

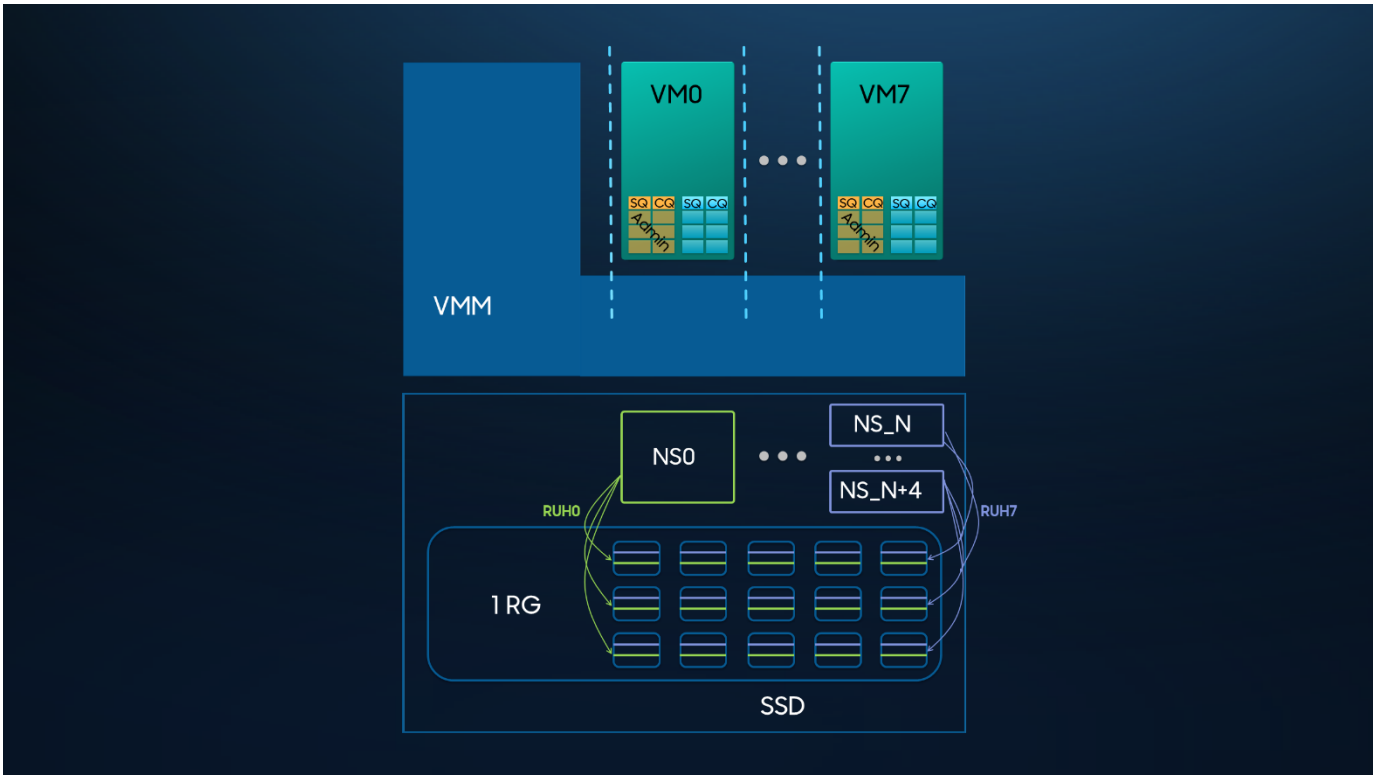

Figure 2. Multiple VMs managed by a VMM

During operation, when a VM decides to create an NS, the Create NS command is routed through the VMM (which is controlling the admin path to the SSD). The VMM alters the command to create an NS with a default RUH populating the placement identifier (PID) list. Figure 2 is showing VM0 creating NS0, and NS0 in turn using RUH0 to write data striped across the NAND. VM7 is illustrated with multiple namespaces, with each assigned to VM7 using the same RUH7. All of the traffic for VM7 will be written together to the same RUH, independent of the NS. If a tenant successfully places writes to keep a WAF of 1, then it will never trigger garbage collection of its RUH and ultimately perceives higher sequential performance. On the other hand, a tenant that does not optimize for a WAF of 1 will trigger GC — but with persistent isolation, the GC traffic will affect only the data associated with this RUH.

Persistently isolated RUHs have the benefit of isolating all of the GC activity for the RUH. By aligning a given tenant to a single RUH, the triggering of any GC activity relates solely to the activity of that tenant — thereby minimizing both the movement of data on the physical NAND and the loss of any WAF optimization for the tenant.

GC activity still happens within the drive, so there will still be resource contention as the GC of other RUHs reads data from some locations and writes it to others. However, this activity is not causing the noisy neighbor data movement of any other tenant.

Virtualized Resource Reporting

Virtualized reporting enables a VM to receive values from the SSD, but under control of the VMM. The manipulated values provided by virtualized reporting let a VM read any value through its curated view of the SSD. Recall that in the software implementation of virtualization, the VMM took away CPU cycles to effect a command intercept. Virtualized reporting provides the key benefit of freeing up those cycles. In addition, by taking the VMM out of the command path it better supports the security needed for a confidential computing environment.

Virtualized reporting in NVMe SSDs is achieved with TP4193 PCIe Exported NVM Subsystems Migration[2]. This TP adds a feature set enabling an exported NVM subsystem to change the reported controller and namespace identifiers, as well as other attributes, according to a template.

NVM Subsystem Abstraction. Applying the capabilities shown in Figure 3 to a hypothetical system like that in Figure 1 provides a good demonstration of the use of virtualized reporting to abstract an apparent subsystem. Assume:

- The SSD supports SR-IOV, and controller G is the primary controller associated with the physical function (PF0).
- The VMM accesses the SSD through primary controller G, and manages all of the underlying components through interactions with the primary controller.
- The VM accesses the SSD through one of the secondary controllers on one of the virtual functions (VFs).

The scenario is based on the parent being a VMM and child being a VM, but the capabilities are extensible to other scenarios.

Controller P and namespace X are both underlying resources in the SSD. Their identifications are assigned by the SSD, and they are permanently globally unique for the SSD. However, some VMs may expect to interact with a predetermined controller H and namespace Y. Potentially, one VM could expect to see and use the identical ID value to that being expected and used by another VM — but these overlapping IDs would violate the requirement for all IDs to be globally unique.

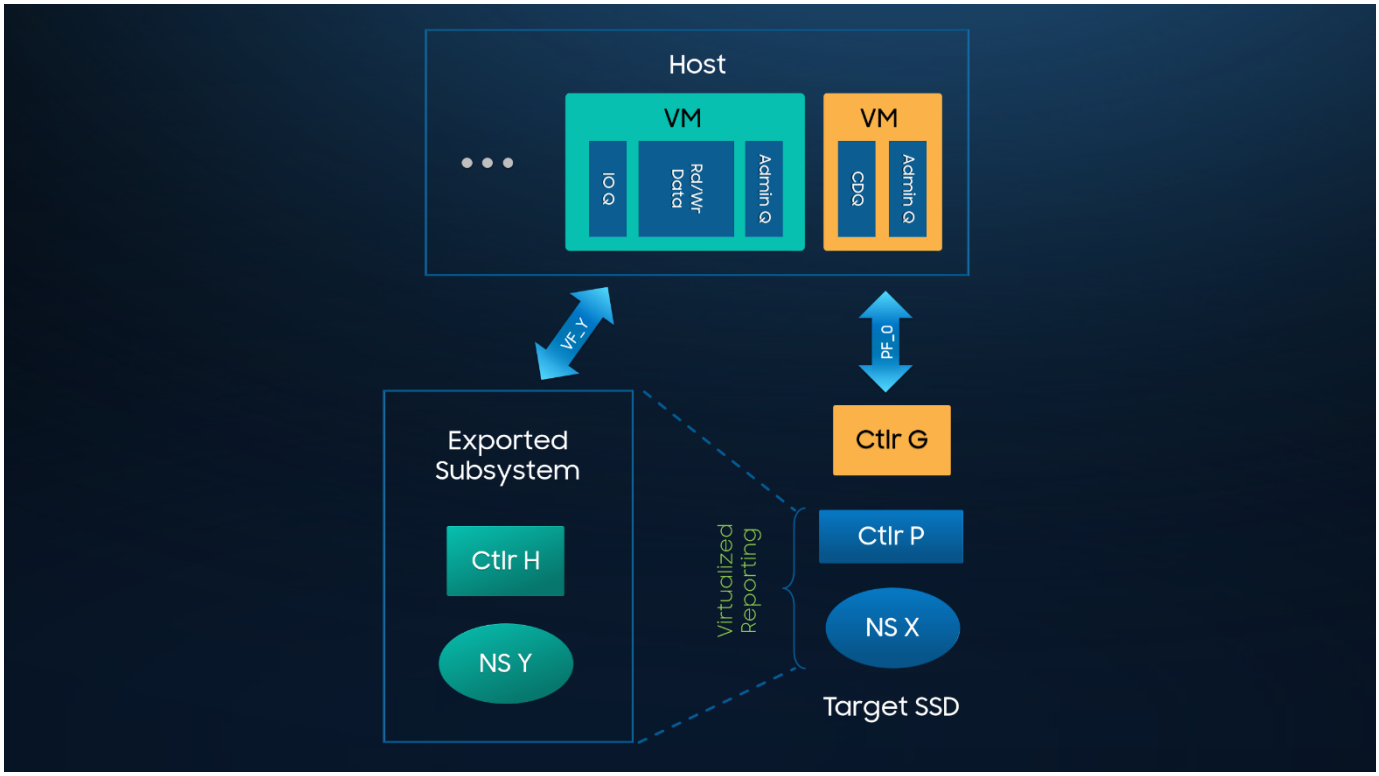

Figure 3. Applying the capabilities shown to a hypothetical system (like that in Figure 1)

2 NVMe Interoperable Migration of PCIe virtual SSDs, https://www.opencompute.org/events/past-events/2025-ocp-global-summit#storage

To resolve this situation, the VMM creates an exported NVM subsystem in which it associates underlying resources controller P and namespace X. The VMM then utilizes a template to change the reporting of the controller and NS attributes within the scope of the exported NVM subsystem, as well as to possibly modify or restrict the functionality of the exported controller. As the VM interacts with the exported NVM subsystem through the VF, it will have a curated view of the reported values.

Other Uses. The example focused on changing the reporting of a controller and NS identifier values. However, an exported NVM subsystem is a very extensible virtualization building block. The feature uses a lightweight template to set default values for all exported NVM subsystems using that template, as a group, and the curated view may extend to numerous NVMe features such as controller capabilities, log page interactions, and other extensive interactions with the SSD through the exported controller's view of the drive.

Live Migration Support

Virtualized reporting enables an abstraction of the storage reported values to make storage interchangeable. Building on this capability, the host could in fact move the tenant to a different storage device altogether. The mechanism is addressed in TP4159 PCIe Infrastructure for Live Migration.

With a VMM managing several VMs as shown in Figure 1, there may be an occasion for the data center to move where the VM is running. Perhaps the data center moves the VMs in order to redistribute the system load, or the VM may be moved in response to a failed resource in the data center infrastructure. For these use cases, one must enable the migration of a VM from a source system to a target system. However, an end user is expecting to continue uninterrupted operations within the VM. The need for continuous VM operation turns the requirement into live migration (LM) of the stored data on the SSD.

The system setup is illustrated in Figure 4, which shows VMMs on both the source and target hosts that are responsible for implementing the data center management and organization within each enclosure. The two VMMs may coordinate to accomplish their shared goals. Also shown is a currently running VM using a secondary controller Y to access its data stored in an NS.

The NVMe live migration capabilities can be used to move the stored data and accessing infrastructure to a different target system and SSD.

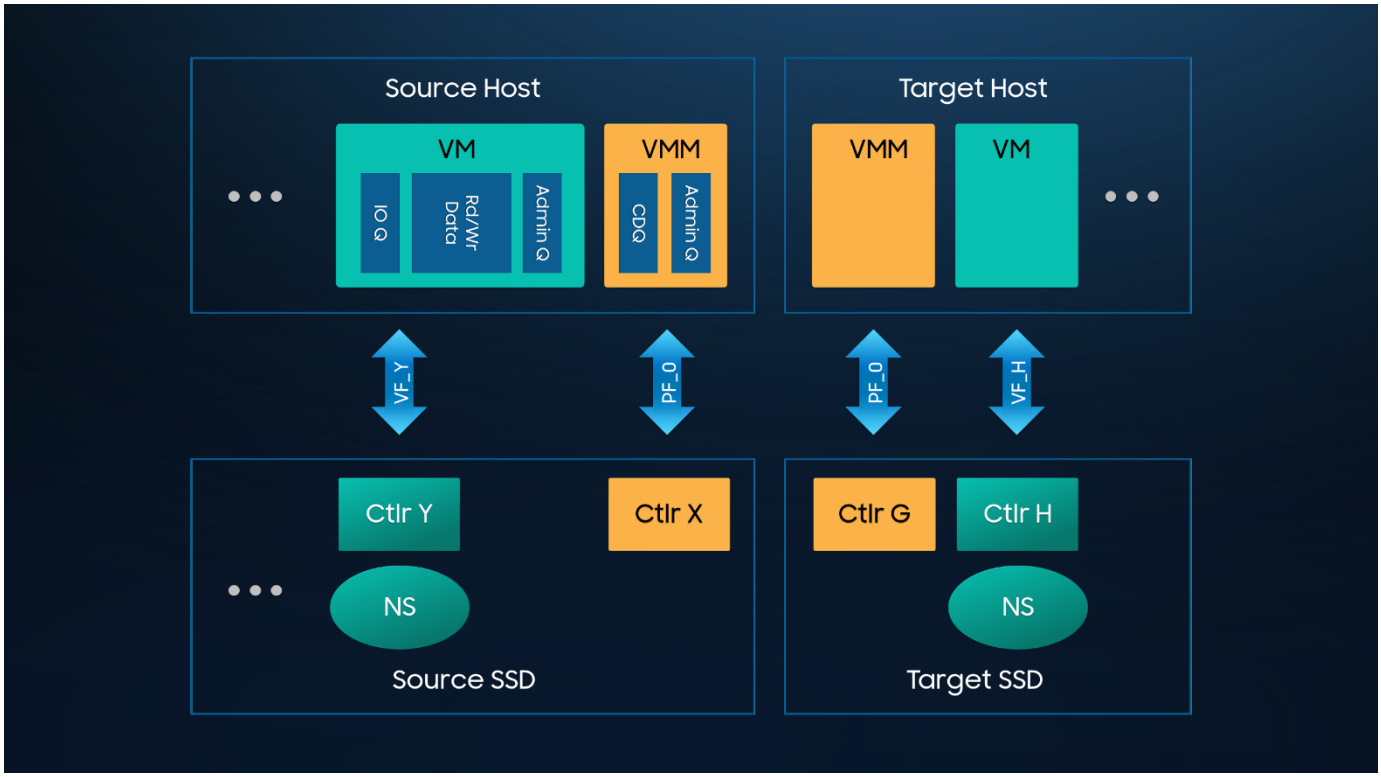

Figure 4. VMMs on source and target hosts responsible for implementing data center management and organization within each enclosure

Procedure. The process of live migration involves copying a snapshot of the source namespaces to the target, while at the same time logging ongoing commands that would change the source snapshot so that they can be reflected on the target copy. The steps are described below.

While not explicitly discussed here, it becomes readily apparent in this scenario that the seamless command and data movement capabilities of NVMe-oF across networks would expedite the process steps listed.

1. Initialization. Using virtualized reporting, the process starts with the creation of an exported NVM subsystem and initialization of the values that will be reported to the VM in the target system. For example, the controller ID and NS ID will be set to the same values as the source system.
2. Send Start Logging Command. The next step is to begin moving the data. While this might be very slow due to the potentially large quantity of stored data accessed by the VM, the VM expects to continue interacting with the data on the source SSD. As shown in Figure 5, the LM process begins with a Start Logging command being sent from the VMM to the primary controller. The VM is unaware of this command, and it continues inputs/outputs (I/Os) with the secondary controller to read or write its data. Meanwhile, the primary controller receives and parses the Start Logging command.

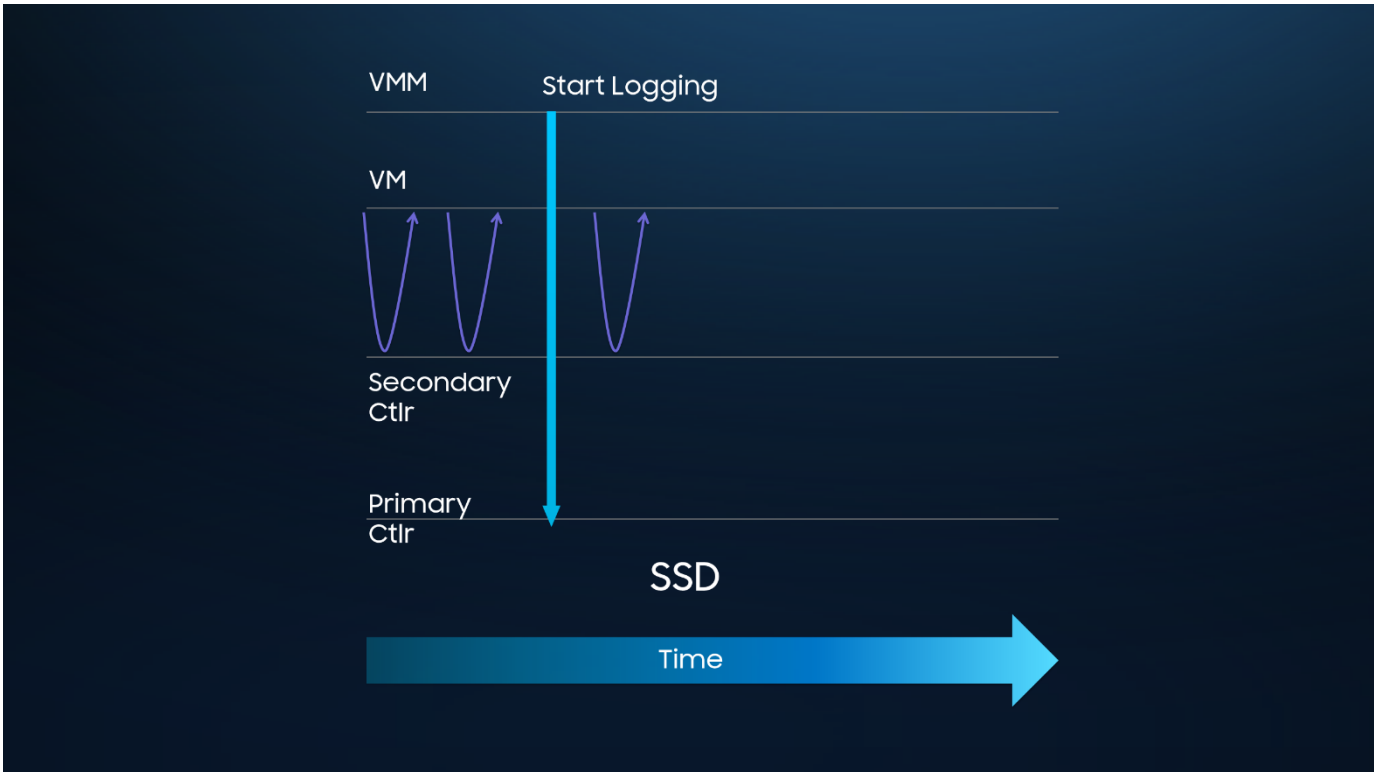

Figure 5. The LM process begins with a Start Logging command being sent from the VMM to the primary controller

3. Logging Begins. The primary controller will begin logging, illustrated in Figure 6 by the I/Os changing from purple to green colored IOs. However, the implementation of the logging with respect to commands that are already in flight is unknown. Red lines illustrate that both short- and long-lived commands from the VM may be in flight during the initiation of the logging by the primary controller.

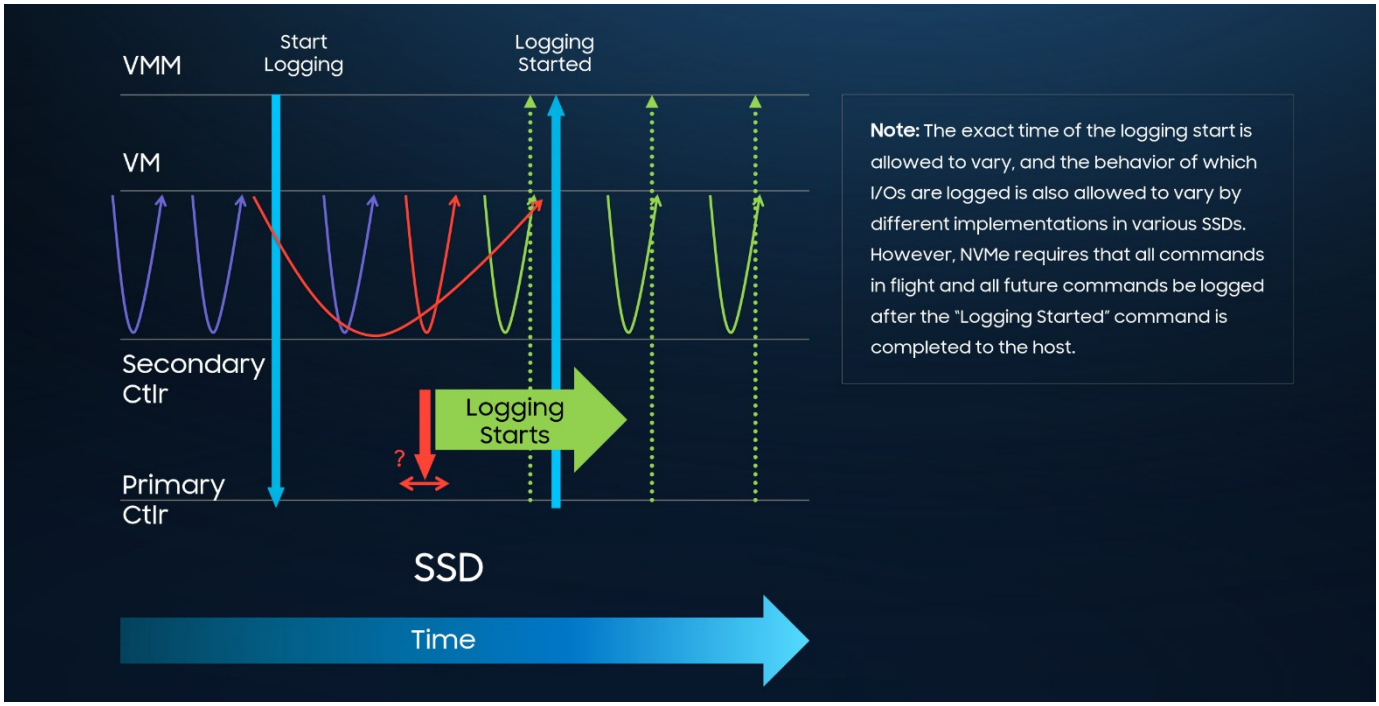

Figure 6. The primary controller will begin logging by the I/Os changing from purple to green colored IOs

With the assurance that all future completing commands from the VM will be logged, the VMM is able to proceed to the next step in the LM process.

4. Move Snapshot of Data. The VMM proceeds to moving a current initial snapshot of the stored data over to the target SSD. One option for moving the data is to copy the entire NS from the source SSD to the target SSD. However, this may be inefficient if the NS is sparsely written.

Figure 7 illustrates a sparsely written NS. The black lines indicate ranges of logical block addresses (LBAs) that contain data, and the white spaces are deallocated. For this sparsely written NS, the VMM can take advantage of the Get LBA Status command of the tracking LBA allocation feature to query the SSD. The primary controller has a granularity attribute, and it will return which granularities contain data. Only the granularities containing data need to be read from the source and written to the target SSD. Optionally, the VMM may submit large reads to the contiguous regions.

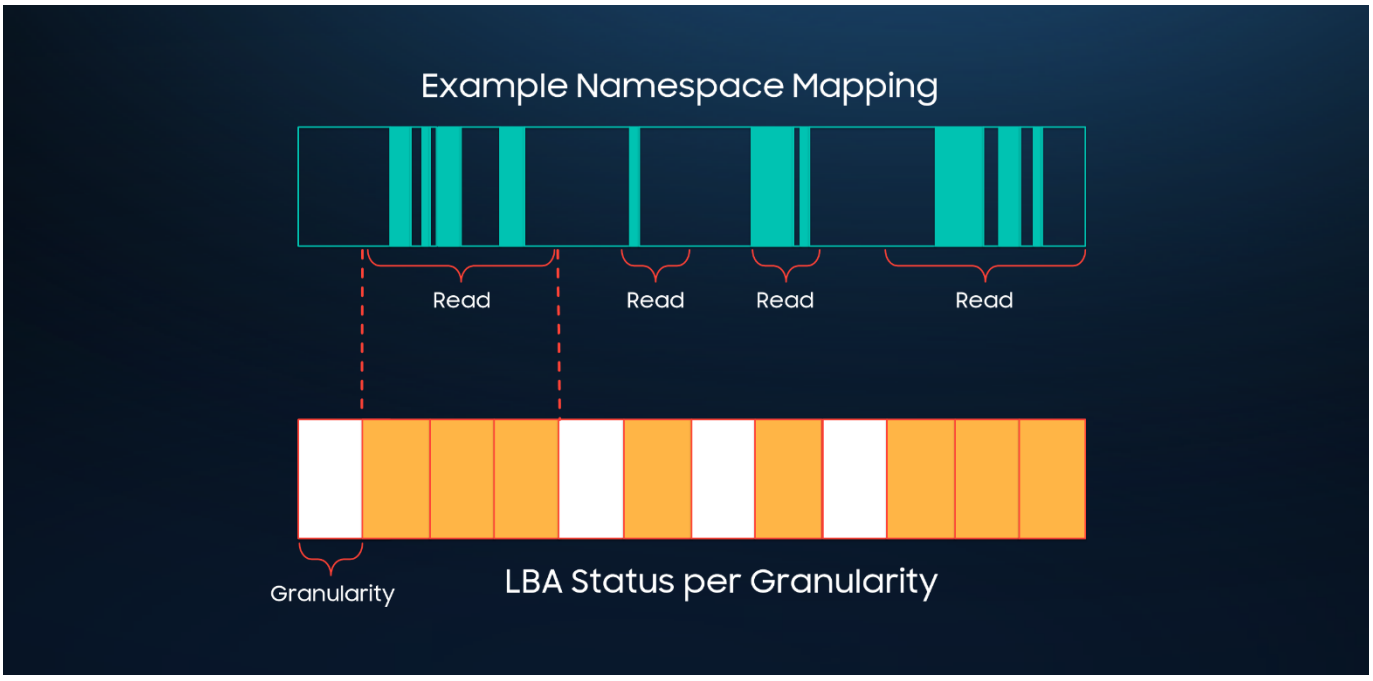

Figure 7. A sparsely written NS

5. Assess Status. Figure 8 shows the current system status of the migration. The VM is continuing to send reads and writes to the SSD through its secondary controller. The primary controller is continuing to log applicable commands to the migration log in the VMM. Since the transfer of the initial data from the source NS to the target NS took time, it is likely the command data queue (CDQ) has accumulated a large number of logged commands. The initial capture of the NS data is likely to have changed.

The VMM is able to parse the log entries in the CDQ to understand which LBAs in the source NS have been written. For each modification of the source NS, the VMM will be able to send a read from the source NS and a write to the target NS. Iteratively, the VMM will catch up to the ongoing changes occurring within the VM's NS, and there will be a small number of changes sent to the source NS.

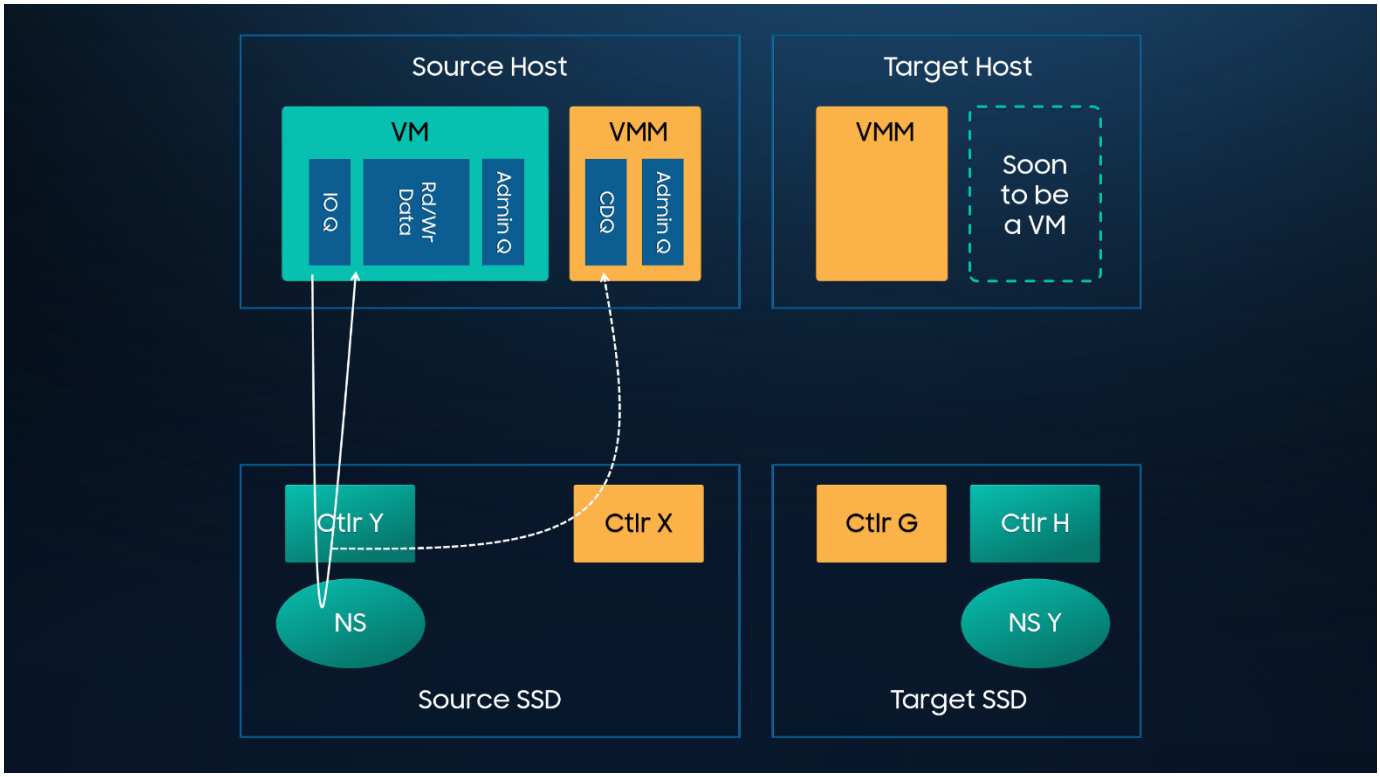

Figure 8. Current system status of the migration

6. Stop and Copy. Once the number of changes occurring to a source NS falls below some threshold, the VMM will initiate the stop and copy phase of the LM. Figure 9 shows this process. The VM continues to send I/Os to the secondary controller, and the primary controller continues to log any applicable interactions.

The VMM sends the Suspend command to the primary controller, which in turn stops the secondary controller from fetching any more commands from the VM. All commands that were in flight continue through until they are completed. Once the primary controller recognizes that all commands have been completed and all completion queue entries from the secondary controller are returned to the VM, then the primary controller is able to complete the Suspend command.

In this state, the source SSD will keep the secondary controller frozen and not fetch any further commands, and the primary controller will be ready in case a Resume command comes from the VMM. This Resume command is only expected if some error condition occurred in the exterior parts of the live migration.

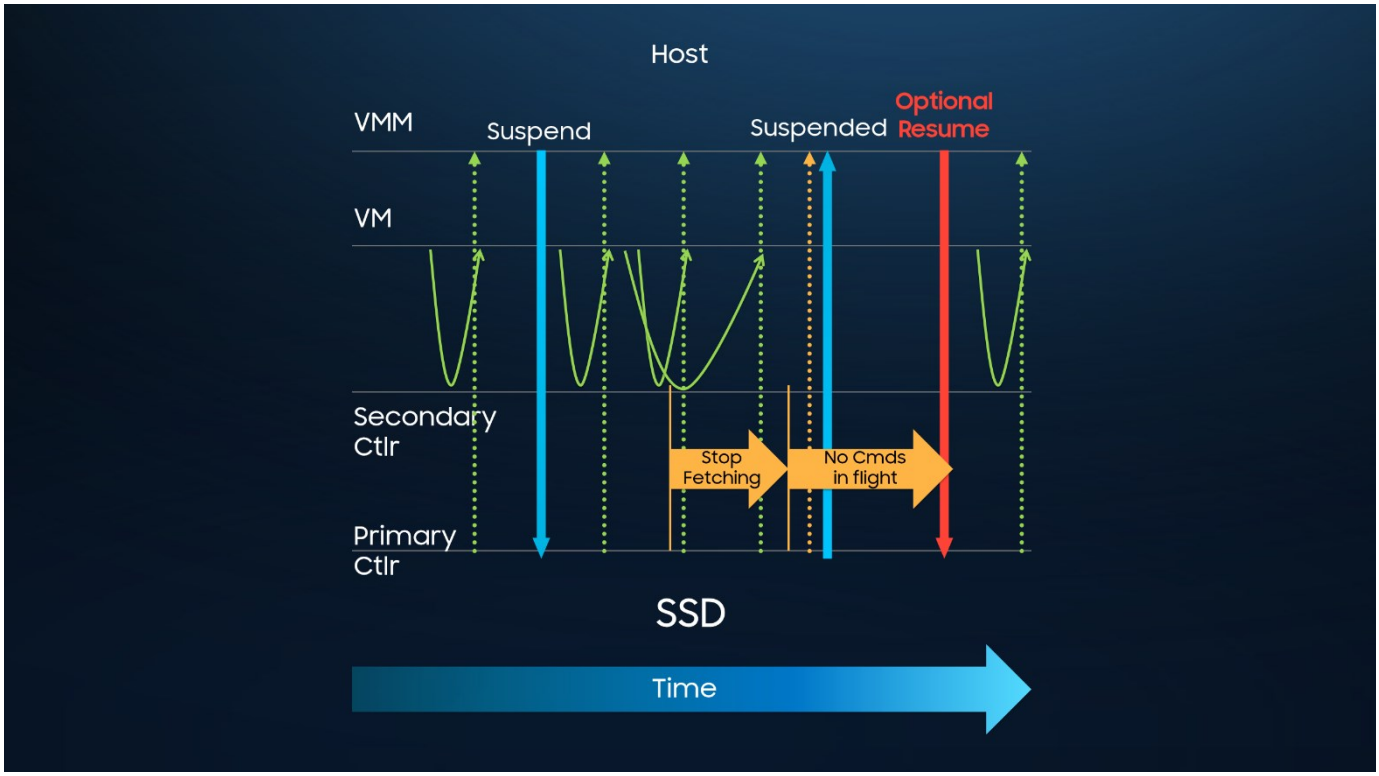

Figure 9. VMM initiating the stop and copy phase of the LM

With the secondary controller in a suspended state, the VMM can complete the live migration. All remaining CDQ entries will be parsed. All outstanding changes to the source NS will be read by the VMM through the primary controller. All of the changes will be written to the target NS on the target SSD. Outside of the scope of the SSDs, the VM process will be migrated from the source host to the target host.

Additionally, the VMM will issue Get Subsystem State to controller X in order to read the current state of the child subsystem. The child subsystem state will include the controller Y state, the associated namespaces, and other subsystem attributes. The subsystem state at the destination will be written with Set Subsystem State sent to controller G in order to initialize the controller H state. The combination of the initialized exported subsystem and this Set Subsystem State will together define all reporting provided to the VM on the target system from controller H.

There has been an ability to set some controller state settings with a similar flow using Get Controller State and written using Set Controller State. However, the Get Subsystem State and Set Subsystem State flows described here are now recommended as a superset of capabilities.

Tracking LBA Allocation

A host system needs to distinguish between LBAs on a storage device that are actively in use (allocated) vs. those that are free. TP4165 Tracking LBA Allocation addresses this need. Use of this feature was highlighted in the Move Snapshot of Data step of the Live Migration discussion.

Future: Open Challenges and Future Directions

Data placement, virtualized reporting, LBA allocation tracking, and live migration constitute powerful virtualization techniques and went a long way toward completing the virtualization toolset. Once implemented and utilized, however, a few remaining issues to be addressed became apparent.

Fair Resource Allocation in RUH-Optimized and Non-Optimized Environments

While data placement serves to let the host actively participate to achieve a low WAF, it does not insulate a given tenant from the behavior of others.

By way of example, consider a host with three tenants using an SSD as shown in Figure 10. Assume tenant 1 and 2 are perfect WAF=1 tenants; perhaps they are both writing a circular buffer. But tenant 3 is writing randomly with very poor WAF. The good news is that in today's SSDs, the reads from all tenants will generally be prioritized above all other traffic. But when writes are considered, performance is not quite perfectly virtualized.

Tenant 1 is using RUH 1, and the data is successfully placed on the NAND compacted together; tenant 2 using RUH 2 shows similar success. Tenant 3 using RUH 3 has the incoming data written compactly, but because the LBAs are written in random order, the data at rest on the NAND is randomly invalidated. The data placement for tenant 3 is not optimized, and any writes by tenant 3 will trigger GC in the drive in order to free up space for more writes to come in.

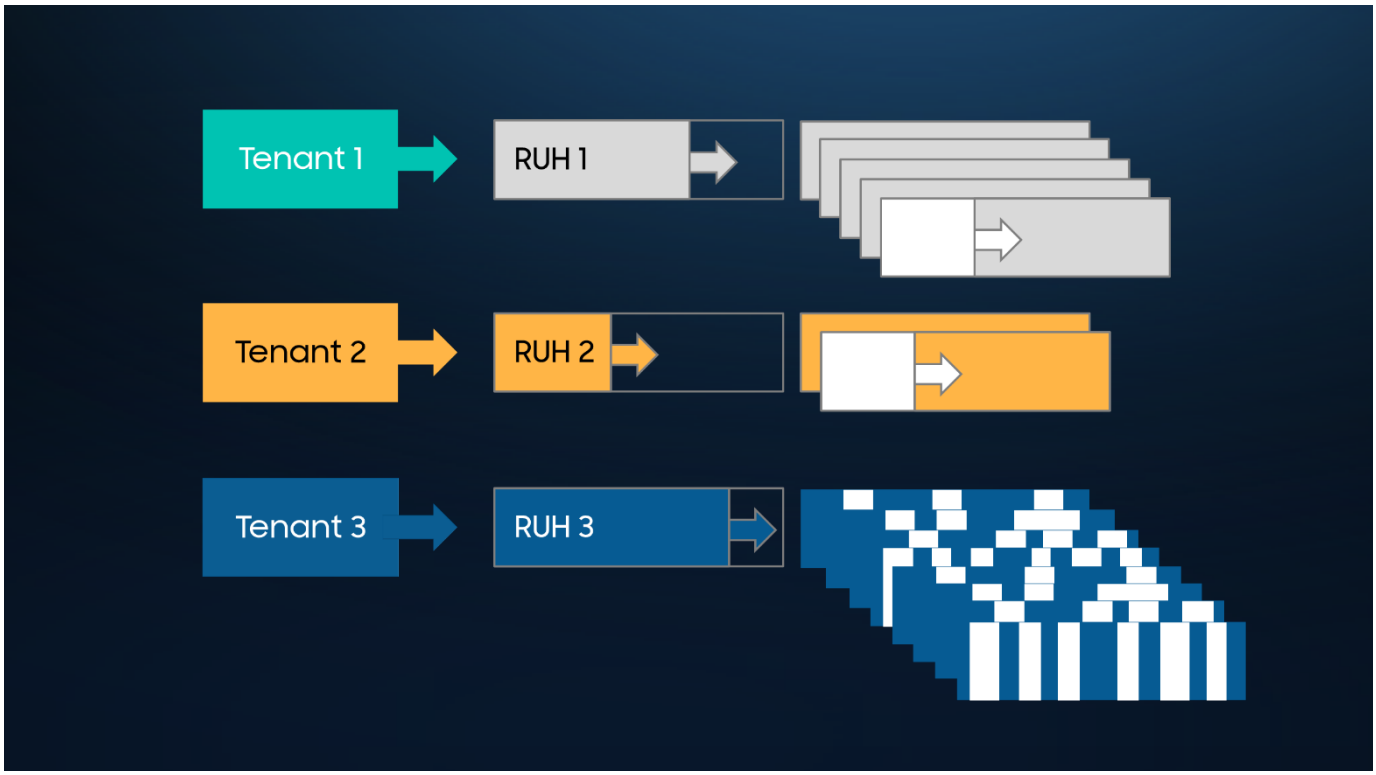

Figure 10. Tenants using FDP for data separation

Quantifying Performance Impact

With this interior state of the NAND, we can describe the maximum possible performance for each of the tenants. Tenants 1 and 2 have a max achievable performance equal to the sequential performance of the SSD. Tenant 3 has a max achievable performance equal to the random write performance of the drive. If one were to assume a WAF of 5 for this scenario, then the maximum random write performance can roughly be approximated as 1/5 the value of the sequential write performance.

These performance expectations of each tenant operating individually mirror the performances SSD users experience with a single tenant using a conventional SSD. One might claim that the SSD is successfully virtualized, which is true if the measure is achieving a WAF behavior that mimics one tenant active at a time on a conventional SSD. Writes, deallocates, and WAF behavior of the FDP SSD may match expectations.

However, these three tenants may be operating at the same time on a shared SSD. If tenants 1 and 2 are active at the same time, then their performances drop from their maximum down to 50% of this value. Ideally, tenants should not be aware of being virtualized — but this is an easily detectable performance hit. Similarly, if all three tenants are active concurrently, then tenants 1 and 2 will only receive approximately 10 – 20% of their maximum performance because tenant 3 will swamp the drive activity with its high WAF. If tenant 1 were continuously active as tenants 2 and 3 came online, then tenant 1 would notice dramatic performance reductions not due to any changes in its own behavior.

NAND-Level Rate Limiting and QoS Control

This performance problem is only solvable with a way to cap or rate limit the performance of each tenant. Furthermore, a rate limit on the tenant must be implemented at the NAND level — a limit on the allocation of NAND time. Only by limiting the NAND time per-tenant can the allocation of NAND usage provided to other tenants be made.

For example, tenant 1 with its sequential time can be allocated only 1/3 of the NAND time available. Due to the WAF=1 behavior of the tenant, the sequential performance achievable by tenant 1 will be 1/3 of the total capabilities of the SSD. Similarly, the same limit can be applied to tenant 2. Now with tenant 1 and 2 both active, they will only consume 66% of the drive capabilities. Both can be active and neither will experience any performance changes as the other tenant changes behaviors.

Extending this example to tenant 3 highlights the need for the rate limits to be communicated as "time on the media." If the rate limit is applied only on the incoming writes, then the WAF impacts will occur after this initial rate limit of incoming writes. The amount of NAND media traffic caused by tenant 3 is 5x larger than by tenant 1 and 2, which would continue to swamp the drive performance.

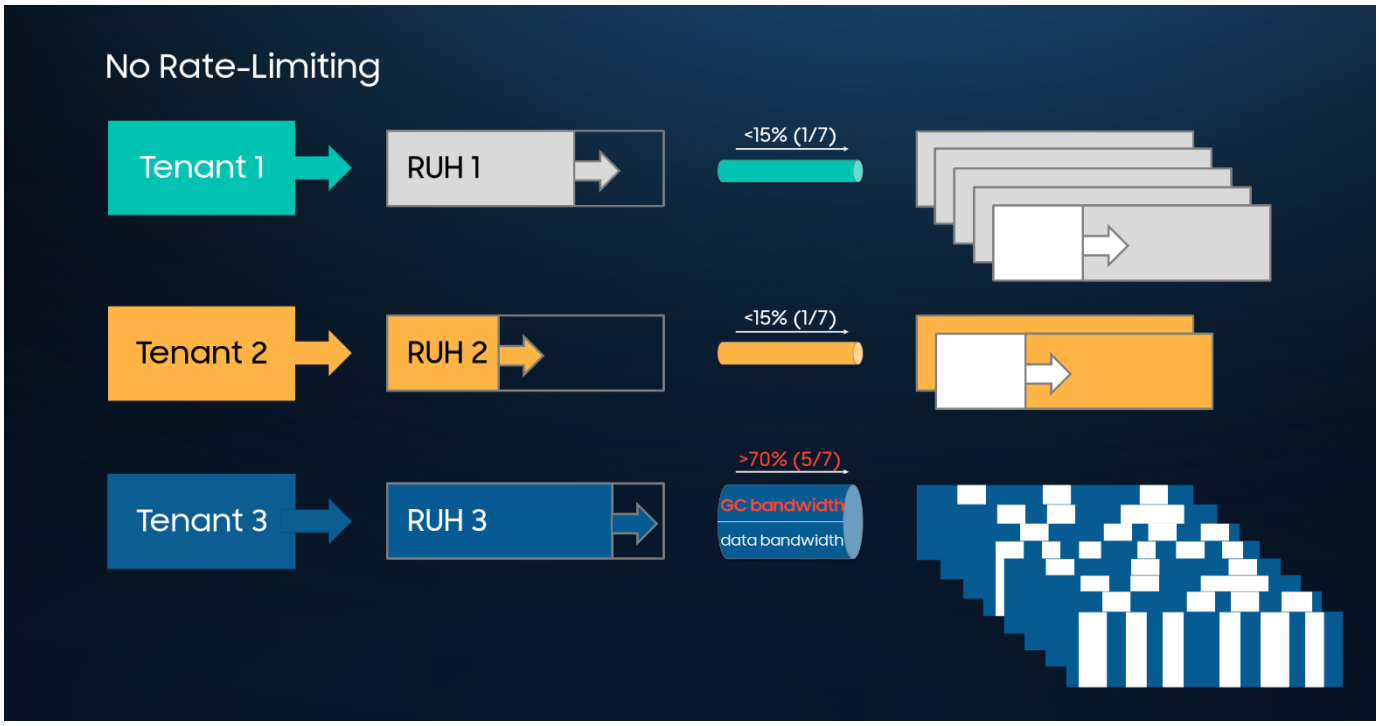

Figure 11. Tenants using FDP with highlighted media utilization rates

By applying the limits at the NAND, 1/3 of the media time can be allocated to each tenant. Tenant 3, with its poor WAF behaviors, will be forced to implement all of their incoming host writes, GC reads, and GC writes within their limit of NAND time. This protects the NAND time allocated to tenant 1 and 2. Tenant 3 is necessarily throttled by their own write traffic to have far less performance of the shared SSD. Since conventional SSDs have a natural limit to the available NAND time as well, this performance would mirror that experienced by tenant 3 in an unshared drive.

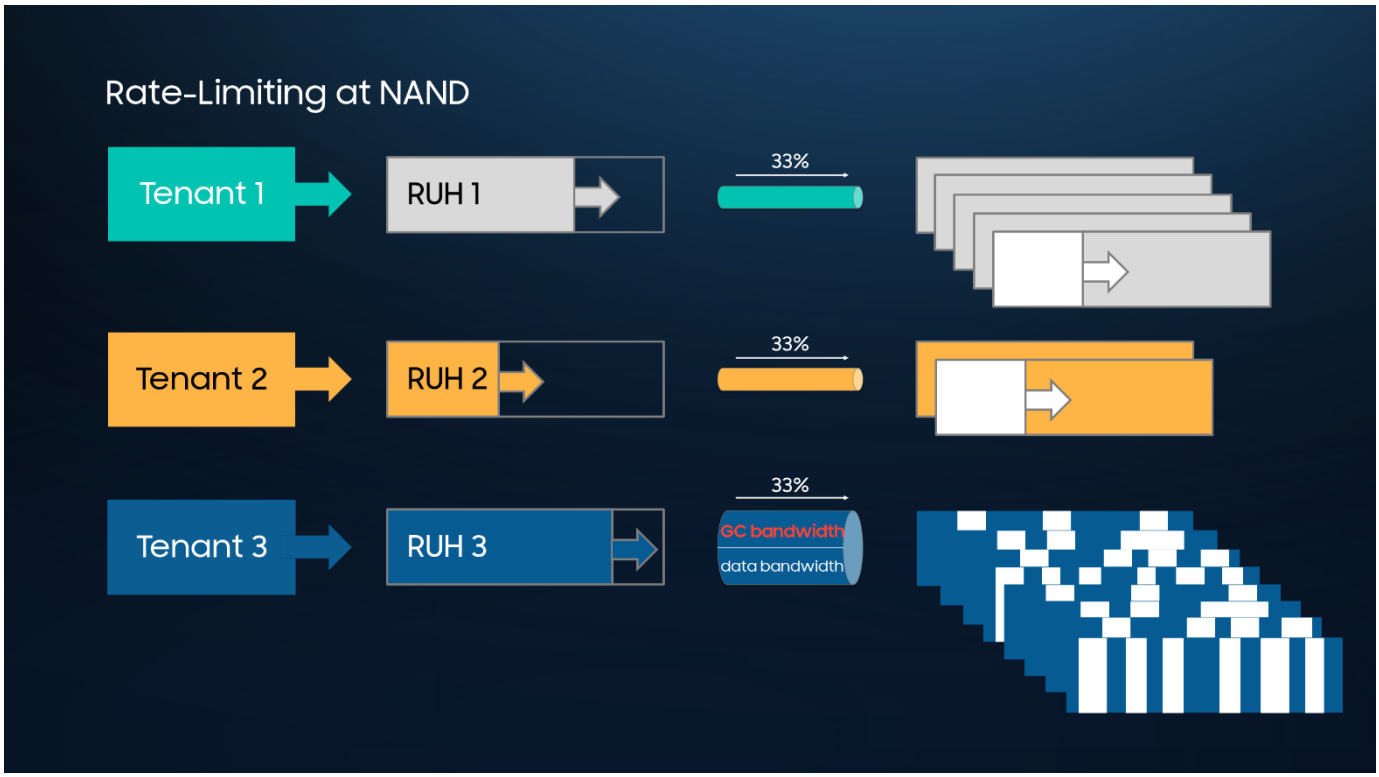

Figure 12. Tenants using FDP with media utilization rate limiting applied

When referring to storage, this topic is considered under the umbrella of quality of service (QoS). It is currently being addressed in NVMe proposal TP4176 Quality of Service for PCIe Bandwidth and IOPS for a Controller, for which Samsung is the primary author and has made a presentation[3] available. There are separate discussions regarding NAND and controller behavior interaction with programmed rate limits. Samsung sees technical reasons to connect the backend WAF and NAND behavior to the front-end rate limits. This will enable more reliable and predictable rate limit implementations in SSDs from multiple vendors.

Potential Architectural Extensions

Not even touched on here are the many other areas for investigation. For example:

- The transfer of data from the source to target system in live migration is a security risk, since the data is not encrypted during this transfer.
- Common standardized solutions for traffic prioritizations do not yet exist.

The open nature of the virtualization concepts underpinned by the virtualization toolset will continue to call for refinements of the techniques already enabled.

3 Unlocking QoS Potential: Optimizing SSD Performance for Emerging Standards, https://nvmexpress.org/wp-content/uploads/03_Helmick-Unlocking-QoS-Potential_Final.pdf

Conclusion

The term “storage virtualization” covers a lot of ground. Features introduced to PCIe and NVMe over the years have addressed topics like data separation, data migration, and data environment isolation, setting the stage for hardware solutions. However, committing aspects such as rate limiting, encrypted live migration, and standardized system traffic prioritizations to hardware are still works in progress.

The virtualization of an SSD has many aspects and myriad use cases, from which derive a large set of requirements. NVMe has successfully enabled many new building blocks of virtualization capabilities as outlined here. Further virtualization needs are under consideration, and many more extensions of virtualization are possible. Virtualization is already a significant SSD feature; it can only increase in importance as SSDs continue to grow in capacity.