SDC

STORAGE DEVELOPER CONFERENCE

SNIA ■ SANTA CLARA, 2017

Update on Windows Persistent Memory Support

Neal Christiansen
Microsoft

Agenda

- What is Persistent Memory (PM)
- Review: Existing Windows PM Support
- What's New
  - New PM APIs
  - Large Page Support
  - Hyper-V Support
  - NVML on Windows
  - Improved Driver Model
  - Uncorrectable Error Handling
- Industry Standards Support

Reminder: What is Persistent Memory

- Non-volatile storage with RAM-like performance
  - Low latency/high bandwidth.
- Resides on the memory bus
- Terms used to describe the hardware:
  - Storage Class Memory (SCM)
  - Non-Volatile Memory (NVM)
  - Persistent Memory (PM) ⟸ Industry converging on this term

Agenda

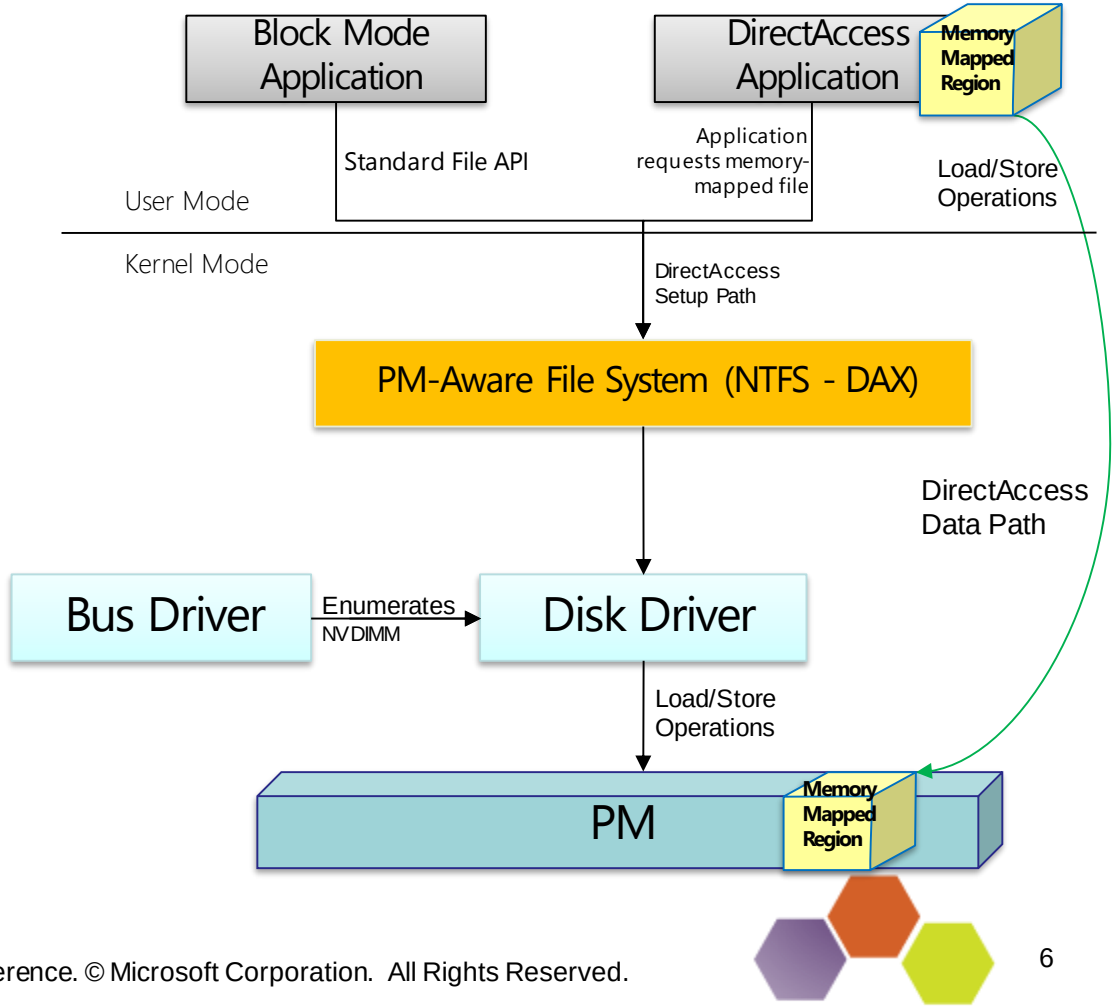
- What is Persistent Memory (PM)
- Review: Existing Windows PM Support
- What's New
  - New PM APIs
  - Large Page Support
  - Hyper-V Support
  - NVML on Windows
  - Improved Driver Model
  - Uncorrectable Error Handling
- Industry Standards Support

Support for JEDEC-defined NVDIMM-N devices

- Released:
  - August, 2016: Windows 10 Anniversary Update
  - September, 2016: Windows Server 2016

How DAX Works

- **The Idea**
  - App has direct access to PM via existing memory-mapping semantics
  - Updates directly modify PM
    - Storage Stack not involved
- **Characteristics**
  - True device performance (no software overhead)
  - Byte-Addressable



Windows DAX Volume Support

- DAX mode is chosen at volume format time
  - Why: compatibility issues with existing components, examples:
    - File system filters
    - Bitlocker (volume level software encryption)
    - Volsnap (volume snapshot provider)
  - Some existing functionality is lost
  - DAX Volumes are only supported by the NTFS file system

Memory Mapped IO on DAX Volumes

- Memory mapped sections map directly to PM hardware
  - No change to existing memory mapping APIs
- An application has direct access to persistent memory
  - Maximizes performance

Cached IO on DAX Volumes

- One Copy IO via the Cache manager
  - Creates a cache map that maps directly to persistent memory
  - Copies directly between user's buffer and persistent memory

Non-cached IO on DAX Volumes

- Is converted to cached IO by the file system
  - Cache manager copies directly between user's buffer and persistent memory

Impacts to File System Functionality on DAX Volumes

- Direct access to PM by applications eliminates the traditional hook points that file systems use to implement various features
- File System functionality that can not be supported on DAX enabled volumes:
  - No NTFS software encryption support (EFS)
  - No NTFS software compression support
  - No NTFS TxF support (Transactional NTFS)
  - No NTFS USN range tracking of memory mapped files
  - No NTFS resident file support

Impacts to File System Functionality on DAX Volumes

- File system no longer knows when a writeable memory mapped section is modified:
  - The following file system features are now updated at the time a writeable mapped section is created:
    - File's modification and access times
    - Marking the file as modified in the USN (change) Journal
    - Signaling directory change notification
  - Functionality not currently supported on DAX volumes:
    - Sparse Files
    - Defragging files that are memory mapped

What is a File System Filter

- A driver that layers above the file system
- Augments file system functionality
  - May interact with all operations as they come into and out of the file system
- Example classes of filters:
  - Anti-virus
  - Replication
  - Hierarchical Storage Management (HSM)
  - Security Enhancer
  - Encryption
  - Compression
  - Quota
  - Activity monitor

File System Filters on DAX Volumes

- To minimize compatibility issues:
  - No existing filters will receive notification when a DAX volume is mounted
  - At filter registration time filters may indicate via a new registration flag that they understand DAX volume semantics

Block Mode Volumes on PM Hardware

Is backwards compatible

- Maintains existing storage semantics
  - All IO operations traverse the storage stack to the PM disk driver
  - Sector atomicity guaranteed by the PM disk driver
  - Has shortened path length through the storage stack to reduce latency
- Fully compatible with existing applications
- Supported by all Windows file systems
- Works with existing file system and volume filter drivers

Sector Atomicity

- BTT – Block Translation Table
  - Algorithm created by Intel and standardized in UEFI 2.7
  - Provides sector level atomicity of writes
    - Eliminates sub-sector torn writes
    - On power loss either see contents of old sector or new sector
    - Provides compatibility for existing applications that have built-in assumptions around storage failure patterns
    - Has performance impact
- Uses small portion of PM space for mapping tables and control structures
  - BTT structures are not visible outside the PM driver
- File system controls if a given write should use BTT or not

Agenda

- What is Persistent Memory (PM)
- Review: Existing Windows PM Support
- What's New
  - New PM APIs
  - Large Page Support
  - Hyper-V Support
  - NVML on Windows
  - Improved Driver Model
  - Uncorrectable Error Handling
- Industry Standards Support

New Flush APIs for DAX mapped regions

- Available from both user and kernel modes
  - Usermode APIs do not transition to kernel mode
- Performs necessary work to optimally flush PM contents from CPU caches
  - Optimized for given hardware architecture
- MSDN documentation avalable at:
  - https://msdn.microsoft.com/en-us/library/windows/hardware/ff553354(v=vs.85).aspx

Rtl APIs for Flushing DAX mappings

- RtlGetNonVolatileToken
- RtlFreeNonVolatileToken
- RtlFlushNonVolatileMemory
- RtlDrainNonVolatileFlush
- RtlFlushNonVolatileMemoryRanges
- RtlWriteNonVolatileMemory

RtlGetNonVolatileToken

```
NTSTATUS
RtlGetNonVolatileToken  (
        VOID *NvBuffer,
        SIZE_T Size,
        VOID **NvToken);
```

- Stores properties about the given DAX region in the returned NvToken object
- If given region is not DAX mapped, usermode callers will fail with STATUS_INVALID_PARAMETER

RtlFreeNonVolatileToken

```
NTSTATUS
RtlFreeNonVolatileToken  (
        VOID *NvToken);
```

- Frees token returned by **RtlGetNonVolatileToken**

RtlFlushNonVolatileMemory

```
NTSTATUS
RtlFlushNonVolatileMemory (
        VOID *NvToken,
        VOID *NvBuffer,
        SIZE_T Size,
        ULONG Flags);
```

- Optimally flushes the given DAX region
- Flag **FLUSH_NV_MEMORY_IN_FLAG_NO_DRAIN** tells the routine to not wait for the flush to drain (via the SFENCE instruction)
  - Allows for efficient flushing of multiple regions

RtlDrainNonVolatileFlush

```
NTSTATUS
RtlDrainNonVolatileFlush (
        VOID *NvToken);
```

- Waits for previous flush operations to complete (via the SFENCE instruction)
- Supports efficient flushing of multiple regions

RtlFlushNonVolatileMemoryRanges

```
NTSTATUS
RtlFlushNonVolatileMemoryRanges (
        VOID *NvToken,
        NV_MEMORY_RANGE *NvRanges,
        SIZE_T TotalRanges,
        ULONG Flags);
```

```
typedef struct _NV_MEMORY_RANGE {
        VOID *BaseAddress;
        SIZE_T Length;
} NV_MEMORY_RANGE;
```

- Only one drain operation is issued across all ranges
- Flag **FLUSH_NV_MEMORY_IN_FLAG_NO_DRAIN** tells the routine to not wait for the flushes to drain (via the SFENCE instruction)

RtlWriteNonVolatileMemory

```
NTSTATUS
RtlWriteNonVolatileMemory (
        VOID *NvToken,
        VOID UNALIGNED *NvDestination,
        VOID UNALIGNED *Source,
        SIZE_T Size,
        ULONG Flags);
```

- Functionally equivalent to memcpy()
- Does **not** flush the copied memory

NUMA information FSCTL

FSCTL_QUERY_VOLUME_NUMA_INFO

```
typedef struct _FSCTL_QUERY_VOLUME_NUMA_INFO_OUTPUT {
    ULONG NumaNode;
} FSCTL_QUERY_VOLUME_NUMA_INFO_OUTPUT;
```

- Windows requires a PM disk to reside on a single NUMA node
- Returns the NUMA node the given DAX volume resides on

Agenda

- What is Persistent Memory (PM)
- Review: Existing Windows PM Support
- What's New
  - New PM APIs
  - Large Page Support
  - Hyper-V Support
  - NVML on Windows
  - Improved Driver Model
  - Uncorrectable Error Handling
- Industry Standards Support

What are Large Pages

- Modern CPUs mange memory using 4K pages
- An applications memory usage is managed via page tables controlled by the operating systems memory manager
- CPU's contain a mapping table cache called the TLB (translation lookaside buffer) that caches page table mappings
- For applications with a large memory footprint -- the CPU can spend a lot of time reading page table entries into the TLB
- A Large Page allows a contiguous 2mb region to be described with a single TLB entry
  - Applications typically see a significant performance improvement

Windows Large Page Support

- DAX partitions are now aligned to 2mb boundaries
- NTFS generically supports cluster sizes up to 2mb (in powers of 2)
  - Former limit was 64K
- A file memory mapped on a DAX volume with a 2mb cluster size is guaranteed to be mapped by the memory manager using Large Pages
- Huge page support will be available in the future
  - Huge pages are 1gb in size

Agenda

- What is Persistent Memory (PM)
- Review: Existing Windows PM Support
- What's New
  - New PM APIs
  - Large Page Support
  - Hyper-V Support
  - NVML on Windows
  - Improved Driver Model
  - Uncorrectable Error Handling
- Industry Standards Support

Hyper-V PM Support

- Windows & Linux guests in generation 2 VMs see virtual PMEM (vPMEM) devices
- New VHD file type: **.VHDPMEM**
  - Can convert between VHDX and VHDPMEM formats (using **convert-vhd** PowerShell cmdlet)
  - Admin decide at create time if the VHDPMEM file has a BTT or not
  - VHDPMEM files can be mounted as a SCSI device on the host for read/write access
- Each vPMEM device is backed by one .VHDPMEM file

Hyper-V PM Support

- DAX and BTT programming models, including Win32 APIs and NVML, supported from guest
- Uses large pages automatically, when available
- No support for VM meta-operations including:
  - Live Migration
  - Checkpoints
  - Backup
  - Save/Restore

Agenda

- What is Persistent Memory (PM)
- Review: Existing Windows PM Support
- What's New
  - New PM APIs
  - Large Page Support
  - Hyper-V Support
  - NVML on Windows
  - Improved Driver Model
  - Uncorrectable Error Handling
- Industry Standards Support

NVML on Windows

- NVML is an open source library originally implemented by Intel
  - Available for Windows and Linux via GitHub
  - **https://github.com/pmem/nvml/**
- Microsoft is working with Intel, HPE and HP Labs on the Windows port
  - It is feature complete

NVML on Windows

- Defines a set of application API's for efficient use of PM hardware
  - Abstracts out OS specific dependencies
  - Underlying implementation uses memory mapped files
    - All access via API calls
  - Makes its own atomicity guarantees
  - Works in both PM and non-PM hardware environments
- Use Case
  - Alternative to handling flushing or creating PM-aware data structures yourself
  - Simpler application development

Overview of NVML Libraries

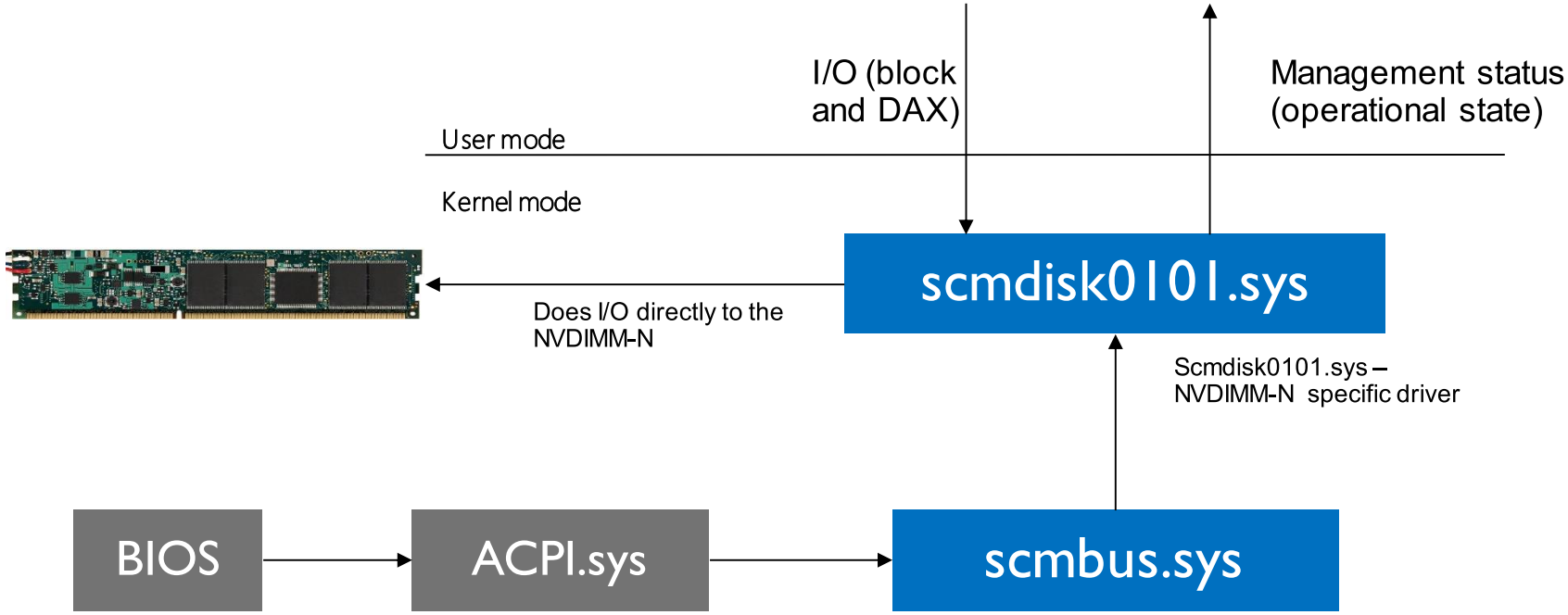
- libpmemobj – transactional object store
- libpmemblk – provides arrays of atomically updated fixed size blocks
- libpmemlog – atomic append to log
- libpmem – low level support for rest of libraries

- **http://pmem.io/nvml**

Agenda

- What is Persistent Memory (PM)
- Review: Existing Windows PM Support
- What's New
  - New PM APIs
  - Large Page Support
  - Hyper-V Support
  - NVML on Windows
  - Improved Driver Model
  - Uncorrectable Error Handling
- Industry Standards Support

Windows Server 2016 architecture



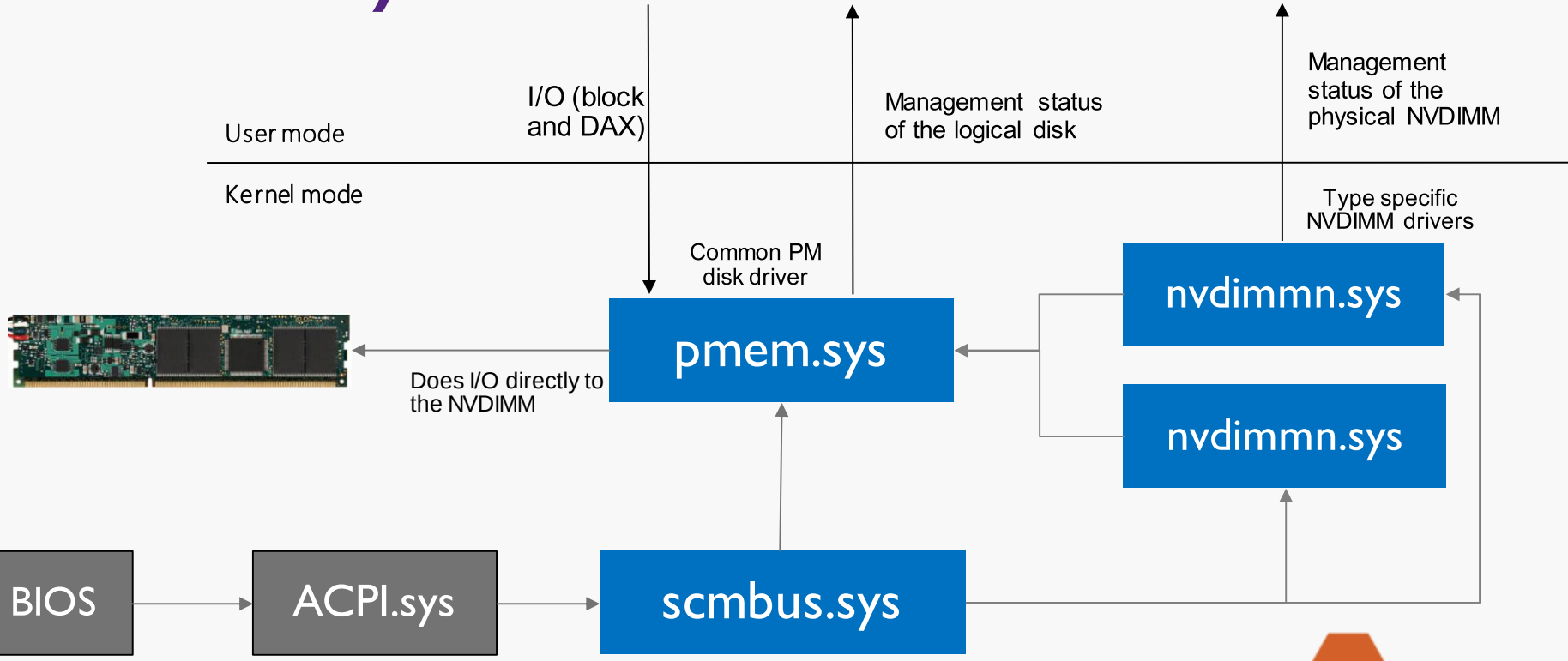
New Architecture

- For NVDIMM-N, ScmDisk0101.sys is replaced by two drivers
  - **Pmem.sys**: controls a byte-addressable interleave set and is responsible for all I/O, BTT etc.
  - **NvdimmN.sys**: controls a physical NVDIMM-N and is responsible for monitoring its health
    - There is one physical NVDIMM PDO per physical NVDIMM on the system
    - On a system with two interleaved NVDIMM-Ns, there will be one pmem.sys PDO and two nvdimmn.sys PDOs
- Physical NVDIMMs are a new device stack, with a new management experience
  - New IOCTL interface

Benefits of the New Architecture

- Easy to support new NVDIMM types
  - Only have to write a physical NVDIMM driver; pmem.sys doesn't change
- Clear separation of responsibilities
  - Pmem.sys manages the logical disk functionalities
  - Physical NVDIMM drivers manage physical devices

New Driver Architecture (post-Window Server 2016)



Agenda

- What is Persistent Memory (PM)
- Review: Existing Windows PM Support
- What's New
  - New PM APIs
  - Large Page Support
  - Hyper-V Support
  - NVML on Windows
  - Improved Driver Model
  - Uncorrectable Error Handling
- Industry Standards Support

Uncorrectable Error Handling

- Server 2016 was limited to boot-time detection only
- Runtime detection now supported
- For detected bad pages the PM disk driver:
  - Fails Block IOs
  - If unmapped:
    - Fails future mapping requests
  - If mapped:
    - Asks the memory manager to unmap the given page
    - Unmapping by memory manager is best effort

Agenda

- What is Persistent Memory (PM)
- Review: Existing Windows PM Support
- What's New
  - New PM APIs
  - Large Page Support
  - Hyper-V Support
  - NVML on Windows
  - Improved Driver Model
  - Uncorrectable Error Handling
- Industry Standards Support

Industry Standards Support

- JEDEC JESD 245, 245A: Byte Addressable Energy Backed Interface
  - Defines the host to device interface and features supported for a NVDIMM-N
- UEFI 2.5 – 2.7
  - Label format
  - Block Translation Table (BTT): sector atomicity support
- ACPI 6.0 – 6.2
  - NVDIMM Firmware Interface Table (NFIT)
  - NVM Root and NVDIMM objects in ACPI namespace
  - Address Range Scrub (ARS)
    - Uncorrectable memory error handling
  - Notification mechanism for NVDIMM health events and runtime detected uncorrectable memory error

Upcoming Windows Release Information

- New support to be Released:
  - Oct 17, 2017: Windows 10 “Fall Creators Update”
  - Windows Server Fall Update

Questions