SQLintersection

Monday, 9:00-4:30

Analyzing and Improving I/O Subsystem Performance

Glenn Berry
glenn@sqlskills.com

SQLskills
immerse yourself in sql server

SQL
intersection

Glenn Berry

SQLskills immerse yourself in sql server

MVP Microsoft Most Valuable Professional

- Consultant/Trainer/Speaker/Author
- Principal Consultant, SQLskills.com
  - Blog: http://www.SQLskills.com/blogs/Glenn
  - Twitter: @GlennAlanBerry
  - Regular presenter at worldwide conferences on hardware, scalability, and DMV queries
  - Author of SQL Server Hardware
  - Chapter author of Professional SQL Server 2012 Internals and Troubleshooting
  - Chapter author of MVP Deep Dives Volumes 1 and 2
- Instructor-led training: Immersion Events
- Online training: pluralsight http://pluralsight.com/
- Consulting: health checks, hardware, performance, upgrades

Overview

- Three main metrics for storage performance
- SQL Server I/O workload metrics
- Tools for testing storage subsystems
- Primary storage types for SQL Server
- RAID levels and SQL Server workloads
- Some comparative storage metrics
- Improving I/O performance
- Index and workload tuning

Three Main Metrics for Storage Performance

- **Latency (ms)**
- **Input/output operations per second (IOPS)**
- **Sequential throughput (MB/sec or GB/sec)**
  - These three measurements are all related, so you can’t just look at one of them in isolation without knowing the others
  - Storage vendors tend to show their best-case numbers in isolation

Latency

- **Latency is the time it takes for an I/O to complete**
  - Sometimes called response time or service time
- **Measurement starts when the OS sends a request to the drive (or controller) and ends when the drive finishes processing the request**
  - Reads are complete when the OS receives the data
  - Writes are complete when the drive informs the OS it has received the data
    - The data may still be in a DRAM cache on the drive or controller

SQL intersection

Input/Output Operations per Second

- **Input/output operations per second (IOPS)**
  - This metric is directly related to latency
    - Constant latency of 1ms means a drive can process 1,000 I/Os per second with a queue depth of 1
  - As more I/Os are added to the queue, latency will increase
  - Flash storage can read/write to multiple NAND channels in parallel
- **IOPS = Queue Depth/Latency**
- **IOPS by itself does not consider the transfer size**
  - You need to know the transfer size when looking at an IOPS measurement
  - You can translate IOPS to MB/s and MB/s to latency as long as you know the queue depth and transfer size

SQL *intersection*

Sequential Throughput

- **Sequential throughput (MB/sec or GB/sec)**
- **MB/sec = IOPS * Transfer Size**
  - 556 MB/sec = 135,759 IOPS * 4096 bytes transfer size
  - 1112 MB/sec = 135,759 IOPS * 8192 bytes transfer size
- **Sequential throughput often gets short-changed in enterprise storage**
  - Bandwidth limitations from the storage interface directly affect this
  - 1Gbps iSCSI limited to about 100 MB/sec
  - 4Gbps FC limited to about 400 MB/sec
- **The disks may be so busy that they can’t deliver full rated throughput**
  - This is fairly common with magnetic disks in DAS and shared SANs

The Importance of Sequential Throughput

- **Sequential throughput is critical for many database server activities**
  - Full database backups and restores
    - Initializing AlwaysOn AG replicas, database mirrors, replication subscribers, log shipping secondaries
  - Index creation and rebuilds
    - Good sequential throughput makes it much easier to do index tuning
  - DW or reporting workload large sequential scans
    - Very important when data does not fit in the buffer pool
    - Unfortunately, SQL Server 2014 BPE does not help with sequential scans

Demo

Measuring sequential throughput

Important SQL Server I/O Workload Metrics (1)

- **What is the read vs. write ratio of the workload?**
  - You can use my DMV Diagnostic Queries to determine this at the file level
  - Ratios will be different for different SQL Server file types and workloads
- **What are the typical I/O rates (IOPS and throughput)?**
  - Reads/sec, writes/sec (PerfMon) is IOPS
  - Disk read bytes/sec, disk write bytes/sec (PerfMon) is throughput

Important SQL Server I/O Workload Metrics (2)

- **What is the average logical disk-level latency?**
  - Average disk sec/read, average disk sec/write (PerfMon) is latency
  - You can use one of my DMV Diagnostic Queries to determine this at the disk level
- **What is the average file-level I/O latency?**
  - You can see this in Windows Resource Monitor
  - You can use one of my DMV Diagnostic Queries to determine this at the file level

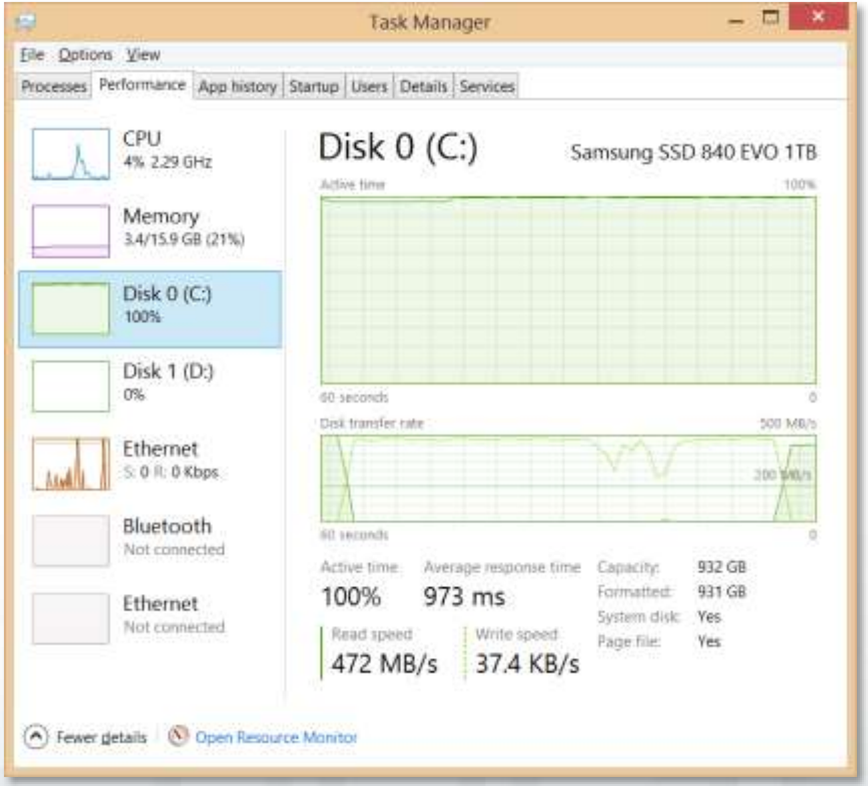
Methods for Measuring I/O Performance (1)

- **Task Manager in Windows Server 2012 and newer**
  - Depending on what kind of storage you are using, not always useful
- **Disk section in Windows Resource Monitor**
  - Shows file-level response time in ms
- **Logical Disk Counters in Performance Monitor**
  - Shows disk-level metrics

Methods for Measuring I/O Performance (2)

- **Disk Benchmark Tools**
  - CrystalDiskMark
    - http://bit.ly/1vm5dPe
  - Microsoft DiskSpd
    - http://bit.ly/1whNzQL
  - Microsoft SQLIO
    - SQLIO is deprecated, so I would not use it for new testing
    - http://bit.ly/1obVdIV
- **SQL Server DMV Diagnostic Queries**
  - http://bit.ly/Q5GAJU

Disk Performance in Windows Task Manager


Task Manager
File Options View
Processes Performance App history Startup Users Details Services
Fewer details
Open Resource Monitor

CPU
4% 2.29 GHz

Memory
3.4/15.9 GB (21%)

Disk 0 (C:)
100%

Disk 1 (D:)
0%

Ethernet
S: 0 R: 0 Kbps

Bluetooth
Not connected

Ethernet
Not connected

Disk 0 (C:) Samsung SSD 840 EVO 1TB

Active time
100%

Average response time
973 ms

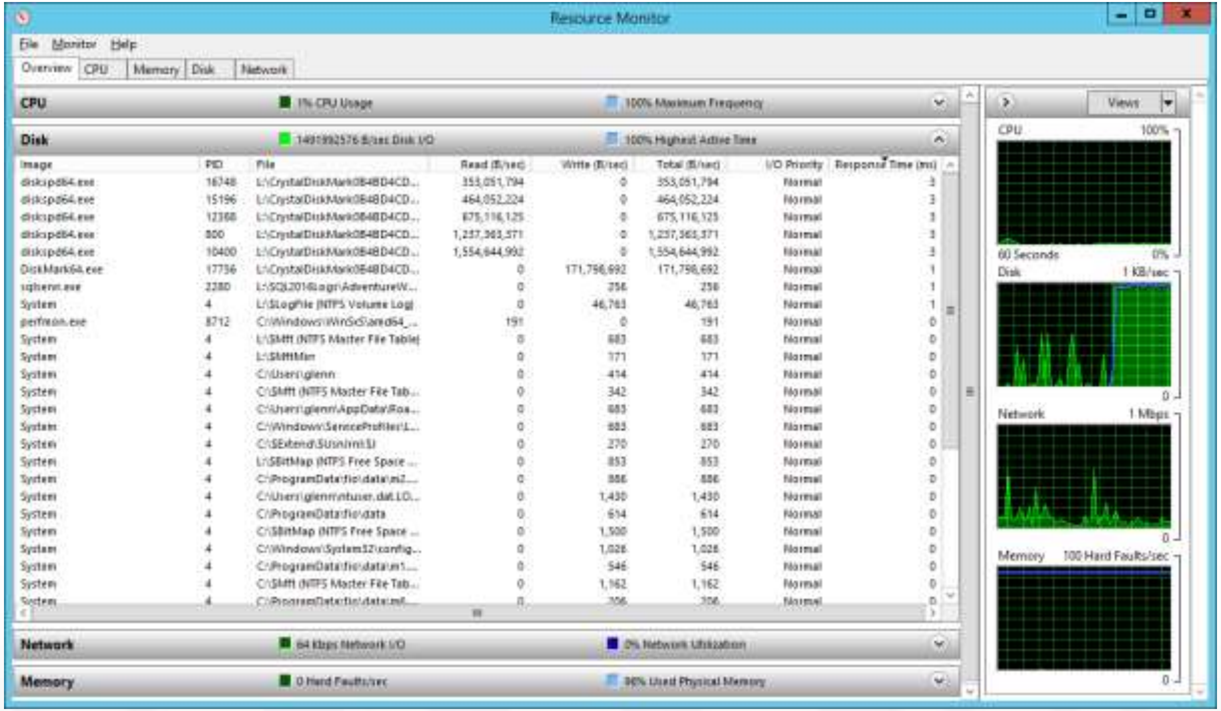
Read speed
472 MB/s

Write speed
37.4 KB/s

Capacity:	932 GB
Formatted:	931 GB
System disk:	Yes
Page file:	Yes

SQL *intersection*

Disk Performance in Windows Resource Monitor



CPU 🟩 1% CPU Usage ▨ 100% Maximum Frequency

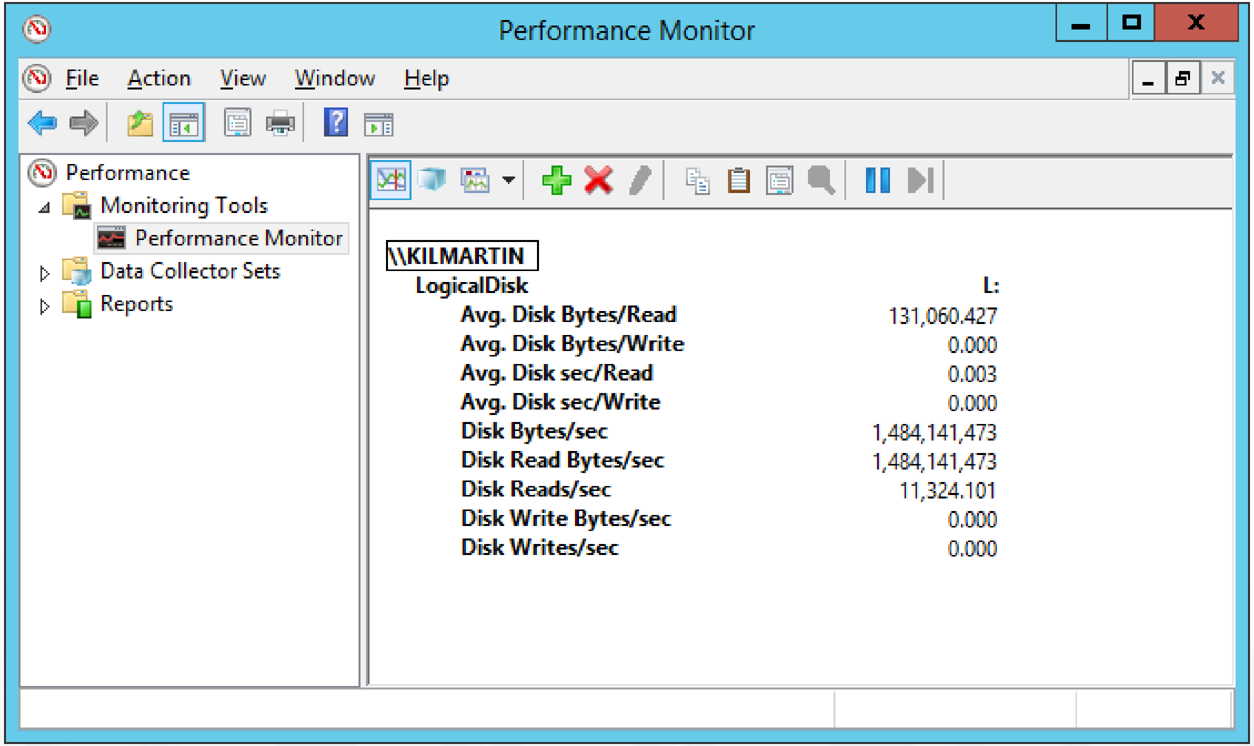
Disk 🟩 1491992576 B/sec Disk I/O ▨ 100% Highest Active Time

Image	PID	File	Read (B/sec)	Write (B/sec)	Total (B/sec)	I/O Priority	Response Time (ms)
diskspd64.exe	16748	L:\CrystalDiskMark0B48D4CD...	353,051,794	0	353,051,794	Normal	3
diskspd64.exe	15196	L:\CrystalDiskMark0B48D4CD...	464,052,224	0	464,052,224	Normal	3
diskspd64.exe	12368	L:\CrystalDiskMark0B48D4CD...	675,116,125	0	675,116,125	Normal	3
diskspd64.exe	800	L:\CrystalDiskMark0B48D4CD...	1,237,363,371	0	1,237,363,371	Normal	3
diskspd64.exe	10400	L:\CrystalDiskMark0B48D4CD...	1,554,644,992	0	1,554,644,992	Normal	3
DiskMark64.exe	17756	L:\CrystalDiskMark0B48D4CD...	0	171,798,692	171,798,692	Normal	1
sqlservr.exe	2280	L:\SQL2014Logs\AdventureW...	0	256	256	Normal	1
System	4	L:\$LogFile (NTFS Volume Log)	0	46,763	46,763	Normal	1
perfmon.exe	8712	C:\Windows\WinSxS\amd64_...	191	0	191	Normal	0
System	4	L:\$Mft (NTFS Master File Table)	0	683	683	Normal	0
System	4	L:\$MftMirr	0	171	171	Normal	0
System	4	C:\Users\glenn	0	414	414	Normal	0
System	4	C:\$Mft (NTFS Master File Tab...	0	342	342	Normal	0
System	4	C:\Users\glenn\AppData\Roa...	0	683	683	Normal	0
System	4	C:\Windows\ServiceProfiles\L...	0	683	683	Normal	0
System	4	C:\$Extend\$UsnJrnl:$J	0	270	270	Normal	0
System	4	L:\$BitMap (NTFS Free Space ...	0	853	853	Normal	0
System	4	C:\ProgramData\fio\data\m2...	0	886	886	Normal	0
System	4	C:\Users\glenn\ntuser.dat.LO...	0	1,430	1,430	Normal	0
System	4	C:\ProgramData\fio\data	0	614	614	Normal	0
System	4	C:\$BitMap (NTFS Free Space ...	0	1,500	1,500	Normal	0
System	4	C:\Windows\System32\config...	0	1,028	1,028	Normal	0
System	4	C:\ProgramData\fio\data\m1...	0	546	546	Normal	0
System	4	C:\$Mft (NTFS Master File Tab...	0	1,162	1,162	Normal	0
System	4	C:\ProgramData\fio\data\m6...	0	206	206	Normal	0

Network 🟩 64 Kbps Network I/O ■ 0% Network Utilization

Memory 🟩 0 Hard Faults/sec ▨ 90% Used Physical Memory

LogicalDisk Counters in Performance Monitor



```
\\KILMARTIN
    LogicalDisk                                   L:
        Avg. Disk Bytes/Read             131,060.427
        Avg. Disk Bytes/Write                  0.000
        Avg. Disk sec/Read                     0.003
        Avg. Disk sec/Write                    0.000
        Disk Bytes/sec                 1,484,141,473
        Disk Read Bytes/sec            1,484,141,473
        Disk Reads/sec                    11,324.101
        Disk Write Bytes/sec                   0.000
        Disk Writes/sec                        0.000
```

Demo

I/O related DMV queries

(from SQL Server DMV Diagnostic Queries)

SQL *intersection*

Common DMV I/O Query Result Patterns

- **Very common to see high write latency to tempdb data files**
  - Make sure you have multiple data files (nstart with 4-8) that are all the same size (follow Bob Ward's guidance)
  - Make sure you are using TF 1118 (not necessary with SQL Server 2016)
  - Consider using local flash-based storage for tempdb, if your workload needs it
- **Common to see high read latency from user database data files**
  - Look for signs of memory pressure, consider adding more RAM and doing standard workload and index tuning
  - Consider using SQL Server 2014 BPE (esp for Standard Edition) with OLTP workloads
    - Make sure to use fast, local flash storage for BPE file

SQL Server 2014 Buffer Pool Extension (BPE)

- **Allows use of a cache file in the file system to cache clean pages**
  - Makes buffer pool appear to be larger
  - Can help with OLTP workloads with lots of random reads
  - Does not help very much with large sequential reads (by design)
  - Cache file must be at least as large as max server memory setting
  - Make sure to use fast, local flash storage!
- **Most useful for SQL Server 2014 Standard Edition**
  - SQL Server 2014 Standard Edition has 128GB RAM limit
  - BPE file can be 4X max server memory setting in Standard Edition
  - Can also be useful with small VMs

Demo

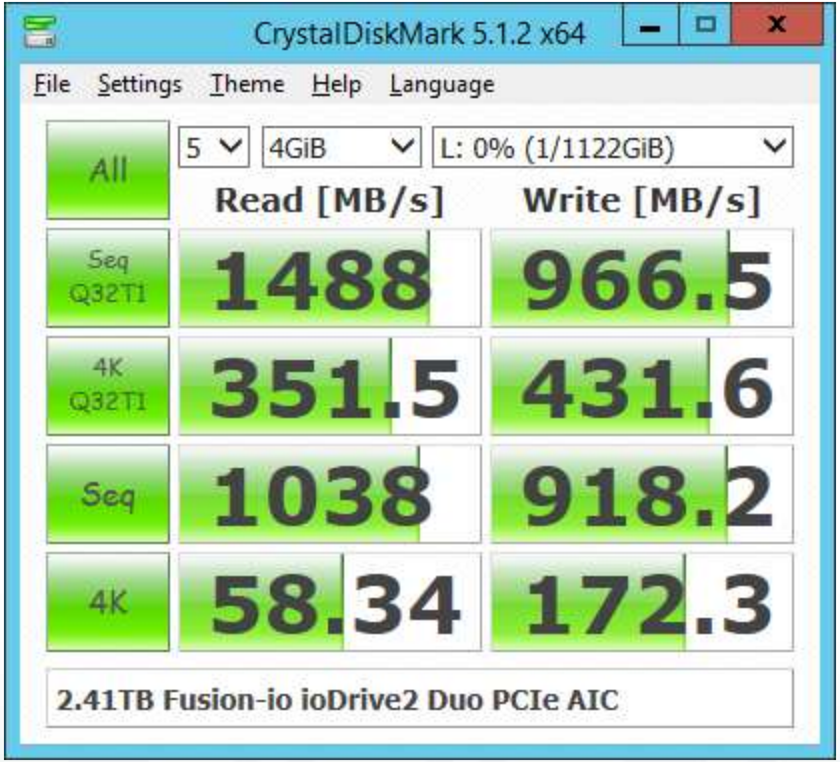
Using Buffer Pool Extensions

SQL intersection

Using CrystalDiskMark To Test Your LUNs

- **Always use CrystalDiskMark for initial quick testing of logical drives**
  - CrystalDiskMark does not work with mount points
  - Test each logical drive before you install SQL Server if possible
  - Make sure to test with a large test file size
    - This will minimize the influence of any hardware cache
  - Make sure to test with both random and non-random test file types
    - Random data is not compressible, non-random data is compressible
    - Some controllers use write compression
  - Make sure to select at least five test runs for the test
    - This reduces the chances of outliers skewing the results

CrystalDiskMark Results (Graphical)

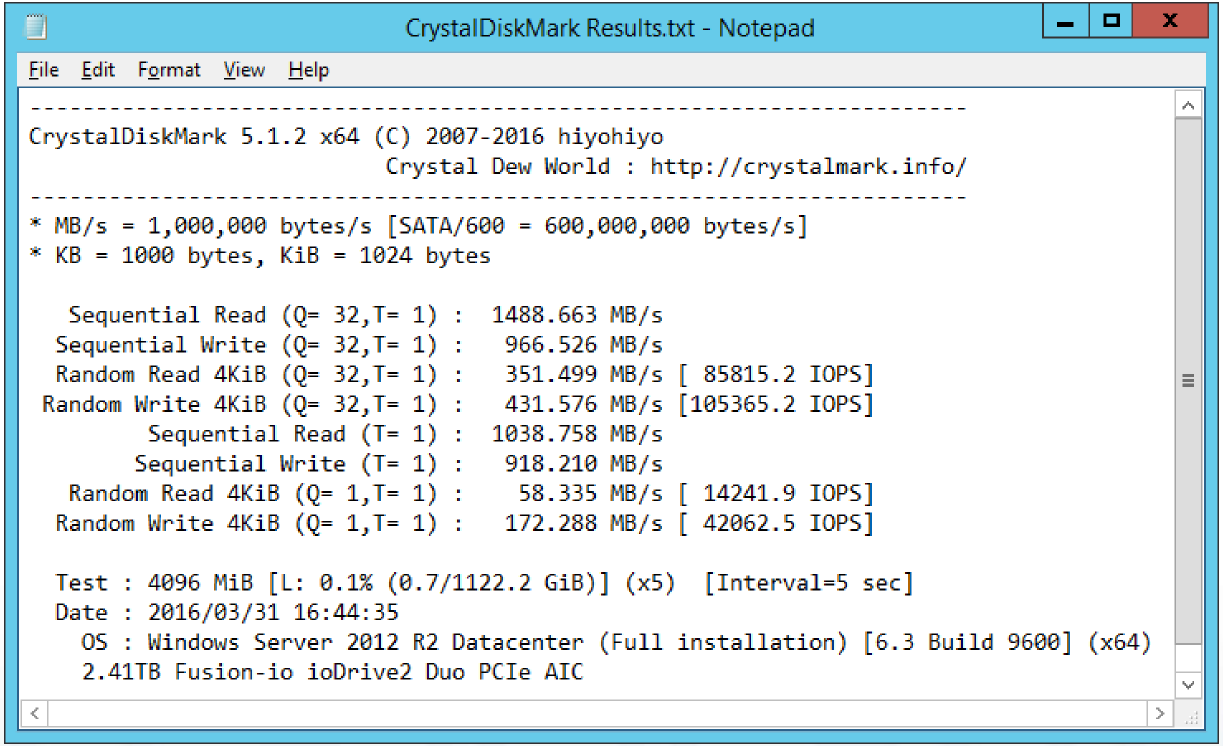


5 | 4GiB | L: 0% (1/1122GiB)

	Read [MB/s]	Write [MB/s]
Seq Q32T1	1488	966.5
4K Q32T1	351.5	431.6
Seq	1038	918.2
4K	58.34	172.3

2.41TB Fusion-io ioDrive2 Duo PCIe AIC

CrystalDiskMark Results (Text)


CrystalDiskMark Results.txt - Notepad
File Edit Format View Help

```
-----------------------------------------------------------------------
CrystalDiskMark 5.1.2 x64 (C) 2007-2016 hiyohiyo
                           Crystal Dew World : http://crystalmark.info/
-----------------------------------------------------------------------
* MB/s = 1,000,000 bytes/s [SATA/600 = 600,000,000 bytes/s]
* KB = 1000 bytes, KiB = 1024 bytes

   Sequential Read (Q= 32,T= 1) :  1488.663 MB/s
  Sequential Write (Q= 32,T= 1) :   966.526 MB/s
  Random Read 4KiB (Q= 32,T= 1) :   351.499 MB/s [ 85815.2 IOPS]
 Random Write 4KiB (Q= 32,T= 1) :   431.576 MB/s [105365.2 IOPS]
         Sequential Read (T= 1) :  1038.758 MB/s
        Sequential Write (T= 1) :   918.210 MB/s
   Random Read 4KiB (Q= 1,T= 1) :    58.335 MB/s [ 14241.9 IOPS]
  Random Write 4KiB (Q= 1,T= 1) :   172.288 MB/s [ 42062.5 IOPS]

  Test : 4096 MiB [L: 0.1% (0.7/1122.2 GiB)] (x5)  [Interval=5 sec]
  Date : 2016/03/31 16:44:35
    OS : Windows Server 2012 R2 Datacenter (Full installation) [6.3 Build 9600] (x64)
    2.41TB Fusion-io ioDrive2 Duo PCIe AIC
```

SQL *intersection*

Demo

Using CrystalDiskMark 5.1.2

Using SQLIO To Test Your Storage

- **SQLIO does not require or use SQL Server for its testing**
  - □ It simply allows you to stress your I/O subsystem in a fairly controlled manner
  - □ SQLIO is deprecated (but still works if you want to use it). I would not…
- **SQLIO has many configuration options**
  - □ Can be time consuming to run full suite of tests. Can be dangerous on shared SANs
- **You can use old style command prompt or PowerShell to run tests**
- **Reference:**
  - □ SQLIO, PowerShell and storage performance: measuring IOPs, throughput and latency for both local disks and SMB file shares
  - □ http://bit.ly/1n7jm0M

Using DiskSpd To Test Your Storage

- **DiskSpd does not require or use SQL Server for its testing**
  - It is a new tool from Microsoft and is far more flexible and powerful than SQLIO
  - It gathers much more information than SQLIO does
- **You can use old style command prompt or PowerShell to run tests**
- **Example command line:**
  - `C:\DiskSpd\diskspd.exe -c100G -d10 -r -w0 -t8 -o8 -b8K -h -L X:\testfile.dat`
- **Reference:**
  - DiskSpd, PowerShell and storage performance: measuring IOPs, throughput and latency for both local disks and SMB file shares
  - http://bit.ly/1CeQauw

SQL intersection

Demo

Using Microsoft DiskSpd

SQL intersection

Primary Storage Types for SQL Server

- **Several different storage types are commonly used**
  - Internal drives (3.5”, 2.5”, or 1.8”)
  - Direct-attached storage (DAS)
  - Storage area networks (SAN)
  - PCIe flash-based AIC storage cards
  - Server Message Block (SMB) 3.0/3.02 file shares
  - Scale-Out File Servers (SOFS)
  - Storage Spaces Direct (S2D) in Windows Server 2016

Internal Drives

- **Internal drives can be adequate for many workloads**
  - Possible to have up to (28) 2.5” drives in some two-socket servers
  - Lots of capacity and drive performance possible with this many drives
  - Can be very well suited for AlwaysOn AG node storage
- **Rack-mount server vertical form factor affects number of drive bays**
  - Drive size (3.5”, 2.5”, or 1.8”) affects drive density
- **Use the best hardware RAID controller(s) available for your server model**
  - Premium RAID controllers have faster processors and larger cache sizes
  - This is especially important for parity-based RAID levels or flash storage

Direct-Attached Storage (DAS)

- **External storage enclosure with multiple drive bays**
  - □ Typically (14-24) 2.5” drives in a single external storage enclosure
  - □ Try to dedicate at least one RAID controller to each storage enclosure
  - □ Storage enclosures should have dual power supplies
- **DAS is easy to configure and manage**
  - □ Does not require special training or expertise or a cranky SAN administrator…
  - □ Does require planning and common sense
- **Can provide excellent sequential read/write performance**
  - □ Limited by PCIe slot bandwidth and RAID controller performance
  - □ Can be very well suited for AlwaysOn AG node storage

SQL *intersection*

DAS Considerations

- **Use one dedicated RAID controller per storage enclosure**
  - You may even want two RAID controllers per enclosure
  - Use the best PCIe RAID controller available
  - Make sure the hardware cache is enabled
- **Pay attention to the PCIe slot throughput limits**
  - Does not require special training or expertise
  - Does require planning and common sense.
  - Try to dedicate the hardware RAID controller cache to writes
  - Disable read-ahead caching
  - The SQL Server buffer pool is a better read cache than the hardware RAID cache

PCIe Slot Bandwidth Limits

- **PCIe 1.0 Bus (one-way)**
  - x4 slot: 750MB/sec
  - x8 slot: 1.5GB/sec
- **PCIe 2.0 Bus (one-way)**
  - x4 slot: 1.5-1.8GB/sec
  - x8 slot: 3.0-3.6GB/sec
- **PCIe 3.0 Bus (one-way)**
  - x4 slot: 3.0-3.6GB/sec
  - x8 slot: 6.0-7.2GB/sec
- **x4 and x8 refer to the number of lanes the slot supports**

PCIe Version Support

- **PCIe 3.0 Support**
  - Intel Xeon E5, E5 v2, E5 v3 and E5 v4 families
    - (Sandy Bridge-EP, Ivy Bridge-EP, Haswell-EP, and Broadwell-EP)
  - Intel Xeon E7 v2 and E7 v3 families (Ivy Bridge-EX and Haswell-EX)
- **PCIe 2.0 Support**
  - Intel Xeon E7 family (Nehalem-EX)
  - Older Intel processors
  - All current AMD processors

PCIe Flash Storage

- **Flash-based storage on a PCIe expansion card**
  - Uses very high bandwidth PCIe slot instead of SAS/SATA port
  - New products using Non Volatile Memory Express (NVMe) have excellent performance!
  - Type and speed of PCIe slot can be limiting factor
  - PCIe flash storage cards can deliver extremely high I/O performance
    - Very high sequential throughput (up to 6.7GB/sec)
    - Extremely high random I/O performance (up to 1.3 million IOPS)
  - Flash storage cards use less electrical power than multiple magnetic drives
    - Can save significantly on electrical and cooling costs, save rack space
    - It is common to use two, with software RAID 1 for redundancy

Storage Area Networks (SAN)

- **Shared external storage enclosure with multiple components**
  - Large number of drive bays, can usually be expanded
  - Storage processors, large dedicated cache, operating system
  - Usually much higher initial capital cost than DAS
  - Requires some training and expertise to setup and manage
  - Cranky SAN administrator included free of charge!
- **Two main types of SANs**
  - Fiber-channel, using host bus adapter (HBA)
  - iSCSI, using dedicated Ethernet cards
- **SANs are usually optimized for IOPs**
  - Sequential throughput can be severely limited by the interface

SQL *intersection*

SAN Administrator Considerations

- **Make an effort to really communicate with your SAN Admin**
  - Let the SAN administrator know the type of workload you have
    - SQL Server OLTP, for example
  - Don’t just give the SAN administrator a space requirement!
    - Try to give them useful performance and SLA requirements
- **Your SAN Admin may have different priorities than you**
  - Has to worry about multiple servers with different workloads
  - Has to worry about running low on space in the SAN
  - Has to worry about DBAs complaining about performance
  - Has to worry about CIO complaining about the capital cost

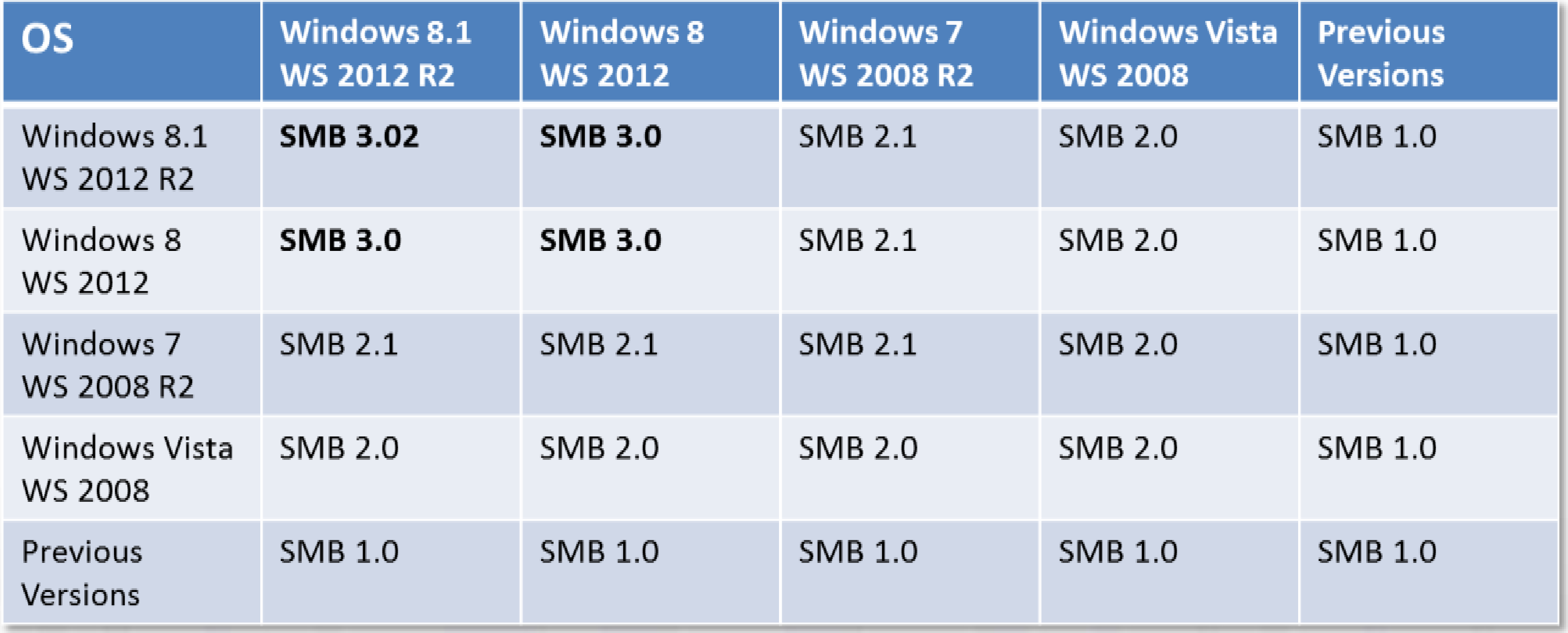
SAN Performance Considerations

- **Consider the complete data path to the SAN**
  - HBA/NIC, switches, SAN ports, etc.
  - Be prepared for inconsistent performance with a shared SAN
  - SANs are not magic: the hardware details still matter!
  - SANs are typically sequential throughput limited

SMB 3.0/3.02 File Shares

- **Server Message Block (SMB) 3.0/3.02**
  - SQL Server 2012+ can store user/system databases on SMB 3.0 file shares
  - SQL Server 2012+ can use SMB 3.0 for traditional FCI instances that require shared storage (without using a SAN)
  - Windows Server 2012 has SMB Direct, which supports the use of network adapters that have Remote Direct Memory Access (RDMA) capability
    - RDMA capable network adapters can function at full speed with very low latency while using very little CPU time on the host
  - Microsoft's Jose Barreto is a great resource about SMB file shares
    - http://blogs.technet.com/b/josebda/

Negotiated Versions of SMB

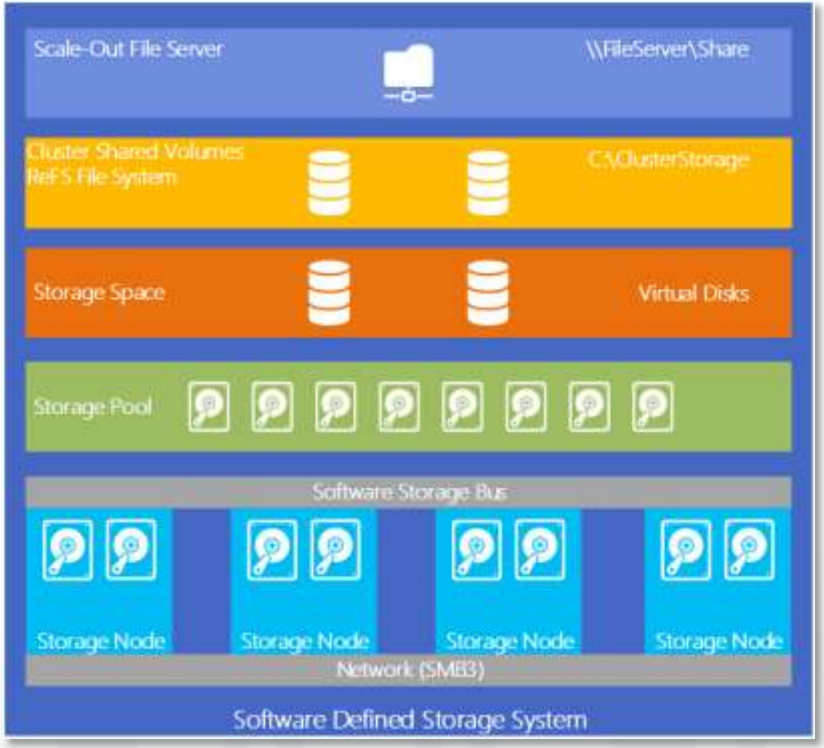


OS	Windows 8.1 WS 2012 R2	Windows 8 WS 2012	Windows 7 WS 2008 R2	Windows Vista WS 2008	Previous Versions
Windows 8.1 WS 2012 R2	**SMB 3.02**	**SMB 3.0**	SMB 2.1	SMB 2.0	SMB 1.0
Windows 8 WS 2012	**SMB 3.0**	**SMB 3.0**	SMB 2.1	SMB 2.0	SMB 1.0
Windows 7 WS 2008 R2	SMB 2.1	SMB 2.1	SMB 2.1	SMB 2.0	SMB 1.0
Windows Vista WS 2008	SMB 2.0	SMB 2.0	SMB 2.0	SMB 2.0	SMB 1.0
Previous Versions	SMB 1.0	SMB 1.0	SMB 1.0	SMB 1.0	SMB 1.0

Storage Spaces Direct in Windows Server 2016

- **What is Storage Spaces Direct?**
  - Software-defined storage that is highly available and scalable
  - Storage for Hyper-V and SQL Server
- **Why Storage Spaces Direct ?**
  - Servers with local storage (PCIe, SAS, SATA)
  - Industry standard commodity hardware
  - Lower cost flash storage with SATA SSDs
  - Better flash performance with NVMe SSDs
  - Can use hybrid storage configurations (NVMe, SATA SSD, SATA HDD)
  - Uses Ethernet/RDMA network as storage fabric

Storage Spaces Direct Diagram



Storage Spaces Direct Hardware Requirements

- **Windows Server certified servers and components**
- **Homogenous server configuration, 4-16 servers in software storage bus**
- **Storage node requirements**
  - Two-socket, Intel Xeon E5-2600 v3 or newer, 128GB of RAM
  - 10GbE or better, RDMA capable NIC strongly recommended
  - Minimum of two caching devices, four capacity devices
  - Simple HBA and expander for SATA/SAS devices
  - RAID controllers are not supported, FC/iSCSI not supported
  - MPIO not supported (single-path SAS is ok)

Each Storage Node Has a Built-In Cache

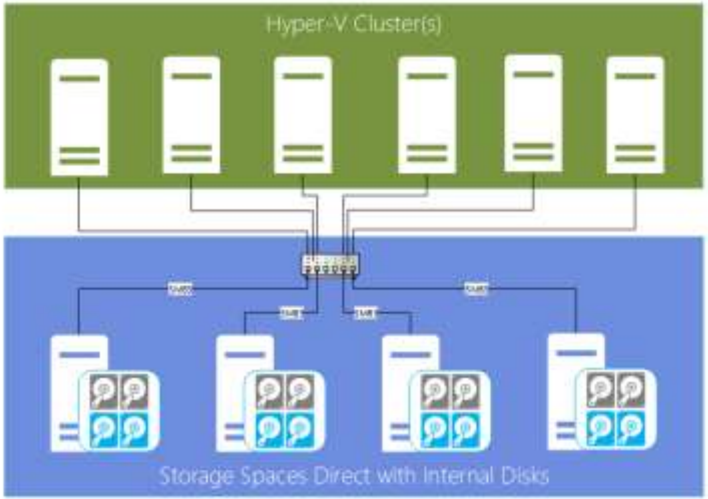
- **Integral part of Software Storage Bus**
- **Cache is coped to local machine, agnostic to storage pools and virtual disks**
- **Read and write cache (depending device type)**
    - Write + read caching when cache device is SSD and capacity device is HDD
    - Write only caching when cache device is SSD and capacity device is SSD
- **Automatic configuration when enabling S2D**
    - Special partition on each caching device
    - Leaves 32GB for pool and virtual disk metadata
    - Round robin binding of SSD to HDD, rebinding with topology change

S2D Volume Types

- **Mirror volume**
  - Optimized for performance, all data is hot, least storage space efficiency (33%)
  - Uses ReFS or NTFS file system, requires at least two nodes
- **Parity volume**
  - Optimized for capacity, all data is cold, most storage space efficiency (57+%)
  - Uses ReFS or NTFS file system, requires at least four nodes
- **Multi-Resilient volume**
  - Optimized for balance, mix of hot and cold data, efficiency depends on mix
  - Uses ReFS file system, requires at least four nodes

SQL *intersection*

Disaggregated Deployment with S2D



Storage Spaces Direct References

- Storage Spaces Direct in Windows Server 2016 Technical Preview
  - http://bit.ly/1oc9053
- Storage Spaces Direct in Technical Preview 4
  - http://bit.ly/1PvUfQs
- Hardware options for evaluating Storage Spaces Direct in Technical Preview 4
  - http://bit.ly/1Mj6YWX
- Storage Spaces Direct – Under the hood with the Software Storage Bus
  - http://bit.ly/1PvUxqK

Considering Your Workload for Storage

- **SQL Server can have several different common workload types**
  - Online Transaction Processing (OLTP)
  - Reporting against OLTP database(s)
  - Relational Data Warehouse (DW)
  - Online Analytical Processing (OLAP)
- **These workload types have different I/O access patterns**
  - Read/write ratio against different file types
  - Sequential vs. random reads and writes

OLTP Workload I/O Access Patterns

- **OLTP workload has frequent writes to data files and log file**
  - Also has frequent reads from data files if the database does not fit in memory
  - Random I/O performance is very important
- **Writes to a single database log file are sequential**
  - Once you have multiple databases with log files on the same LUN, the write activity becomes more random

DW and Reporting Workload I/O Access Patterns

- **DW/Reporting workload has large sequential reads from data files**
  - Frequent reads from data files if the database does not fit in memory
  - Very little use of log file (except during data loads)
  - Sequential read I/O performance is very important

OLAP Workload I/O Access Patterns

- **OLAP workload has lots of random reads from cube files**
  - Random I/O performance is very important
  - Sequential write performance to cube files is important during cube generation

SQL *intersection*

RAID Levels and SQL Server Workloads

- **Consider your SQL Server workload type(s)**
  - It directly affects your desired RAID level
  - RAID 10 is better for write-intensive workloads
- **Different types of workloads have different I/O patterns**
  - Percentage of reads/writes, sequential vs. random I/O
  - Use DMV query metrics to determine this, don't guess
- **Different SQL Server file types have different I/O patterns**
  - Data files, log files, tempdb files, backup files, etc.
- **You also need to consider your availability requirements**
  - Some RAID levels are more robust than others: RAID 10 > RAID 50 > RAID 5

Selecting a RAID Level For Your SLA

- **RAID is not a substitute for a good backup/restore plan!**
  - No matter what anyone in your organization tells you…
- **RAID is not a substitute for an effective HA/DR strategy**
  - No matter what any vendor tells you…
- **An appropriate RAID level reduces the chance of unplanned downtime**
  - It also reduces the chance of data loss due to disk failure(s)
- **RAID 10 and 50 are the most robust common RAID levels**
  - RAID 5 can only lose one disk in an array before the array is lost
  - Having a higher number of disks in a RAID 5 array increases the statistical chances that any one disk will fail

SQL intersection

Choosing Storage Types Based on Workload Type

- **Flash-based storage gives great random I/O performance**
  - It also gives better sequential performance than magnetic storage
  - Flash-based storage is the most expensive storage (per GB), but prices are declining rapidly and approaching parity with magnetic storage
- **Magnetic storage gives fair sequential performance**
  - Magnetic storage gives quite poor random I/O read and write performance
  - Large controller caches can help mask poor random I/O write performance
- **Flash-based storage is the best choice if you have the budget**
  - Use flash-based storage where you have heavy random I/O
  - Use flash-based storage where you have any type of I/O bottlenecks

Configuring Storage for SQL Server File Types

- **SQL Server data files**
  - Common to use magnetic storage (flash becoming more popular as cost declines)
  - Most common to use RAID 5, 50, or 10
- **SQL Server log files**
  - Common to use magnetic storage (flash becoming more popular as cost declines)
  - Most common to use RAID 10
- **SQL Server tempdb data and log files**
  - Common to use flash-based storage
  - Most common to use RAID 10
  - Acceptable to use magnetic storage if your workload does not heavily use tempdb

HA/DR Effects on Storage Choices

- **Traditional FCI requires some form of shared storage**
  - Usually a SAN, but SMB 3.0/3.02 can be used with SQL Server 2012 or newer
  - SQL Server 2012 or newer can use local storage for tempdb files with FCI
    - Often a good use for flash storage
    - Better performance and reduces load on the SAN
- **AlwaysOn AGs must use the Windows clustering feature**
  - Can use shared storage, such as a SAN or SMB 3.0/3.02, but is not required
  - Can also use any type of non-shared storage
- **Other HA/DR technologies can use any type of storage**
  - Consider using non-shared storage to eliminate the single point of failure, and get more consistent performance

SQL *intersection*

Sizing Your Storage Subsystem

- **Use a RAID calculator to ensure you have more than enough disk space**
  - Consider performance advantages of “short-stroking” for magnetic storage
  - Flash-based storage also benefits from ample free space
- **After you have enough space, concentrate on performance**
  - Don’t negotiate with yourself! Ask for flash-based storage, ask for RAID 10
  - Consider your workload as you make budget-driven compromises
- **Aim for 10,000-20,000 or more IOPS on all LUNs**
  - More is always better
- **Aim for 1GB/sec or more of sequential throughput on all LUNs**
  - This gives you good performance for common administrative tasks

Solid State Drives (SSDs)

- **SSD access time does not depend on moving parts**
  - Access time is very fast and consistent across cells
  - Excellent for random I/O reads and writes
- **PCIe flash AIC storage cards allow for much higher sequential throughput**
  - Bypasses traditional SAS/SATA interface bandwidth limitations
- **SSDs are enterprise ready for SQL Server usage**
  - We have many enterprise clients running on them
  - Don’t just put tempdb or transaction logs on SSDs!
  - Don’t ignore index fragmentation when using SSDs!

Flash Storage Interfaces and Protocols

- **The interface and protocol have a huge affect on flash performance**
  - SATA/SAS
    - 3Gbps, 6Gbps, 12Gbps (275MB/sec, 550MB/sec, and 1100MB/sec)
    - Typically use Advanced Host Controller Interface (AHCI) protocol
    - AHCI limited to one command queue, 32 commands per queue
  - PCI Express (PCIe)
    - Uses PCIe slot on mother board (or in a front drive bay on some new servers)
  - PCIe Non-Volatile Memory Express (NVMe) protocol
    - NVMe protocol has 65535 queues, 65536 commands per queue
    - Much lower latency and CPU utilization than AHCI

SQL *intersection*

Flash Storage NAND Types

- **Different NAND types affect latency, endurance and cost**
  - Single-Level Cell (SLC)
    - Lowest latency, highest endurance, highest cost
  - Multi-Level Cell (MLC)
    - Higher latency than SLC, lower endurance, lower cost
  - Triple-Level Cell (TLC)
    - Higher latency than MLC, lower endurance, lower cost
    - Write latency suffers more with MLC and TLC
  - Common to use SLC NAND for a small cache in front of MLC or TLC NAND

Magnetic Storage vs. Flash-Based Storage

- **Magnetic storage has fair sequential performance**
  - 100-200MB/sec per disk
- **Magnetic storage has very poor random I/O performance**
  - 100-200 IOPS per disk
- **Flash-based storage has very good sequential performance**
  - 12Gbps SAS/SATA does 1100MB/sec, 6Gbps SAS/SATA does 550MB/sec
  - PCIe storage cards can do up to about 6.5GB/sec per card
- **Flash-based storage has excellent random I/O performance**
  - 6Gbps SAS/SATA drives can do about 100,000 IOPS
  - PCIe AIC flash storage cards can do up to about 1.3 million IOPS

Typical HDD Metrics vs. SSD Metrics

Metric	15K Hard Drive	SATA 3 SSD
Capacity	900GB	400GB
Average Read Latency (us)	2000	50
Read Bandwidth (MB/s)	202 MB/s	550 MB/s
Read IOPS (4K QD32)	150-200	**90,000**
Power (Active/Idle)	4.25W	5.2W/0.6W

Comparative Sequential QD32 Performance

Drive Type	Sequential Reads	Sequential Writes
(2) 15K Magnetic SAS in RAID 1	154.6 MB/s	126.2 MB/s
(6) 15K Magnetic SAS in RAID 10	531.7 MB/s	414.6 MB/s
1TB Samsung 850 EVO SATA 3 SSD	555.8 MB/s	530.5 MB/s
400GB Intel 750 PCIe NVMe AIC	2382.3 MB/s	1076.2 MB/s
512GB Samsung 950 PRO M.2 NVMe card	2598.4 MB/s	1524.7 MB/s
640GB Fusion-io Duo MLC PCIe AIC	746.6 MB/s	516.2 MB/s
2.41TB Fusion-io ioDrive2 Duo PCIe AIC	1488.6 MB/s	966.5 MB/s
1.6TB LSI Nytro WarpDrive PCIe AIC	1483.1 MB/s	1520.2 MB/s

Comparative Random 4K QD32 Performance

Drive Type	Random Reads	Random Writes
(2) 15K Magnetic SAS in RAID 1	790 IOPS	1028 IOPS
(6) 15K Magnetic SAS in RAID 10	2867 IOPS	3048 IOPS
1TB Samsung 850 EVO SATA 3 SSD	68,908 IOPS	70,954 IOPS
400GB Intel 750 PCIe NVMe AIC	199,216 IOPS	175,012 IOPS
512GB Samsung 950 PRO M.2 NVMe card	189,250 IOPS	103,901 IOPS
640GB Fusion-io Duo MLC PCIe AIC	49,678 IOPS	52,655 IOPS
2.41TB Fusion-io ioDrive2 Duo PCIe AIC	85,815 IOPS	105,365 IOPS
1.6TB LSI Nytro WarpDrive PCIe AIC	98,259 IOPS	78,641 IOPS

Improving I/O Performance

- **Improving I/O performance at multiple levels**
  - Server hardware evaluation and selection
  - Server hardware configuration settings
  - Storage hardware evaluation and selection
  - Storage hardware configuration settings
  - Operating system configuration settings
  - SQL Server instance-level configuration settings
  - SQL Server database property settings
  - Index tuning
  - Workload tuning

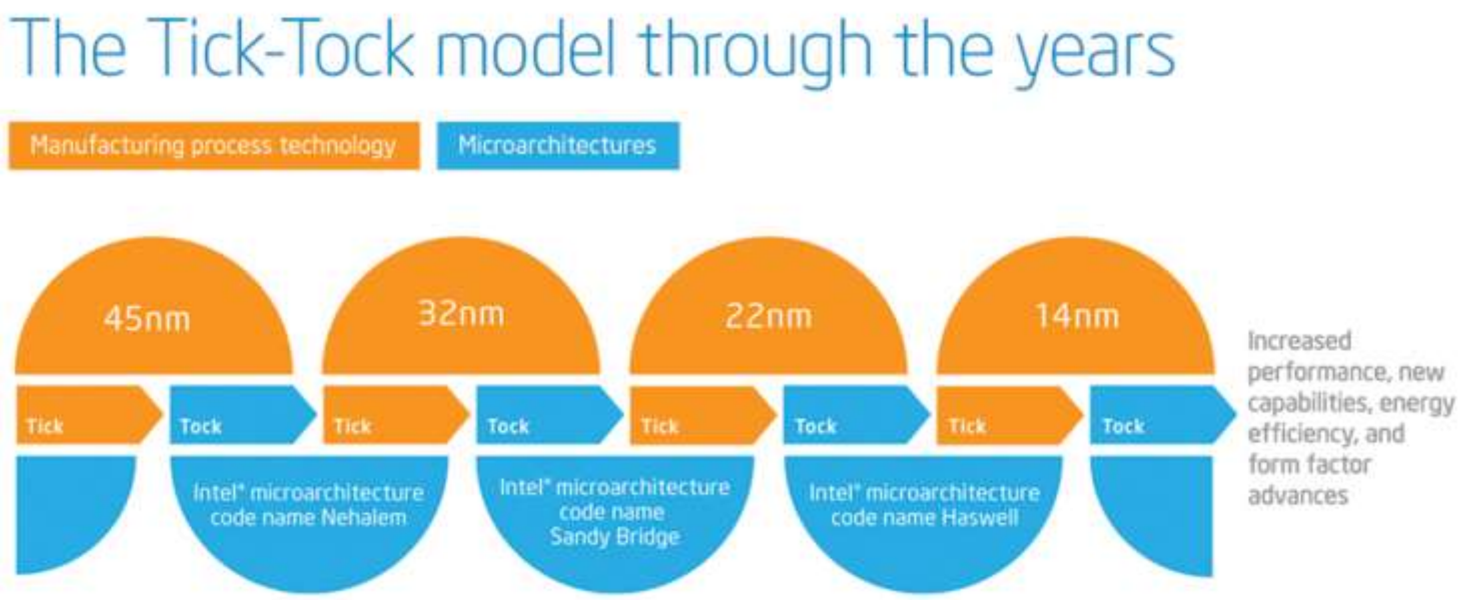
Server Hardware Evaluation and Selection

- **Very important to have relatively modern server hardware**
  - Intel-based servers have many performance and scalability advantages
- **Try to have Xeon E5 or newer (Sandy Bridge-EP or newer)**
  - PCIe 3.0 support, good memory capacity and performance
  - Up to 768GB of RAM with 32GB DIMMs in a two-socket server
  - Up to 9.6 GT/sec QPI speed
- **Try to have Xeon E7 v2 or newer (Ivy Bridge-EX or newer)**
  - PCIe 3.0 support, good memory capacity and performance
  - Up to 3TB of RAM with 32GB DIMMs in a four-socket server
  - Up to 9.6 GT/sec QPI speed

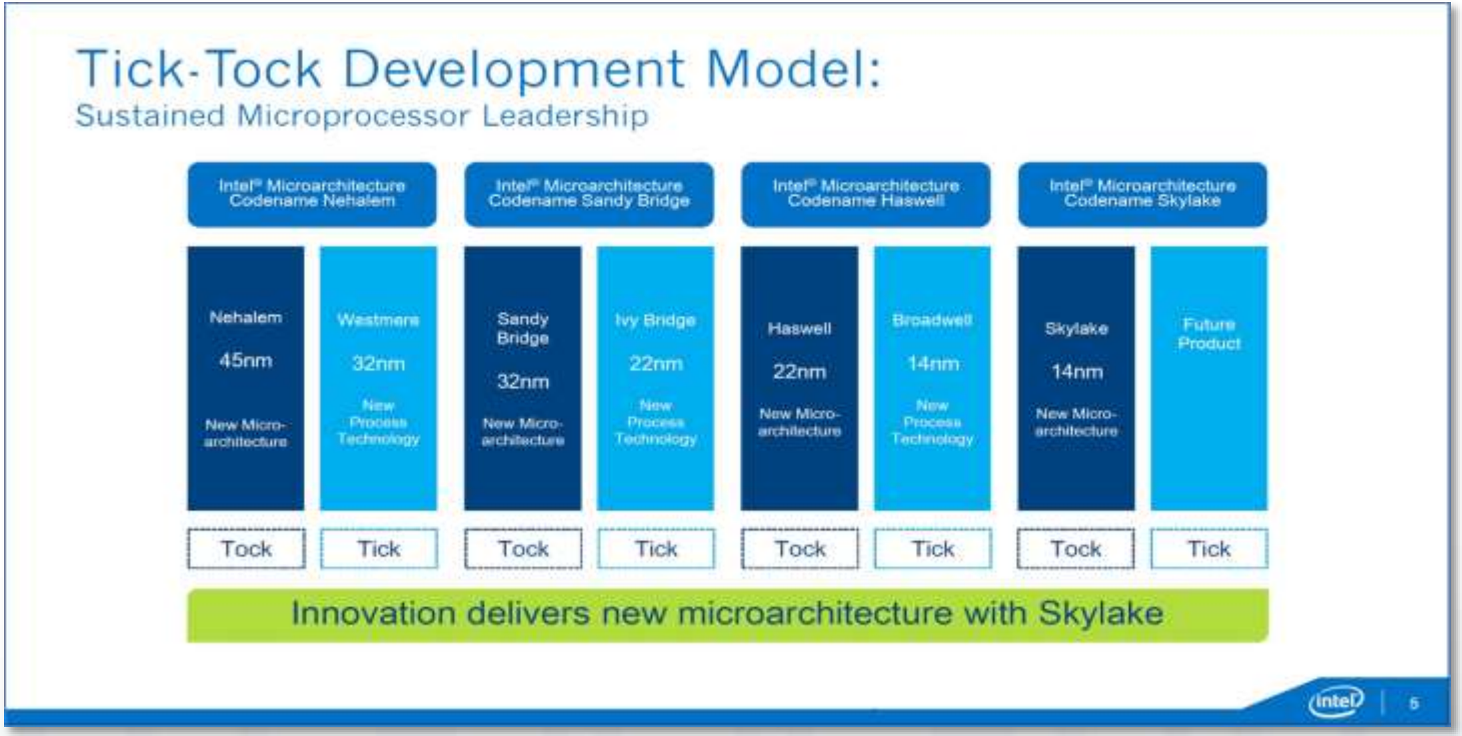
General Processor Considerations

- **Purposely over-provision processors (if you have the budget)**
  - Better single-threaded performance is very important
  - Higher core counts increase overall capacity and scalability, but increase SQL Server license costs
  - Consider lower core count, “frequency optimized” processor models
- **Processors are relatively inexpensive**
  - Adding I/O performance capacity is often more expensive than a good processor
  - The license cost per core is the same, so pick the right processor!
  - Don’t pick a lower clock speed CPU with the same core count to save money

Intel Tick Tock Release Strategy


The Tick-Tock model through the years
Manufacturing process technology
Microarchitectures
45nm
32nm
22nm
14nm
Tick
Tock
Tick
Tock
Tick
Tock
Tick
Tock
Intel® microarchitecture code name Nehalem
Intel® microarchitecture code name Sandy Bridge
Intel® microarchitecture code name Haswell
Increased performance, new capabilities, energy efficiency, and form factor advances

Current Intel Tick Tock Release Strategy



Tick-Tock Development Model:

Sustained Microprocessor Leadership

Intel® Microarchitecture Codename Nehalem		Intel® Microarchitecture Codename Sandy Bridge		Intel® Microarchitecture Codename Haswell		Intel® Microarchitecture Codename Skylake	
Nehalem 45nm New Micro-architecture	Westmere 32nm New Process Technology	Sandy Bridge 32nm New Micro-architecture	Ivy Bridge 22nm New Process Technology	Haswell 22nm New Micro-architecture	Broadwell 14nm New Process Technology	Skylake 14nm New Micro-architecture	Future Product
Tock	Tick	Tock	Tick	Tock	Tick	Tock	Tick

Innovation delivers new microarchitecture with Skylake

Intel Broadwell-EP Family (Xeon E5-2600 v4)

- **Intel Tick release (Q1 2016)**
  - 14nm process, up to twenty-two cores, up to 55MB L3 cache
  - PCIe 3.0, QPI 1.1, four DDR4 memory controllers
- **Replacement for Haswell-EP(Xeon E5-2600 v3 series)**
  - More physical cores than Ivy Bridge-EP
  - Also has lower core count, frequency-optimized models
- **Xeon E5-2699 v4 is the "top of the line" model**
  - 2.2GHz base, Turbo Boost 2.0 to 3.6GHz, 55MB L3 cache
  - Twenty-two cores, plus hyper-threading, 145W TDP
  - DDR4 2400 support, twelve DIMMs per socket

Preferred Broadwell-EP Processors – High Core Count

Model	Cores/L3 Cache	Base Speed	Turbo Speed	Price
E5-2699 v4	22/55 MB	2.2 GHz	3.6 GHz	$4,115.00
E5-2698 v4	20/50 MB	2.2 GHz	3.6 GHz	$3,226.00
E5-2697 v4	18/45 MB	2.3 GHz	3.6 GHz	$2,702.00
E5-2697A v4	16/40 MB	2.6 GHz	3.6 GHz	$2,891.00
E5-2690 v4	14/35 MB	2.6 GHz	3.6 GHz	$2,090.00

SQL *intersection*

Preferred Broadwell-EP Processors – Low Core Count

Model	Cores/L3 Cache	Base Speed	Turbo Speed	Price
E5-2687W v4	12/30 MB	3.0 GHz	3.5 GHz	$2,141.00
E5-2640 v4	10/25 MB	2.4 GHz	3.4 GHz	$939.00
E5-2667 v4	8/25 MB	3.2 GHz	3.6 GHz	$2,057.00
E5-2643 v4	6/20 MB	3.4 GHz	3.7 GHz	$1,552.00
E5-2637 v4	4/15 MB	3.5 GHz	3.7 GHz	$996.00

Intel Haswell-EP Family (Xeon E5-2600 v3)

- **Intel Tock release (Q3 2014)**
  - 22nm process, up to eighteen cores, up to 45MB L3 cache
  - PCIe 3.0, QPI 1.1, four DDR4 memory controllers
- **Replacement for Ivy Bridge-EP (Xeon E5-2600 v2 series)**
  - 50% more physical cores than Ivy Bridge-EP
  - Also has lower core count, frequency-optimized models
- **Xeon E5-2699 v3 is the "top of the line" model**
  - 2.3GHz base, Turbo Boost 2.0 to 3.6GHz, 45MB L3 cache
  - Eighteen cores, plus hyper-threading, 145W TDP
  - DDR4 2133 support, twelve DIMMs per socket

SQL
intersection

Preferred Haswell-EP Processors

Model	Cores/L3 Cache	Base Speed	Turbo Speed	Price
E5-2699 v3	18/45 MB	2.3 GHz	3.6 GHz	N/A
E5-2698 v3	16/40 MB	2.3 GHz	3.6 GHz	N/A
E5-2697 v3	14/35 MB	2.6 GHz	3.6 GHz	$2,702.00
E5-2690 v3	12/30 MB	2.6 GHz	3.5 GHz	$2,094.00
E5-2660 v3	10/15 MB	2.6 GHz	3.3 GHz	$1,449.00
E5-2667 v3	8/20 MB	3.2 GHz	3.6 GHz	$2,057.00
E5-2643 v3	6/20 MB	3.7 GHz	3.7 GHz	$1,552.00
E5-2637 v3	4/15 MB	3.5 GHz	3.7 GHz	$996.00

SQL
intersection

Intel Haswell-EX Family (Xeon E7-4800/8800 v3)

- **Intel Tock release (May 2015)**
  - 22nm process, up to eighteen cores, up to 45MB L3 cache
  - PCIe 3.0, QPI 1.1, four DDR4 memory controllers
- **Replacement for Ivy Bridge-EX (Xeon E7-4800/8800 v2 series)**
  - 20% more physical cores than Ivy Bridge-EX
  - Intel Transactional Synchronization New Instructions (TSX-NI)
- **Xeon E5-8890 v3 is the "top of the line" model**
  - 2.5GHz base, Turbo Boost 2.0 to 3.3GHz, 45MB L3 cache
  - Eighteen cores, plus hyper-threading, 165W TDP
  - DDR4 1833 support, 24 DIMMs per socket

Preferred Haswell-EX Processors

Model	Cores/L3 Cache	Base Speed	Turbo Speed	Price
E7-8890 v3	18/45 MB	2.5 GHz	3.3 GHz	$7,175.00
E7-8867 v3	16/45 MB	2.5 GHz	3.3 GHz	$4,672.00
E7-4850 v3	14/35 MB	2.2 GHz	2.8 GHz	$3,003.00
E7-4830 v3	12/30 MB	2.1 GHz	2.7 GHz	$2,170.00
E7-8891 v3	10/45 MB	2.8 GHz	3.5 GHz	$6,841.00
E7-8893 v3	4/45 MB	3.2 GHz	3.5 GHz	$6,841.00

General Memory Considerations

- **Maximize your physical RAM (within SQL Server license limits)**
  - Larger buffer pool cache reduces physical reads from disk subsystem
    - More data in the buffer pool (logical vs. physical reads)
  - RAM is faster than any disk subsystem
    - RAM may be less expensive than enterprise-class storage
    - Orders of magnitude difference in latency
  - Can reduce the frequency of lazy writes and checkpoints
    - Helps even out the write workload to your data files

DDR4 PC4-17000 ECC Memory Prices

32GB module	$250.00	$7.81/GB
16GB module	$115.00	$7.19/GB
8GB module	$ 62.00	$7.75/GB

- Retail prices from Crucial.com (3/31/2016)

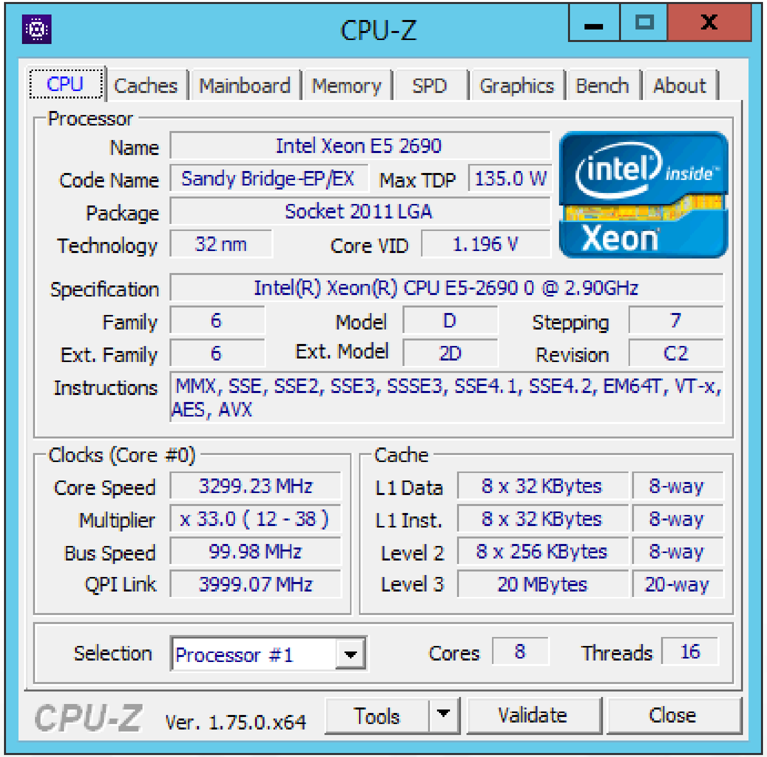
- **Current capacity/price sweet spot is 32GB modules!**

Server Hardware Configuration Settings

- **Intel Hyper-threading**
  - Gives 20-30% more CPU capacity, not more performance
  - Should be enabled with most workloads
    - Exceptions: Virtualization host, some DW or reporting workloads
- **Intel Turbo Boost**
  - Boosts clock speed of individual cores, should always be enabled
  - Make sure to check processor core speed with CPU-Z
- **BIOS or UEFI power management settings**
  - Set to OS control or disable. BIOS-level power management will override the Windows Power Plan setting

SQL intersection

CPU-Z



Processor

Name Intel Xeon E5 2690

Code Name Sandy Bridge-EP/EX Max TDP 135.0 W

Package Socket 2011 LGA

Technology 32 nm Core VID 1.196 V

Specification Intel(R) Xeon(R) CPU E5-2690 0 @ 2.90GHz

Family 6 Model D Stepping 7

Ext. Family 6 Ext. Model 2D Revision C2

Instructions MMX, SSE, SSE2, SSE3, SSSE3, SSE4.1, SSE4.2, EM64T, VT-x, AES, AVX

Clocks (Core #0)

Core Speed 3299.23 MHz

Multiplier x 33.0 (12 - 38)

Bus Speed 99.98 MHz

QPI Link 3999.07 MHz

Cache

L1 Data	8 x 32 KBytes	8-way
L1 Inst.	8 x 32 KBytes	8-way
Level 2	8 x 256 KBytes	8-way
Level 3	20 MBytes	20-way

Selection Processor #1 Cores 8 Threads 16

CPU-Z Ver. 1.75.0.x64

Demo

Using CPU-Z

SQL
intersection

Storage Hardware Evaluation and Selection

- **Do your research, and check for online reviews from established sites**
  - StorageReview
  - SSDReview
- **Run your own storage benchmarks on an evaluation unit if possible**
  - Definitely run storage benchmarks on each logical drive before you install SQL Server
- **Do more storage testing after you install SQL Server**
  - Using a representative workload if possible
  - Doing common administrative tasks

Storage Hardware Configuration Settings

- **Consult any available documentation from the storage vendor**
  - Many vendors have SQL Server specific guidance for their product
  - Several SQL Server "personalities" work for major storage vendors
    - Jimmy May – SanDisk
    - Argenis Fernandez – Pure Storage

Operating System Configuration Settings

- **Change Windows Power Plan to High Performance**
  - Default setting is still Balanced, even in Windows Server 2016
  - Can have a substantial effect on processor and storage performance
- **Enable Windows Instant File Initialization**
  - Huge effect on database restore times, database data file growth times
  - Grant “Perform volume maintenance tasks” right to SQL Server Service account
- **Use Lock Pages in Memory (LPIM)**
  - Prevents OS from paging out SQL Server data
  - Grant “Lock pages in memory” right to SQL Server Service account

SQL *intersection*

Demo

Granting OS rights to SQL Server

SQL intersection

SQL Server Instance-Level Configuration Settings

- **Several sp_configure settings should be changed from default values**
  - Backup checksum default should be 1 (new in SQL Server 2014)
  - Backup compression default should be 1 (in most cases)
  - Cost threshold for parallelism often should be raised above 5 (in most cases)
  - Max degree of parallelism should be set to the number of cores in a NUMA node
  - Max server memory should be set to an appropriate value based on the workload
  - Optimize for ad hoc workloads should be 1

Demo

Changing instance-level configuration settings

SQL Server tempdb Settings

- **Start with 4-8 tempdb data files, to reduce allocation contention**
  - Make sure they are all the same size, with the same auto growth setting
  - Make sure they are not using percent growth
  - In most cases, it is ok for them to be on the same LUN, and to have the tempdb log file in the same location
- **Use dedicated, fast local storage if possible**
  - Consider using flash storage if your workload requires it
- **Make sure to enable TF 1118**
  - Not necessary in SQL Server 2016

SQL Server Database Property Settings (1)

- **Use a MAIN file group with at least two data files with new databases**
  - Make the MAIN file group the default file group. This will put your user objects in the MAIN file group and the system objects in the PRIMARY file group
  - This gives you more flexibility to lay out your data files and potentially more I/O performance
- **Make sure to use a reasonable auto growth size in MB**
  - Try to manually manage file growth, but leave autogrow enabled
  - Don’t use percent growth for data or log files

SQL Server Database Property Settings (2)

- **Control the VLF counts on your database log file**
  - Manually grow the log file in larger chunks (1000, 2000, or 4000MB)
  - Set auto grow to a similar large growth increment
- **Keep VLF counts below 100-200 (depending on log file size)**
  - Full recovery model
    - Transaction log backup, then shrink the log file. May have to repeat several times
    - May have to generate some log activity to get the log file to shrink
  - Simple recovery model
    - Checkpoint, then shrink the log file. May have to repeat several times

SQL Server Database Property Settings (3)

- **Auto update statistics asynchronously**
  - Should be enabled with most workloads
  - Make sure you have a new enough build of SQL Server for your major version
- **Delayed durability**
  - New for SQL Server 2014
  - Can noticeably improve transaction rates if writing to transaction log is your main bottleneck
  - Some risk of data loss, so understand how it works!

ALTER DATABASE SCOPED CONFIGURATION

- **New feature in SQL Server 2016, lets you control database-level configuration**
  - Enable/disable legacy cardinality estimation, independent of compatibility level
  - Enable/disable parameter sniffing
  - Enable/disable query optimizer hotfixes (TF 4199)
  - Set max degree of parallelism for individual databases
  - The four options above can be set for the primary replica or for secondary replicas
  - Clear the plan cache for an individual database
- Using ALTER DATABASE SCOPED CONFIGURATION in SQL Server 2016
  - http://bit.ly/1Rvok7b

SQL intersection

Demo

Using ALTER DATABASE SCOPED CONFIGURATION

SQL intersection

Index Tuning

- **Proper index tuning can have huge positive performance benefits**
  - Reduced CPU, memory, and I/O pressure
  - Reduced query execution times
  - Reduced locking, blocking and deadlock issues
- **Consider your overall workload and individual table volatility**
  - Indexes help read performance, but hurt write performance
  - Look for missing indexes and missing index warnings in the plan cache
  - Look for unused or duplicate indexes
- **Consider data compression or clustered columnstore indexes**

SQL *intersection*

Demo

Index Tuning Queries

SQL intersection

Demo

Using SQL Server Data Compression

SQL intersection

Demo

Using SQL Server Clustered Columnstore Indexes

SQL intersection

Workload Tuning

- **Use my “bad man list” DMV queries to find expensive stored procedures**
  - SP execution counts, SP avg elapsed time, SP worker time, SP logical reads
- **Focus on the top five stored procedures in each list**
  - Prioritize the area where instance is under the most stress
  - Make it a team effort and an iterative process, and repeat as necessary

Demo

Bad Man List queries

SQL intersection

Demo

Using Resource Governor to limit I/O

SQL intersection

References (1)

- Windows Server 2012 R2: Which version of the SMB protocol (SMB 1.0, SMB 2.0, SMB 2.1, SMB 3.0 or SMB 3.02) are you using?
  - □ http://bit.ly/18uOEI4
- Updated Links on Windows Server 2012 R2 File Server and SMB 3.02
  - □ http://bit.ly/1iJKMWb
- Storage Review SQL Server OLTP Benchmark
  - □ http://bit.ly/1jEDu9m
- My Pluralsight courses
  - □ http://bit.ly/1EUh7v9

References (2)

- **Geekbench**
  - http://bit.ly/UGrGbu
- **TPC-E OLTP benchmark**
  - http://bit.ly/UGs2Pm
- **CPU-Z tool**
  - http://bit.ly/korH23
- **Intel Ark database**
  - http://ark.intel.com/

SQL *intersection*

Review

- **SQL Server has five primary storage types**
  - Internal, PCIe flash, DAS, SANs, and SMB 3.0 file shares with SOFS and S2D
- **Different types of SQL Server workloads affect I/O patterns**
  - OLTP, DW, OLAP, mixed, database maintenance, etc.
- **Different SQL Server file types have different I/O patterns**
  - Data files, log files, tempdb files, backup files, etc.
- **Choose an appropriate RAID level for your workload**
  - You also need to consider your SLA requirements
- **Make sure to consider your sequential throughput**
  - Very important for day-to-day operations and DR requirements

Questions?

SQLskills
immerse yourself in sql server

Don’t forget to complete an online evaluation on EventBoard!

Analyzing and Improving I/O Subsystem Performance

By Glenn Berry

Your evaluation helps organizers build better conferences and helps speakers improve their sessions.

SQL *intersection*

Thank you!