Microsoft

SQL Server I/O and Database Structure

Module 2

Learning Units covered in this Module

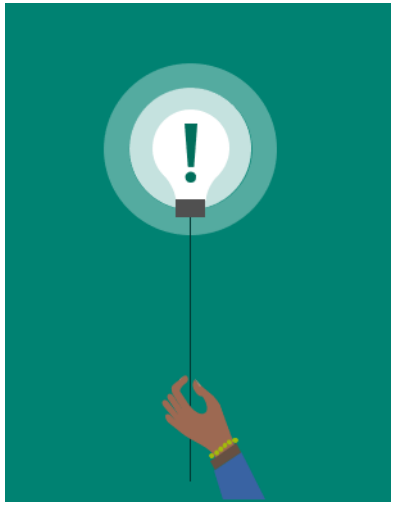
- Lesson 1: SQL Server Disk I/O
- Lesson 2: SQL Server Page Structure
- Lesson 3: SQL Server Data File Structure
- Lesson 4: SQL Server Log File Structure
- Lesson 5: SQL Server TempDB File Structure

Lesson 1: SQL Server Disk I/O

Objectives

After completing this learning, you will be able to:

- Identify SQL Server disk I/O operations.
- Identify I/O patterns for data files and log files.
- Monitor SQL Server I/O using:
  - Performance Monitor Counters
  - Dynamic Management Views
  - Wait Statistics



Database files and filegroups

Database files

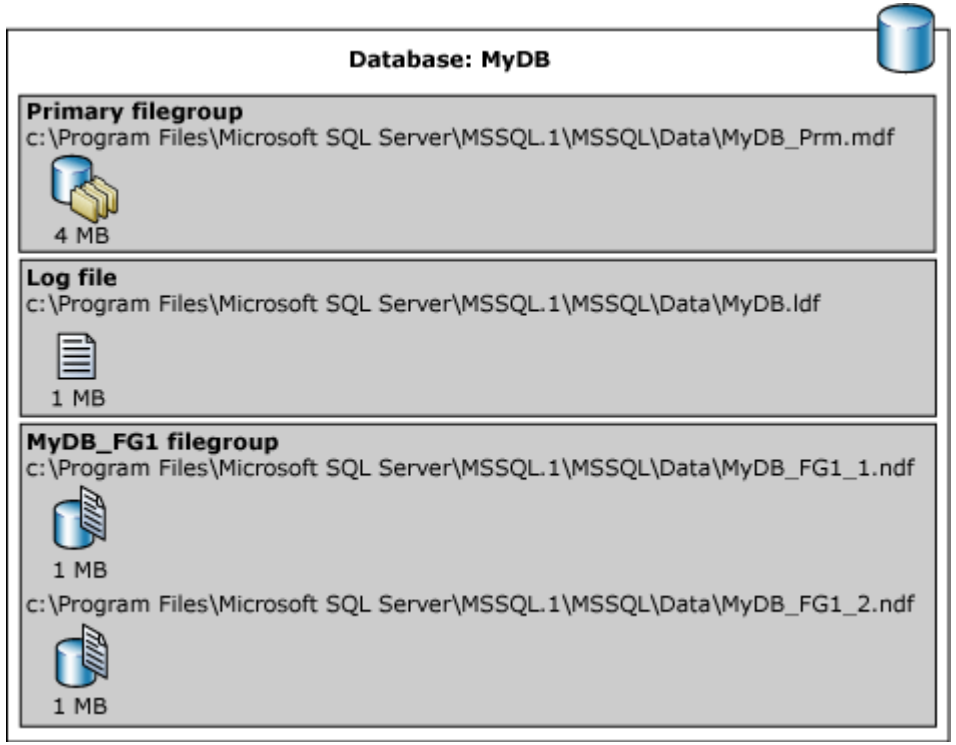
A database is composed by at least two operating system files:

Data files

- Contain database objects and data
- First data file is called primary data file. This file has a .mdf extension
- A database may have additional data files, known as secondary data files. They use .ndf extension
- Can be grouped together in filegroups for allocation and administration purposes

Log file

- Contain Log Records and entries are sequenced



SQL Server disk I/O patterns:

Data Files

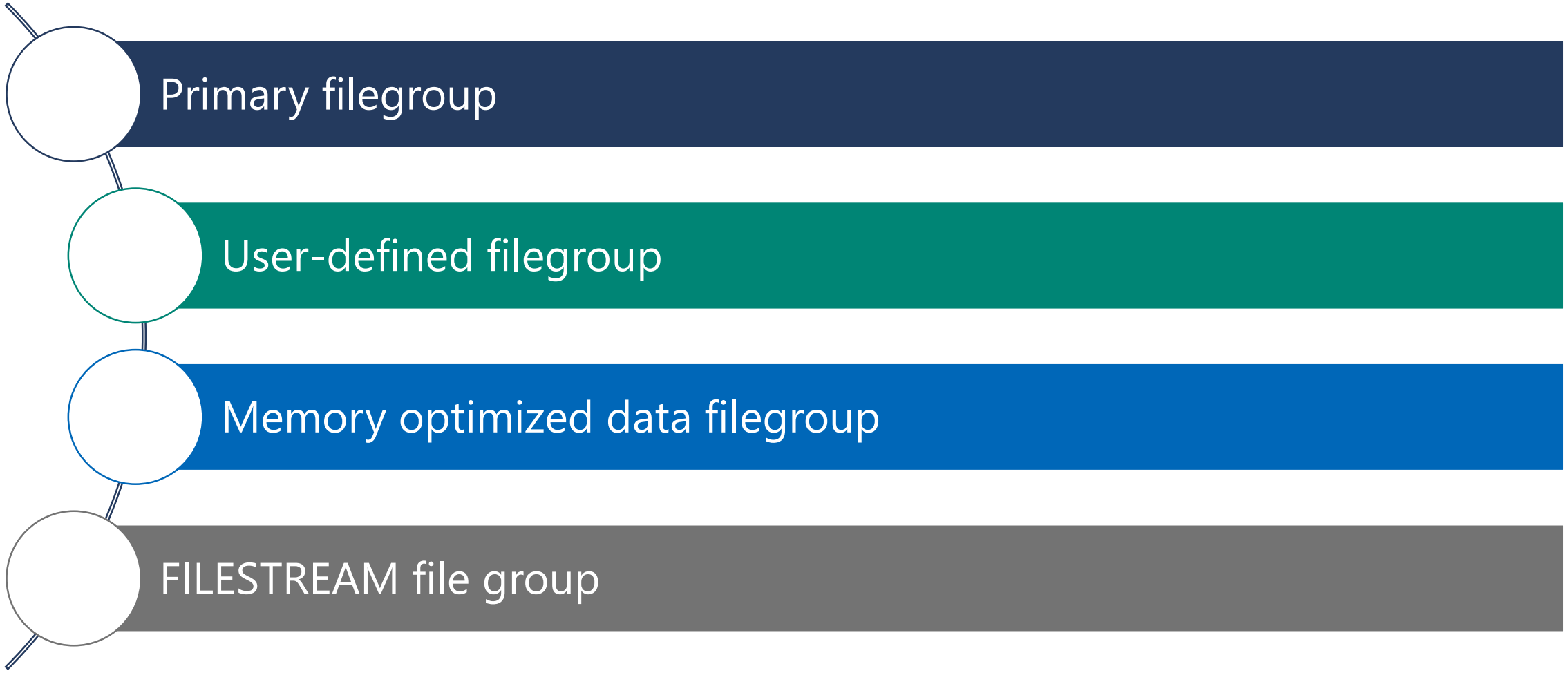
- One .mdf file per database
- May have one or more .ndf file
- Random reads and writes
  - Read activity during backups; other activity varies depending on query activity and buffer pool size
  - Write activity during checkpoints, recovery, and lazy writes

Log Files

- One* .ldf file per database
- Sequential reads and writes
- Write activity during the log buffer flush operations
- Read activity during checkpoints, backups, and recovery
- Features such as Always On Availability Groups and replication will increase read and write activity

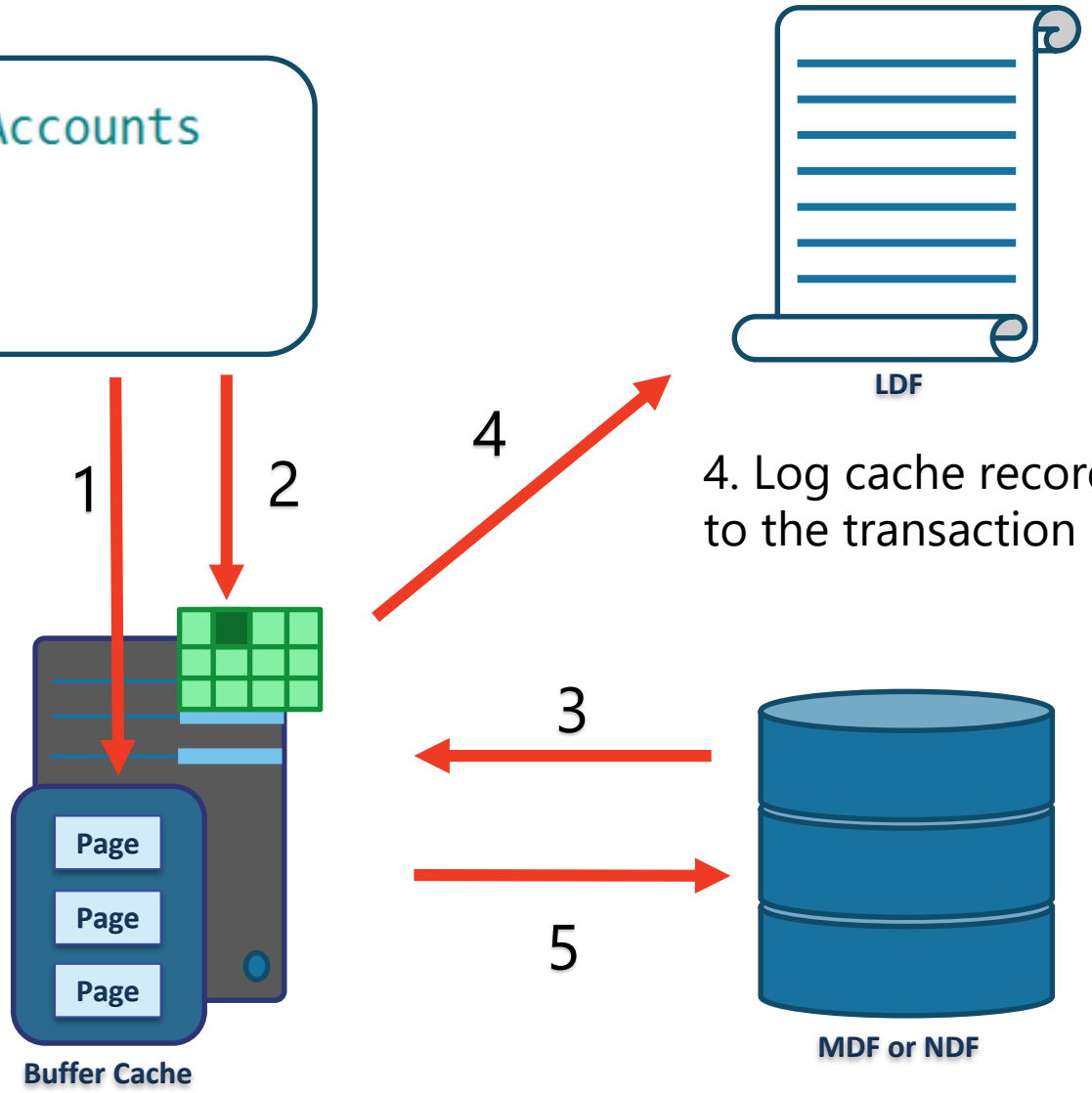
Database files and filegroups

Types of filegroups



SQL Server Disk I/O (Write-Ahead Logging)

```
UPDATE Accounting.BankAccounts
SET Balance -= 200
WHERE AcctID = 1
```



1. Data modification is sent to buffer cache in memory.

2. Modification is recorded in the log cache.

3. Data pages are located or read into the buffer cache and then modified.

4. Log cache record is flushed to the transaction log

5. At checkpoint, dirty data pages are written to the database file.

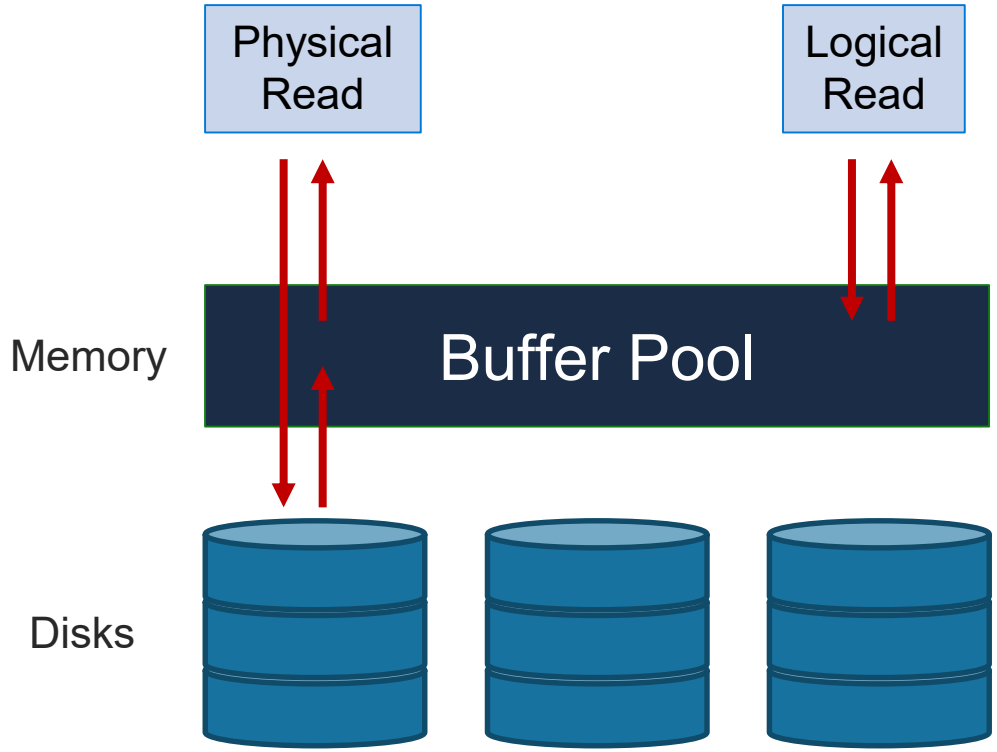
SQL Server Buffer Pool

Stores 8 kilobytes (KB) pages of data to avoid repeated disk I/O.

- Pages held in the buffer until the space is needed by something else.

Lazy Writer searches for eligible buffers.

- If the buffer is dirty, an asynchronous write (lazy write) is posted so that the buffer can later be freed.
- If the buffer is not dirty, it is freed.



Log Buffer Flushing

SQL Server will flush the log buffer to the log file

- SQL Server gets a commit request of a transaction that changes data.
- The log buffer fills up. (Max size 60kb.)
- SQL Server needs to harden dirty data pages (checkpoints)
- Manually request a log buffer flush using the sys.sp_flush_log procedure

Log buffer flushing results in a WRITELOG wait type.

Checkpoints

Flushes dirty pages from the buffer pool to the disk. Frequency of checkpoints varies based on the database activity and recovery interval.

Automatic (default) – Database engine issues checkpoints automatically based on the server level "recovery interval" configuration option

Indirect (new in SQL Server 2012) – Database engine issues checkpoints automatically based on the database level TARGET_RECOVERY_TIME

```
ALTER DATABASE [AdventureWorksPTO] SET TARGET_RECOVERY_TIME = 60 SECONDS
```

Manual – Issued in the current database for your connection when you execute the T-SQL CHECKPOINT command

Internal – Issued by various server operations

SET STATISTICS IO

```
SET STATISTICS IO ON
GO
SET STATISTICS TIME ON
SELECT SOH.SalesOrderID, SOH.CustomerID,
OrderQty, UnitPrice, P.Name
FROM Sales.SalesOrderHeader AS SOH
JOIN Sales.SalesOrderDetail AS SOD
ON SOH.SalesOrderID = SOD.SalesOrderID
JOIN Production.Product AS P
ON P.ProductID = SOD.ProductID
SET STATISTICS IO, TIME OFF
```

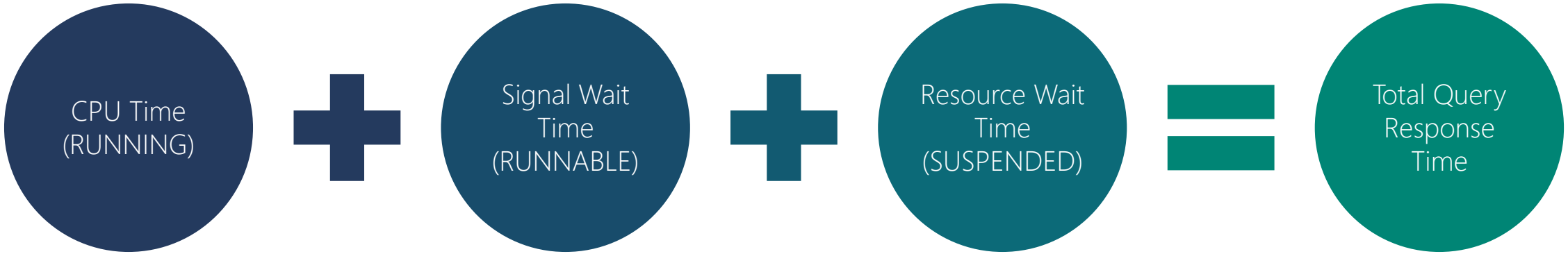
Used to identify physical reads and logical reads for a query

```
(121317 rows affected)
Table 'Workfile'. Scan count 0, logical reads 0, physical reads 0, page server r
Table 'Worktable'. Scan count 0, logical reads 0, physical reads 0, page server
Table 'SalesOrderDetail'. Scan count 1, logical reads 428, physical reads 0, pag
Table 'Product'. Scan count 1, logical reads 15, physical reads 0, page server r
Table 'SalesOrderHeader'. Scan count 1, logical reads 57, physical reads 0, page

 SQL Server Execution Times:
   CPU time = 94 ms,  elapsed time = 1653 ms.
```

Total Query Response Time

- The full cycle between the several task states, for how many times it needs to cycle, is what we experience as the total query response time.

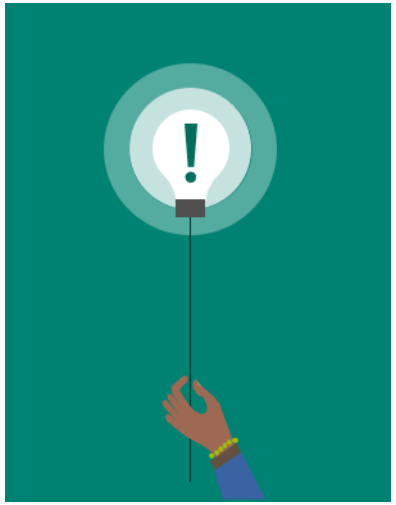


Lesson 2: SQL Server Page Structure

Objectives

After completing this learning, you will be able to:

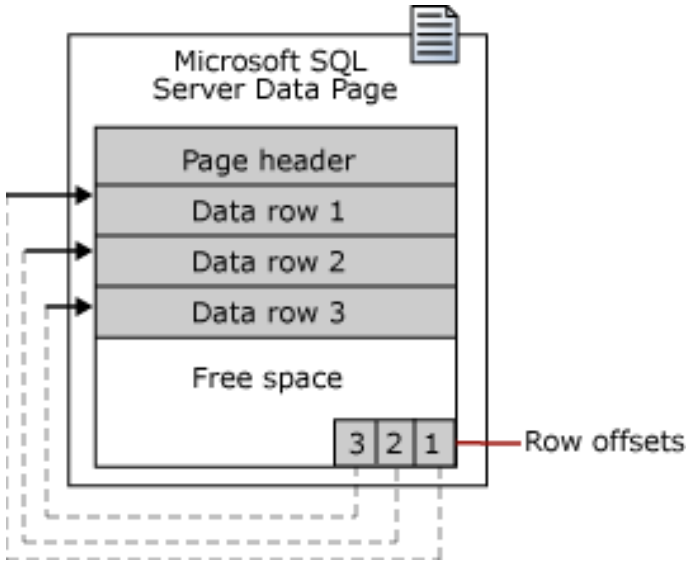
- Understand the architecture of pages and extents.



Pages and Extents architecture

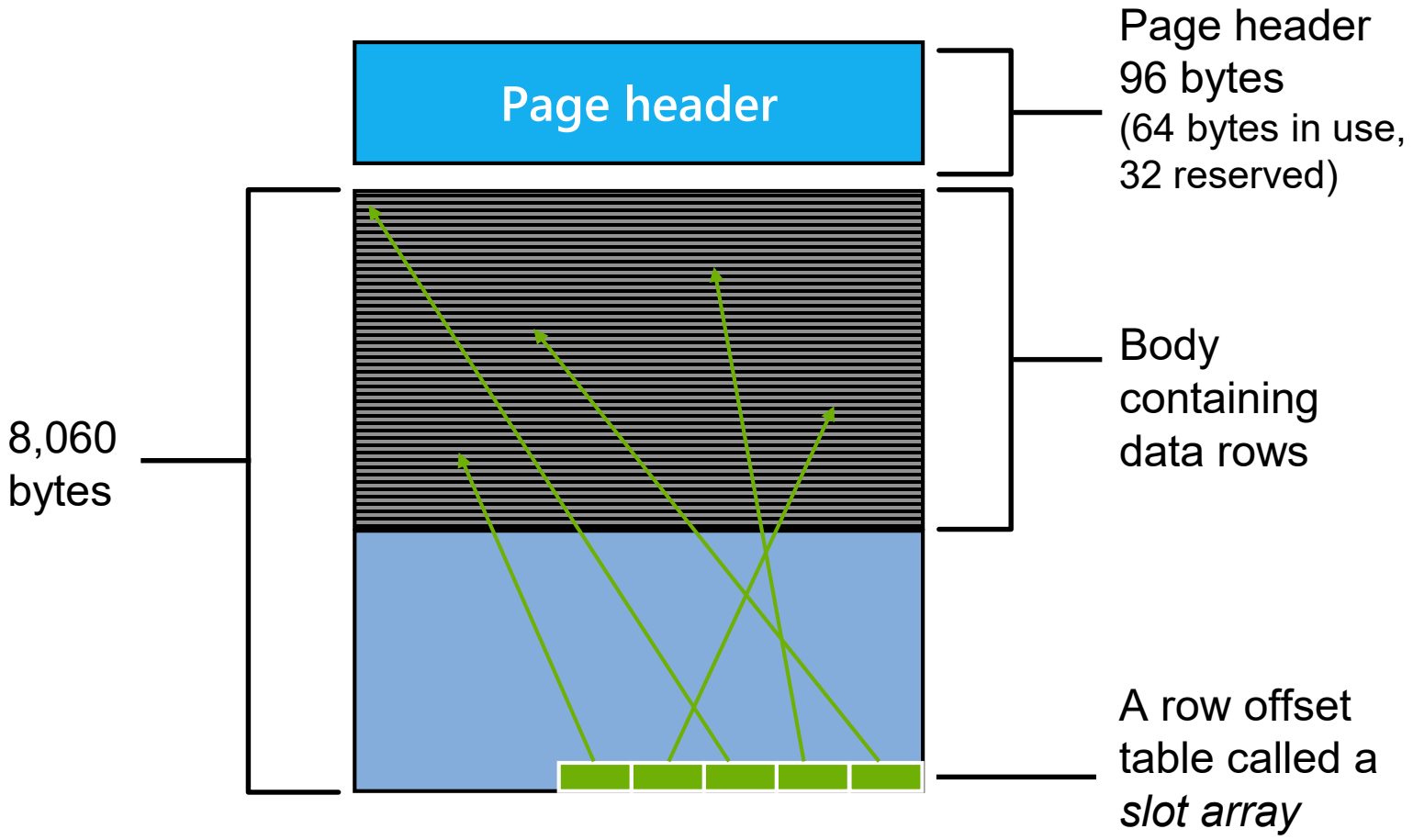
A data page is the fundamental unit of data storage in SQL Server.

- The disk space allocated to a data file (.mdf or .ndf) is logically divided into pages.
- Each page is 8 KB in size
- Pages are numbered contiguously from 0 to n.
- Disk I/O operations are performed at the page level.



Extents are a collection of eight physically contiguous pages (64KB) and are used to efficiently manage the pages.

Data Page structure



Page types

Types	Page Type (ID)	Description
Data and Index	Data (1)	Data rows except text, ntext, image, varchar(max), nvarchar(max), varbinary(max), and xml data, when **text in row** is set to **ON**
	Index (2)	Index Entries
	Text/Image (3 or 4)	Large Object Data Type, variable length columns when the data row exceeds 8 kilobytes (KB)
Allocation	GAM, SGAM (8 and 9)	Extent Allocation information
	PFS (11)	Information about page allocation and free space available on pages
	IAM (10)	Information about extents used by a table or index per allocation unit
Restore	Bulk Changed Map (17)	Information about extents modified by bulk operations since the last BACKUP LOG statement per allocation unit
	Differential Changed Map (16)	Information about extents that have changed since the last BACKUP DATABASE statement per allocation unit
Metadata	Boot (13)	Information about the database; Each database has only one Boot page
	File Header (15)	Information about the file. It is the first page (page 0) in every file

Row Storage

IN_ROW_DATA

- Fixed length data must be store here.
- Rows cannot extend beyond pages
- Data Page is 8060 bytes

LOB_DATA (For out of row storage)

- varchar(max) / nvarchar(max) / varbinary(max)
- 16-byte point to out of row tree
- Uses text page to store a stream of data

ROW_OVERFLOW_DATA (SLOB)

- varchar(8000) / nvarchar(4000) / varbinary(8000)
- When a column can’t fit onto a page
- No control over which column overflows

DBCC IND

```
USE AdventureWorks2012
DBCC TRACEON(3604) -- Print to results pane
DBCC IND(0,'HumanResources.Employee',-1)
-- Parameter 1: Is the DatabaseName, 0 is current database
-- Parameter 2: The table name
-- Parameter 3: Index ID, -1 Shows all indexes, -2 shows only IAM Pages
```

Results | Messages

	PageFID	PagePID	IAMFID	IAMPID	ObjectID	IndexID	PartitionNumber	PartitionID	iam_chain_type	PageType	IndexLevel	NextPageFID	NextPagePID	PrevPageFID	PrevPagePID
1	1	874	NULL	NULL	1237579447	1	1	72057594045136896	In-row data	10	NULL	0	0	0	0
2	1	875	1	874	1237579447	1	1	72057594045136896	In-row data	2	1	0	0	0	0
3	1	1048	1	874	1237579447	1	1	72057594045136896	In-row data	1	0	1	1049	0	0
4	1	1049	1	874	1237579447	1	1	72057594045136896	In-row data	1	0	1	1050	1	1048
5	1	1050	1	874	1237579447	1	1	72057594045136896	In-row data	1	0	1	1051	1	1049
6	1	1051	1	874	1237579447	1	1	72057594045136896	In-row data	1	0	1	1052	1	1050
7	1	1052	1	874	1237579447	1	1	72057594045136896	In-row data	1	0	1	1053	1	1051
8	1	1053	1	874	1237579447	1	1	72057594045136896	In-row data	1	0	1	1054	1	1052
9	1	1054	1	874	1237579447	1	1	72057594045136896	In-row data	1	0	0	0	1	1053
10	1	9287	NULL	NULL	1237579447	2	1	72057594050510848	In-row data	10	NULL	0	0	0	0
11	1	9286	1	9287	1237579447	2	1	72057594050510848	In-row data	2	0	0	0	0	0
12	1	9289	NULL	NULL	1237579447	3	1	72057594050576384	In-row data	10	NULL	0	0	0	0

Query executed successfully. | STUDENTSERVER (12.0 RTM) | STUDENTSERVER\Student ... | AdventureWorks2012 | 00:00:0

DBCC PAGE

```
DBCC TRACEON(3604) -- Print to results pane
DBCC PAGE (0,1,0,3)
-- Parameter 1: Is the DatabaseName, 0 is current database
-- Parameter 2: The File ID
-- Parameter 3: The Page ID
-- Parameter 4: The print option, 3 is verbose
```

.00 %

Messages

```
PAGE HEADER:


Page @0x0000000027757A000

m_pageId = (1:0)                    m_headerVersion = 1                 m_type = 15
m_typeFlagBits = 0x0                m_level = 0                         m_flagBits = 0x208
m_objId (AllocUnitId.idObj) = 99    m_indexId (AllocUnitId.idInd) = 0   Metadata: AllocUnitId = 6488064
Metadata: PartitionId = 0           Metadata: IndexId = 0               Metadata: ObjectId = 99
m_prevPage = (0:0)                  m_nextPage = (0:0)                  pminlen = 0
m_slotCnt = 1                       m_freeCnt = 6989                    m_freeData = 7831
m_reservedCnt = 0                   m_lsn = (181:50952:34)              m_xactReserved = 0
m_xdesId = (0:0)                    m_ghostRecCnt = 0                   m_tornBits = -820886669
DB Frag ID = 1
```

New DMF

sys.dm_db_page_info

- Returns information about a page in a database.
- The function returns one row that contains the **header** information from the page, including the object_id, index_id, and partition_id.
- This function replaces the need to use DBCC PAGE in most cases.
- Output sample:

database_id	file_id	page_id	page_header_version	page_type	page_type_desc	page_flag_bits	page_flag_bits_desc	page_lsn	page_level	object_id	index_id	partition_id
5	1	11712	1	1	DATA_PAGE	0x200	HAS_CHECKSUM	00000025:000004cc:0133	0	1029578706	1	72057594047889408

sys.dm_db_page_info is currently supported only in SQL Server 2019 (15.x) and later.

Demonstration

Examining Data Pages

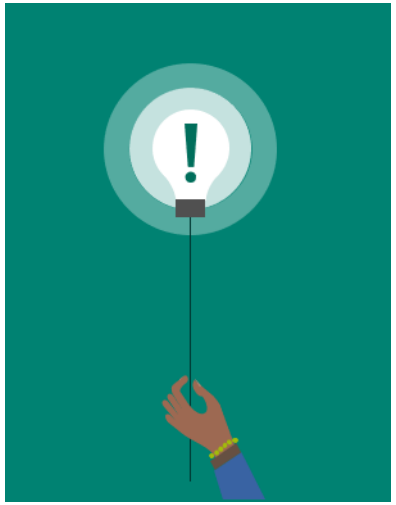
Questions?

Lesson 3: SQL Server Data File Structure

Objectives

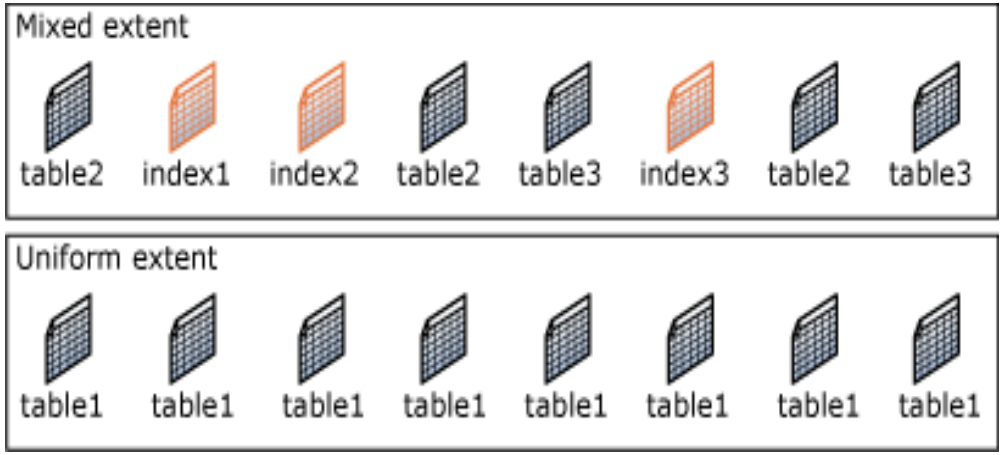
After completing this learning, you will be able to:

- Understand the data file structure.
- Describe SQL Server allocation objects, and object allocation process.



SQL Server object allocation

- Data files are structured in extents.
- Each extent (64 KB) has eight pages of 8 KB each.
- Two types of extents:
  - Mixed extents
    - Up to 8 distinct objects can reside in the same Mixed Extent.
    - Controlled by SGAM (Shared Global Allocation Map) Object.
  - Uniform extents
    - All pages belong to the same object.
    - Controlled by GAM (Global Allocation Map) object.



The Role of Allocation Pages in Object Allocation

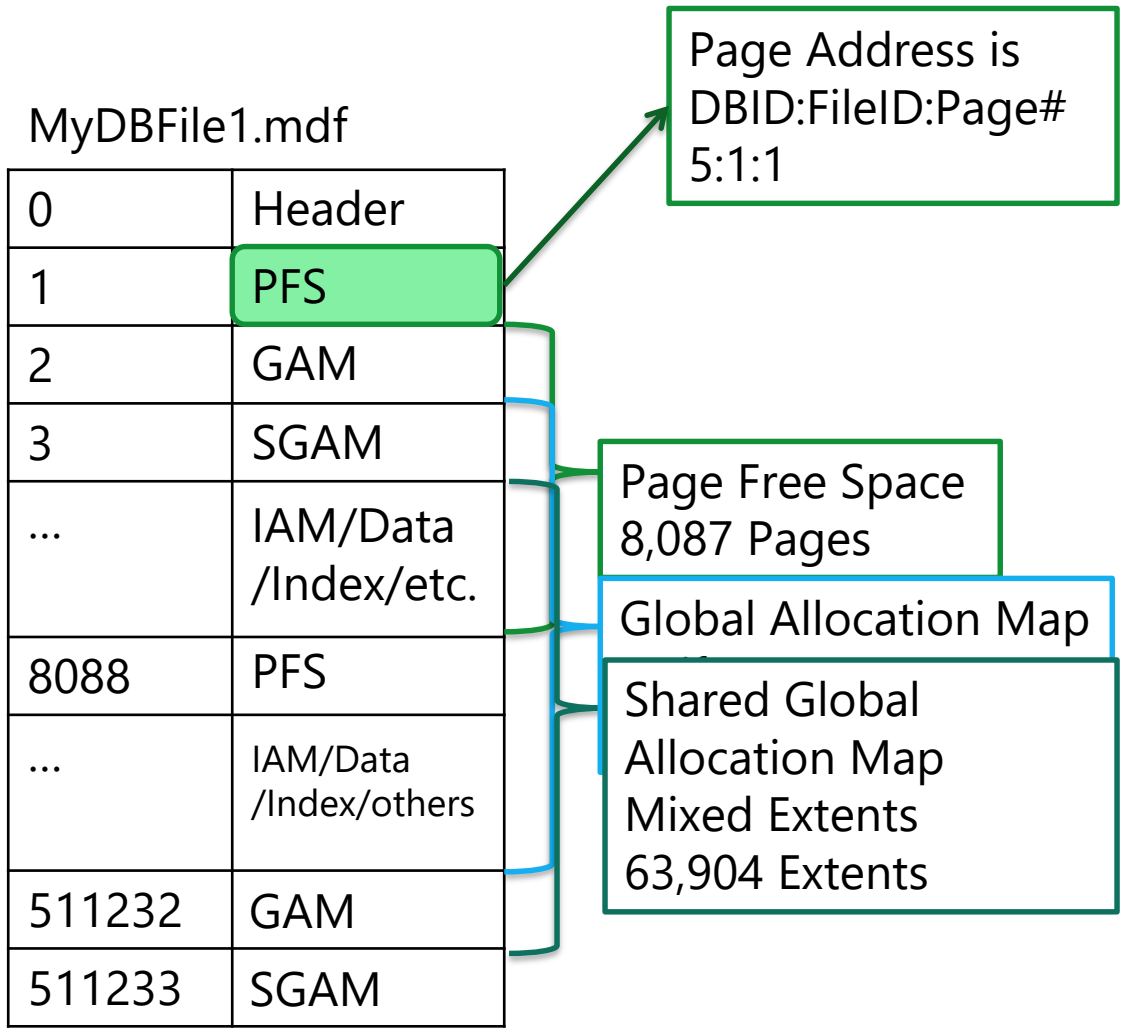
PFS and IAM are used to determine when an object needs a new extent allocated

GAMs and SGAMs are used to allocate the extent

Allocation objects

Page Free Space (PFS)	Global Allocation Map (GAM)	Shared Global Allocation Map (SGAM)	Index Allocation Map (IAM)
• Tracks free space on a page uses 1 Byte/Page • Covers 64 MB worth of pages	• Tracks Uniform extents that have been allocated uses 1 Bit/extent • Covers 64,000 extents (4 GB worth of data)	• Tracks Mixed extents that have all 8 pages allocated uses 1 Bit/extent • Covers 64,000 extents (4 GB worth of data)	• Tracks extents that are allocated to an allocation unit • Covers 4 GB worth of data • One IAM chain per table, per index, per partition, per allocation unit type

Database File page layout



MyDBFile2.ndf

0	Header
1	PFS
2	GAM
3	SGAM
…	IAM/Data /Index/others
8088	PFS
…	IAM/Data /Index/others
511232	GAM
511233	SGAM

SQL Server object allocation

Up to, and including, SQL Server 2014 (12.x)

- On object creation 2 pages from a mixed extents are allocated
- After 8 data pages, new allocation comes from Uniform Extent

Starting with SQL Server 2016 (13.x)

- Default for allocations in the database is Uniform extents for Data pages
- Decreases contention on SGAM objects

SQL Server object allocation (Trace Flag 1118)

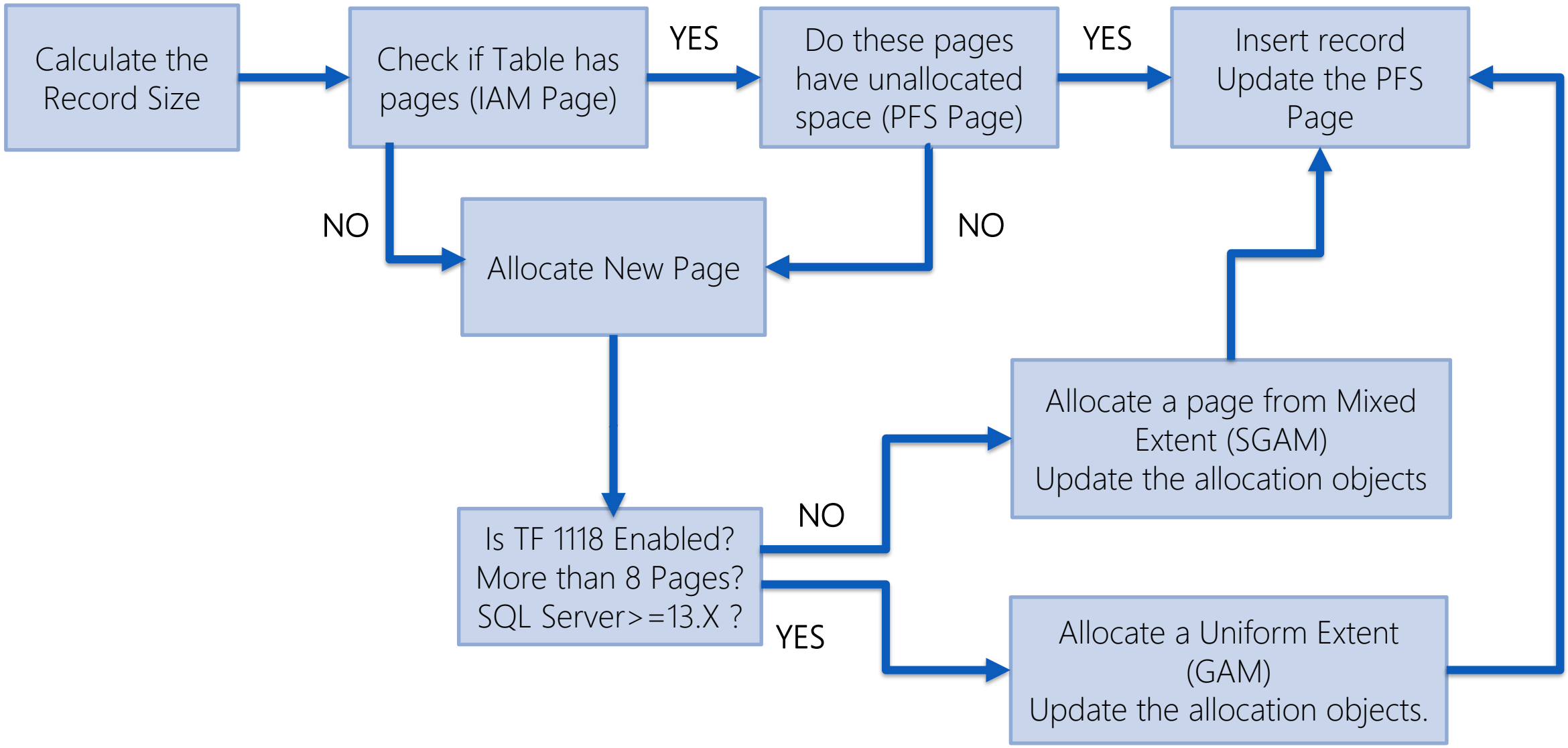
Up to, and including, SQL Server 2014 (12.x)

- Trace flag 1118 is used to change default allocation to use uniform extents

Starting with SQL Server 2016 (13.x)

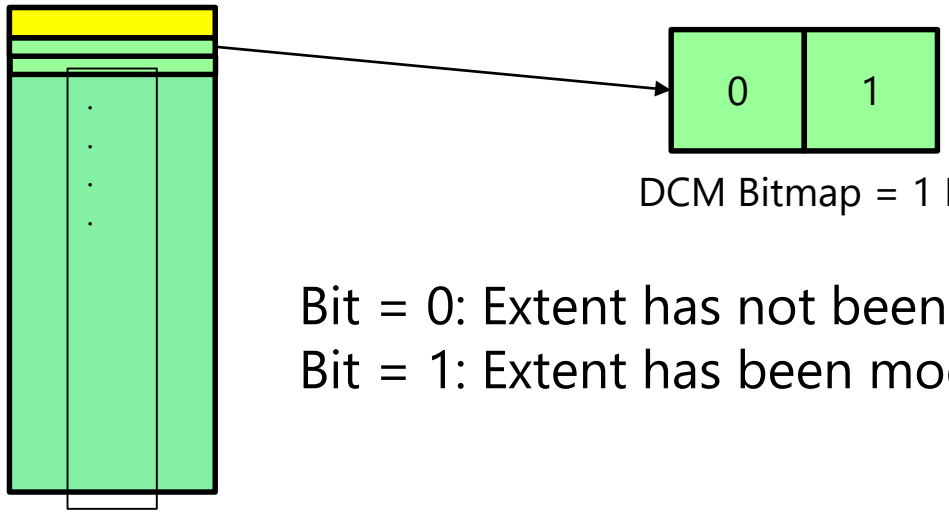
- For TempDB: TF 1118 functionality is automatically enabled.
- For user databases: behavior controlled with SET MIXED_PAGE_ALLOCATION option of ALTER DATABASE
  - default value set to OFF
  - TF 1118 has no effect.

Tying it all together



Differential Changed Map (DCM)

- Differential backups read the DCM pages to determine which extents have been modified and needs to be backed up.
- Tracks the extents that have changed since the last BACKUP DATABASE statement.

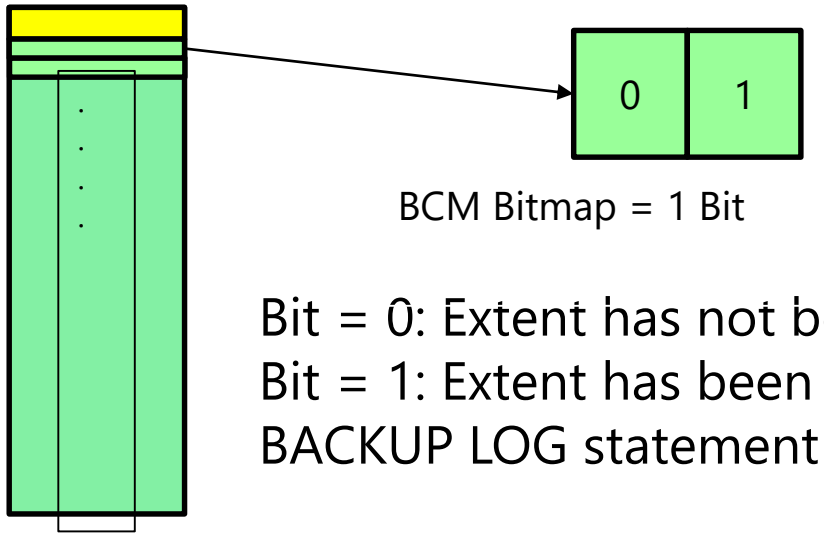


DCM Bitmap = 1 Bit

Bit = 0: Extent has not been modified
Bit = 1: Extent has been modified

Bulk Changed Map (BCM)

- This tracks the extents that have been modified by bulk logged operations (bcp, BULK INSERT, INSERT... SELECT, SELECT INTO, ALTER INDEX REBUILD, and others) since the last BACKUP LOG statement.



BCM Bitmap = 1 Bit

Bit = 0: Extent has not been modified by bulk logged operations.
Bit = 1: Extent has been modified by a bulk logged operation after the last BACKUP LOG statement

Although BCM pages appear in all databases, they are only relevant when the database is using the bulk-logged recovery model.

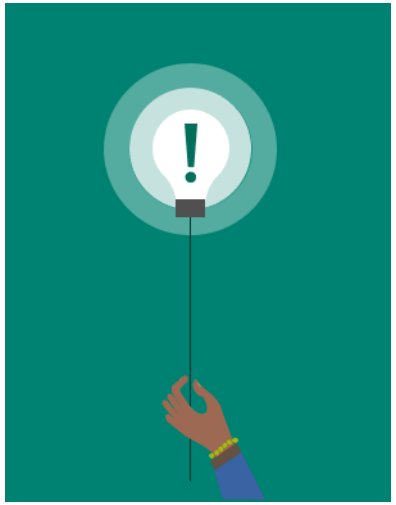
Questions?

Lesson 4: SQL Server Log File Structure

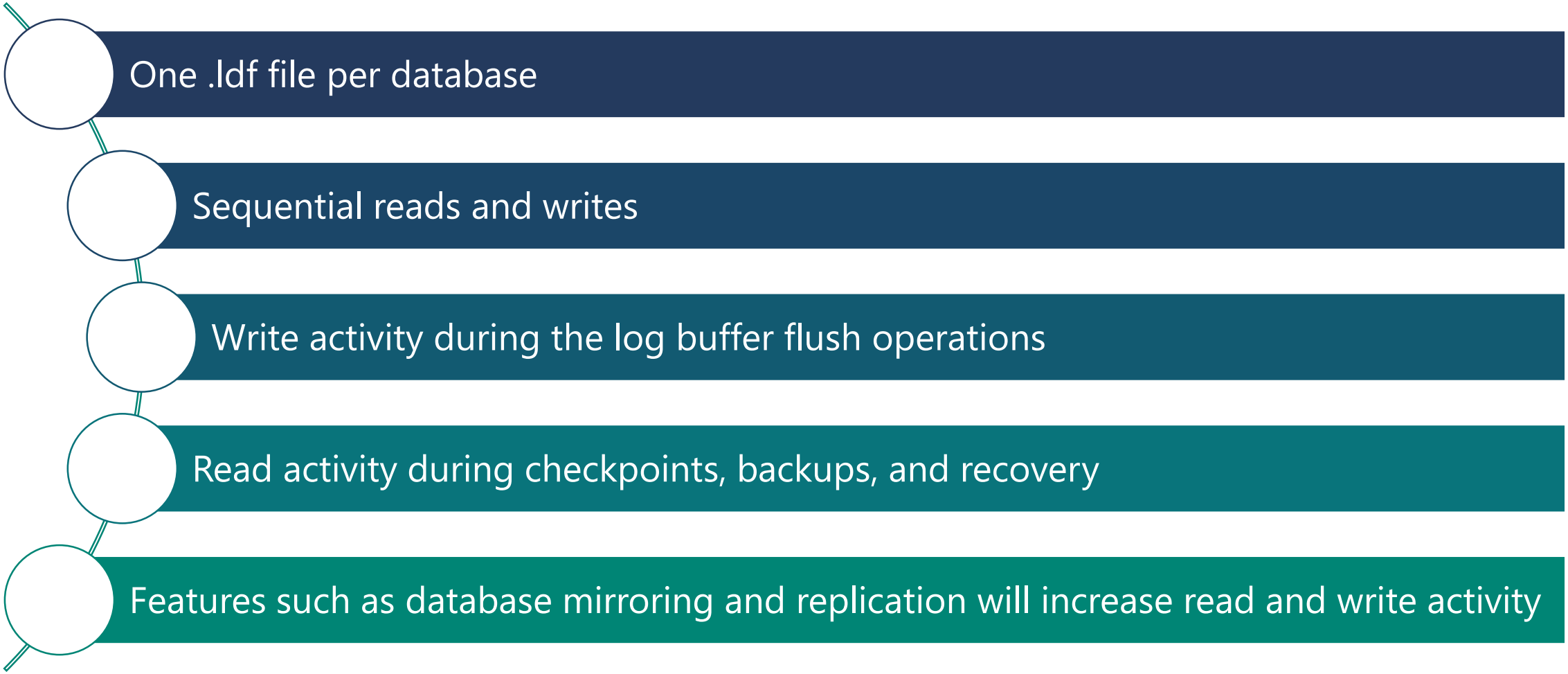
Objectives

After completing this learning, you will be able to:

- Understand the log file structure.
- Explain SQL Server logging process.



SQL Server disk I/O patterns: transaction log



Transaction Log

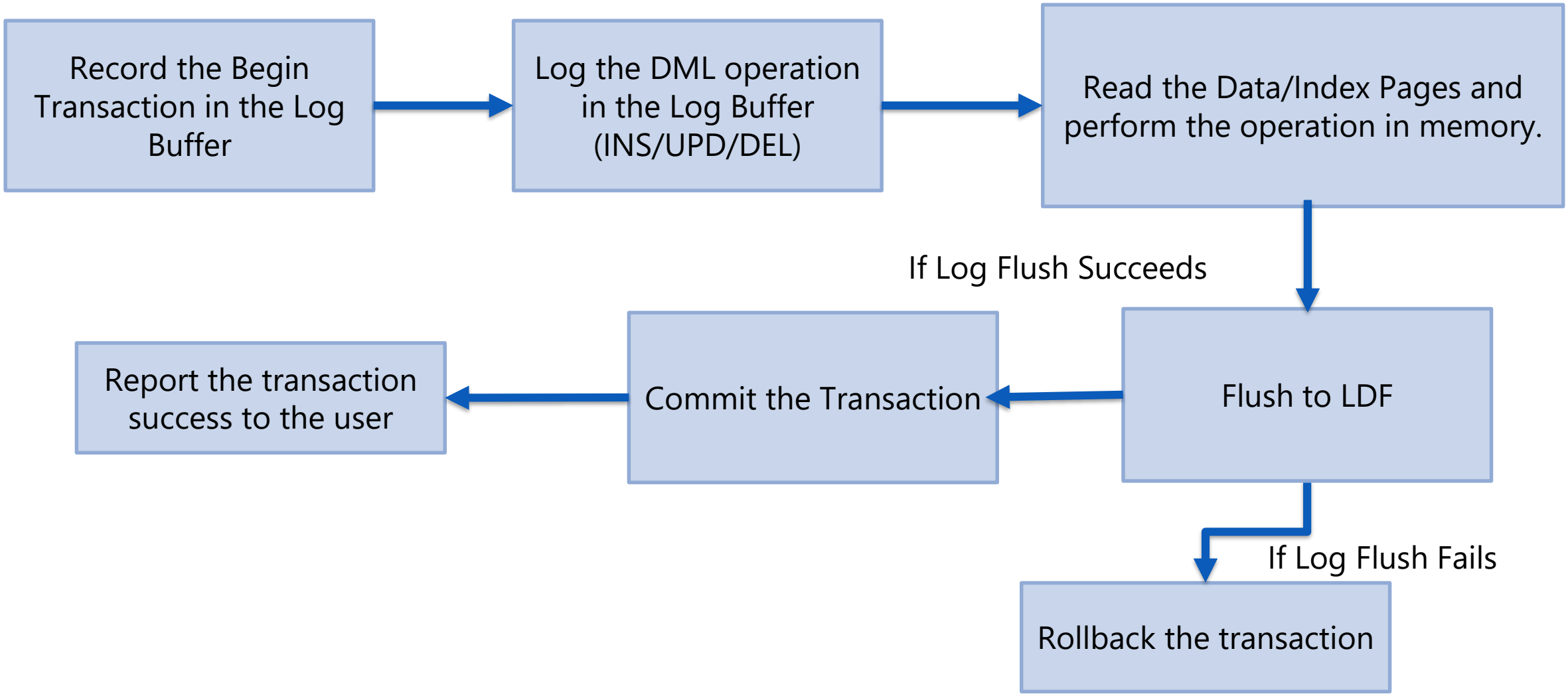
Sequence of log records contained in one or more physical files

Records identified by increasing Logical Sequence Numbers (LSNs)

Recorded operations:

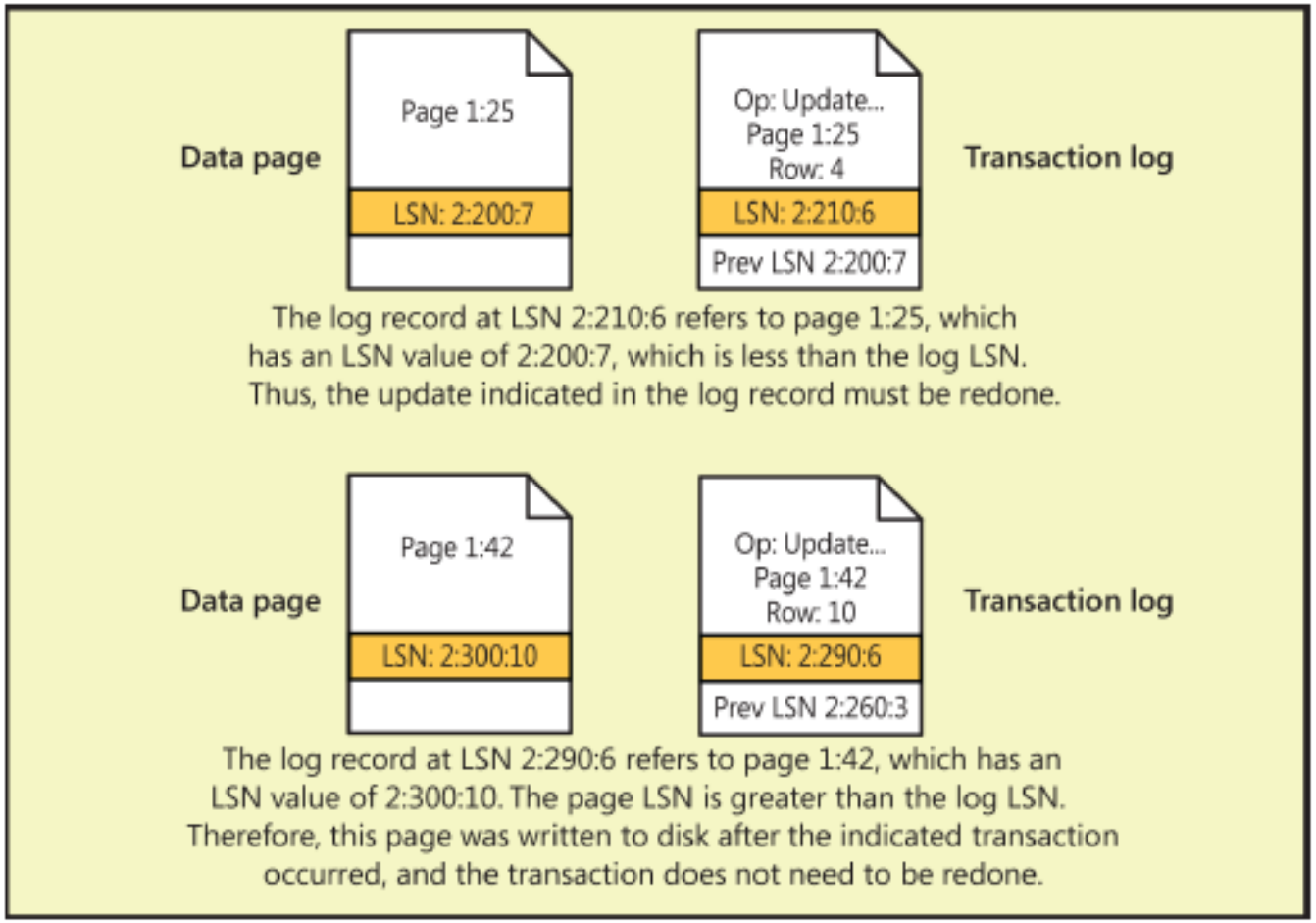
- Start and end of each transaction
- All database modifications
- Extent and page allocation or deallocation
- Creating and dropping objects

Microsoft SQL Server Transaction Logging



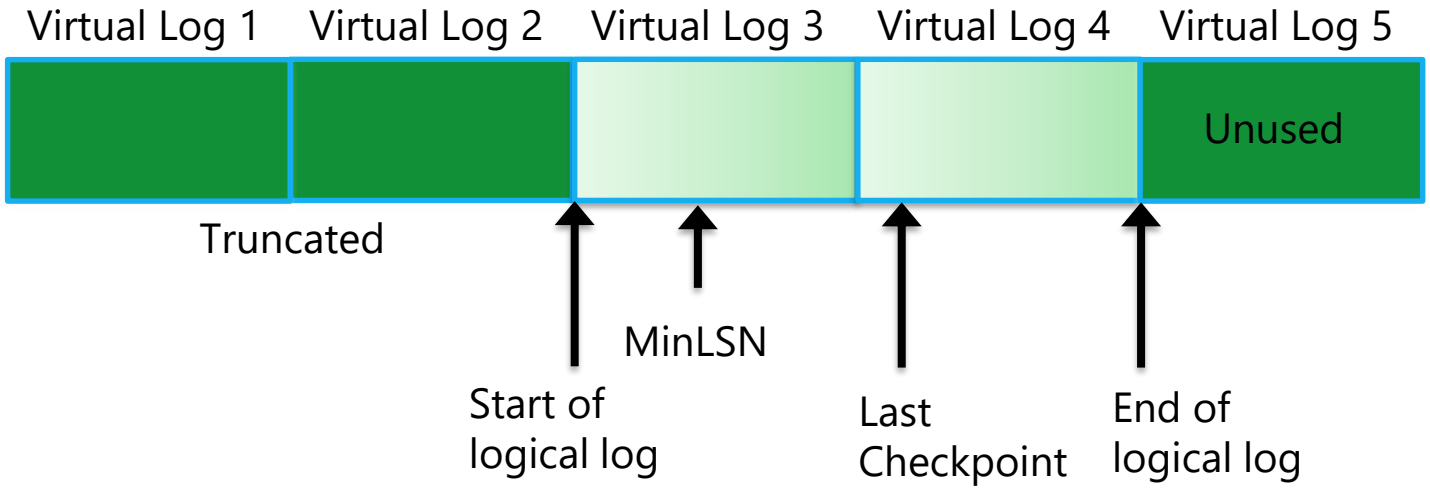
Page LSN and recovery

- Last LSN in the page header
- Log Record has two LSNs
  - Previous LSN from the data page
  - Current log record LSN
- All used for recovery



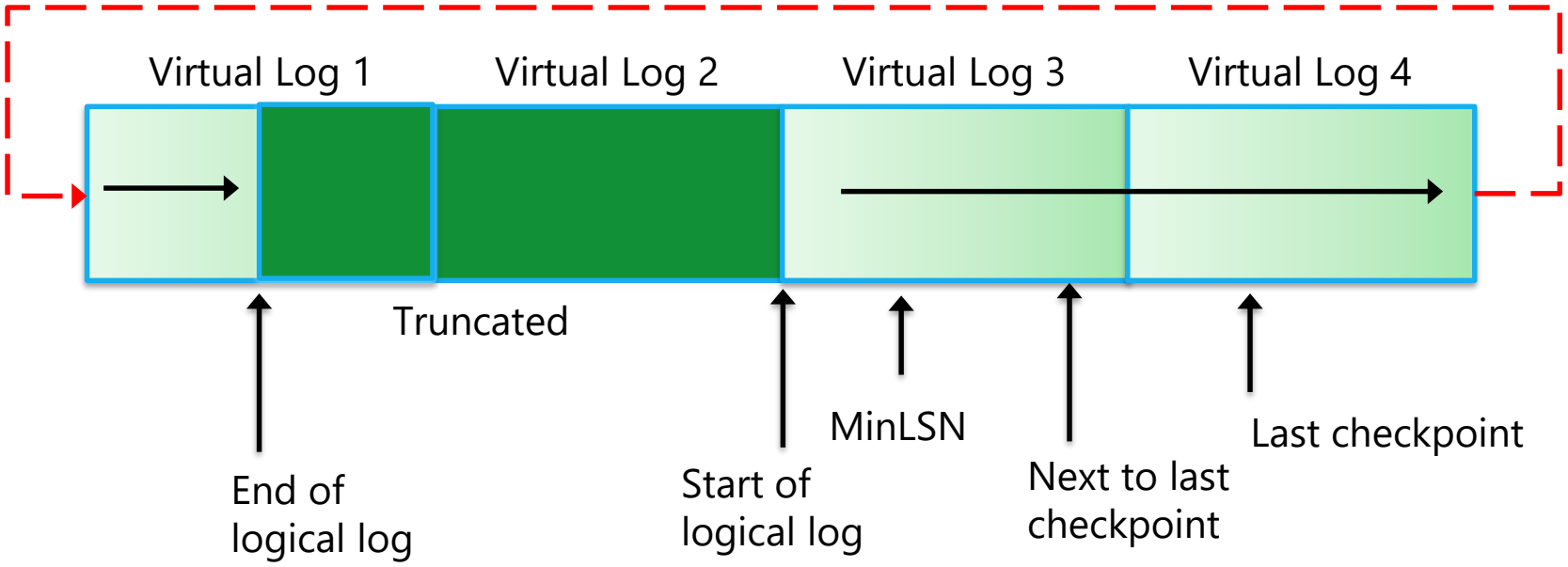
Physical Log File Structure

- The physical file is divided into virtual log files (VLFs).
- SQL Server works to keep the number of VLFs small.
- VLF size and number is dynamic and cannot be configured or set.



Physical Log File Structure (Continued)

- Log file is circular.
- When the end of logical log meets the beginning, the physical log file is extended.



Addressing VLF Counts

VLF count T-LOG file creation

Size <= 64 MB → 4 VLFs

Between 64 MB and 1 GB → 8 VLFs

Size > 1GB →16 VLFs

VLF count at T-LOG file growth

Growth <= 64 MB → 4 VLFs

Between 64 MB and 1GB → 8 VLFs

Growth > 1GB → 16 VLFs

(SQL 2014 and higher)

If growth is less than 1/8th of current size → add 1 VLF

SQL Server 2014 VLF Growth Improvement

- Is the growth size less than 1/8 the size of the current log size?
  - Yes: create 1 new VLF equal to the growth size
  - No: use the previous formula
- Example of a 256 MB log file with an autogrowth setting of 5 MB
  - 2012 and earlier: 10 auto-grows of 5MB would add 4 VLFs x 10 auto-grows
  - 2014 and later: 10 auto-grows of 5MB each would only create 10 VLFs

Grow Iterations + Log size	Up to SQL Server 2012	From SQL Server 2014
0 (256 MB)	8	8
10 (306 MB)	48	18
20 (356 MB)	88	28
80 (656 MB)	328	88
250 (1.2 GB)	1008	258
3020 (15 GB)	12091	3028

Addressing VLF Counts

To avoid VLF fragmentation

- Pre-size log files to avoid unplanned file growth
- Set autogrowth to an appropriate fixed size

To view VLFs

- DBCC LOGINFO (<database_id>)
- sys.dm_db_log_info (SQL Server 2016 SP2 and higher)
- Active VLFs have a status of 2
- SQL Server Error Log (SQL 2012 and higher)

Demonstration

Examining log use

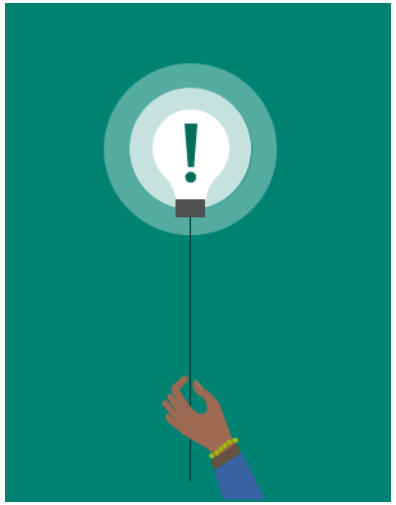
Questions?

Lesson 5: SQL Server TempDB File Structure

Objectives

After completing this learning, you will be able to:

- Understand the TempDB database structure.
- Optimize TempDB database.
- Use the newest improvements in SQL Server for TempDB database.



TempDB database

System database

- Available to all users with the same structure as user databases.
- Operations are minimally logged.
- Re-created every time SQL Server is started.

Workload

- Used for temporary (non-durable) storage.
- Object and data frequently being created and destroyed.
- Very high concurrency.
- Backup and restore operations are not allowed on TempDB.

What is stored in TempDB?

Temporary user objects	• Global or local temporary tables and indexes • Temporary stored procedures • Table variables • Tables returned in table-valued functions, or cursors
Internal objects	• Worktables to store intermediate results for spools, cursors, sorts, and temporary LOB storage. • Work files for hash join or hash aggregate operations. • Intermediate sort results for operations such as creating or rebuilding indexes (if SORT_IN_TEMPDB is specified), or certain GROUP BY, ORDER BY, or UNION queries.
Version stores	• Common version store • Online-index-build version store

Physical properties of TempDB

File	Logical name	Physical name	Initial size	File growth
Primary data	tempdev	tempdb.mdf	8 MB	Autogrow by 64 MB until the disk is full
Secondary data files*	temp#	tempdb_mssql_#.ndf	8 MB	Autogrow by 64 MB until the disk is full
Log	templog	templog.ldf	8 MB	Autogrow by 64 megabytes to a maximum of 2 terabytes

If the number of logical processors is less than or equal to eight (8), use the same number of data files as logical processors.

If the number of logical processors is greater than eight (8), use eight data files.

If contention continues, increase the number of data files by multiples of four (4) up to the number of logical processors

Alternatively, make changes to the workload or code.

Optimizing TempDB performance

Consider instant file initialization

Pre-allocate space for all TempDB files

Divide TempDB into multiple data files of equal size

Put the TempDB database on a fast I/O subsystem

Use disk striping if there are many directly attached disks.

Put the TempDB database on separate disks from user databases

Performance improvements in TempDB

Starting with SQL Server 2016 (13.x)

Trace Flags 1117 and 1118 behavior enabled by default for TempDB

Temporary tables and table variables are cached.

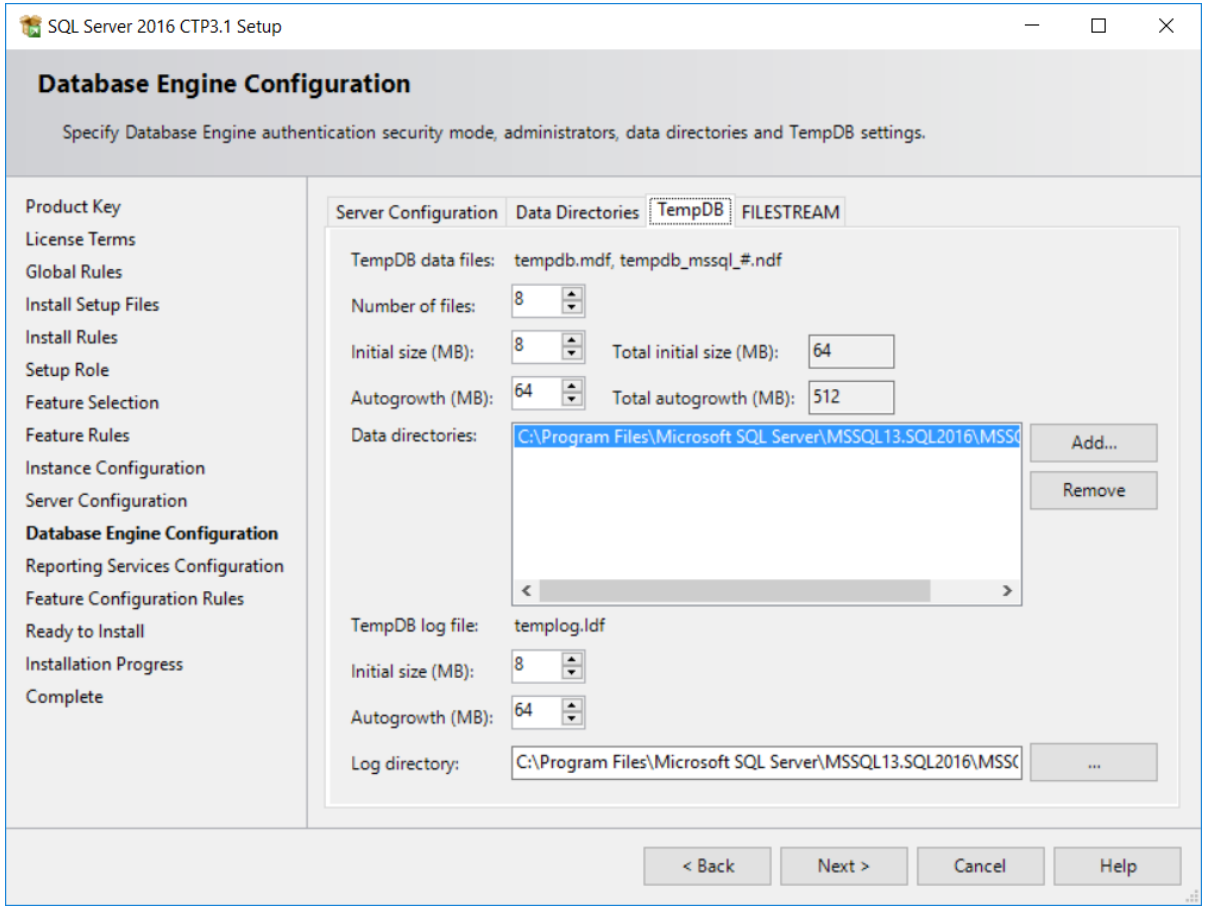
Allocation page latching protocol improved.

Logging overhead for TempDB is reduced.

Performance improvements in TempDB

Starting with SQL Server 2016 (13.x)

- Setup adds multiple TempDB data files during instance installation.
- By default, setup adds as many TempDB data files as the logical processor count or eight, whichever is lower.



Performance improvements in TempDB

Starting with SQL Server 2019 (15.x)

Default	Opt-in
• Temp table cache improvements • Concurrent PFS updates	• Memory-Optimized TempDB Metadata

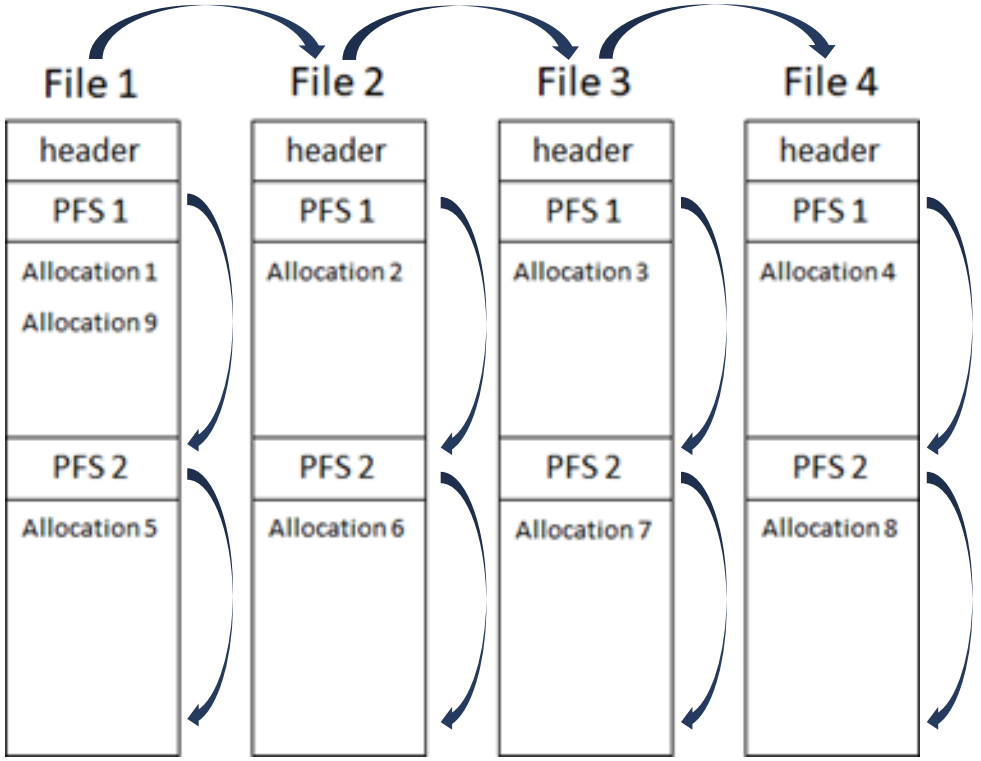
TEMPDB Files, Trace Flags, and Updates by Pam Lahoud

How (and When) To: Memory Optimized TempDB

Concurrent PFS updates

Starting with SQL Server 2019 (15.x)

New algorithm to round robin between files, and between PFS pages within the files.



With this change, not only will increasing the number of files help with PFS contention also increasing the size of the files.

Demonstration

Memory-Optimized TempDB metadata

Questions?

Knowledge Check

What is stored in TempDB?

How can you boost TempDB performance?