SQLskills Immersion Event

IEPTO2: Performance Tuning and Optimization

Module 3: Wait Statistics

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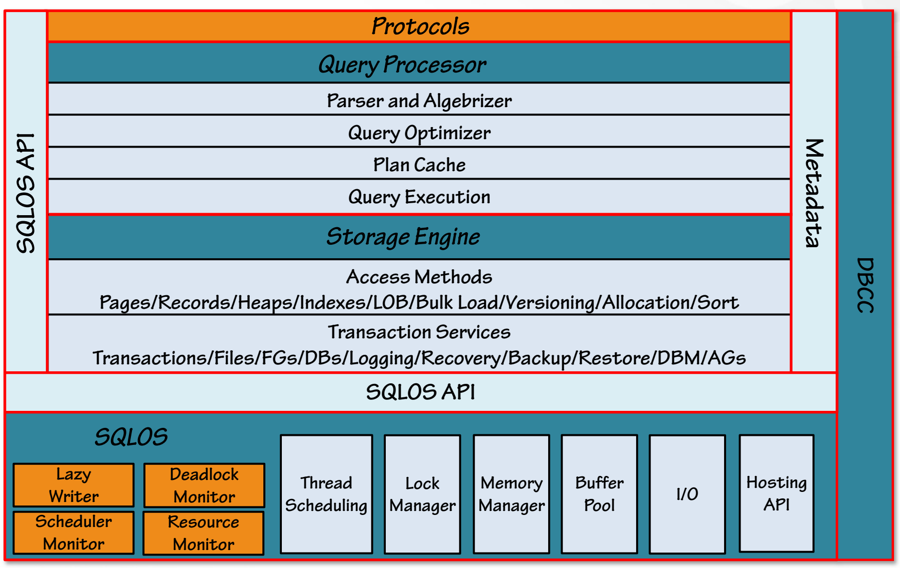
Server Architecture



Overview

- **How thread scheduling works in SQL Server**
- **Fundamentals of waits, latches, and spinlocks**
- **Investigating waits, latches, and spinlocks using DMVs**
- **Common scenarios, including:**
  - Data and log file I/O
  - Latch contention in tempdb and user tables
  - Parallelism
  - Quantum exhaustion

Don't Assume Symptom = Root Cause

- **Performance troubleshooting is not an exact science**
  - The same symptoms can result from many root causes
- **For example, how many different things could cause I/O latencies?**
  - Overloaded/incorrectly-configured I/O subsystem
  - Synchronous I/O-subsystem mirroring
  - Buffer pool memory pressure
    - From plan cache bloat
    - From external Windows pressure
    - From an ad hoc query
    - From an inefficient query plan
  - Network latency
  - And more…

Interpreting the Data

- **Don't do 'knee-jerk' performance troubleshooting**
  - Work through the data to see what may be the root cause
  - You'll end up spending less time overall
- **Proficiency in using wait statistics data comes from:**
  - Retrieving the data correctly
  - Understanding what common wait types mean
  - Recognizing patterns
  - Avoiding inappropriate Internet advice
  - Practice!
- **Even better is to have a series of snapshots of wait statistics over time**
  - Allows identification of changes and the time of the change
  - Allows trending
  - E.g., Michael Swart's GitHub to trend/chart at https://sqlskills.com/p/122
- **Remember: not as valuable when SQL Server is running well**

What are Waits?

- **The term 'wait' means that a thread running on a processor cannot proceed because a resource it requires is unavailable**
  - It has to wait until the resource is available
- **The resource being waited for is tracked by SQL Server**
  - Each resource maps to a wait type
- **Example resources that may be unavailable:**
  - A lock (LCK_M_XX wait type)
  - A data file page in the buffer pool (PAGEIOLATCH_XX wait type)
  - Results from part of a parallel query (CXPACKET wait type)
  - A latch (LATCH_XX wait type)

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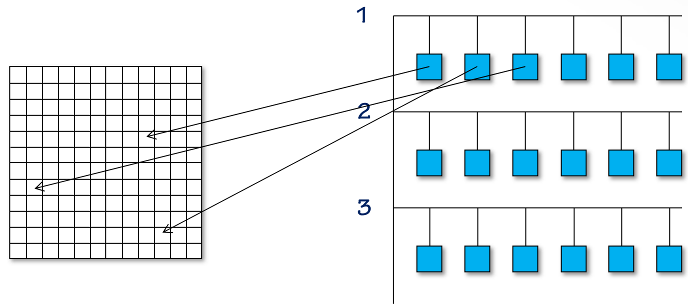
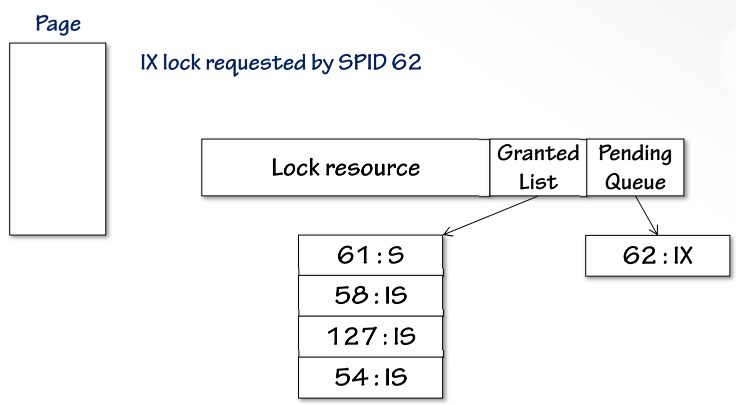
Page Read Example

- Hash list of BUF structures per database, ordered by page ID, for quick access and determining if a particular page is in memory or not



- If requested page not in memory, thread starts asynchronous physical read and has to wait for it to complete (PAGEIOLATCH_SH or _EX)

Locking Example



- If the lock isn't available, the thread enters itself on the lock's pending queue and has to wait (LCK_M_IX)

Why are Resources Unavailable?

- **Some other thread is holding the resource, or the 'resource' needs some process to occur (e.g. page read from disk)**
- **Examples:**
  - For a LCK_M_XX wait, another thread holding an incompatible lock
  - For a PAGEIOLATCH_XX wait, the I/O subsystem needs to complete the I/O
  - For a CXPACKET wait, another thread needs to complete its portion of work
  - For a LATCH_XX wait, another thread holding an incompatible latch
- **Resource waits are investigated using DMVs, performance counters, and other tools**

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Wait Statistics Analysis

- **Very powerful method to get initial direction on a problem**
  - Avoid flailing and investigating the wrong problem
  - Can also show problems that are not obvious
- **Whitepaper**
  - SQL Server Performance Tuning Using Wait Statistics: A Beginners Guide
  - (Resource links at end of deck)
- **Comprehensive waits and latches library**
  - https://www.SQLskills.com/help/waits
- **Most commercial performance monitoring tools capture and show wait statistics**
  - Many free tools also do this, such as sp_whoisactive
- **Various releases of SQL Server have provided wait statistics views**

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Thread Scheduling

- **SQL Server performs its own thread scheduling**
  - Called non-preemptive scheduling
  - More efficient for SQL Server than relying on Windows scheduling
  - Performed by the SQLOS layer of the Storage Engine
- **Each processor core (whether logical or physical) has a scheduler**
  - A scheduler is responsible for managing the execution of work by threads
  - Schedulers exist for user threads and for internal operations
  - Use the sys.dm_os_schedulers DMV to view schedulers
- **When SQL Server has to call out to the OS, it must switch the calling thread to preemptive mode so the OS can interrupt it if necessary**

How Many Threads?

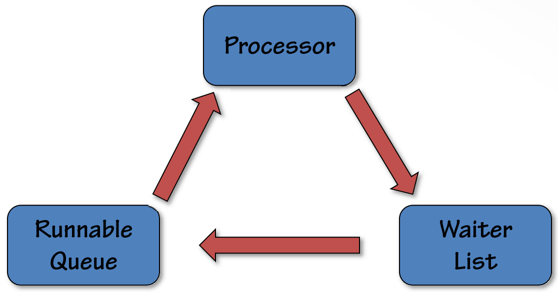
- **Startup calculation to determine the maximum number of threads for the thread pool, although a much smaller number created initially**

# logical cores	# threads
1 (or <2GB mem)	256 (only on 2017+)
<= 4	512
> 4 and <= 64	512 + ((cores – 4) * 16)
> 64	512 + ((cores – 4) * 32)

- **E.g. my laptop with 8 cores has a maximum of 576 threads**
- **Can be changed using 'max worker threads' sp_configure option**
- **The thread pool will dynamically grow and shrink as needed**

Components of a Scheduler

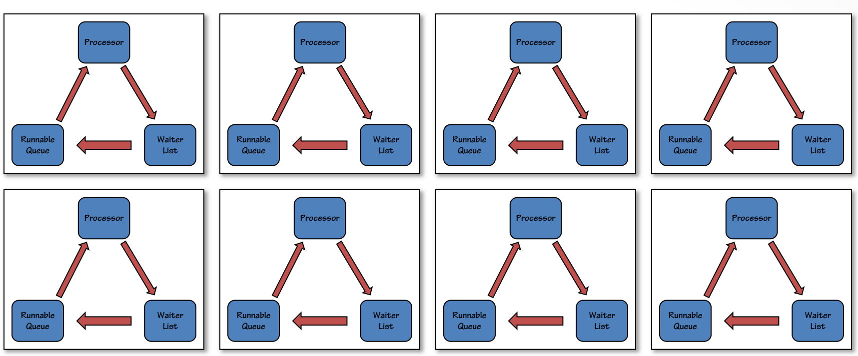
- All schedulers are composed of three 'parts'



- Threads transition around these parts until their work is complete

Schedulers in SQL Server

- One scheduler per logical or physical processor core
  - Plus some extra ones for internal tasks and the Dedicated Admin Connection
- For example, for a server with four physical processor cores, with hyper-threading enabled, there will be eight user schedulers

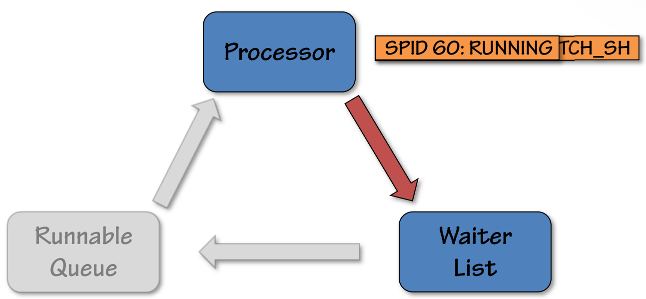


Thread States

- **A thread can be in one of three states when being actively used as part of processing a query**
- **RUNNING**
  - The thread is currently executing on the processor
- **SUSPENDED**
  - The thread is currently on a Waiter List waiting for a resource/operation
- **RUNNABLE**
  - The thread is currently on the Runnable Queue waiting to execute on the processor
- **Threads transition between these states until their work is complete**

Transition: RUNNING to SUSPENDED

- **A thread continues executing on the processor until it must wait for a resource to become available**
  - The thread's state changes from RUNNING to SUSPENDED
  - The thread moves to a Waiter List (on the scheduler or for a resource)
  - This process is called being 'suspended'

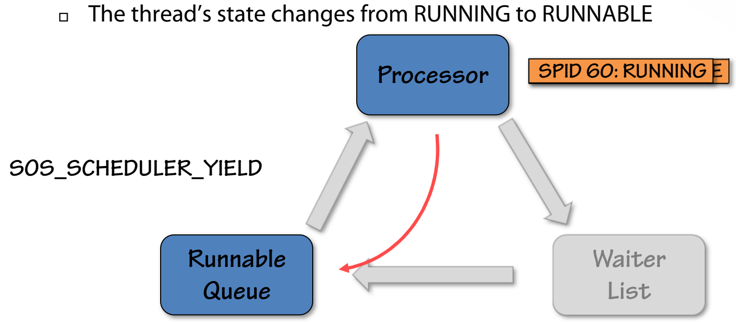


The Waiter List

- **The "Waiter List" is set of threads that are suspended on that scheduler**
  - I/O and timer-task waiter lists for the scheduler
  - Pending queues for other resources (e.g. locks, latches)
- **Any thread can be notified at any time that the resource it is waiting for is now available**
- **No limit to how long a thread remains on a waiter list**
  - Although execution timeouts or lock timeouts may take effect
- **No limit to how many of a scheduler's threads may be waiting**
- **The sys.dm_os_waiting_tasks DMV shows which threads are currently waiting and what they are waiting for**

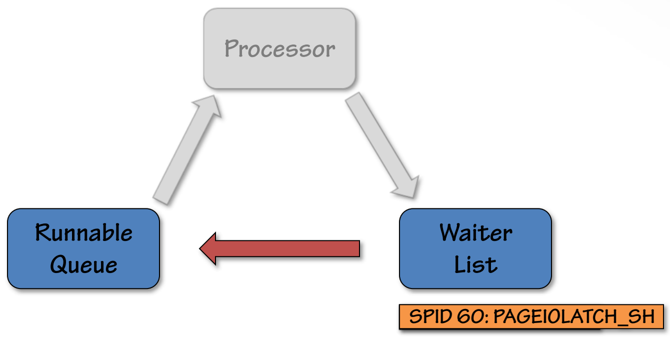
Special Case: Quantum Exhaustion

- **If a thread does not need to wait for a resource, it will continue executing until its quantum is exhausted**
  - Thread quantum is fixed at 4 milliseconds and cannot be changed
- **If this occurs, thread moves to bottom of the Runnable Queue**
  - The thread's state changes from RUNNING to RUNNABLE



Transition: SUSPENDED to RUNNABLE

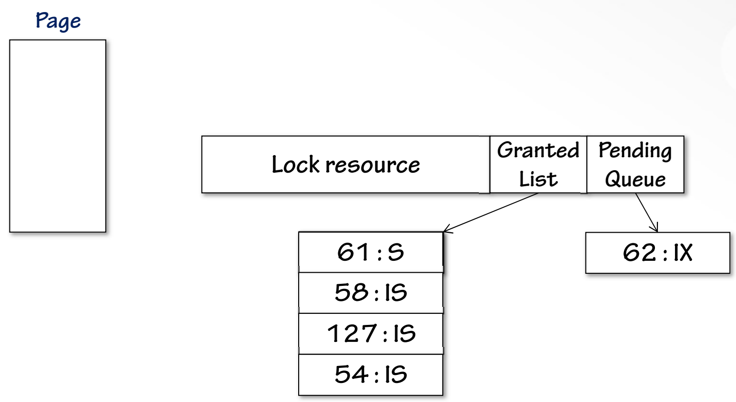
- **A thread continues to wait until it is told that the resource is available**
  - The thread's state changes from SUSPENDED to RUNNABLE
  - The thread moves to the Runnable Queue
  - This process is called being 'signaled'



Page Read Example

- **Thread is suspended waiting for the asynchronous physical read to complete, but how does it know when that is?**
  - It can't run any code to check!
- **When it issued the I/O, it essentially added itself to the scheduler's list of threads waiting for I/Os to complete**
- **Another thread on the scheduler checks the list and signals any threads whose I/Os have completed**

Locking Example



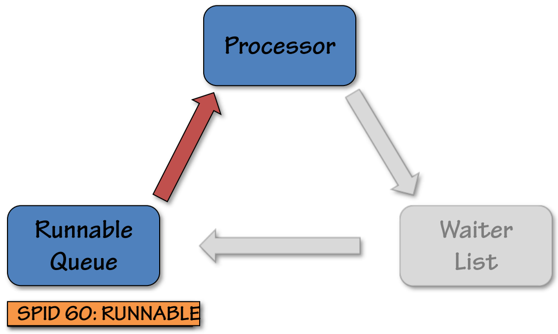
- **Thread dropping a lock checks whether any other locks can be granted, does that, and signals the waiting thread**

The Runnable Queue

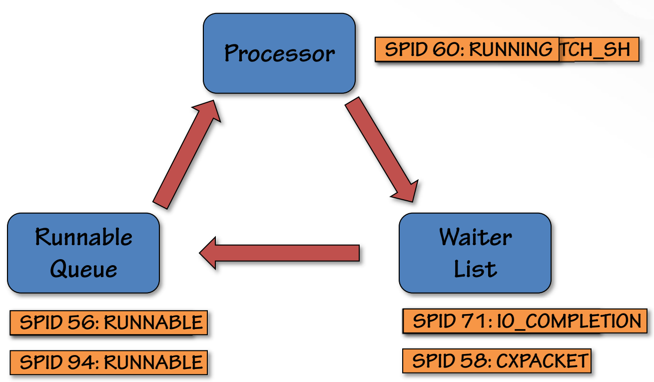
- **Scheduling code chooses which thread to execute next**
  - When the currently executing thread is suspended or exhausts its quantum
- **The Runnable Queue is mostly a First-In-First-Out (FIFO) queue**
  - Threads enter queue at bottom and progress to top
  - Special case to avoid unfair scheduling in 2016+
    - E.g. two threads where T1 can use entire 4ms, but T2 only 0.5ms
    - Pre-2016, T1 will get 8x the CPU time of T2
    - 2016+: T1 and T2 will get roughly equal CPU time
    - See blog post at https://sqlskills.com/p/077
    - This helps with things like the log writer background threads
  - Special case with Resource Governor High/Medium/Low priority workload groups, but rarely used
- **The size of the Runnable Queue can be seen from the runnable_tasks_count column in sys.dm_os_schedulers**

Transition: RUNNABLE to RUNNING

- **The thread waits on the Runnable Queue until it is chosen as the next thread when the processor becomes available**
  - The thread's state changes from RUNNABLE to RUNNING
  - 2019+: it might move to a different scheduler in the same NUMA node



Pulling It All Together



Wait Times Definition (1)

- **Total time spent waiting:**
  - Known as 'wait time'
  - Time spent transitioning from RUNNING, through SUSPENDED, to RUNNABLE, and back to RUNNING
- **Time spent waiting for the resource to be available:**
  - Known as 'resource wait time'
  - Time spent on a Waiter List with state SUSPENDED
- **Time spent waiting to get the processor after resource is available:**
  - Known as 'signal wait time'
  - Time spent on the Runnable Queue with state RUNNABLE
- **Wait time = resource wait time + signal wait time**

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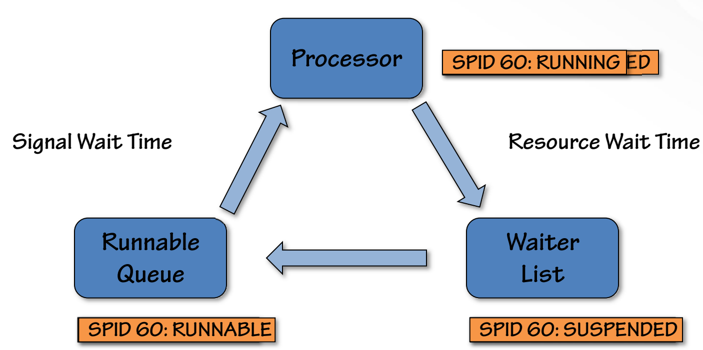
Wait Times Definition (2)



Wait Time = Resource Wait Time + Signal Wait Time

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sys.dm_os_waiting_tasks DMV

- **This DMV shows all threads that are currently suspended**
- **Think of it as the 'what is happening right now?' view of a server**
- **Most useful information this DMV provides:**
  - Session ID and execution context ID of each thread
  - Wait type for each suspended thread
  - Description of the resource for some wait types
    - E.g. for locking wait types, the lock level and resource is described
  - Wait time for each suspended thread
  - If the thread is blocked by another thread, the ID of the blocking thread
    - Useful to find what's at the head of a blocking chain
    - Can show non-intuitive patterns
- **Usually very first thing to run when approaching a 'slow' server**
  - The data is more useful when joined with other DMV results

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sys.dm_os_wait_stats DMV

- **This DMV shows aggregated wait statistics for all wait types**
  - Aggregated since the server started or the wait statistics were cleared
- **Think of this as the 'what has happened in the past?' view of a server**
- **This DMV provides:**
  - The name of each wait type
  - The number of times a wait has been for this wait type
  - The aggregate overall wait time for all waits for this wait type
  - The maximum wait time of any wait for this wait type
  - The aggregate signal wait time for all waits for this wait type
- **Some math is required to make the results useful**
  - Calculating the resource wait time and averages

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Additional Sources of Wait Info

- **sys.dm_exec_session_wait_stats added in 2016**
  - Gives all waits for the entire session, not per batch, so be careful
  - When connection pooling, clears wait info when connection reset
- **Actual query execution plan contains wait info in 2016 SP1+**
  - All waits encountered by the execution
  - Look in Properties of left-most operator
    - Must be using 2016 SP1 or higher SSMS
  - Look in plan XML for the <waitstats> node
  - **Not accurate with parallel plan**
- **Query store captures wait statistics**
  - Aggregated into groups, not individual wait types
  - See sys.dm_db_query_store_wait_stats

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Collecting Waits on Azure SQL Database

- **sys.dm_os_wait_stats gives stats for the container the Azure SQL Database is in, so do not use it**
- **Use sys.dm_db_wait_stats for waits for just the database**

- **Tim Radney explains how to get it working here:**
  - https://sqlskills.com/p/078

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Filtering Benign Waits

- **An extremely important point to bear in mind is that waits ALWAYS occur inside SQL Server**
  - I.e. just because waits exist does not mean there is a perf problem
- **Rather than looking at all waits, most useful is to focus on highly prevalent wait types**
  - More processing of the sys.dm_os_wait_stats results is required
  - Common method is to show the top 95% of all waits by wait time
- **Some wait types are almost always benign and can be safely ignored**
  - Some have pathological, very rare cases where they can be problematic
- **For example, the WAITFOR wait type**
  - Only occurs when a WAITFOR DELAY statement is executed
  - When filtering the top 95% of waits by total wait time, not filtering out this wait can badly skew the results

What's Relevant?

- **Just because there are waits, does not mean they are the problem**
  - Look for actionable items and filter out things like background tasks
  - Look at the demo code to see what I mean
- **Need to identify the top, relevant waits and then drill in**
- **Example:**
  - 100,000 waits for LCK_M_S over 8 hours
  - Is it a potential problem?
  - No, if over 8 hours total wait time for the LCK_M_S locks was only 50s altogether, each wait is only 0.5ms
  - Yes, if *each* LCK_M_S wait was for 50s

Demo

Simple example: waits DMVs and filtering

Storing Wait Statistics

- **Capturing wait statistics information over time allows:**
  - Trending
  - Point-in-time analysis to see when a problem started to occur
- **Simple method:**
  - Use sys.dm_os_wait_stats demo script and add a GETDATE () call
  - Store the results in a table
  - Create SQL Agent job to capture the wait statistics every hour or so
  - Create another SQL Agent job to purge wait statistics older than a month

Methodology (1)

- Gather information about exactly when the performance problem arose and the user-visible characteristics of the problem
- Gather information about what changed before the problem arose
- Is the problem still happening?
- Examine any historical data sets from before the change and correlate through the time the problem arose
  - Look to see how the pattern of waits changes over time
- Examine the output from sys.dm_os_waiting_tasks/dm_os_wait_stats
  - What is happening on the server right now?
  - What has happened in the past?

Methodology (2)

- Look at the top 3-4 relevant waits
  - If LATCH_XX is present, examine the output from sys.dm_os_latch_stats
- Avoid the temptation to knee-jerk and equate symptoms with the root-cause
- Gather further info from relevant sources to pin-point problem
  - DMVs, query plans, performance counters, code analysis
  - Try one solution to see if that solves the problem
    - Repeat analysis, etc.

Using Extended Events

- **When a wait starts and ends, the sqlos.wait_info event fires**
  - Captures similar information to sys.dm_os_wait_stats
  - Also the sqlos.wait_completed event added in SQL Server 2014
    - **Note:** has same resource description as DMV from SQL Server 2016 – very useful!
- **For preemptive waits, the sqlos.wait_info_external event fires**
  - Used when a thread is waiting for a call out to the OS and has to switch from non-preemptive to preemptive scheduling
- **Using the Extended Events system allows:**
  - Capturing of all wait types for a single operation
  - Monitoring for specific wait types occurring
  - Advanced analysis of SQL Server internals

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What are Latches?

- **A latch is a synchronization mechanism between threads**
  - Many people equate latches with locks, but they are quite different
- **A latch protects access to an in-memory data structure**
  - Whereas a lock protects transactional consistency
- **Latches are lightweight and are held only for a short time**
  - Whereas a lock may be held until the end of a transaction
- **Latches cannot be controlled by SQL Server users**
  - Whereas locks can be controlled with hints and configuration options
- **Latches have a variety of modes, equating to the level of access to the in-memory data structure that is required**
  - E.g. an EX latch is required to change a data structure, and a SH latch is required to read most data structures
  - This is similar to the modes that a lock can have
- **SQL Server tracks latch wait times just like other waits**

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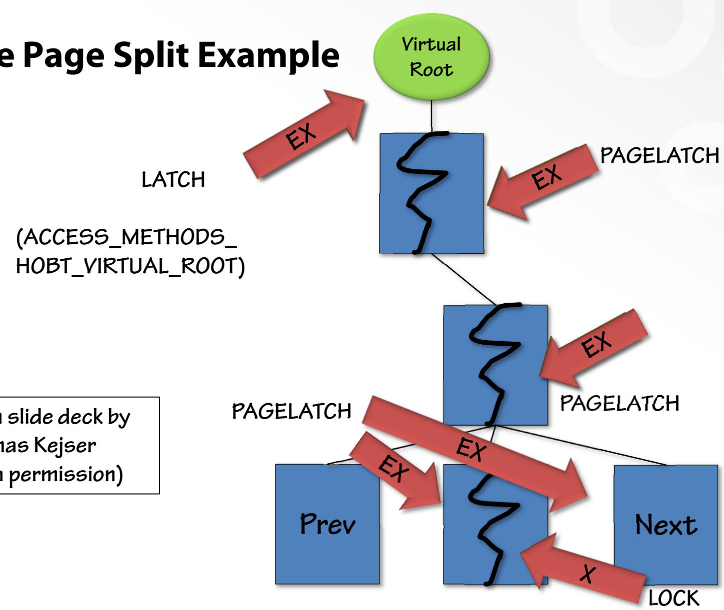
Types of Latches

- **There are three types of latches:**
  - Latches waiting for data file pages to be read from disk into memory
    - Manifest as PAGEIOLATCH_XX waits
  - Latches for access to in-memory data file pages
    - Manifest as PAGELATCH_XX waits
  - Latches for access to all other data structures
    - Manifest as LATCH_XX waits
- **Examples of non-page latches:**
  - FGCB_ADD_REMOVE
  - ACCESS_METHODS_HOBT_VIRTUAL_ROOT

B-tree Page Split Example



From slide deck by Thomas Kejser (with permission)

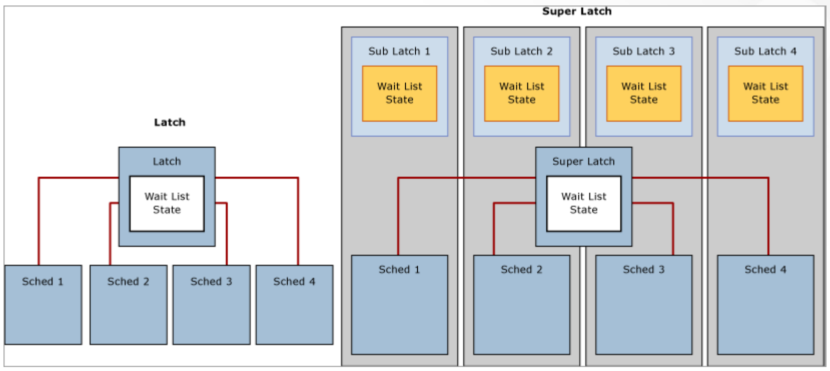
Latch Contention

- **Just like with locks, latches can be a source of contention**
  - This means that what appears to be traditional blocking involving locks may actually be blocking involving latches
- **If one thread has a latch held exclusively then other threads must wait until that thread releases the exclusive latch**
- **This does not become a performance problem until there are many concurrent threads competing for access to the same latch**
  - As latches are only held for a short duration, a single thread waiting a very short time for another thread does not cause a problem
  - However, if hundreds of threads are waiting for a single thread, then that aggregates into a noticeable performance problem
- **Whitepaper on investigating latch contention: https://sqlskills.com/p/079**

Superlatches

- **When the Engine detects lots of SH latch requests on a buffer in the buffer pool, it can promote the latch to a super latch**
- **The latch is partitioned so there is one sub-latch per scheduler, rather than one latch overall**
  - Reduces contention, as even SH latch access requires coordination
- **The superlatch will be demoted again if a series of EX latch requests are detected, once the page is dropped from the buffer pool**
  - As an EX request for a superlatch requires EX latching each superlatch
- **See Latches perfmon counters for total, promotions, demotions**
- **May see this error:**
  - *Message Warning: Failure to calculate super-latch promotion threshold.*
  - Benign message as thresholds are recalculated every 60s by the lazy writer
  - If seeing it lots, check OS power plan is set to High Performance

Superlatches



- Source: Latches whitepaper at https://sqlskills.com/p/079

sys.dm_os_latch_stats DMV

- **This DMV shows aggregated wait statistics for all non-page latch classes**
  - Aggregated since the server started or the latch statistics were cleared
- **This DMV provides:**
  - The name of each latch class
  - The number of times a wait has been for this latch class
  - The aggregate overall wait time for all waits for this latch class
  - The maximum wait time of any wait for this latch class
  - It does NOT list the latch modes being acquired
- **Some math is required to make the results useful**
  - Calculating the average times rather than the total times

Clearing Wait and Latch Statistics

- **Clearing the aggregated wait statistics can be done at any time using the code below:**
  - DBCC SQLPERF ('sys.dm_os_wait_stats', CLEAR);
- **And for latch statistics:**
  - DBCC SQLPERF ('sys.dm_os_latch_stats', CLEAR);
- **Clearing the wait statistics allows the effect of a workload change to be measured against previous wait statistics**
- **Be careful if you are taking periodic snapshots of wait statistics as this will invalidate your series of snapshots**
- **When were they last cleared? https://sqlskills.com/p/080**

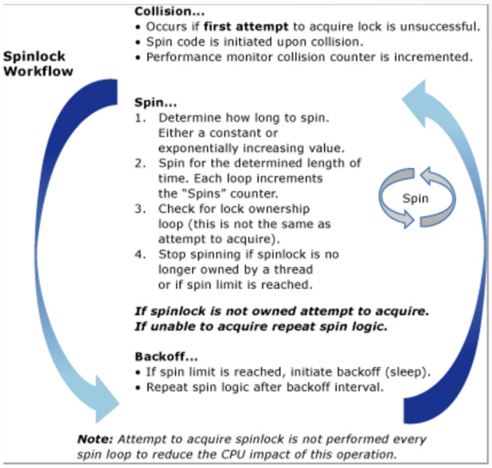
Using Extended Events

- **For very advanced troubleshooting there are events that allow tracking of latches**
  - sqlserver.latch_suspend_begin
  - sqlserver.latch_suspend_end
  - Similar to the sqlos.wait_info and sqlos.wait_info_external events but have a lot more information about the latch itself
- **Demo of this later in the module**

What are Spinlocks?

- **A spinlock is an even lighter-weight thread synchronization mechanism than a latch**
  - Used like a latch for data structure access control
- **Spinlocks are used when the data structure access will be for an extremely short time so the overhead of acquiring a latch is too much**
- **Examples of spinlocks:**
  - FGCB_PRP_FILL
  - BUF_FREE_LIST
- **Troubleshooting spinlocks usually requires very deep knowledge of SQL Server internals**
  - However, it is interesting and useful to know what spinlocks are
- **Great spinlocks post from Chris Adkin at https://sqlskills.com/p/082**

Spinlock Mechanism



- Source: Spinlocks whitepaper at https://sqlskills.com/p/081

Spinlock Mechanism

- **There is no waiting mechanism for spinlocks like there is for latches**
  - Once a thread starts acquiring a spinlock, it will remain on the processor until it has acquired and then dropped the spinlock
- **A thread tests the spinlock to see if it can be acquired**
- **If not, the thread sits in a loop checking whether it has the spinlock**
  - When the thread cannot acquire the spinlock, this is called a 'collision'
  - The thread then loops and tries again, this is called a 'spin'
  - Spins required after a collision do not count as more collisions
  - The number of collisions and the number of spins are tracked
- **After a certain number of spins, the thread stops trying for a bit**
  - This is called a 'backoff'
  - Simply calls the Windows sleep() function and stays on the processor
  - Can cause other threads to have high signal wait times
- **SQL Server tracks all of this**

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Spinlock Contention

- **When a large number of threads are contending for access to a single spinlock, this can lead to performance problems**
- **All these symptoms must be present for high CPU usage to potentially be from spinlock contention:**
  - High and increasing spins and backoffs for a spinlock (billions or more)
  - High CPU usage with many connections to the server, OLTP workload
  - CPU usage, spins, and backoffs increasing much faster than the workload is increasing (possibly an exponential divergence)
- **However, it is likely to NOT be spinlock contention so investigate other waits and latches first**
  - Common for some spinlocks to have very high spins with an OLTP workload
- **Troubleshooting spinlock contention is very advanced**
- **Whitepaper on investigating spinlock contention https://sqlskills.com/p/081**

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Some Common Spinlocks (1)

- OPT_IDX_STATS
  - Updating counters for sys.dm_db_index_usage_stats / missing_index_stats
  - This could be from many concurrent updates to table with lots of indexes
- LOCK_HASH
  - Lock Manager looking in the list of hash buckets for lock hash collisions
  - Consider smaller transactions, using NOLOCK, turning off page locks
- LOGFLUSH_ACCESS and LOGFLUSHQ
  - Involved with writing log buffers to disk – see WRITELOG wait
  - Contention could be from very heavy load of very small transactions
- XVB_LIST
  - Involved with versioning system
  - Contention investigation blog post at https://sqlskills.com/p/124
  - SQL2019 bug fixed in CU9 – see https://sqlskills.com/p/123

Some Common Spinlocks (2)

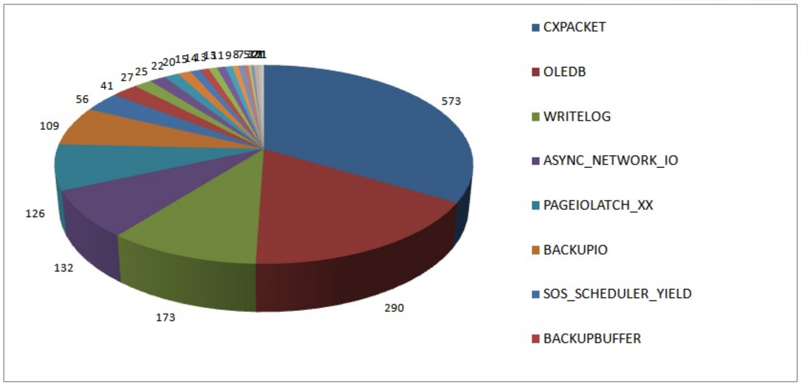
- DP_LIST
  - Used to control access to the dirty page list for indirect checkpoints
    - Allows much faster checkpoint mechanism
  - Indirect checkpoint in very busy tempdb – see https://sqlskills.com/p/041
  - Fixed in latest builds of 2016 and 2017
- SOS_CACHESTORE
  - Bug: when plan cache reaches maximum size – https://sqlskills.com/p/109
    - Enable trace flag 174 to increase cache size
  - Also can be a problem with excessive use of temp tables
    - Contention for adding/removing from the temp table cache
    - Alleviated in SQL Server 2019

Transaction Log Example

- **Taking the transaction log and the logging system as an example, there are waits, latches, and spinlocks associated with it**
- **Waits:**
  - WRITELOG, LOGBUFFER, LOGGENERATION, LOGMGR, LOGMGR_FLUSH, LOGMGR_QUEUE, LOGMGR_RESERVE_APPEND
- **Latches:**
  - LOG_MANAGER, LOGBLOCK_GENERATIONS
- **Spinlocks:**
  - BUF_WRITE_LOG, LOGCACHE_ACCESS, LOGFLUSHQ, LOGLC, LOGLFM
- **From waits to latches to spinlocks, understanding the uses and troubleshooting becomes progressively harder and less likely to be required**
  - This is common across the SQL Server Engine

Top Wait Types

- **Survey results from 1700+ SQL Server instances across Internet**



- **Source: my blog at https://sqlskills.com/p/083**

PAGEIOLATCH_XX Wait

- **What does it mean:**
  - Waiting for a data file page to be read from disk into memory
  - Common modes to see are SH and EX
    - SH mode means the page will be read
    - EX mode means the page will be changed
- **Avoid knee-jerk response:**
  - Do not assume the I/O subsystem is the problem
- **Further analysis:**
  - Determine which tables/indexes are being read
    - Take the page ID and follow steps in this post: https://sqlskills.com/p/084
  - Analyze I/O subsystem latencies with sys.dm_io_virtual_file_stats and Avg Disk secs/Read performance counters
  - Correlate with CXPACKET waits, suggesting parallel scans
  - Examine query plans for parallel scans and implicit conversions
  - Investigate buffer pool memory pressure and Page Life Expectancy

PAGEIOLATCH_XX Wait Solutions

- **Create appropriate nonclustered indexes to reduce scans**
- **Update statistics to allow efficient query plans**
- **Move the affected data files to faster I/O subsystem**
- **If data volume has simply increased, consider increasing memory**
- **Possibly In-Memory OLTP in SQL Server 2014+**

- **A quick band-aid could be to add more memory regardless to increase the buffer pool size**
    - Cheap to do, provides temporary relief, maybe less risky than immediate code change

Data Reading

- **Reads can be:**
  - Single/multiple pages from a data file
  - Single/multiple extents from a data file
  - Variable size chunks of FILESTREAM files
  - Usually random, except for large scans and backups
- **Misconception that SQL Server always reads extents**
  - But it will do sometimes to 'ramp up' the buffer pool
- **Read performance can be dramatically affected by:**
  - Number of files and file placement
  - I/O subsystem configuration
  - Buffer pool memory and memory pressure
  - Query plan choice
  - Ability to perform efficient read-ahead on indexes

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Buffer Pool Usage

- **Unfortunately the query optimizer knows nothing about the contents of the buffer pool otherwise it might choose a less optimal index that's already in memory (to save physical reads)**
- **sys.dm_os_buffer_descriptors**
  - Lists all pages currently in memory
  - Allows aggregating by database, table
  - Allows view of aggregate empty space in pages in memory
  - Can look at how memory pressure affects need to perform physical vs. logical I/Os

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Demo

Buffer pool usage

Data Writing

- **Data file writes can be:**
  - Single/multiple pages
  - Single/multiple extents (for bulk operations)
  - Up to 32 contiguous pages before 2016, up to 128 in 2016+
- **Data file pages are written when:**
  - A checkpoint occurs (for whatever reason)
  - The lazy writer forces a dirty page from the buffer pool
  - A bulk operation flush occurs (a.k.a. 'eager writes')
  - A database mirror is processing log records
    - Dirty pages are continuously flushed out, leading to heavy I/O load
      - Use trace flag 3499 on the mirror to disable this
    - Does not happen for Availability Groups
- **Write performance can be dramatically affected by:**
  - Number of files and file placement
  - I/O sub-system configuration

Read/Write Latency

- **Many systems these days are I/O bound, but is the problem the I/O subsystem or your queries?**
- **If you've optimized your queries and performance is still slow, look into the I/O subsystem**
- **sys.dm_io_virtual_file_stats**
  - Gives total stall time (aggregated latencies) for reads and writes along with read/write counts
  - Explanation: https://sqlskills.com/p/085
  - Snapshot over time: https://sqlskills.com/p/086
  - Better than Physical Disk performance counters as these DMVs are per database file and give SQL Server's view of the I/O subsystem
- **sys.dm_io_pending_io_requests**
  - Lists all pending I/Os, and usually joined with sys.dm_io_virtual_file_stats
- **To use on Azure SQL Database, see https://sqlskills.com/p/078**

Demo

I/O latencies

PAGELATCH_XX Wait

- **What does it mean:**
  - Waiting for access to an in-memory data file page
  - Common modes to see are SH and EX
    - SH mode means the page will be read
    - EX mode means the page will be changed
- **Avoid knee-jerk response:**
  - Do not confuse these with PAGEIOLATCH_XX waits
  - Does not mean add more memory or I/O capacity
- **Further analysis:**
  - Determine the page(s) that the thread is waiting for access to
  - Analyze the queries encountering this wait
  - Analyze the table and index structures involved

PAGELATCH_UP Wait Explanation

- **Some query workloads cause multiple concurrent threads to repeatedly create/drop small temp tables and/or worktables**
  - Can also be from repeated population/truncation of temp tables
- **Easy to cause PAGELATCH_UP contention on allocation bitmaps prior to SQL Server 2019, especially PFS**
  - Use sys.dm_os_waiting_tasks to see waits on PAGELATCH_UP
  - SGAM page to manipulate mixed extents (resource 2:1:3)
  - PFS page to allocate/deallocate pages (resource 2:1:1 and then any page ID that's a multiple of 8088)
- **Contention can occur in all versions, but much reduced in 2019+**
- **This can sometimes (rarely) happen in user databases with VERY high-end allocation workloads**

PAGELATCH_UP Wait Solutions

- **TF 1118 (KB 328551) removes mixed extents (SGAM contention)**
  - **All instances across the world should have this enabled before 2016**
  - **Behavior on by default in SQL Server 2016+**
- **Use multiple data files to reduce contention (KB 2154845)**
  - <= 8 cores: #files = #cores; > 8 cores, #files=8, then increase by 4 at a time
  - 2016+ install automatically configures multiple tempdb data files
  - Adding just one file may not work (see https://sqlskills.com/p/029)
  - Investigation article on Simple Talk: https://sqlskills.com/p/030
- **Alleviated a bit in latest 2016/2017 builds by spreading allocations over multiple PFS intervals (see https://sqlskills.com/p/106 and 108)**
- **2019 enhancements**
  - No latch for PFS updates, using special CPU instructions
  - Temp table cache optimizations to reduce spinlock contention when adding/removing entries

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Demo

tempdb allocation bitmap contention

Temp Table Misuse

- **Very common for us to see temp table problems**
- **Lack of filtering when populating a temp table**
  - Bad: pulling columns into a temp table that are not used
  - Large waste of space and CPU
  - Minimize the column list in a temp table
- **Incorrect temp table indexing**
  - Bad: creating indexes before populating the table
  - Bad: creating indexes that are not used
- **Temp table when none is required**
  - Forcing an intermediate result set into a temp table could disrupt the efficient data pipeline through a query
  - Query may run much faster without a temp table
- **Great post on temp table usage: https://sqlskills.com/p/089**

Tempdb Space Tracking

- **On several client systems I have an automated tempdb space tracking system (that I'll show you)**
- **sys.dm_db_file_space_usage**
  - How is space usage broken out per use (internal/user/version store)
    - Tempdb only before SQL Server 2012
  - Internal is allocations done automatically by SQL Server
    - Work tables for cursor or spool operations and temporary large object (LOB) storage, work files for operations such as a hash join, sort runs
- **sys.dm_db_task_space_usage**
  - Tracks cumulative page allocation and deallocation counts for each thread
  - Can see parallelism happening

Tempdb Log Space Investigation

- **Tempdb log grows out of control – what's going on?**
- **Use my script based on sys.dm_tran_database_transactions**
- **Easy to get confused:**
  - Lots of tempdb log growth, but…
  - …only active transaction(s) have small amounts of space usage
- **Where did the space usage come from?**
  - Lots of already-committed smaller transactions
  - One long-running transaction that doesn't do much still makes the log grow by preventing log clearing/truncation
- **Solution**
  - Don't allow long-running tempdb transactions

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Demo

Tempdb space tracking

PAGELATCH_EX Wait Explanations and Solutions

- **Tempdb system table contention – see next slide**
- **Excessive page splits occurring in indexes**
  - Change to a non-random index key
  - Avoid updating index records to be longer
  - Provision an index FILLFACTOR to alleviate page splits
- **Insertion point hotspot in an index with ever-increasing key and row size such that multiple rows fit on a page**
  - Spread the insertion points in the index using a random or composite key, plus provision a FILLFACTOR to prevent page splits
  - Shard into multiple partitions/tables/databases/servers
  - Increase row size so only one row fits per page
  - Evaluate in-memory tables as a staging area
  - Try OPTIMIZE_FOR_SEQUENTIAL_KEY in 2019+, but might make it worse!
    - Limits number of threads, try when # connections > # schedulers
    - Will cause BTREE_INSERT_FLOW_CONTROL waits to appear

tempdb System Table Contention

- **Some query workloads cause multiple concurrent threads to repeatedly create/drop small temp tables and/or worktables**
  - Can cause PAGELATCH_SH/EX contention on sysobjvalues and sysseobjvalues tables ('insert hotspot')
  - Use sys.dm_os_waiting_tasks to see waits on PAGELATCH_SH/EX in tempdb
  - Check whether the page is in a system table using DBCC PAGE
- **Fixed somewhat in SQL Server 2016 builds**
  - See https://sqlskills.com/p/107 and /108
- **Can remove completely in 2019+ by setting system tables in-memory**
  - ALTER SERVER CONFIGURATION SET MEMORY_OPTIMIZED TEMPDB_METADATA = ON;
  - Restart instance
- **Also a new trace flag 3427 in latest 2016 builds that speeds up small transactions using tempdb (see https://sqlskills.com/p/108)**
  - Removes overhead from Common Criteria Compliance auditing

LCK_M_XX Wait

- **What does it mean:**
  - A thread is waiting for a lock that cannot be granted because another thread is holding an incompatible lock
- **Avoid knee-jerk response:**
  - Do not assume that locking is the root cause
- **Further analysis:**
  - Follow the blocking chain using sys.dm_os_waiting_tasks to see what the lead blocking thread is waiting for
  - Use the blocked process report to capture information on queries waiting too long for locks
    - See Michael Swart's blog post for details about the various methods and further links (https://sqlskills.com/p/090)
  - Are there any LCK_M_RS_XX locks? If so serializable isolation level was used

LCK_M_XX Wait Solutions

- **Lock escalation from a large update or table scan**
  - Possibly configure partition-level lock escalation, if applicable
  - Consider a different indexing strategy to use nonclustered index seeks
  - Consider breaking large updates into smaller transactions
  - Consider using snapshot isolation, a different isolation level, or locking hints
  - All the general strategies for alleviating blocking problems
- **Unnecessary locks for the data being accessed**
  - Consider using snapshot isolation, a different isolation level, or locking hints
- **Something preventing a transaction from releasing its locks quickly**
  - Determine what the bottleneck is and solve it appropriately
- **Serializable isolation level being used erroneously**
  - Distributed transactions, .Net TransactionScope default

Demo

Insert hotspots

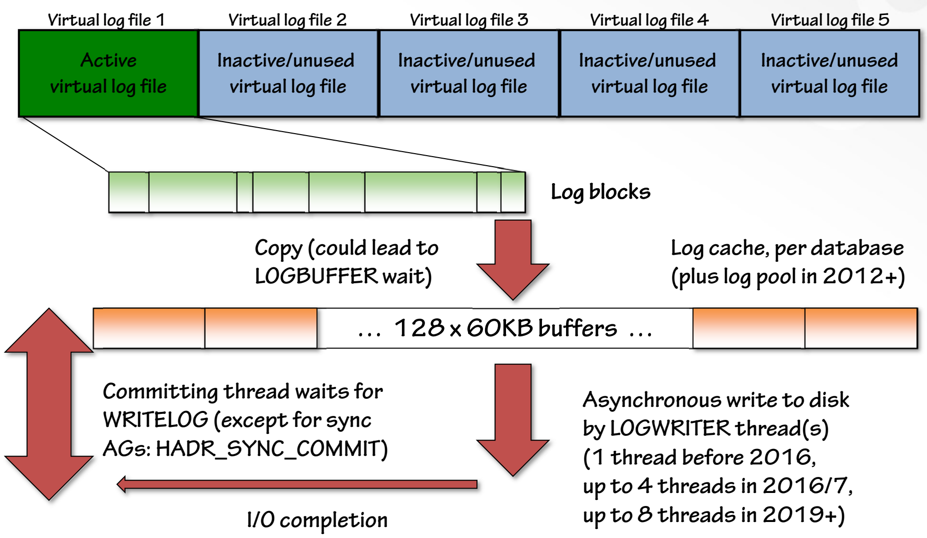
WRITELOG Wait

- **What does it mean:**
  - Waiting for a transaction log block buffer to flush to disk
- **Avoid knee-jerk response:**
  - Do not assume that the transaction log file I/O system is overloaded (although this is often the case)
  - Do not create additional transaction log files
- **Further analysis:**
  - Correlate WRITELOG wait time with I/O subsystem latency using sys.dm_io_virtual_file_stats
    - Look for LOGBUFFER waits, showing internal contention for log buffers
  - Look at average disk write queue length for log drive
    - If constantly 111/112 (31/32 prior to 2012) then the internal limit has been reached for outstanding transaction log writes for a single database
  - Look at average size and volume of transactions
  - Are all the log files for all databases on the same volume?

Transaction Log Writes

- **Writes are always sequential**
- **No performance gain from having multiple log files (except for NVDIMM case)**
  - SQL Server ALWAYS perform sequential writes of log records
- **There are specific limits on transaction log writes**
- **Limit on number of in-flight log writes**
  - 2012+: 112 outstanding writes
  - Older versions: 32 outstanding writes
- **Limit on total size of log writes of 3,840KB at any given time**
  - 32 in-flight writes of up to 60KB each plus 32 log blocks waiting to be written

Transaction Log Flushes



WRITELOG Wait Solutions

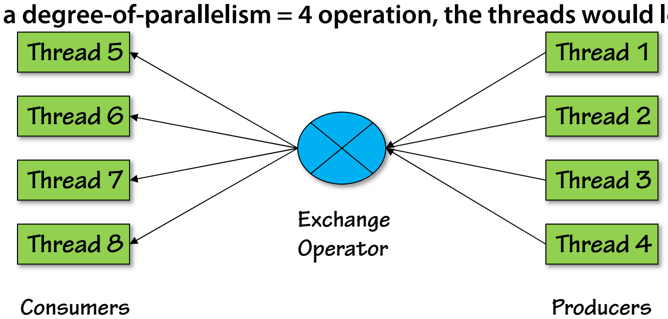
- **Move the log to a faster I/O subsystem**
  - E.g., NVDIMM for log tail in 2016+ - https://sqlskills.com/p/038
- **Spread log files from multiple databases over multiple volumes**
- **Increase size of transactions to reduce small log block flushes to disk**
- **Implement delayed durability in SQL Server 2014+**
- **Check for incorrect CACHE size on SEQUENCE objects**
- **Remove unused nonclustered indexes**
  - Reduce logging overhead from maintaining them during DML operations
- **Change index keys or introduce fillfactors to reduce page splits**
- **Are synchronous database mirroring/AGs causing delays?**
- **Potentially split the workload over multiple databases or servers**
- **Potentially isolate log writer threads – see https://sqlskills.com/p/091**
  - Remove their CPUs from the CPU affinity mask so no user threads there

Demo

Slow transaction log

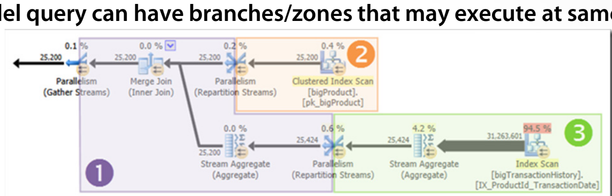
Parallel Threads Example

- As part of a query plan, you may see the operator, for example
  - This is a Repartition Streams operation
  - Producer threads fill packets of rows, fed into the exchange
  - Consumer threads read rows from the exchange output
  - No link/tie/mapping between producer and consumer threads
- For a degree-of-parallelism = 4 operation, the threads would look like:



Threads in a Parallel Query

- Always a single thread, thread ID 0, the parent, exists at the start of the query
  - Creates all other threads, based on DOP the query is able to run at, and runs query
- A parallel query can have branches/zones that may execute at same time

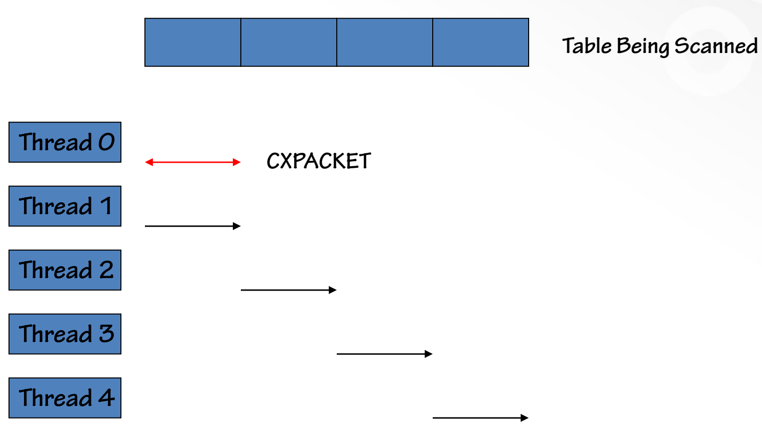


- Each zone can use up to degree-of-parallelism threads, reserved at start
  - MAXDOP limits the number of threads per parallel zone
  - Each thread on a different scheduler, so MAXDOP also limits number of schedulers
- Total possible threads:
  - Per query: (DOP x concurrent zones) + parent (which may be on different scheduler)
  - Per operator: DOP x 2
- More details: https://sqlskills.com/p/092 /093 /118 /119 /125

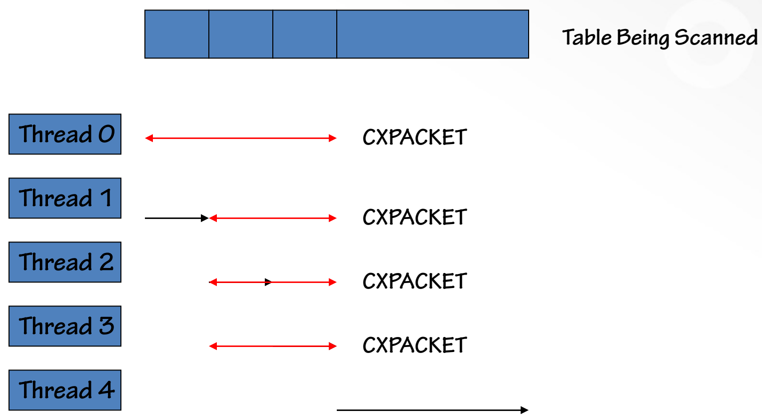
CXPACKET Wait Explanation

- **What does it mean:**
  - Parallel operations are taking place
  - Accumulating very fast implies skewed work distribution amongst threads or one of the workers is being blocked by something
- **Avoid knee-jerk response:**
  - Do not set server-wide MAXDOP to 1, disabling parallelism
- **Further analysis:**
  - Correlation with PAGEIOLATCH_SH waits? Implies large scans
  - Examine query plans of requests that are accruing CXPACKET waits to see if the query plans make sense for the query being performed
  - Are there non-zero ID threads showing CXPACKET wait?
  - If seeing many CXCONSUMER waits in sys.dm_os_waiting_tasks:
    - Long CXCONSUMER waits may indicate skewed parallelism
    - Many short CXCONSUMER waits may indicate a problem on the producer side like a poor join condition making producer threads not push rows through

CXPACKET Wait Example (1)



CXPACKET Wait Example (2)

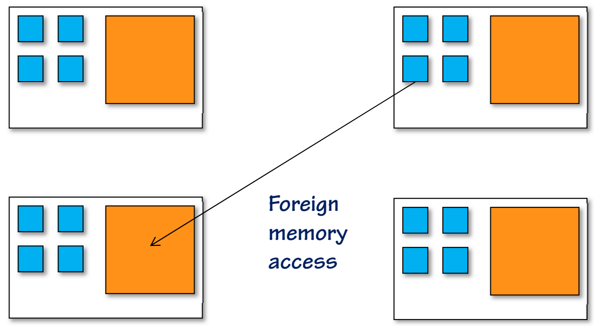


CXPACKET Wait Solutions

- **Possible root-causes:**
  - Just parallelism occurring
  - Table scans because of missing nonclustered indexes or incorrect query plan
  - Out-of-date statistics or cardinality issue causing skewed work distribution
- **If there is actually a problem:**
  - Make sure statistics are up-to-date and appropriate indexes exist
  - MAXDOP for a query? Or just a database (in 2016+)? Or Resource Governor?
  - MAXDOP for the instance? Test to figure out best value for *you*:
    - No NUMA then = # cores, up to max of 8
    - NUMA = # logical cores per NUMA node, up to 16 (2016+) or 8 (< 2016)
    - General guidance, soft-NUMA complicates this
  - Set 'cost threshold for parallelism' higher to avoid some parallel plans
    - Jon's blog post at https://sqlskills.com/p/094 provides a guestimate
    - Always set and test, don't just set to some blogger's value and walk away

NUMA

- Example with four NUMA nodes with four physical cores in each
- Buffer pool is split into four partitions, one per NUMA node using the node-local memory
- Foreign memory accesses are very expensive



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Demo

Parallelism

SOS_SCHEDULER_YIELD Wait

- **What does it mean:**
  - A thread exhausted its 4 millisecond quantum and voluntarily yielded
- **Avoid knee-jerk response:**
  - Do not assume that CPU pressure is the problem
    - High signal wait times show CPU pressure
  - Do not assume that spinlock contention is the problem
- **Further analysis:**
  - Examine query plans to see whether scans are occurring
    - Check if there is a very small or non-existent number of PAGEIOLATCH_XX waits occurring, which indicates that the workload is memory-resident
    - Look for long Runnable Queues
  - Capture SQL Server code call stacks to see where the waits are occurring
- **Note: these waits have zero resource wait time so regular methods of aggregating and prioritizing waits will miss them**
  - They do not appear in sys.dm_os_waiting_tasks

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SOS_SCHEDULER_YIELD Solutions

- **Possible root-causes:**
  - SQL Server is executing code that can use a lot of CPU without having to wait for a resource (e.g. a large scan with few PAGEIOLATCH_SH waits)
  - Look also for long Runnable Queues, indicating CPU pressure
  - Virtual machine delays causing spurious SOS_SCHEDULER_YIELDs
- **Solutions:**
  - On slower processors, potentially enable hyper-threading to give more schedulers and more potential for concurrent work, especially for OLTP workloads
  - Make sure query plans are correct for query being executed
  - Fix any VM issues

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Using Extended Events to Examine Call Stacks

- **The only way to see exactly why SOS_SCHEDULER_YIELD waits are occurring is to examine SQL Server code call stacks**
- **Download the correct symbols**
  - See my blog post at https://sqlskills.com/p/095
  - Or use the Callstack Resolver tool https://sqlskills.com/p/120
- **Enable trace flag 3656 to allow symbol resolution (and 2592 on 2019)**
  - Also disable error log printing about dbghelp.dll version
- **Create an Extended Event session that:**
  - Captures sqlos.wait_info events for wait_type = 120 (or 124 for 2012+)
  - Captures the package0.callstack action
  - Uses the package0.histogram target
- **Run the workload and examine the captured call stacks**
- **Very advanced!**
  - See my blog post for a walk-through example (https://sqlskills.com/p/096)

Demo

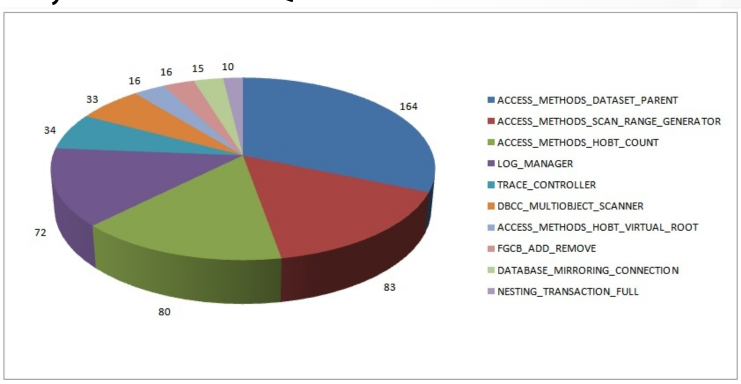
SOS_SCHEDULER_YIELD waits

LATCH_XX Wait

- **A non-page latch is the point of contention**
- **Further analysis:**
  - Use sys.dm_os_latch_stats to investigate which latch(s) are experiencing high wait times
  - Correlate with other prevalent wait statistics
    - For example, CXPACKET waits with LATCH_EX waits where the prevalent latch class is ACCESS_METHODS_SCAN_RANGE_GENERATOR
- **Possible root-causes and solutions:**
- **Depend on the latch class**
  - These are not documented so look in my waits/latches library
    - https://www.sqlskills.com/help/latches/

Top Latch Classes

- **Survey results from 581 SQL Server instances across Internet**



- **Source: my blog at https://sqlskills.com/p/097**

FGCB_ADD_REMOVE Latch

- **Access to the File Group Control Block (FGCB) when adding, removing, shrinking, or growing files in the filegroup**
- **Further analysis:**
  - Analyze the auto-growth settings of the file in all filegroups
  - Extended Events must be used to determine which database is involved
    - Use the latch_suspend_begin and latch_suspend_end events with latch class 48, and correlate to the database_data_file_size_change event using causality tracking
- **Possible root-causes:**
  - Auto-growth settings for a file are very low, requiring frequent growth, coupled with heavy, concurrent use of the filegroup

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Demo

Using Extended Events to show effect of poor auto-growth settings

DBCC_XX Latches

- **Examples:**
  - DBCC_MULTIOBJECTSCANNER (the most common to see)
  - DBCC_CHECK_AGGREGATE
  - DBCC_OBJECT_METADATA
- **Do not stop running consistency checks**
- **Further analysis: none necessary as these are all DBCC CHECKDB**
- **Possible root-causes:**
  - DBCC_MULTIOBJECTSCANNER latch was identified as a contention point and fixed in 2012 and under a trace flag in SQL Server 2008 R2
    - See Bob Ward's post (https://sqlskills.com/p/098) and KB article 2634571
  - DBCC_OBJECT_METADATA is a bottleneck with computed column indexes
    - See my post at https://sqlskills.com/p/0099

PREEMPTIVE_XX_YY Waits

- **What does it mean:**
  - Usually a thread has called out to the OS
    - Sometimes a thread staying in SQL Server but doesn't want to give up CPU
  - Threads must switch to preemptive mode when doing so
  - Note that the thread status will be RUNNING instead of SUSPENDED
- **Further analysis:**
  - ~200 PREEMPTIVE waits
  - These waits are very minimally and poorly documented
  - To determine what the thread is doing, look in my waits library
    - https://www.sqlskills.com/help/waits/#p
- **Possible root-causes and solutions:**
  - Depends on the wait type
  - For instance, increasing PREEMPTIVE_OS_CREATEFILE waits occur when using FILESTREAM on an incorrectly prepared NTFS volume

PREEMPTIVE_OS_WRITEFILEGATHER Wait

- **What does it mean:**
  - A thread is calling out to Windows to write to a file
- **Avoid knee-jerk response that I/O subsystem has a problem**
- **Further analysis:**
  - What database operations are under way? E.g. restore or file growth
- **Possible root-causes and solutions:**
  - Zeroing a large transaction log file during a restore or log file growth
  - Zeroing a large data file during restore or data file growth
    - Enable instant file initialization and set manage growth appropriately
    - Do not delete existing database files before performing a restore
  - Described in KB article 2091024 (https://sqlskills.com/p/100)

PREEMPTIVE_OS_WAITFORSINGLEOBJECT Wait

- **What does it mean:**
  - Thread calling Windows to wait on state change of synchronization object
  - Commonly seen with ASYNC_NETWORK_IO wait
- **Further analysis:**
  - Follow instructions/solutions as for ASYNC_NETWORK_IO
  - Check whether transactional replication is running
- **Possible root-causes and solutions:**
  - As for ASYNC_NETWORK_IO (see next slide)
  - Could also be transactional replication Agent jobs (such as the Log Reader and Distribution Agent jobs)
    - See Joe Sack's blog post for more details (https://sqlskills.com/p/101)

ASYNC_NETWORK_IO Wait

- **What does it mean:**
  - SQL Server is waiting for a client to acknowledge receipt of sent data
- **Avoid knee-jerk response:**
  - Do not assume that the problem is network latency
- **Further analysis:**
  - Analyze client application code and client app server
  - Analyze network latencies
- **Possible root-causes and solutions:**
  - Nearly always a poorly-coded application that is processing results one record at a time (RBAR = Row-By-Agonizing-Row)
    - Very easy to demonstrate using a large query and SQL Server Management Studio running on the same machine as SQL Server
  - Could be from using MARS with large result sets or BCP inbound
  - Otherwise look for network hardware issues, incorrect duplex settings, or TCP chimney offload problems (see https://sqlskills.com/p/102)

OLEDB Wait

- **What does it mean:**
  - The OLE DB mechanism is being used
- **Avoid knee-jerk response:**
  - Do not assume that linked servers are being used
- **Further analysis:**
  - What are the queries doing that are waiting for OLEDB?
  - If linked servers are being used, what is causing the delay on the linked server?
- **Possible root-causes:**
  - DBCC CHECKDB and related commands use OLE DB internally
  - Many DMVs use OLE DB internally so it could be a third-party monitoring tool that is repeatedly calling DMVs (especially if they're very short waits)
  - Poor performance of a linked server

Miscellaneous Other Common Wait Types

- THREADPOOL
  - Waiting for a worker thread to become available, for example on a heavily-loaded system with a lot of parallel queries running
- RESOURCE_SEMAPHORE
  - Waiting for a query execution memory grant, for example for a sort
  - Usually indicates concurrent, memory-hungry queries
- MSQL_XP
  - Waiting for an extended stored procedure call to complete

Demo

Other wait types

Real-World Example: Symptoms

- **Auto dealership hosting service**
  - Lots of auto dealers from across the US hosted on one site
  - Each auto dealer uploads inventory each day
  - One large Listing table storing all inventory for all dealers
  - One large Visitor table tracking clicks on web pages
  - No DBA
- **System had performance problem:**
  - User queries on inventory and prices regularly timed out
  - Inventory updates regularly timed out
  - Climbing CPU usage
  - Response time getting longer and longer
  - Car dealers pressuring hosting service for fixes
- **First step: analyze wait statistics…**

Real-World Example: Analysis

- **No historical data so gathered wait statistics data using the queries**
- **Both DMVs showed the same three wait types:**
  - CXPACKET wait = parallelism
  - PAGEIOLATCH_SH wait = reading data file pages from disk
  - WRITELOG wait = waiting for log writes, with average wait more than 20ms
- **Possible issues from just wait statistics**
  - Many queries doing parallel table scans of data that is not memory resident
  - I/O subsystem for the log file over-loaded and/or high number of log flushes
- **Investigated further using DMVs to analyze:**
  - Query plans
  - Index and table structures, index usage, fragmentation, and statistics
  - I/O subsystem latencies
- **Next step: determine root-causes…**

Real-World Example: Root-Causes

- **Both large tables had random GUID cluster keys**
  - High fragmentation in the clustered indexes leading to poor readahead
  - Lots of page-split transaction log activity during web page click tracking
- **Both large tables had more than 50 single-column nonclustered indexes**
  - Indexes not being used for seeks, resulting in table scans
  - Large amounts of nonclustered index maintenance from inserts, updates, deletes contributing to transaction log activity
- **Insufficient buffer pool memory for application workload data**
- **Poorly laid out I/O subsystem contributing to high latencies**
- **Poorly written code from using an ORM system**
- **Final step: propose and implement solution**

Real-World Example: Solution

- **Solution included:**
  - Increasing server memory and provisioning more appropriate I/O subsystem
  - Changing main tables to have bigint IDENTITY cluster keys
  - Removing useless nonclustered indexes
  - Analyzing ORM-generated code and query plans to determine appropriate nonclustered indexes
    - ORM system could not be removed for political reasons
  - Implementing index maintenance and periodic health checks
- **End result: no performance problems and a happy client, with minimal investigation time**

Key Takeaways

- Wait statistics are a key part of performance problem diagnosis
- Don't knee-jerk, follow the easy methodology
- Practice gathering and analyzing wait statistics using the DMVs
- Remember that waits always happen
- Don't get into latches and spinlocks unless absolutely necessary
  - Too many potential red herrings
- Know what the common waits mean and don't mean

Resources

- Waits/latches repository
  - https://www.SQLskills.com/helps/waits
- Whitepapers:
  - SQL Server Performance Tuning Using Wait Statistics: A Beginners Guide
    - https://sqlskills.com/p/103
  - Diagnosing and Resolving Latch Contention on SQL Server
    - https://sqlskills.com/p/079
  - Diagnosing and Resolving Spinlock Contention on SQL Server
    - https://sqlskills.com/p/081
- Blog post categories
  - https://www.sqlskills.com/blogs/paul/category/wait-stats/ and /latches/ and /spinlocks/
- Pluralsight: SQL Server: Performance Tuning Using Wait Statistics

Review

- **How thread scheduling works in SQL Server**
- **Fundamentals of waits, latches, and spinlocks**
- **Investigating waits, latches, and spinlocks using DMVs**
- **Common scenarios, including:**
  - Data and log file I/O
  - Latch contention in tempdb and user tables
  - Parallelism
  - Quantum exhaustion

Questions?