Scalability Improvements in the InnoDB Storage Engine in MariaDB

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Scalability in Databases

- A database management system implements concurrent transactions
  - Transactions must be ACID (Atomic, Consistent, Isolated, and Durable).
- Users need concurrent access to the same tables, records, or data pages
  - **Concurrency** may be limited due to **locking conflicts** or **contention**.
  - **Transactional locks** will be held until `COMMIT` or `ROLLBACK`.
- `READ UNCOMMITTED`, `READ COMMITTED`, and `REPEATABLE READ` bypass transactional locks but not any (hopefully short-duration) **internal latches**
  - Mini-transactions (atomic modifications of multiple pages) hold page latches
  - Buffer pool (requesting, flushing, or evicting pages), redo log writes, …

A Layered Implementation of Transactions

Low Layers in the OSI Model

- **Transport:** Retransmission, flow control (TCP/IP)
- **Network:** IP, ICMP, UDP, BGP, DNS, … (router/switch)
- **Data link:** Packet framing, checksums
- **Physical:** Ethernet (CSMA/CD), WLAN (CSMA/CA), …

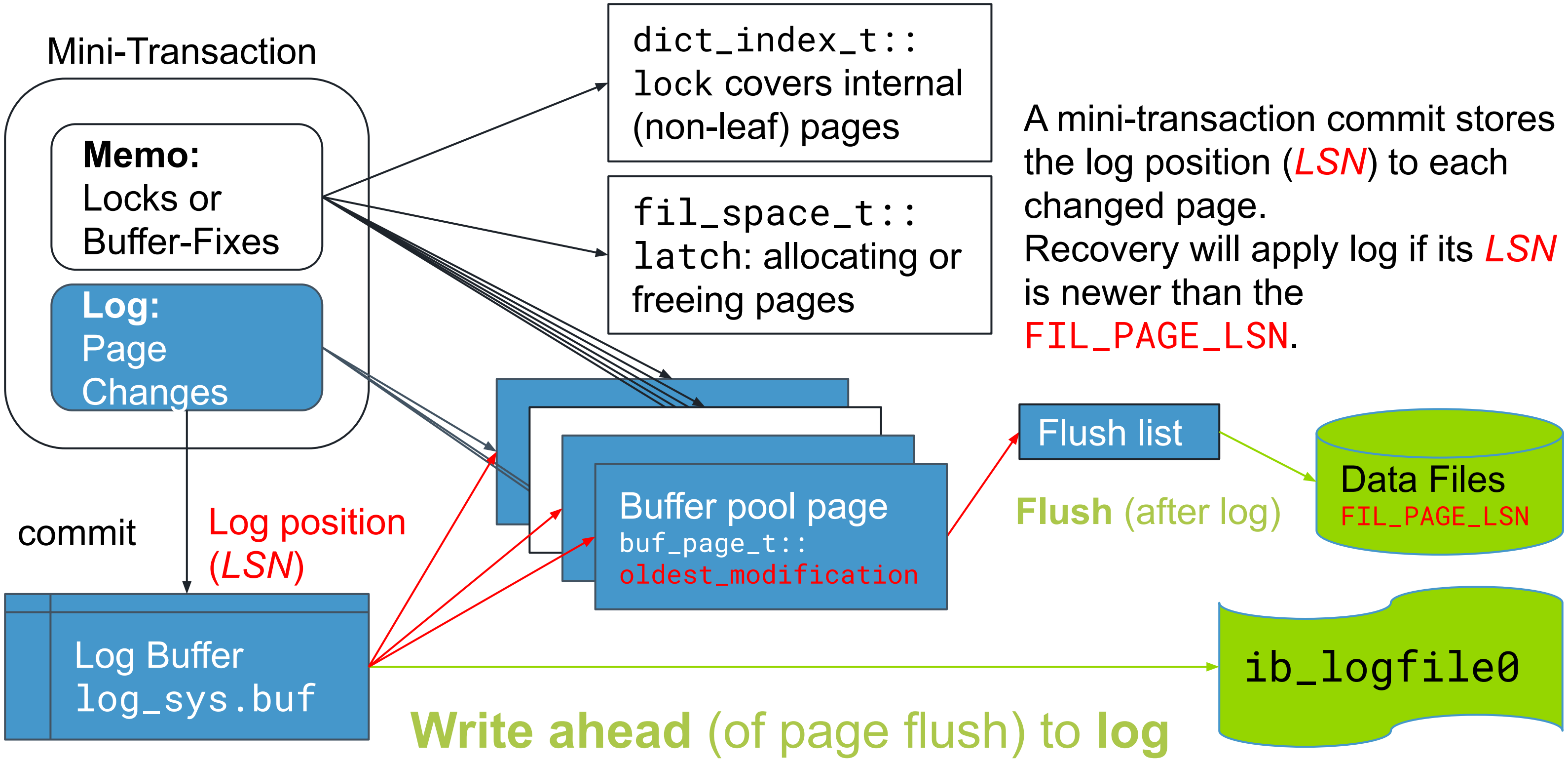
A Storage Engine in a DBMS

- **Transaction:** ACID, MVCC
- **Mini-transaction (+buffer pool):** Atomic changes to multiple files, Durable (with recovery)
- **File system (+cache):** ext4, XFS, ZFS, NTFS, NFS, …
- **Storage:** HDD, SSD, PMEM, …

Write Dependencies and ACID

- A log sequence number (*LSN*) totally orders the output of ***mini-transactions***.
  - The mini-transaction's **atomic** change to one or multiple pages is **durable** if all log up to the end *LSN* has been written.
- Undo log pages implement ACID ***transactions*** (implicit locks, rollback, MVCC)
  - A user transaction `COMMIT` is durable if its undo page change is durable.
- Write-ahead logging: Must **write log before changed pages**, at least up to the `FIL_PAGE_LSN` of the changed page that is about to be written
- Log checkpoint: **write all changed pages older than the checkpoint** *LSN*
- Recovery will have to process log from the checkpoint *LSN* to last durable *LSN*

Atomic Mini-Transactions: Latches and Log


Mini-Transaction
Memo: Locks or Buffer-Fixes
Log: Page Changes
`dict_index_t::lock` covers internal (non-leaf) pages
`fil_space_t::latch`: allocating or freeing pages
commit
Log position (*LSN*)
Log Buffer `log_sys.buf`
Buffer pool page `buf_page_t::oldest_modification`
Flush list
Flush (after log)
Data Files `FIL_PAGE_LSN`
`ib_logfile0`
Write ahead (of page flush) to **log**

A mini-transaction commit stores the log position (*LSN*) to each changed page.
Recovery will apply log if its *LSN* is newer than the `FIL_PAGE_LSN`.

Log Format Changes for More Write Speed and Faster Recovery

Improvements to the Redo Log

- Fewer writes and reads of data pages thanks to new log records
  - We now avoid writes of freed pages after `DROP` (or rebuild) operations.
  - The doublewrite buffer is not used for newly (re)initialized pages.
- An improved group commit reduces contention and improves scalability
- We can **write log without system calls** to persistent memory module
- The physical format is **easy to parse**, thanks to explicitly encoded lengths
  - Optimized memory management on recovery (or `mariabackup --prepare`).

Fewer Writes and Reads of Data Pages

- Page (re)initialization will write an `INIT_PAGE` record
  - **Recovery will avoid reading** the page and reconstruct it based on log records.
  - Page flushing can safely **skip the doublewrite** buffer.
- Freeing a page will write a `FREE_PAGE` record to log, and
  - Freed pages will not be written back, nor read by crash recovery!
  - If scrubbing is enabled, flushing will overwrite freed pages with zeroes.
  - Short-lived pages may avoid being written completely.

Faster InnoDB Redo Log Writes

- Vladislav Vaintroub introduced a `group_commit_lock` for more efficient synchronization of redo log writing and flushing.
    - The goal was to reduce CPU consumption on `log_write_up_to()`, to reduce spurious wakeups, and improve the throughput in write-intensive benchmarks.
    - Benchmarks highlighted that performance is very sensitive to redo log volume. Logical `UNDO_APPEND`, `INSERT`, `DELETE` records are more compact than purely physical log covering changes to many header or pointer fields.
- Sergey Vojtovich and Eugene Kosov wrote an optional `libpmem` interface to improve performance on Intel® Optane™ DC Persistent Memory Module
    - Write to a memory-mapped file, and execute `CLFLUSH` to make it durable.

Improved Backup and Recovery

- Recovery (and `mariabackup`) must parse and buffer all log records that were durably written since the last completed log checkpoint *LSN*
- The new log record format In MariaDB Server 10.5 makes this faster:
    - Explicitly encoded lengths simplify parsing.
    - Simpler memory management: A record can never exceed `innodb_page_size`.
- The recovery of logical `INSERT`, `DELETE` includes validation of page contents
    - Corrupted data can be detected more reliably.

Code Cleanup in MariaDB Server 10.5

Cleanup of Background Threads and Tasks

- InnoDB used to have a single “master thread”
- MySQL 5.5, 5.6, 5.7, MariaDB 10.1: more and more threads for simple tasks
  - Most threads would be idle for much of the time, consuming OS resources.
- MariaDB Server 10.5: Most background *tasks* are run in a *thread pool*
- MariaDB Server 10.5: Purge tasks sort work by `table_id`
  - Reduces look-up of non-existent tables and contention between purge tasks.
  - Acquire MDL, process several records for the same table, release MDL.
- Future work: Scale background activity based on foreground workload

Removal of InnoDB thread throttling

- Back in the MySQL 5.1 times, throughput would collapse when exceeding 8 concurrent connections, due to `kernel_mutex`, `buf_pool->mutex`, …
  - Workaround: `innodb_thread_concurrency`, `innodb_commit_concurrency`
- But, we test MariaDB with ‘insane’ number of connections without seeing a dramatic drop of total throughput
  - MariaDB Server 10.3 significantly reduced `trx_sys.mutex` contention
  - MariaDB Server 10.5 reduced some contention in `buf_pool` and `dict_sys`
  - MariaDB Server 10.5.5 removes the throttling code that has become useless, and deprecating and ignoring the parameters. MariaDB Server 10.6 will remove them.

More Predictable Change Buffer

- InnoDB aims to avoid read-before-write when it needs to modify a secondary index B-tree leaf page that is not in the buffer pool.
    - Insert, delete-mark and purge (delete) operations can be written to a *change buffer* in the system tablespace, to be merged to the final location later.
- MariaDB Server 10.5 no longer merges buffered changes in the background
    - Change buffer merges can no longer cause hard-to-predict I/O spikes.
    - A corrupted index can only cause trouble when it is being accessed.
- This was joint work with Thirunarayanan Balathandayuthapani
- Future work: Simpler, logical format; use it also on `ROLLBACK`

InnoDB Data Dictionary Cleanup

- Thirunarayanan Balathandayuthapani extended the use of metadata locks (MDL)
  - Background operations must ensure that the table not be dropped.
  - This used to be covered by `dict_operation_lock` (or `dict_sys.latch`), which covers any InnoDB table!
  - It suffices to acquire MDL on the table name.
- In a future release, we hope to remove `dict_sys.latch` altogether, and to replace internal transactional table locks with MDL.

Some Changes to the InnoDB Buffer Pool

- The InnoDB buffer pool is a page cache (user tables, indexes, or undo logs)
- In 2006, MySQL 5.0.30 introduced `buf_block_t::mutex` to reduce some contention on `buf_pool->mutex`
- In 2010, MySQL 5.5.7 partitioned the buffer pool by hash on page identifier
- In 2020, MariaDB Server 10.5 reverted back to a single buffer pool
    - Some unnecessarily global data was removed (e.g., `buf_page_t::flush_type`).
    - Some remaining contention was addressed by making more use of C++11 `std::atomic` in data structures, and `buf_block_t::mutex` was removed.
    - Simpler `buf_pool.page_hash` with cache-friendly latching improves concurrency.

MariaDB

The Way Ahead

Ideas for Faster Writes and Startup

- Asynchronous `COMMIT`: send OK packet on write completion
  - Execute next statement(s) without waiting for `COMMIT`. (Idea: Vladislav Vaintroub)
- Complete the InnoDB recovery in the background, while allowing connections
  - Basically, just remove a special ‘recovery mode’ from page flushing.
  - The rollback of recovered incomplete transactions was always performed in the background.
  - We could also allow read-only startup on a data directory when recovery is needed (so that you can look what is inside, without modifying anything).

Limitations in Current File Formats

- Secondary indexes are missing a per-record transaction ID
  - MVCC, purge, and checks for implicit locks could be much simpler and faster.
- `DB_ROLL_PTR` and the undo log format limit us to 128 rollback segments
  - Cannot possibly scale beyond 128 concurrently starting write transactions.
- Redo log: 512-byte block size causes copying and mutex contention
  - Block framing forces log records to be split or padded.
  - A mutex must be held while copying, padding, encrypting, computing checksums.

Flash-Friendly Log Format

- Write information about checkpoints and file operations into separate file
  - That file can be written to without affecting the *LSN*.
  - Instead of writing `.delta` files, `mariabackup` could append to this file!
  - No need for `mariabackup --prepare` before server startup!
- For the circular file, allow arbitrary block size (e.g., 1 to 16,384 bytes)
  - Write special ‘ignore next N bytes’ records when writing an incomplete block, observing the block size of the underlying storage. Avoids initializing pad bytes!
  - Encrypt records and compute checksums before acquiring mutex for copying!
  - `mtr_t::commit()` could copy directly to a memory-mapped file?

Conclusion

- MariaDB Server 10.5 makes better use of the available hardware resources
  - Useless or harmful parameters were removed, others made dynamic.
  - Performance and scalability were improved for various types of workloads.
- **Performance** must never come at the cost of **reliability** or **compatibility**
  - Our stress tests are based on some formal methods and state-of-the-art tools.
  - We also test in-place upgrades of existing data files.
- Watch out for more improvements in future releases

Thoughts on Testing

Concurrency is Hard

- Global locks around entire subsystems will easily guarantee correctness
  - It is easy to read and write sequential (single-threaded) algorithms.
  - But, a coarse lock or mutex will destroy any concurrency!
  - Multi-core CPUs demand fine-grained locking and multi-threaded execution.
- We need a **machine-readable specification** to catch errors
  - Assertions in debug builds
  - AddressSanitizer (ASAN) and MemorySanitizer (MSAN) with custom instrumentation
- Regression test (`mtr`) on CI systems; manual testing with random input

Repeatable Execution Traces of Failures

- https://rr-project.org by the Mozilla Foundation records an execution trace that can be used for deterministic debugging with `rr replay`
  - Breakpoints and watchpoints will work and can catch data races!
  - Much smaller than core dumps, even though all intermediate states are included.
- Even the most nondeterministic bugs become tractable and fixable
  - Recovery bugs: need a trace of the killed server and the recovering server.
  - We recently found and fixed several elusive 10-year-old bugs.
- Best of all, this can be combined with ASAN and Random Query Generator

Performance Testing

- Performance regressions can be hard to catch due to huge variation of types of workload and hardware
  - Read-only vs. read-mostly vs. write-heavy
  - Small buffer pool vs. large buffer pool (in-memory workload)
  - Different storage characteristics: HDD, SSD, NAS, PMEM
- MariaDB Server 10.5 generally improves performance
  - We have identified some bottlenecks.
  - This is work in progress.