A Lock-Free Cache-Aware Pipeline for High Throughput Joins

SIGMOD 2025 Programming Contest

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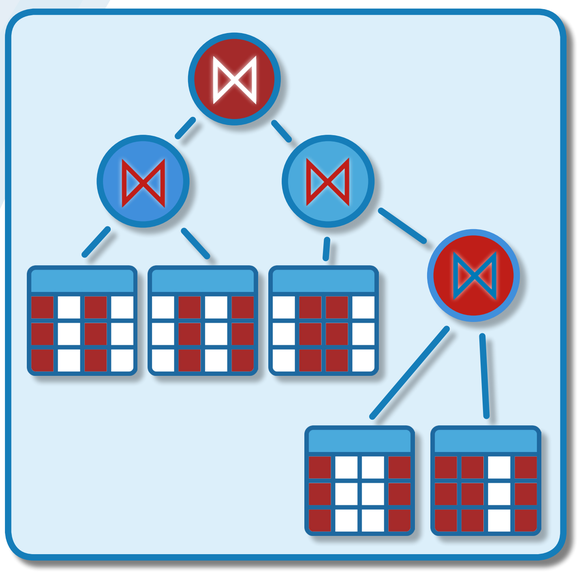
Summary

- **A cache-efficient, multi-threaded, lock-free join pipeline implementation utilizing a memory-efficient hash table optimized for joins.**
- **630x speedup over the reference solution!**

Task Overview

- Develop an efficient, in-memory join pipeline executor delivering high performance across a wide range of hardware architectures and configurations.
- Evaluated on anonymized data and queries sampled from the J.O.B. (IMDB Dataset).
- Input Data provided **in memory** as column-store, paginated tables.
- Optimized Join Plan provided by PostgreSQL.
- Joins only on Integers, with Doubles and Strings also appearing in the results.

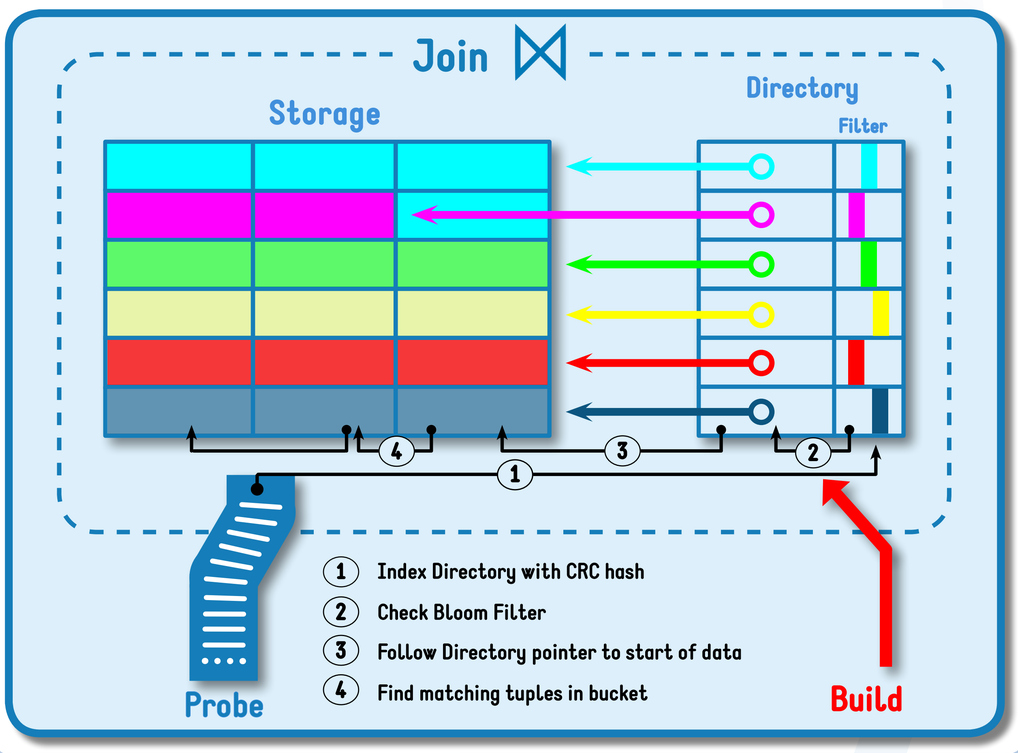


1. Loading and Preprocessing

- Classify columns as join fields, output-only attributes or unused.
- Vast majority of pagenated columns have no null values and can be accessed in place in constant time with a single division.
- Serial access can eliminate the division from the hot path.
- Copy remaining useful columns in contiguous arrays to enable random access.
- **Lazily** copy Strings only when needed in the result.
- **Lazy-load** output-only columns in the background to start join execution early.
- 99+% of columns are never loaded or get processed in the background, approximating a **zero-copy** solution!

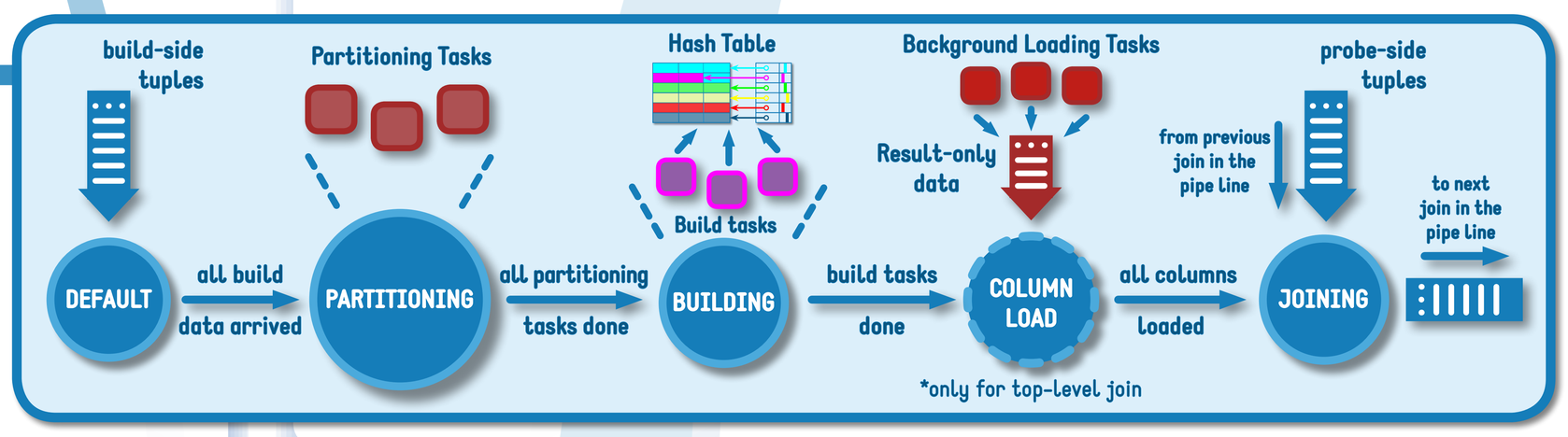
2. Unchained Hash Table

- Hash Table optimized for joins[1].
- Distinct phases for building and probing.
- Partition data among workers to parallelize building.
- All the entries of the table lie in a single large **contiguous** block, massively improving cache locality.
- Use of *CRC* hardware instruction for quick hashing with adequate collision resistance.
- **Bloom Filter** in the lower 16-bits of the directory pointer.



3. Join Data Flow & Materialization

- **Late Materialization** to eliminate unnecessary data copies and reduce cache pollution.
- Each join materializes the column needed for the next join in the pipeline to improve memory access patterns.
- Joins at the root of the tree materialize the final output.



4. Parallel Data Processing

- Priority-Based Task Queue that dynamically assigns tasks on available hardware threads.
- Prioritize tasks that enable processing of interdependent joins.
- *Morsel-driven Parallelism*[2] : break down heavier jobs into **self-contained tasks**, each responsible for independently processing a smaller chunk of the data.
- **Lock-free** chunk feeder mechanism to efficiently handle *skew*: tasks that finish early can dynamically "**steal**" pages from siblings to balance workload.
- Each task **independently** produces paginated results and deposits them in dedicated **per-worker slots** without any synchronization cost.
- Dynamic Job Batching for very small tasks to reduce overhead.
- Properly align concurrently accessed data structures to eliminate false sharing.

5. Pipeline

- Chunk and immediately forward intermediate results so the next join can also progress while the data are still hot in the cache.
- Schedule further processing of the data to the same hardware thread that produced it to optimize cache efficiency.
- **Lock-free** pipeline implemented with atomic instructions to minimize synchronization overhead and enable finer granularity tasks.
- Every completed task executes part of the pipeline control logic - appropriately advancing pipeline state and kickstarting tasks for the next stages or joins.

Acknowledgements & References

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[1] Birler, Altan, et al. "Simple, Efficient, and Robust Hash Tables for Join Processing." *Proceedings of the 20th international workshop on data management on new hardware*. 2024.

[2] Leis, Viktor, et al. "Morsel-Driven Parallelism: a NUMA-Aware Query Evaluation Framework for the Many-Core Age." *Proceedings of the 2014 ACM SIGMOD international conference on Management of data.* 2014.

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