

TIMESCALE ARCHITECTURE FOR REAL-TIME ANALYTICS

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Abstract

Timescale provides a powerful application database for real-time analytics on time-series data. It integrates seamlessly with the PostgreSQL ecosystem and enhances it with automatic time-based partitioning, hybrid row-columnar storage, and vectorized execution—enabling high-ingest performance, sub-second queries, and full SQL support at scale.

By making use of incrementally updated materialized views and advanced analytical functions, Timescale reduces compute overhead and improves query efficiency. Developers can continue using familiar SQL workflows and tools, while benefiting from a database purpose-built for fast, scalable analytics.

Timescale combines TimescaleDB, an open-source PostgreSQL extension, and Timescale Cloud, a cloud-native database service.

This document outlines the architectural choices and optimizations that power Timescale’s performance and scalability while preserving PostgreSQL’s reliability and transactional guarantees.

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1 INTRODUCTION

1.1 What Is Real-Time Analytics?

Real-time analytics enables applications to process and query data as it is generated and as it accumulates, delivering immediate and ongoing insights for decision-making. Unlike traditional analytics, which relies on batch processing and delayed reporting, real-time analytics supports *both* instant queries on fresh data and fast exploration of historical trends—powering applications with sub-second query performance across vast, continuously growing datasets.

Many modern applications depend on real-time analytics to drive critical functionality:

- **IoT monitoring systems** track sensor data over time, identifying long-term performance patterns while still surfacing anomalies as they arise. This allows businesses to optimize maintenance schedules, reduce costs, and improve reliability.
- **Financial and business intelligence platforms** analyze both current and historical data to detect trends, assess risk, and uncover opportunities—from tracking stock performance over a day, week, or year to identifying spending patterns across millions of transactions.
- **Interactive customer dashboards** empower users to explore live and historical data in a seamless experience—whether it’s a SaaS product providing real-time analytics on business operations, a media platform analyzing content engagement, or an e-commerce site surfacing personalized recommendations based on recent and past behavior.

Real-time analytics isn’t just about reacting to the latest data, although that is critically important. It’s also about delivering fast, interactive, and scalable insights across all your data, enabling better decision-making and richer user experiences. Unlike traditional ad-hoc analytics used by analysts, real-time analytics powers applications—driving dynamic dashboards, automated decisions, and user-facing insights at scale.

To achieve this, real-time analytics systems must meet several key requirements:

- **Low-latency queries** ensure sub-second response times even under high load, enabling fast insights for dashboards, monitoring, and alerting.
- **Low-latency ingest** minimizes the lag between when data is created and when it becomes available for analysis, ensuring fresh and accurate insights.
- **Data mutability** allows for efficient updates, corrections, and backfills, ensuring analytics reflect the most accurate state of the data.
- **Concurrency and scalability** enable systems to handle high query volumes and growing workloads without degradation in performance.
- **Seamless access to both recent and historical data** ensures fast queries across time, whether analyzing live, streaming data, or running deep historical queries on days or months of information.
- **Query flexibility** provides full SQL support, allowing for complex queries with joins, filters, aggregations, and analytical functions.

1.2 Timescale: Real-Time Analytics from PostgreSQL

Timescale is a high-performance database that brings real-time analytics to applications. It combines fast queries, high ingest performance, and full SQL support—all while ensuring scalability and reliability. Timescale extends PostgreSQL with the TimescaleDB extension. It enables sub-second queries on vast amounts of incoming data while providing optimizations designed for continuously updating datasets.

Timescale achieves this through the following optimizations:

- **Efficient data partitioning:** automatically and transparently partitioning data into chunks, ensuring fast queries, minimal indexing overhead, and seamless scalability
- **Row-columnar storage:** providing the flexibility of a row store for transactions and the performance of a column store for analytics
- **Optimized query execution:** using techniques like chunk and batch exclusion, columnar storage, and vectorized execution to minimize latency
- **Continuous aggregates:** precomputing analytical results for fast insights without expensive reprocessing
- **Cloud-native operation:** compute/compute separation, elastic usage-based storage, horizontal scale out, data tiering to object storage
- **Operational simplicity:** offering high availability, connection pooling, and automated backups for reliable and scalable real-time applications

With Timescale, developers can build low-latency, high-concurrency applications that seamlessly handle streaming data, historical queries, and real-time analytics while leveraging the familiarity and power of PostgreSQL.

2 DATA MODEL

Today’s applications demand a database that can handle real-time analytics and transactional queries without sacrificing speed, flexibility, or SQL compatibility (including joins between tables). Timescale achieves this with **hypertables**, which provide an automatic partitioning engine, and **hypercore**, a hybrid row-columnar storage engine designed to deliver high-performance queries and efficient compression (up to 95

2.1 Efficient Data Partitioning

Timescale provides hypertables, a table abstraction that automatically partitions data into chunks in real time (using time stamps or incrementing IDs) to ensure fast queries and predictable performance as datasets grow. Unlike traditional relational databases that require manual partitioning, hypertables automate all aspects of partition management, keeping locking minimal even under high ingest load.

At ingest time, hypertables ensure that PostgreSQL can deal with a constant stream of data without suffering from table bloat and index degradation by automatically partitioning data across time. Because each chunk is ordered by time and has its own indexes and storage, writes are usually isolated to small, recent chunks—keeping index sizes small, improving cache locality, and reducing the overhead of vacuum and background maintenance operations. This localized write pattern minimizes write amplification and ensures consistently high ingest performance, even as total data volume grows.

At query time, hypertables efficiently exclude irrelevant chunks from the execution plan when the partitioning column is used in a **WHERE** clause. This architecture ensures fast query execution, avoiding the gradual slowdowns that affect non-partitioned tables as they accumulate millions of rows. Chunk-local indexes keep indexing overhead minimal, ensuring index operations scans remain efficient regardless of dataset size.

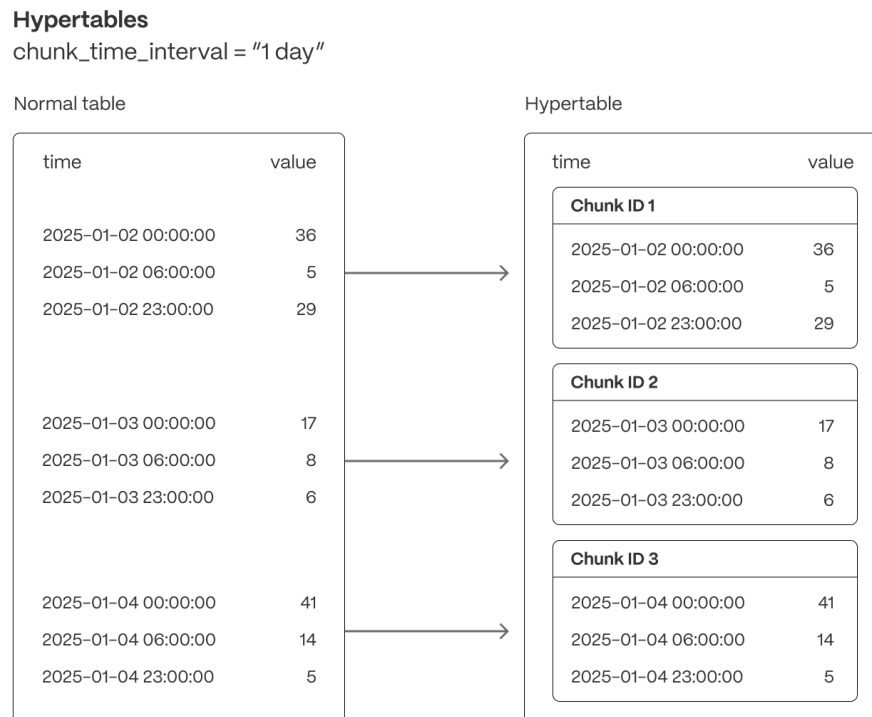


Figure 1: Hypertable creation

Hypertables are the foundation for all of TimescaleDB’s real-time analytics capabilities. They enable

seamless data ingestion, high-throughput writes, optimized query execution, and chunk-based lifecycle management—including automated data retention (drop a chunk) and data tiering (move a chunk to object storage).

2.2 Row-Columnar Storage

Traditional databases force a trade-off between fast inserts (row-based storage) and efficient analytics (columnar storage). Hypercore eliminates this trade-off, allowing real-time analytics without sacrificing transactional capabilities.

Hypercore dynamically stores data in the most efficient format for its lifecycle:

- **Row-based storage for recent data:** The most recent chunk (and possibly more) is always stored in the rowstore, ensuring fast inserts, updates, and low-latency single record queries. Additionally, row-based storage is used as a writethrough for inserts and updates to columnar storage.
- **Columnar storage for analytical performance:** Chunks are automatically compressed into the columnstore, optimizing storage efficiency and accelerating analytical queries.

Unlike traditional columnar databases, hypercore allows data to be inserted or modified at any stage, making it a flexible solution for both high-ingest transactional workloads and real-time analytics—within a single database.

2.3 Columnar Storage Layout

TimescaleDB’s columnar storage layout optimizes analytical query performance by structuring data efficiently on disk, reducing scan times, and maximizing compression rates. Unlike traditional row-based storage, where data is stored sequentially by row, columnar storage organizes and compresses data by column, allowing queries to retrieve only the necessary fields in batches rather than scanning entire rows. But unlike many column store implementations, Timescale’s columnstore supports full mutability—inserts, upserts, updates, and deletes, even at the individual record level—with transactional guarantees. Data is also immediately visible to queries as soon as it is written.

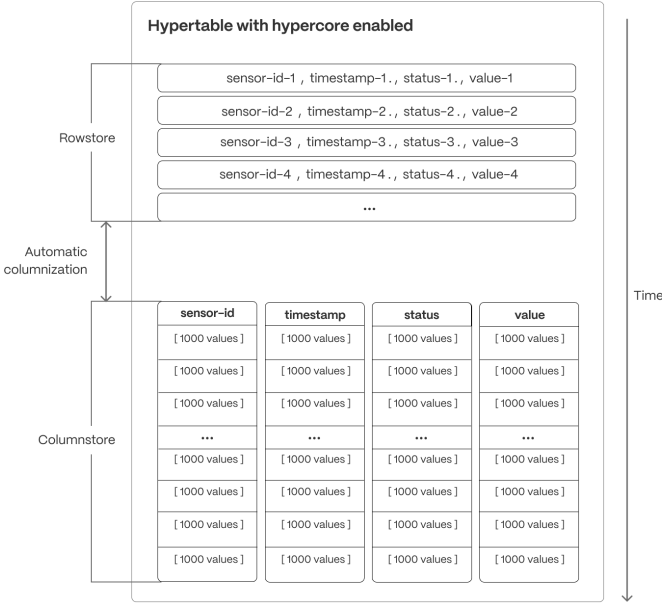


Figure 2: Hypertable with hypercore enabled

2.3.1 Columnar batches

TimescaleDB uses columnar collocation and columnar compression within row-based storage to optimize analytical query performance while maintaining full PostgreSQL compatibility. This approach ensures efficient storage, high compression ratios, and rapid query execution.

A rowstore chunk is converted to a columnstore chunk by successfully grouping together sets of rows (typically up to 1000) into a single batch, then converting the batch into columnar form.

Each compressed batch does the following:

- Encapsulates columnar data in compressed arrays of up to 1,000 values per column, stored as a single entry in the underlying compressed table
- Uses a column-major format within the batch, enabling efficient scans by co-locating values of the same column and allowing the selection of individual columns without reading the entire batch
- Applies advanced compression techniques at the column level, including run-length encoding, delta encoding, and Gorilla compression, to significantly reduce storage footprint (by up to 95%) and improve I/O performance.

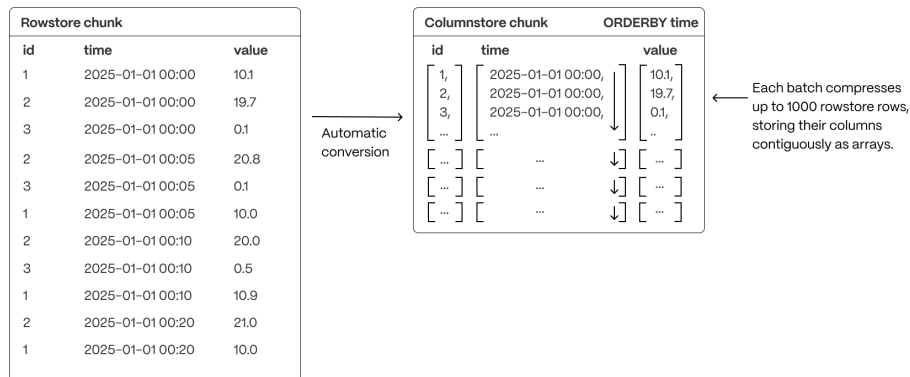


Figure 3: Conversion of rowstore to columnstore

While the chunk interval of rowstore and columnstore batches usually remains the same, Timescale can also combine columnstore batches so they use a different chunk interval.

This architecture provides the benefits of columnar storage—optimized scans, reduced disk I/O, and improved analytical performance—while seamlessly integrating with PostgreSQL’s row-based execution model.

2.3.2 Segmenting and ordering data

To optimize query performance, TimescaleDB allows explicit control over how data is physically organized within columnar storage. By structuring data effectively, queries can minimize disk reads and execute more efficiently, using vectorized execution for parallel batch processing where possible.

- **Group related data together to improve scan efficiency.** Organizing rows into logical segments ensures that queries filtering by a specific value only scan relevant data sections. For example, in the above, querying for a specific ID is particularly fast. (*Implemented with SEGMENTBY.*)
- **Sort data within segments to accelerate range queries.** Defining a consistent order reduces the need for post-query sorting, making time-based queries and range scans more efficient. (*Implemented with ORDERBY.*)

- **Reduce disk reads and maximize vectorized execution.** A well-structured storage layout enables efficient batch processing (Single Instruction, Multiple Data, or SIMD vectorization) and parallel execution, optimizing query performance.

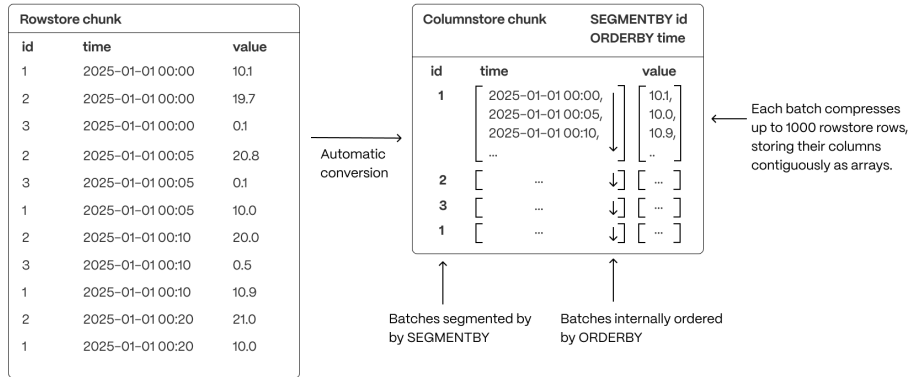


Figure 4: Conversion of rowstore to columnstore with segmentation

By combining segmentation and ordering, Timescale ensures that columnar queries are not only fast but also resource-efficient, enabling high-performance real-time analytics.

2.4 Data Mutability

Traditional databases force a trade-off between fast updates and efficient analytics. Fully immutable storage is impractical in real-world applications, where data needs to change. Asynchronous mutability—where updates only become visible after batch processing—introduces delays that break real-time workflows. In-place mutability, while theoretically ideal, is prohibitively slow in columnar storage, requiring costly decompression, segmentation, ordering, and recompression cycles.

Hypercore navigates these trade-offs with a hybrid approach that enables immediate updates without modifying compressed columnstore data in place. By staging changes in an interim rowstore chunk, hypercore allows updates and deletes to happen efficiently while preserving the analytical performance of columnar storage.

2.4.1 Real-time writes without delays

All new data which is destined for a columnstore chunk is first written to an interim rowstore chunk, ensuring high-speed ingestion and immediate queryability. Unlike fully columnar systems that require ingestion to go through compression pipelines, hypercore allows fresh data to remain in a fast row-based structure before being later compressed into columnar format in ordered batches as normal.

Queries transparently access both the rowstore and columnstore chunks, meaning applications always see the latest data instantly, regardless of its storage format.

2.4.2 Efficient updates and deletes without performance penalties

When modifying or deleting existing data, hypercore avoids the inefficiencies of both asynchronous updates and in-place modifications. Instead of modifying compressed storage directly, affected batches are decompressed and staged in the interim rowstore chunk, where changes are applied immediately.

These modified batches remain in row storage until they are recompressed and reintegrated into the columnstore (which happens automatically via a background process). This approach ensures updates are immediately visible, but without the expensive overhead of decompressing and rewriting entire chunks. This approach avoids:

- The rigidity of immutable storage, which requires workarounds like versioning or copy-on-write strategies
- The delays of asynchronous updates, where modified data is only visible after batch processing
- The performance hit of in-place mutability, which makes compressed storage prohibitively slow for frequent updates
- The restrictions some databases have on not altering the segmentation or ordering keys

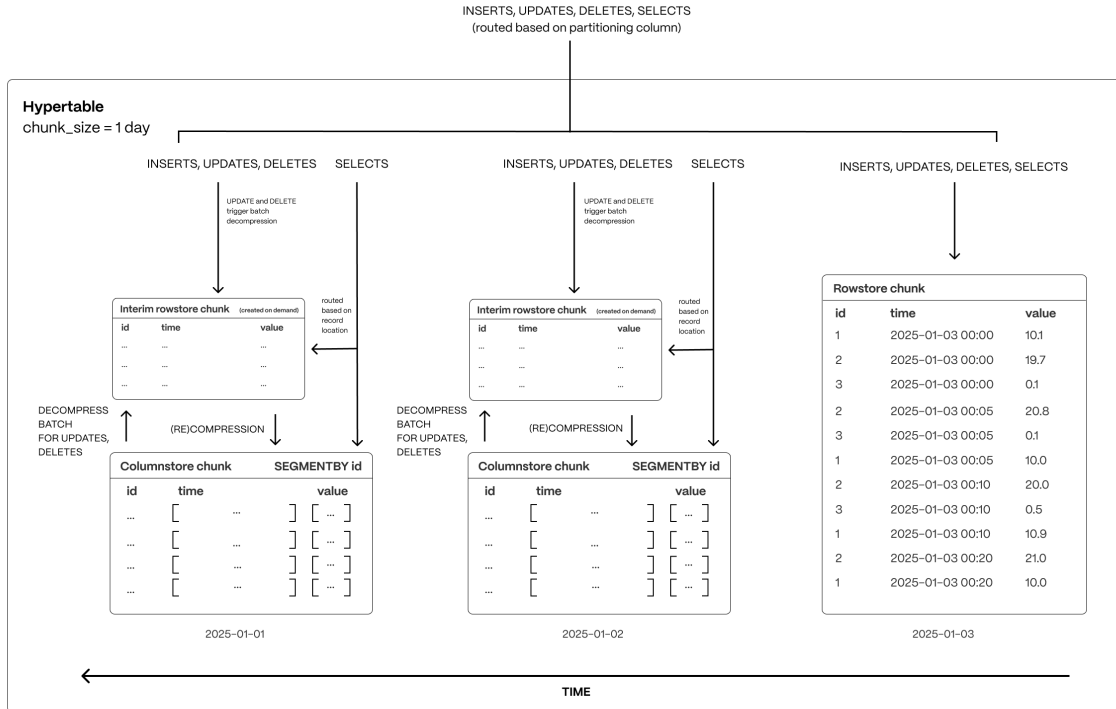


Figure 5: Data mutability across rowstore and columnstore

3 QUERY OPTIMIZATIONS

Real-time analytics isn't just about raw speed—it's about executing queries efficiently, reducing unnecessary work, and maximizing performance. Timescale optimizes every step of the query lifecycle to ensure that queries scan only what's necessary, make use of data locality, and execute in parallel for sub-second response times over large datasets.

3.1 Skip unnecessary data

Timescale minimizes the amount of data a query touches, reducing I/O and improving execution speed:

3.1.1 Primary partition exclusion (row and columnar)

Queries automatically skip irrelevant partitions (chunks) based on the primary partitioning key (usually a timestamp), ensuring they only scan relevant data.

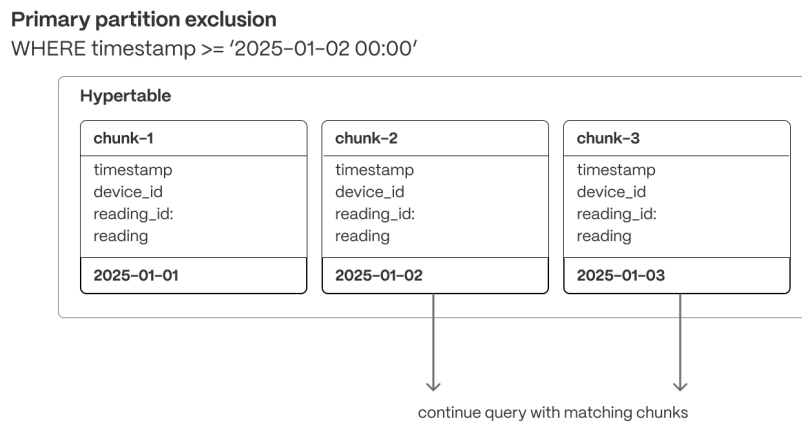


Figure 6: Primary partition exclusion

3.1.2 Secondary partition exclusion (columnar)

Min/max metadata allows queries filtering on correlated dimensions (e.g., `order_id` or secondary timestamps) to exclude chunks that don't contain relevant data.

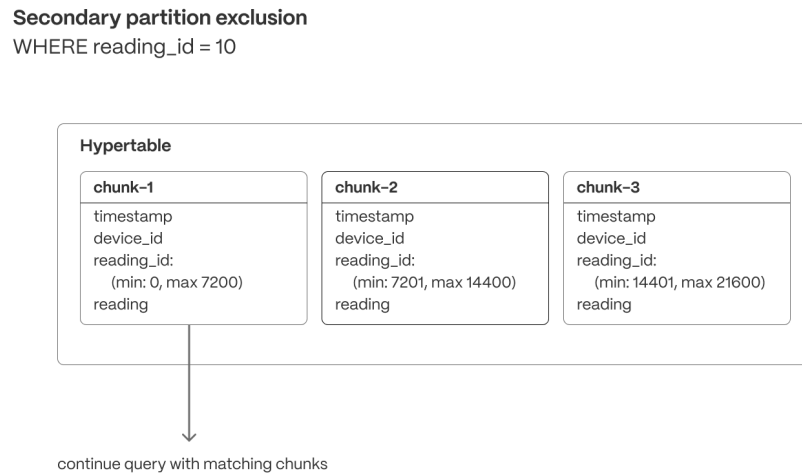


Figure 7: Secondary partition exclusion

3.1.3 PostgreSQL indexes (row and columnar)

Unlike many databases, Timescale supports standard PostgreSQL indexes on columnstore data (B-tree and hash currently, when using the hypercore table access method), allowing queries to efficiently locate specific values within both row-based and compressed columnar storage. These indexes enable fast lookups, range queries, and filtering operations that further reduce unnecessary data scans.

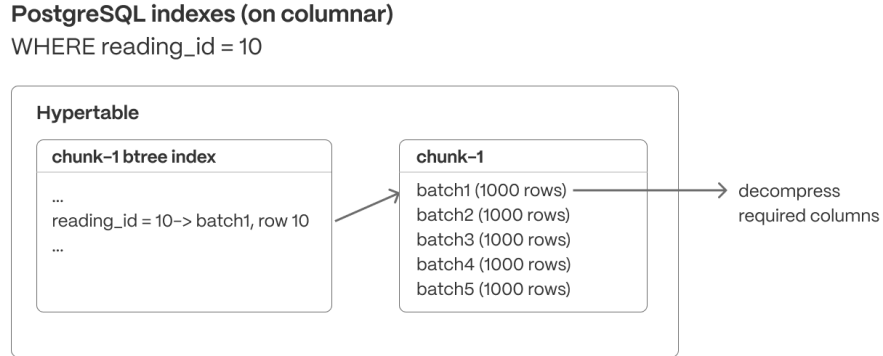


Figure 8: PostgreSQL indexes on columnstore

3.1.4 Batch-level filtering (columnar)

Within each chunk, compressed columnar batches are organized using `SEGMENTBY` keys and ordered by `ORDERBY` columns. Indexes and min/max metadata can be used to quickly exclude batches that don't match the query criteria.

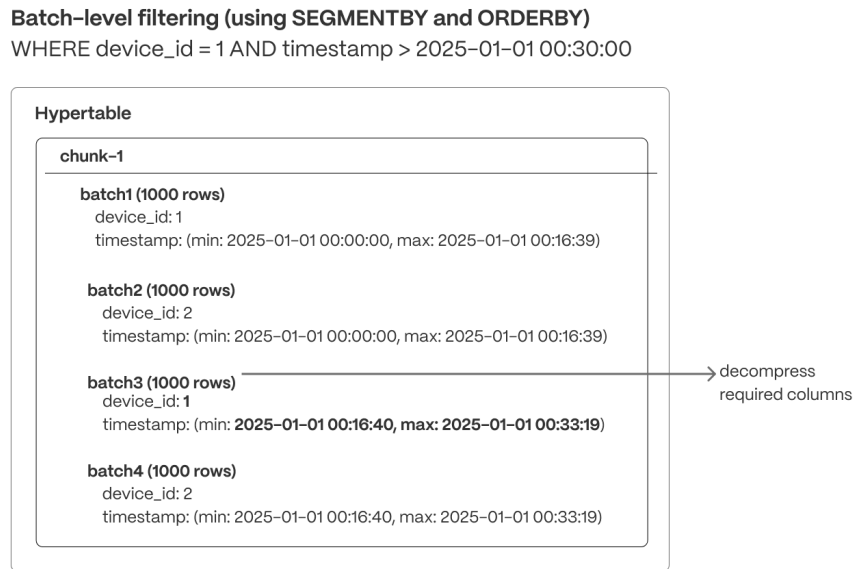


Figure 9: Batch skipping indexes

3.2 Maximize locality

Organizing data for efficient access ensures queries are read in the most optimal order, reducing unnecessary random reads and reducing scans of unneeded data.

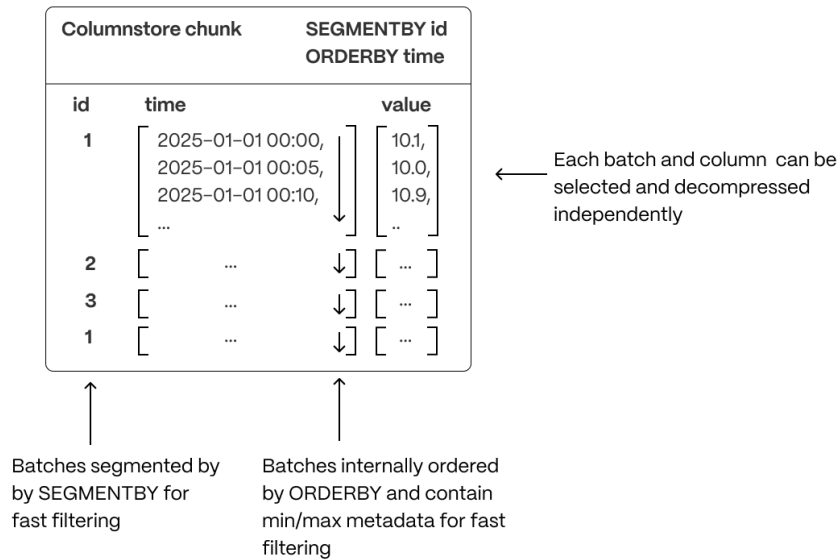


Figure 10: Segmentby and orderby for data locality

- **Segmentation:** Columnar batches are grouped using `SEGMENTBY` to keep related data together, improving scan efficiency.
- **Ordering:** Data within each batch is physically sorted using `ORDERBY`, increasing scan efficiency (and reducing I/O operations), enabling efficient range queries, and minimizing post-query sorting.
- **Column selection:** Queries read only the necessary columns, reducing disk I/O, decompression overhead, and memory usage.

3.3 Parallelize execution

Once a query is scanning only the required columnar data in the optimal order, Timescale is able to maximize performance through parallel execution. As well as using multiple workers, Timescale accelerates columnstore query execution by using Single Instruction, Multiple Data (SIMD) vectorization, allowing modern CPUs to process multiple data points in parallel.

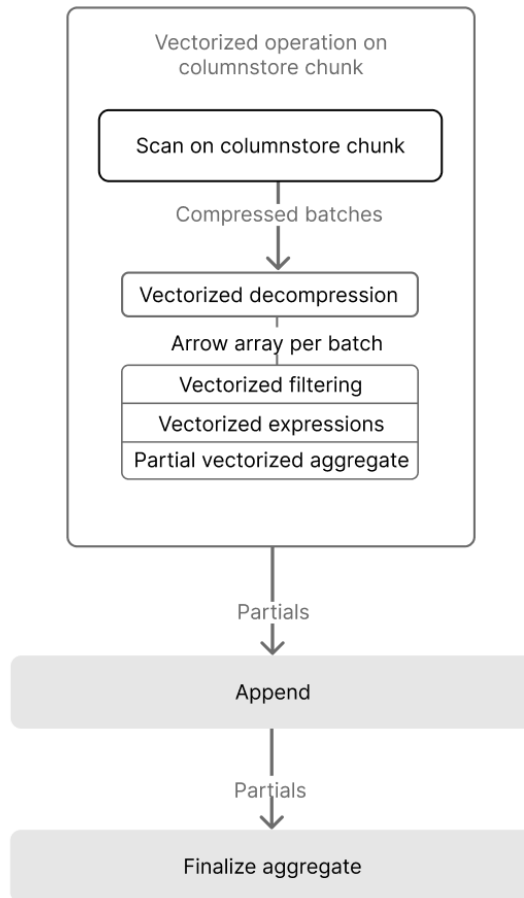


Figure 11: Vectorized SIMD execution over columnstore

The Timescale implementation of SIMD vectorization currently allows:

- **Vectorized decompression**, which efficiently restores compressed data into a usable form for analysis.
- **Vectorized filtering**, which rapidly applies filter conditions across data sets.
- **Vectorized aggregation**, which performs aggregate calculations, such as sum or average, across multiple data points concurrently.

4 ACCELERATING QUERIES WITH CONTINUOUS AGGREGATES

Aggregating large datasets in real time can be expensive, requiring repeated scans and calculations that strain CPU and I/O. While some databases attempt to brute-force these queries at runtime, compute and I/O are always finite resources—leading to high latency, unpredictable performance, and growing infrastructure costs as data volume increases.

Continuous aggregates, Timescale’s implementation of incrementally updated materialized views, solve this by shifting computation from every query run to a single, asynchronous step after data is ingested. Only the time buckets that receive new or modified data are updated, and queries read precomputed results instead of scanning raw data—dramatically improving performance and efficiency.

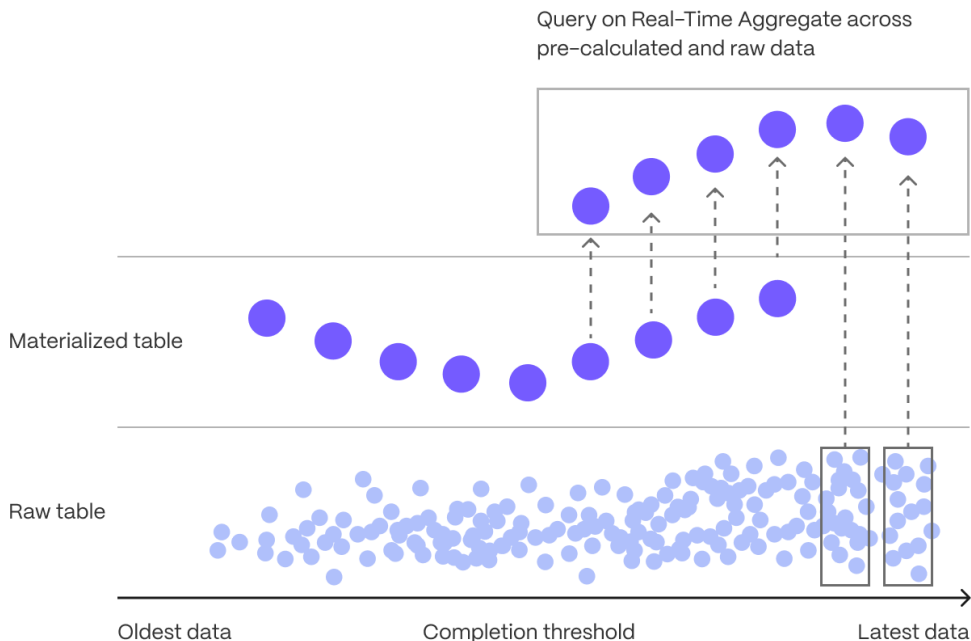


Figure 12: Selecting data from a continuous aggregate

When you know the types of queries you’ll need ahead of time, continuous aggregates allow you to pre-aggregate data along meaningful time intervals—such as per-minute, hourly, or daily summaries—delivering instant results without on-the-fly computation.

Continuous aggregates also avoid the time-consuming and error-prone process of maintaining manual rollups, while continuing to offer data mutability to support efficient updates, corrections, and back-fills. Whenever new data is inserted or modified in chunks which have been materialized, Timescale stores invalidation records reflecting that these results are stale and need to be recomputed. Then, an asynchronous process re-computes regions that include invalidated data, and updates the materialized results. Timescale tracks the lineage and dependencies between continuous aggregates and their underlying data, to ensure the continuous aggregates are regularly kept up-to-date. This happens in a resource-efficient manner, and where multiple invalidations can be coalesced into a single refresh (as opposed to refreshing any dependencies at write time, such as via a trigger-based approach).

Continuous aggregates themselves are stored in hypertables, and they can be converted to columnar storage for compression, and raw data can be dropped, reducing storage footprint and processing cost. Continuous aggregates also support hierarchical rollups (e.g., hourly to daily to monthly) and real-time

mode, which merges precomputed results with the latest ingested data to ensure accurate, up-to-date analytics.

This architecture enables scalable, low-latency analytics while keeping resource usage predictable—ideal for dashboards, monitoring systems, and any workload with known query patterns.

4.1 Hyperfunctions for Real-time Analytics

Real-time analytics requires more than basic SQL functions—efficient computation is essential as datasets grow in size and complexity. Hyperfunctions, available through the `timescaledb_toolkit` extension, provide high-performance, SQL-native functions tailored for time-series analysis. These include advanced tools for gap-filling, percentile estimation, time-weighted averages, counter correction, and state tracking, among others.

A key innovation of hyperfunctions is their support for partial aggregation, which allows Timescale to store intermediate computational states rather than just final results. These partials can later be merged to compute rollups efficiently, avoiding expensive reprocessing of raw data and reducing compute overhead. This is especially effective when combined with continuous aggregates.

Consider a real-world example: monitoring request latencies across thousands of application instances. You might want to compute p95 latency per minute, then roll that up into hourly and daily percentiles for dashboards or alerts. With traditional SQL, calculating percentiles requires a full scan and sort of all underlying data—making multi-level rollups computationally expensive.

With Timescale, you can use the `percentile_agg` hyperfunction in a continuous aggregate to compute and store a partial aggregation state for each minute. This state efficiently summarizes the distribution of latencies for that time bucket, without storing or sorting all individual values. Later, to produce an hourly or daily percentile, you simply combine the stored partials—no need to reprocess the raw latency values.

This approach provides a scalable, efficient solution for percentile-based analytics. By combining hyperfunctions with continuous aggregates, Timescale enables real-time systems to deliver fast, resource-efficient insights across high-ingest, high-resolution datasets—without sacrificing accuracy or flexibility.

5 CLOUD-NATIVE ARCHITECTURE

Real-time analytics requires a scalable, high-performance, and cost-efficient database that can handle high-ingest rates and low-latency queries without overprovisioning. Timescale Cloud is designed for elasticity, enabling independent scaling of storage and compute, workload isolation, and intelligent data tiering.

5.1 Independent Storage and Compute Scaling

Real-time applications generate continuous data streams while requiring instant querying of both fresh and historical data. Traditional databases force users to pre-provision fixed storage, leading to unnecessary costs or unexpected limits. Timescale Cloud eliminates this constraint by dynamically scaling storage based on actual usage:

- Storage expands and contracts automatically as data is added or deleted, avoiding manual intervention.
- Usage-based billing ensures costs align with actual storage consumption, eliminating large upfront allocations.
- Compute can be scaled independently to optimize query execution, ensuring fast analytics across both recent and historical data.

With this architecture, databases grow alongside data streams, enabling seamless access to real-time and historical insights while efficiently managing storage costs.

5.2 Workload Isolation for Real-Time Performance

Balancing high-ingest rates and low-latency analytical queries on the same system can create contention, slowing down performance. Timescale Cloud mitigates this by allowing read and write workloads to scale independently:

- The primary database efficiently handles both ingestion and real-time rollups without disruption.
- Read replicas scale query performance separately, ensuring fast analytics even under heavy workloads.

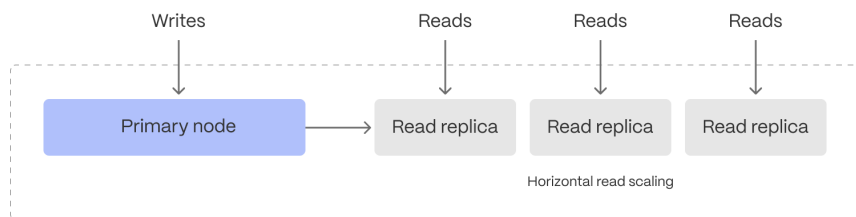


Figure 13: Compute compute separation with read replicas

This separation ensures that frequent queries on fresh data don't interfere with ingestion, making it easier to support live monitoring, anomaly detection, interactive dashboards, and alerting systems.

5.3 Intelligent Data Tiering for Cost-Efficient Real-Time Analytics

Not all real-time data is equally valuable—recent data is queried constantly, while older data is accessed less frequently. Timescale Cloud can be configured to automatically tier data to cheaper bottomless object storage, ensuring that hot data remains instantly accessible, while historical data is still available.

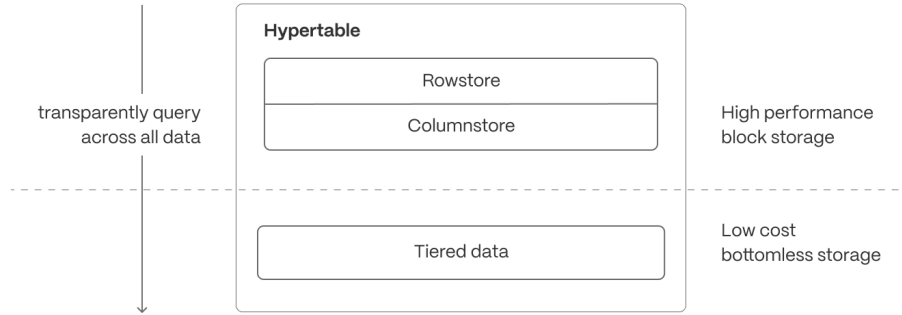


Figure 14: Data tiering to object storage

- **Recent, high-velocity data** stays in high-performance storage for ultra-fast queries.
- **Older, less frequently accessed data** is automatically moved to cost-efficient object storage but remains queryable and available for building continuous aggregates.

While many systems support this concept of data cooling, Timescale ensures that the data can still be queried from the same hypertable regardless of its current location. For real-time analytics, this means applications can analyze live data streams without worrying about storage constraints, while still maintaining access to long-term trends when needed.

5.4 Cloud Native Database Observability

Real-time analytics doesn't just require fast queries—it requires the ability to understand why queries are fast or slow, where resources are being used, and how performance changes over time. That's why Timescale is built with deep observability features, giving developers and operators full visibility into their database workloads.

At the core of this observability is Insights, Timescale's built-in query monitoring tool. Insights captures per-query statistics from our whole fleet in real time, showing you exactly how your database is behaving under load. It tracks key metrics like execution time, planning time, number of rows read and returned, I/O usage, and buffer cache hit rates—not just for the database as a whole, but for each individual query.

Insights lets you do the following:

- Identify slow or resource-intensive queries instantly
- Spot long-term performance regressions or trends
- Understand query patterns and how they evolve over time
- See the impact of schema changes, indexes, or continuous aggregates on workload performance
- Monitor and compare different versions of the same query to optimize execution

All this is surfaced through an intuitive interface, available directly in Timescale Cloud, with no instrumentation or external monitoring infrastructure required.

Beyond query-level visibility, Timescale also exposes metrics around service resource consumption, compression, continuous aggregates, and data tiering, allowing you to track how data moves through the system—and how those background processes impact storage and query performance.

Together, these observability features give you the insight and control needed to operate a real-time

analytics database at scale, with confidence, clarity, and performance you can trust.

6 ENSURING RELIABILITY AND SCALABILITY

Maintaining high availability, efficient resource utilization, and data durability is essential for real-time applications. Timescale provides robust operational features to ensure seamless performance under varying workloads.

- **High-availability (HA) replicas:** Deploy multi-AZ HA replicas to provide fault tolerance and ensure minimal downtime. In the event of a primary node failure, replicas are automatically promoted to maintain service continuity.
- **Connection pooling:** Optimize database connections by efficiently managing and reusing them, reducing overhead and improving performance for high-concurrency applications.
- **Backup and recovery:** Leverage continuous backups, Point-in-Time Recovery (PITR), and automated snapshotting to protect against data loss. Restore data efficiently to minimize downtime in case of failures or accidental deletions.

These operational capabilities ensure Timescale remains reliable, scalable, and resilient, even under demanding real-time workloads.

7 CONCLUSION

Real-time analytics is critical for modern applications, but traditional databases struggle to balance high-ingest performance, low-latency queries, and flexible data mutability. Timescale extends PostgreSQL to solve this challenge, combining automatic partitioning, hybrid row-columnar storage, and intelligent compression to optimize both transactional and analytical workloads.

With continuous aggregates, hyperfunctions, and advanced query optimizations, Timescale ensures sub-second queries even on massive datasets that combine current and historic data. Its cloud-native architecture further enhances scalability with independent compute and storage scaling, workload isolation, and cost-efficient data tiering—allowing applications to handle real-time and historical queries seamlessly.

For developers, this means building high-performance, real-time analytics applications without sacrificing SQL compatibility, transactional guarantees, or operational simplicity.

Timescale delivers the best of PostgreSQL, optimized for real-time analytics.