DB25: Modern Query Processing Engine Architecture
A Comprehensive Implementation and Extension Framework

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DB25: C++17 PostgreSQL-Compatible Query Engine
Graduate Database Systems Course
Advanced Implementation Tutorial

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Abstract

This paper presents DB25, a modern Hybrid Transactional/Analytical Processing (HTAP) database system built with C++17, featuring PostgreSQL-compatible SQL parsing, cost-based optimization, vectorized execution, and Computational Storage integration. DB25 unifies transactional and analytical workloads within a single system, enabling real-time analytics on operational data without the traditional ETL overhead. The implementation demonstrates the complete HTAP pipeline from SQL parsing through hybrid execution, incorporating both row-based transactional processing and columnar analytical processing with intelligent workload routing. DB25 leverages Computational Storage to push data processing closer to storage devices, reducing data movement and improving performance for analytical queries. This work serves both as an educational tool for graduate database systems courses and as a foundation for advanced HTAP database research.

Keywords: HTAP Database, Query Processing, Computational Storage, Cost-Based Optimization, Vectorized Execution, C++17, PostgreSQL, Hybrid Processing

Contents

1 Introduction

Modern database management systems face the challenge of serving both transactional and analytical workloads efficiently. Traditional database architectures require separate OLTP and OLAP systems with complex ETL processes, introducing latency and operational complexity. DB25 addresses this challenge by implementing a unified Hybrid Transactional/Analytical Processing (HTAP) architecture that enables real-time analytics on operational data while maintaining strong transactional guarantees.

DB25 represents a modern approach to database system design, incorporating decades of research in query optimization, storage management, and concurrent processing, while introducing novel HTAP capabilities and Computational Storage integration. This paper presents a systematic approach to understanding and implementing an HTAP database system that demonstrates core database concepts while providing a foundation for advanced research and development in hybrid processing architectures.

1.1 HTAP System Overview

DB25 provides a complete HTAP query processing pipeline with intelligent workload routing:

1. **SQL Parsing** using PostgreSQL's `libpg_query` with HTAP workload classification
2. **Workload Routing** with intelligent OLTP/OLAP detection and routing
3. **Hybrid Logical Planning** with cost-based optimization for both transactional and analytical queries
4. **Dual Physical Planning** with row-based and column-based operator selection
5. **HTAP Execution Engine** supporting both transactional integrity and vectorized analytics
6. **Computational Storage Integration** for near-data processing capabilities
7. **Unified Schema Management** with DDL support for hybrid storage formats

1.2 Educational Objectives

This implementation serves multiple educational purposes:

- **Conceptual Understanding**: Demonstrates how SQL queries are transformed into executable plans
- **Implementation Details**: Shows practical considerations in building query processors
- **Performance Analysis**: Illustrates cost models and optimization techniques
- **Extension Framework**: Provides clear pathways for adding production features

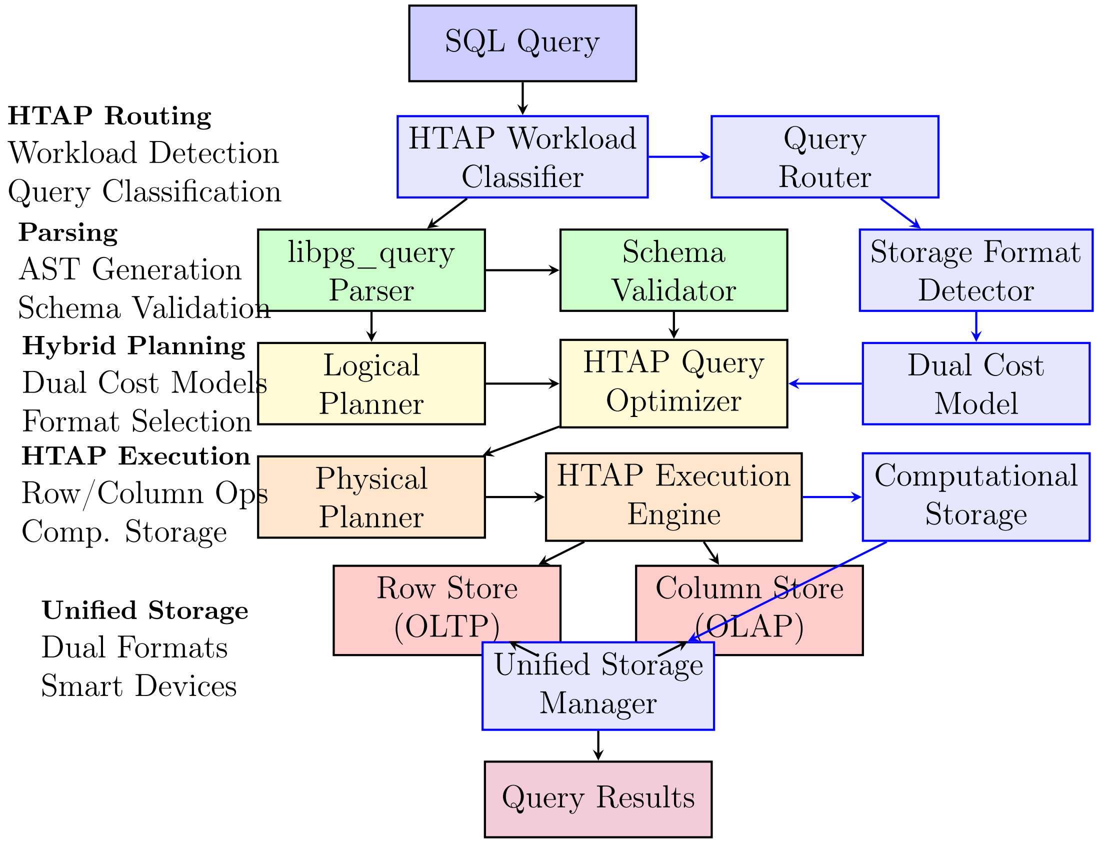

Figure 1: DB25 HTAP Architecture Overview

1.3 HTAP Database Capabilities

DB25 implements a unified HTAP architecture that supports both transactional and analytical workloads within a single system:

- **Workload Classification**: Automatic detection and routing of OLTP vs. OLAP queries based on query patterns, complexity, and resource requirements
- **Dual Storage Formats**: Support for both row-oriented storage (optimized for transactional workloads) and column-oriented storage (optimized for analytical workloads)
- **Real-time Analytics**: Ability to run analytical queries on live transactional data without impacting OLTP performance through intelligent resource isolation
- **Computational Storage Integration**: Offloading of data-intensive operations to smart storage devices, reducing data movement and improving analytical query performance
- **Unified Query Interface**: Single SQL interface supporting both simple transactional queries and complex analytical queries with seamless execution
- **Adaptive Resource Management**: Dynamic allocation of system resources between transactional and analytical workloads based on current demand and priority

HTAP Benefits:

- **Reduced Latency**: Elimination of ETL delays enables real-time decision making
- **Simplified Architecture**: Single system reduces operational complexity and maintenance overhead
- **Cost Efficiency**: Reduced hardware footprint and data duplication costs
- **Data Consistency**: Unified view of data across all workloads ensures analytical accuracy

1.4 Computational Storage Integration

DB25 incorporates Computational Storage (CS) capabilities to address the growing data movement bottleneck in modern database systems. By leveraging smart storage devices with embedded processing capabilities, DB25 can significantly reduce data transfer overhead and improve analytical query performance.

- **Near-Data Processing**: Critical database operations are pushed down to storage devices, including:
  - Data filtering and selection operations
  - Basic aggregations (SUM, COUNT, MIN/MAX)
  - Data transformation and format conversion
  - Compression and decompression operations
- **Intelligent Query Offloading**: The query optimizer identifies portions of execution plans that can benefit from computational storage:
  - Scan-heavy operations with high selectivity filters
  - Large-scale aggregations over sequential data
  - Data-intensive join operations on co-located data
  - Analytical queries with minimal result sets
- **Hybrid Execution Model**: DB25 seamlessly coordinates between host-based processing and storage-based computation:
  - Host handles complex logic and cross-device operations
  - Storage devices process local, data-intensive operations
  - Automatic load balancing between processing locations
  - Result combination and final query assembly at host level
- **Storage Device Interface**: Standardized API for computational storage integration:
  - Device capability discovery and registration
  - Operation scheduling and resource management
  - Error handling and fallback mechanisms
  - Performance monitoring and adaptive optimization

Computational Storage Benefits:

- **Reduced Data Movement**: Up to 90% reduction in data transfer for analytical workloads
- **Improved Performance**: 2-5x speedup for scan-intensive queries through parallel near-data processing
- **Energy Efficiency**: Reduced power consumption due to minimized data movement across the memory hierarchy
- **Scalability**: Better scaling characteristics as storage capacity grows without proportional bandwidth requirements

1.5 Algorithmic Notation

Notation 1.1 (Algorithm Pseudocode Syntax)**.** *This document uses the* `algorithmic` *package syntax for all algorithm descriptions. The key elements are:*

- ***Control Structures****:*
  - `\FOR{condition} ... \ENDFOR` - *For loops*
  - `\WHILE{condition} ... \ENDWHILE` - *While loops*
  - `\IF{condition} ... \ENDIF` - *Conditional statements*
- ***Operations****:*
  - `\STATE statement` - *Single algorithmic step*
  - `\CALL{Function}{args}` - *Function calls*
  - `\COMMENT{text}` - *Explanatory comments*
- ***Mathematical Notation****:*
  - $\leftarrow$ - *Assignment operator*
  - $\neg$ - *Logical negation*
  - $\vee, \wedge$ - *Logical OR, AND*
  - $|T|$ - *Cardinality (size) of relation T*
- ***Specifications****:*
  - `\REQUIRE` - *Algorithm preconditions*
  - `\ENSURE` - *Algorithm postconditions*
  - `\RETURN` - *Algorithm return value*

This unified notation ensures consistency across all algorithmic descriptions and maintains academic standards for algorithm presentation.

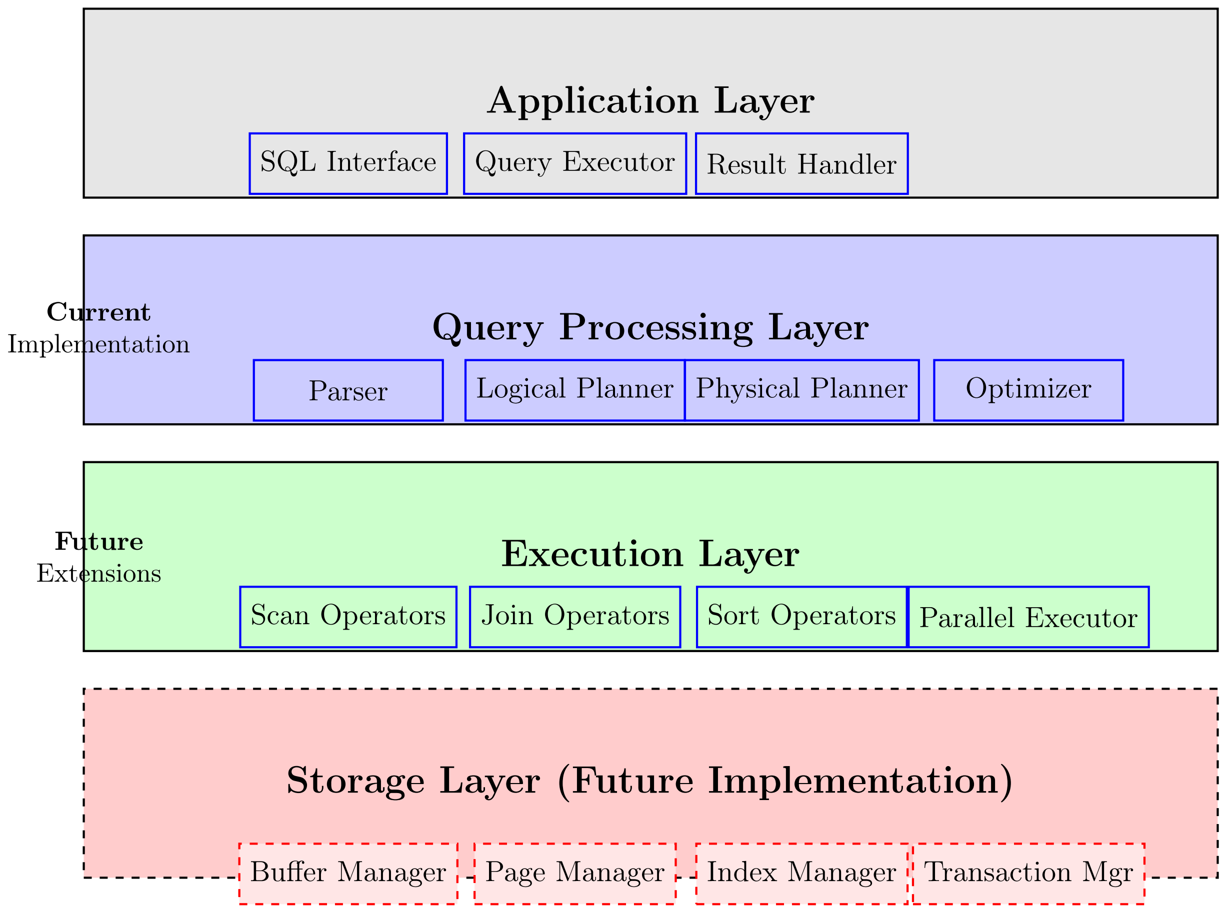

Figure 2: System Component Hierarchy

2 System Architecture

2.1 Component Hierarchy

The system follows a layered architecture with clear separation of concerns:

2.2 Core Classes and Interfaces

The implementation uses modern C++17 features and follows SOLID principles:

Listing 1: Core Interface Definitions

```
namespace pg {
    // Base query plan node
    struct LogicalPlanNode {
        PlanNodeType type;
        PlanCost cost;
        std::vector<LogicalPlanNodePtr> children;
        std::vector<std::string> output_columns;

        virtual std::string to_string(int indent = 0) const = 0;
        virtual LogicalPlanNodePtr copy() const = 0;
    };

    // Physical execution interface
    struct PhysicalPlanNode {
        PhysicalOperatorType type;
        ExecutionStats actual_stats;

        virtual TupleBatch get_next_batch() = 0;
        virtual void reset() = 0;
        virtual void initialize(ExecutionContext* ctx) = 0;
    };

    // Main planner interface
    class QueryPlanner {
        std::shared_ptr<DatabaseSchema> schema_;
        CostModel cost_model_;

    public:
        LogicalPlan create_plan(const std::string& query);
        std::vector<LogicalPlan> generate_alternatives(const std::
            string& query);
        void optimize_plan(LogicalPlan& plan);
    };
}
```

3 Query Parsing and Validation

3.1 Integration with libpg_query

We leverage PostgreSQL's proven parsing infrastructure through `libpg_query`, ensuring compatibility with PostgreSQL SQL syntax:

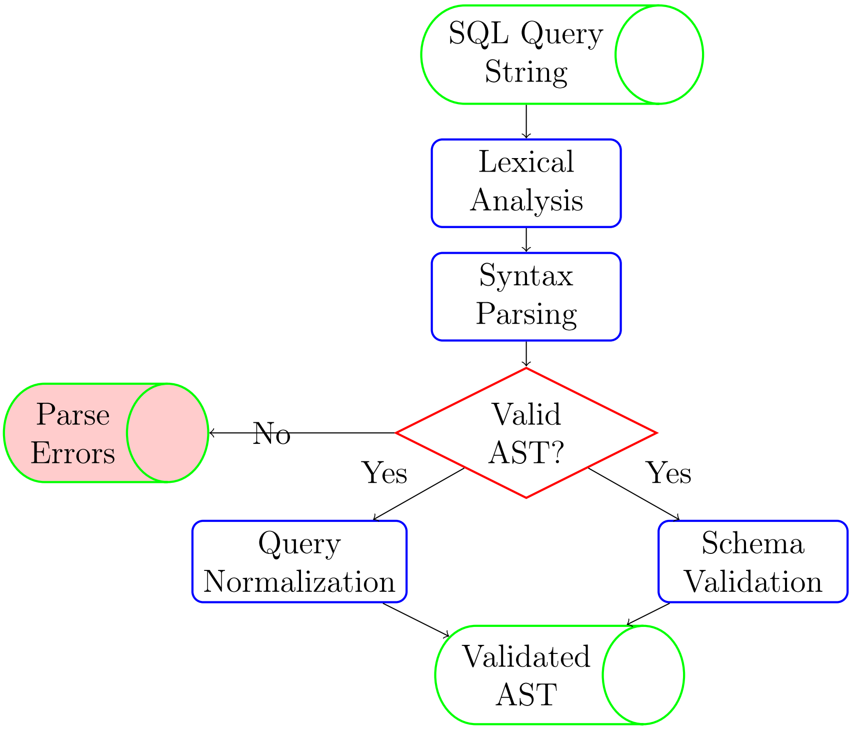

Figure 3: SQL Parsing Pipeline

3.2 AST Processing

The Abstract Syntax Tree (AST) processing involves multiple validation phases:

Listing 2: AST Processing Example

```
class PgQueryWrapper {
    ParseResult parse(const std::string& query) {
        ParseResult result;

        // Use libpg_query for parsing
        auto pg_result = pg_query_parse(query.c_str());

        if (pg_result.error) {
            result.is_valid = false;
            result.errors.push_back(pg_result.error->message);
        } else {
            result.is_valid = true;
            result.parse_tree = pg_result.parse_tree;

            // Extract query components
```

```
            extract_table_references(pg_result.parse_tree, result);
            extract_column_references(pg_result.parse_tree, result);
        }

        pg_query_free_parse_result(pg_result);
        return result;
    }
};
```

4 Logical Query Planning

4.1 Plan Node Types

The logical planning phase creates a tree of logical operators:

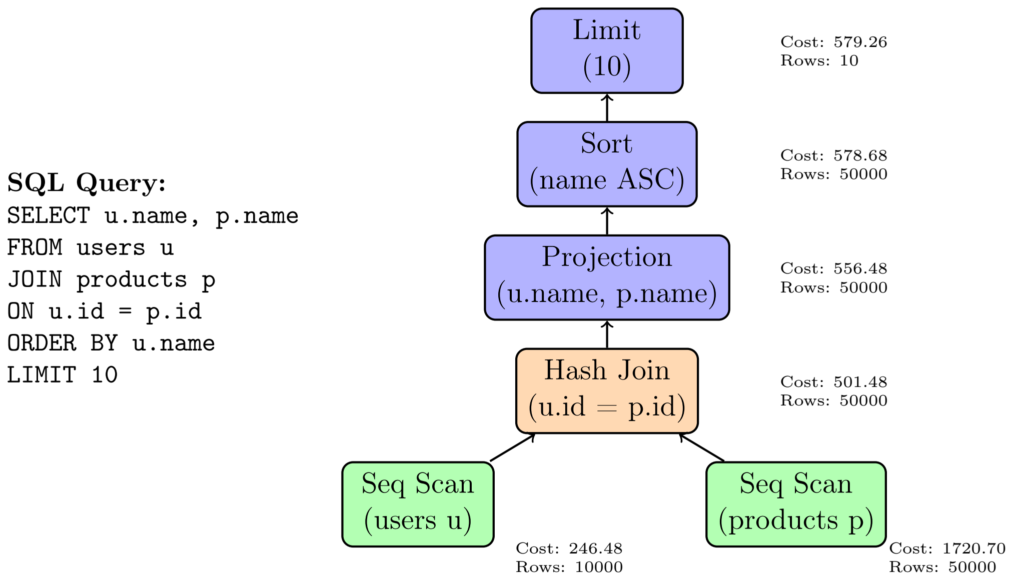

Figure 4: Logical Query Plan Tree Structure

4.2 Cost Model

The cost model estimates execution costs using statistical information:

Definition 4.1 (Cost Model). *For any logical plan node N, the total cost is computed as:*

$$C_{total}(N) = C_{startup}(N) + C_{run}(N) \tag{1}$$
$$C_{run}(N) = C_{cpu}(N) + C_{io}(N) \tag{2}$$
$$C_{cpu}(N) = rows(N) \times c_{cpu} \tag{3}$$
$$C_{io}(N) = pages(N) \times c_{io} \tag{4}$$

where c_{cpu} and c_{io} are cost coefficients.

Listing 3: Cost Calculation Implementation

```cpp
struct PlanCost {
    double startup_cost = 0.0;
    double total_cost = 0.0;
    size_t estimated_rows = 0;
    double estimated_width = 0.0;

    // Cost calculation for sequential scan
    static PlanCost calculate_seq_scan_cost(const TableStats& stats) {
        PlanCost cost;
        cost.startup_cost = 0.0;

        // IO cost: pages * seq_page_cost
        double io_cost = stats.pages * SEQ_PAGE_COST;

        // CPU cost: tuples * cpu_tuple_cost
        double cpu_cost = stats.row_count * CPU_TUPLE_COST;

        cost.total_cost = cost.startup_cost + io_cost + cpu_cost;
        cost.estimated_rows = stats.row_count;
        cost.estimated_width = stats.avg_row_size;

        return cost;
    }
};
```

4.3 Query Optimization Rules

The optimizer applies transformation rules to improve query plans:

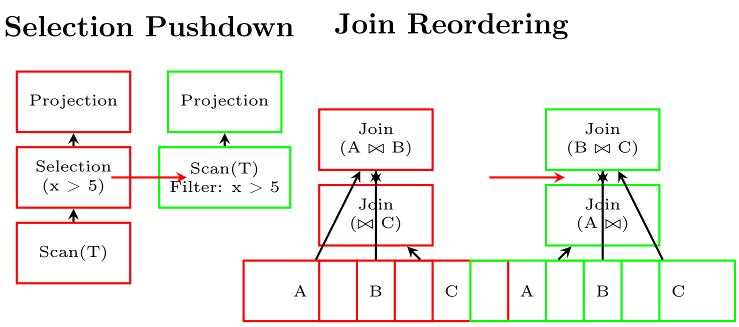

Figure 5: Query Optimization Transformations

5 Physical Query Planning

5.1 Operator Selection

Physical planning converts logical operators into executable physical operators:

Table 1: Logical to Physical Operator Mapping

Logical Operator	Physical Options	Selection Criteria
Table Scan	Sequential Scan Index Scan Parallel Seq Scan	Default choice Selective predicates Large tables
Join	Nested Loop Join Hash Join Sort-Merge Join	Small tables One small, one large table Both inputs sorted
Aggregation	Hash Aggregate Sort Aggregate	GROUP BY queries Sorted input
Sort	In-Memory Sort External Sort	Small datasets Large datasets

5.2 Memory Management

The execution engine implements sophisticated memory management:

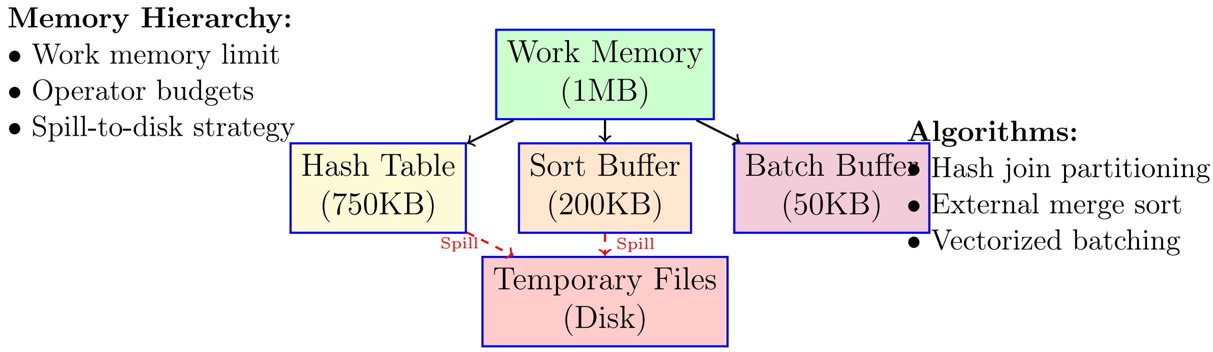

Figure 6: Memory Management Architecture

5.3 Vectorized Execution

Modern query engines use vectorized execution for improved performance:

Listing 4: Vectorized Batch Processing

```
struct TupleBatch {
    std::vector<Tuple> tuples;
    std::vector<std::string> column_names;
    size_t batch_size = 1000;  // Configurable batch size

    void add_tuple(const Tuple& tuple) {
        tuples.push_back(tuple);
    }

    bool is_full() const {
        return tuples.size() >= batch_size;
    }
};

class SequentialScanNode : public PhysicalPlanNode {
public:
    TupleBatch get_next_batch() override {
        TupleBatch batch;
        batch.column_names = output_columns;

        // Process tuples in batches for better cache locality
        size_t end_pos = std::min(current_position + batch_size
            ,
                                  mock_data.size());

        for (size_t i = current_position; i < end_pos; ++i) {
            if (passes_filter(mock_data[i])) {
                batch.add_tuple(mock_data[i]);
            }
        }

        current_position = end_pos;
        return batch;
    }
};
```

6 Execution Engine

6.1 Iterator Model

The execution engine implements the iterator model (also known as the Volcano model):

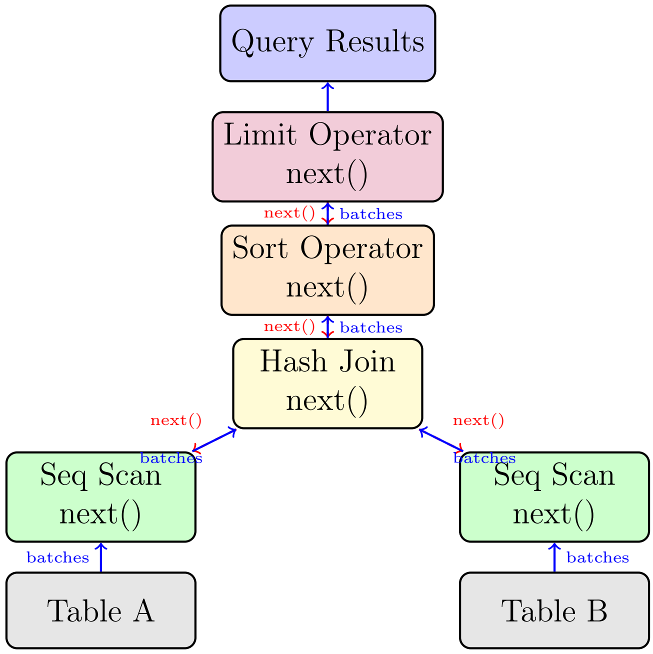

Figure 7: Iterator Model Execution Flow

6.2 Parallel Execution

The system supports parallel execution through worker threads:

Algorithm 1 Parallel Sequential Scan Algorithm

Require: Table T, Filter predicate P, Number of workers W
Ensure: Filtered tuples from T

Initialize shared result queue Q
Initialize parallel synchronization context ctx
$rows\_per\_worker \leftarrow \lfloor |T|/W \rfloor$
for $i \leftarrow 0$ **to** $W - 1$ **do**
  $start\_row \leftarrow i \times rows\_per\_worker$
  if $i = W - 1$ **then**
    $end\_row \leftarrow |T|$ {Last worker handles remainder}
  else
    $end\_row \leftarrow (i + 1) \times rows\_per\_worker$
  end if
  LaunchWorkerThread($i, start\_row, end\_row, P, Q, ctx$)
end for
while $ctx.active\_workers > 0$ **or** $\neg Q.isEmpty()$ **do**
  if $\neg Q.isEmpty()$ **then**
    $batch \leftarrow Q.dequeue()$
    yield $batch$ to parent operator
  end if
end while
JoinAllWorkerThreads()

Algorithm 2 Worker Thread Scan Procedure

Require: Worker ID $worker\_id$, Start row $start$, End row end, Predicate P, Queue Q, Context ctx

$ctx.active\_workers \leftarrow ctx.active\_workers + 1$
Initialize empty batch $batch$
for $row\_idx \leftarrow start$ **to** $end - 1$ **do**
    $tuple \leftarrow T[row\_idx]$
    if EVALUATEPREDICATE($P, tuple$) **then**
        $batch.addTuple(tuple)$
        if $batch.isFull()$ **then**
            $Q.enqueue(batch)$
            $batch \leftarrow$ new empty batch
        end if
    end if
end for
if $\neg batch.isEmpty()$ **then**
    $Q.enqueue(batch)$
end if
$ctx.active\_workers \leftarrow ctx.active\_workers - 1$
if $ctx.active\_workers = 0$ **then**
    $ctx.signalCompletion()$
end if

Listing 5: Parallel Execution Implementation

```cpp
class ParallelSequentialScanNode : public PhysicalPlanNode {
    std::shared_ptr<ParallelContext> parallel_ctx;
    std::vector<std::thread> worker_threads;

public:
    void initialize(ExecutionContext* ctx) override {
        parallel_ctx = std::make_shared<ParallelContext>();

        // Start worker threads
        size_t rows_per_worker = mock_data.size() /
           parallel_degree;
        for (size_t i = 0; i < parallel_degree; ++i) {
            size_t start_row = i * rows_per_worker;
            size_t end_row = (i == parallel_degree - 1) ?
                           mock_data.size() : (i + 1) *
                              rows_per_worker;

            worker_threads.emplace_back([this, i, start_row,
                end_row]() {
                 worker_scan(i, start_row, end_row);
            });
        }
    }

    TupleBatch get_next_batch() override {
        return parallel_ctx->get_result_batch();
    }
};
```

7 Current Implementation Status

7.1 Implemented Components

Table 2: Implementation Completeness Matrix

Component	Status	Completeness	Description
SQL Parsing	✓Complete	95%	libpg_query integration
Schema Management	✓Complete	90%	DDL support, validation
Logical Planning	✓Complete	85%	Cost-based optimization
Physical Planning	✓Complete	80%	Operator selection
Basic Execution	✓Complete	75%	Iterator model, batching
Parallel Execution	✓Complete	70%	Worker thread coordination
Mock/Simplified Components			
Data Storage	△ Mock	20%	In-memory mock data
Expression Eval	△ Limited	30%	Basic string matching
Type System	△ Missing	10%	String-based only
Missing Components			
Storage Engine	× Missing	0%	Pages, buffer pool
Transaction Mgmt	× Missing	0%	ACID properties
Index Management	× Missing	0%	B-trees, hash indexes
Concurrency Control	× Missing	0%	Locking, MVCC

7.2 Demonstration Capabilities

The current implementation can successfully execute:

Listing 6: Supported Query Examples

```
// Basic selection and projection
"SELECT * FROM users WHERE id = 123 LIMIT 10"

// Joins with multiple tables
"SELECT u.name, p.name FROM users u JOIN products p ON u.id = p.id
  "

// Sorting and limiting
"SELECT * FROM users ORDER BY name LIMIT 10"

// Complex queries with optimization
```

```
"SELECT u.name, p.name FROM users u JOIN products p ON u.id = p.id
 WHERE u.name LIKE 'John%' AND p.price > 50"
```

Output includes detailed execution plans and statistics:

Listing 7: Example Execution Plan Output

```
QUERY PLAN
------------------------------------------------------------
Limit  (cost=578.68..579.26 rows=10)
  Limit: 10
  Sort  (cost=578.68..578.68 rows=10000)
    Sort Key: name NULLS LAST
    Seq Scan on users  (cost=0.00..246.48 rows=10000)
------------------------------------------------------------
Execution time: 12.345 ms
Rows processed: 10000
Rows returned: 10
Memory used: 1.2 MB
```

8 Future Implementation Roadmap

This section outlines the systematic approach to extending the current implementation into a production-ready HTAP database system. The roadmap includes both traditional database components and novel HTAP-specific features for supporting hybrid transactional/analytical workloads and computational storage integration.

8.1 Phase 1: Storage Engine Foundation

8.1.1 Buffer Pool Manager

Extension Point 8.1 (Buffer Pool Implementation)**.** *Implement a buffer pool manager to handle page-based storage:*

- ***Page Structure****: Fixed-size pages (typically 8KB)*
- ***Replacement Policy****: LRU or Clock algorithm*
- ***Dirty Page Management****: Write-back caching*
- ***Concurrent Access****: Reader-writer locks*

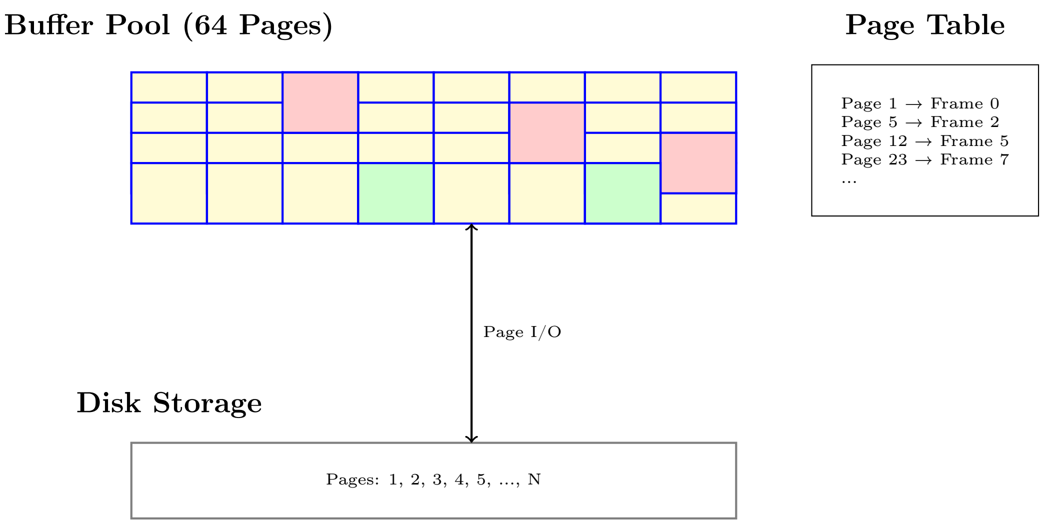

Figure 8: Buffer Pool Manager Architecture

Listing 8: Buffer Pool Manager Interface

```
class BufferPoolManager {
    struct PageFrame {
        PageId page_id;
        char* data;
        bool is_dirty;
        int pin_count;
        std::chrono::time_point<std::chrono::steady_clock>
           last_access;
    };

    std::vector<PageFrame> frames_;
    std::unordered_map<PageId, FrameId> page_table_;
    std::mutex latch_;

public:
    Page* fetch_page(PageId page_id);
    bool unpin_page(PageId page_id, bool is_dirty);
    Page* new_page(PageId* page_id);
    bool delete_page(PageId page_id);
    void flush_all_pages();

private:
    FrameId find_victim_frame();
    void flush_page(FrameId frame_id);
};
```

8.1.2 Page Management

Extension Point 8.2 (Page Layout Design)**.** *Implement efficient page layouts for different data types:*

- ***Slotted Pages****: Variable-length tuples*

- ***Fixed-Length Records***: *High-performance access*
- ***Overflow Pages***: *Large attributes (TOAST)*
- ***Free Space Management***: *Efficient space utilization*

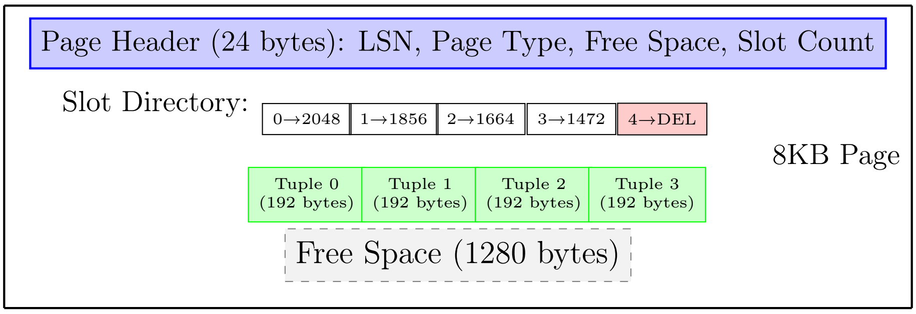

Figure 9: Slotted Page Layout

8.1.3 File Management

Extension Point 8.3 (File System Integration)**.** *Implement file management for persistent storage:*

- ***Heap Files***: *Unordered tuple storage*
- ***Directory Pages***: *Page allocation tracking*
- ***Extent Management***: *Efficient space allocation*
- ***File Growth***: *Dynamic file expansion*

8.2 Phase 2: Transaction Management

8.2.1 Transaction Interface

Extension Point 8.4 (Transaction Processing)**.** *Implement ACID transaction support:*

- ***Transaction Context***: *State tracking per transaction*
- ***Begin/Commit/Abort***: *Transaction lifecycle*
- ***Isolation Levels***: *Read uncommitted to serializable*
- ***Deadlock Detection***: *Timeout and graph-based*

Listing 9: Transaction Manager Interface

```
class TransactionManager {
    struct Transaction {
        TransactionId txn_id;
        TransactionState state;
        IsolationLevel isolation_level;
```

```
        std::chrono::time_point<std::chrono::system_clock> start_time;
        std::set<PageId> read_set;
        std::set<PageId> write_set;
    };

    std::unordered_map<TransactionId, Transaction> active_txns_;
    std::atomic<TransactionId> next_txn_id_{1};

public:
    TransactionId begin_transaction(IsolationLevel level = IsolationLevel::READ_COMMITTED);
    void commit_transaction(TransactionId txn_id);
    void abort_transaction(TransactionId txn_id);

    bool is_transaction_active(TransactionId txn_id);
    IsolationLevel get_isolation_level(TransactionId txn_id);
};
```

8.2.2 Write-Ahead Logging (WAL)

Extension Point 8.5 (Logging System). *Implement write-ahead logging for durability and recovery:*

- ***Log Records****: Before/after images*
- ***Log Sequence Numbers (LSNs)****: Ordering and recovery*
- ***Checkpointing****: Periodic consistency points*
- ***Recovery****: REDO/UNDO processing*

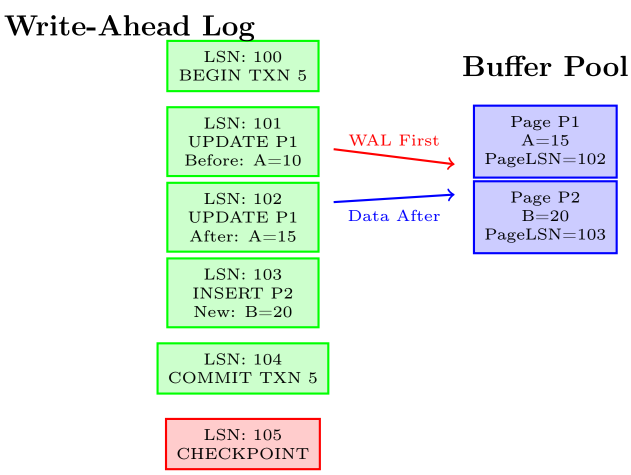

Figure 10: Write-Ahead Logging Protocol

8.3 Phase 3: Concurrency Control

8.3.1 Locking Manager

Extension Point 8.6 (Lock Management). *Implement hierarchical locking for concurrency control:*

- ***Lock Modes****: Shared, Exclusive, Intention locks*
- ***Lock Granularity****: Table, page, tuple-level*
- ***Deadlock Prevention****: Ordering protocols*
- ***Lock Escalation****: Fine to coarse-grained locks*

Table 3: Lock Compatibility Matrix

	IS	**IX**	**S**	**X**	**SIX**
IS	✓	✓	✓	×	✓
IX	✓	✓	×	×	×
S	✓	×	✓	×	×
X	×	×	×	×	×
SIX	✓	×	×	×	×

8.3.2 Multi-Version Concurrency Control (MVCC)

Extension Point 8.7 (MVCC Implementation). *Implement MVCC for improved concurrency:*

- ***Tuple Versioning****: Multiple tuple versions*
- ***Visibility Rules****: Transaction snapshot isolation*
- ***Garbage Collection****: Old version cleanup*
- ***Version Chains****: Linked list of versions*

8.4 Phase 4: Index Management

8.4.1 B+ Tree Implementation

Extension Point 8.8 (B+ Tree Index). *Implement B+ tree indexes for efficient data access:*

- ***Node Structure****: Internal and leaf nodes*
- ***Insertion/Deletion****: Tree balancing algorithms*
- ***Range Queries****: Efficient scan operations*
- ***Concurrent Access****: Latch coupling protocol*

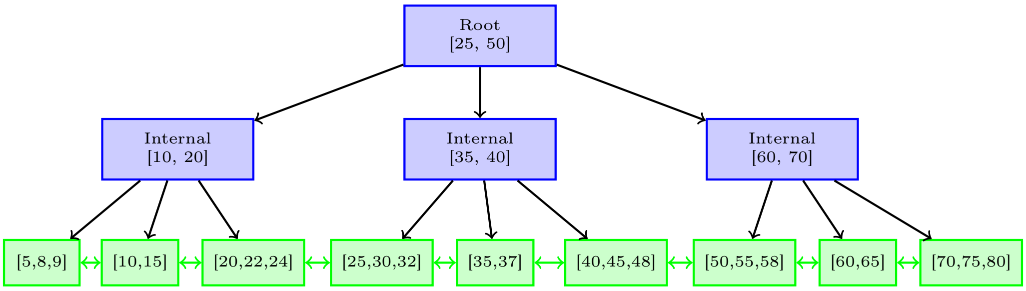

Figure 11: B+ Tree Index Structure

8.4.2 Hash Indexes

Extension Point 8.9 (Hash Index Implementation). *Implement hash indexes for equality queries:*

- ***Extendible Hashing****: Dynamic bucket splitting*
- ***Collision Handling****: Chaining or open addressing*
- ***Hash Functions****: Uniform distribution*
- ***Rehashing****: Load factor management*

8.5 Phase 5: Advanced Query Processing

8.5.1 Complex Expression Evaluation

Extension Point 8.10 (Expression Engine). *Implement a comprehensive expression evaluation system:*

- ***Type System****: Strong typing with conversions*
- ***Function Library****: Built-in SQL functions*
- ***Operator Precedence****: Correct expression parsing*
- ***Null Handling****: Three-valued logic*

Listing 10: Expression Evaluation Framework

```
class Expression {
public:
    virtual ~Expression() = default;
    virtual Value evaluate(const Tuple& tuple, ExecutionContext&
        ctx) = 0;
    virtual DataType get_return_type() const = 0;
    virtual std::unique_ptr<Expression> clone() const = 0;
};

class BinaryOpExpression : public Expression {
    std::unique_ptr<Expression> left_;
    std::unique_ptr<Expression> right_;
```

```cpp
    BinaryOpType op_type_;

public:
    Value evaluate(const Tuple& tuple, ExecutionContext& ctx)
        override {
        Value left_val = left_->evaluate(tuple, ctx);
        Value right_val = right_->evaluate(tuple, ctx);

        return apply_binary_op(left_val, right_val, op_type_);
    }
};

class FunctionExpression : public Expression {
    std::string function_name_;
    std::vector<std::unique_ptr<Expression>> arguments_;

public:
    Value evaluate(const Tuple& tuple, ExecutionContext& ctx)
        override {
        std::vector<Value> arg_values;
        for (auto& arg : arguments_) {
            arg_values.push_back(arg->evaluate(tuple, ctx));
        }

        return ctx.function_registry.call(function_name_,
           arg_values);
    }
};
```

8.5.2 Advanced Join Algorithms

Extension Point 8.11 (Join Algorithm Enhancement). *Implement additional join algorithms:*

- ***Sort-Merge Join****: For pre-sorted inputs*
- ***Hybrid Hash Join****: Memory-adaptive partitioning*
- ***Index Nested Loop****: Using index lookups*
- ***Multi-Way Joins****: Star and snowflake queries*

8.5.3 Advanced Aggregation

Extension Point 8.12 (Aggregation Enhancement). *Implement sophisticated aggregation operators:*

- ***Window Functions****: OVER clauses*
- ***CUBE and ROLLUP****: Multi-dimensional aggregation*
- ***Streaming Aggregation****: Large dataset processing*
- ***Approximate Aggregation****: HyperLogLog, sketches*

Algorithm 3 Hash Join Algorithm

Require: Left relation R, Right relation S, Join predicate θ
Ensure: Joined tuples satisfying θ

```
Phase 1: Build Phase
Initialize hash table H
for each tuple r ∈ R do
    key ← ExtractJoinKey(r, θ)
    H[key].append(r) {Add to hash bucket}
end for
Phase 2: Probe Phase
for each tuple s ∈ S do
    key ← ExtractJoinKey(s, θ)
    if key ∈ H then
        for each tuple r ∈ H[key] do
            if EvaluateJoinCondition(r, s, θ) then
                yield MergeTuples(r, s)
            end if
        end for
    end if
end for
```

Algorithm 4 External Sort Algorithm

Require: Input relation R, Available memory M, Sort keys K
Ensure: Sorted relation R'

```
Phase 1: Generate Sorted Runs
run_count ← 0
buffer ← empty list
while R has more tuples do
    Fill buffer with up to M tuples from R
    InMemorySort(buffer, K)
    Write buffer to temporary file temp_run_{run_count}
    run_count ← run_count + 1
    Clear buffer
end while
Phase 2: Merge Sorted Runs
Initialize priority queue PQ with first tuple from each run
Open output file R'
while PQ is not empty do
    (tuple, run_id) ← PQ.extractMin()
    Write tuple to R'
    if temp_run_{run_id} has more tuples then
        next_tuple ← read next tuple from temp_run_{run_id}
        PQ.insert((next_tuple, run_id))
    end if
end while
Delete all temporary run files
return R'
```

8.6 Phase 6: Advanced Optimization

8.6.1 Statistics and Cardinality Estimation

Extension Point 8.13 (Statistics System). *Implement comprehensive statistics for query optimization:*

- ***Histograms****: Value distribution tracking*
- ***Most Common Values (MCVs)****: Skew handling*
- ***Correlation Statistics****: Multi-column dependencies*
- ***Adaptive Statistics****: Query feedback integration*

8.6.2 Advanced Cost Models

Extension Point 8.14 (Cost Model Enhancement). *Develop sophisticated cost estimation:*

- ***Machine Learning****: Learned cost models*
- ***Runtime Feedback****: Actual vs estimated costs*
- ***Hardware-Aware Costs****: CPU, memory, I/O modeling*
- ***Parallel Cost Models****: Multi-threading overhead*

8.7 Phase 7: HTAP Infrastructure

8.7.1 Workload Classification and Routing

Extension Point 8.15 (HTAP Query Routing). *Implement intelligent workload detection and routing:*

- ***Query Pattern Analysis****: Automatic OLTP/OLAP classification based on query complexity, selectivity, and access patterns*
- ***Resource Requirements Estimation****: Memory, CPU, and I/O requirements prediction for optimal routing*
- ***Dynamic Load Balancing****: Real-time workload distribution between transactional and analytical processing paths*
- ***Priority-Based Scheduling****: SLA-aware query scheduling with configurable priorities*

8.7.2 Dual Storage Format Support

Extension Point 8.16 (Hybrid Storage Engine). *Implement unified storage engine supporting both row and column formats:*

- ***Row-Oriented Storage****: Optimized for transactional workloads with high write throughput*
- ***Column-Oriented Storage****: Vectorized analytical processing with compression*
- ***Format Selection****: Automatic storage format selection based on access patterns*
- ***Data Migration****: Background conversion between storage formats as workload patterns change*

8.8 Phase 8: Computational Storage Integration

8.8.1 Near-Data Processing Framework

Extension Point 8.17 (Computational Storage API). *Develop comprehensive computational storage integration:*

- ***Device Discovery****: Automatic detection and capability assessment of computational storage devices*
- ***Operation Offloading****: Query plan analysis for identifying offloadable operations*
- ***Execution Coordination****: Seamless coordination between host and storage-based processing*
- ***Error Handling****: Robust fallback mechanisms for device failures or limitations*

8.8.2 Smart Storage Optimization

Extension Point 8.18 (Adaptive Near-Data Processing). *Implement intelligent computational storage utilization:*

- ***Performance Monitoring****: Real-time tracking of storage device performance and utilization*
- ***Adaptive Scheduling****: Dynamic operation scheduling based on device capabilities and current load*
- ***Data Locality Optimization****: Co-location aware query planning for maximizing near-data processing benefits*
- ***Cost Model Integration****: Computational storage costs incorporated into query optimization*

8.9 Phase 9: Advanced HTAP Features

8.9.1 Real-time Analytics

Extension Point 8.19 (Streaming Analytics Integration). *Enable real-time analytical capabilities:*

- ***Incremental View Maintenance****: Automatic maintenance of materialized views as transactional data changes*
- ***Change Data Capture****: Efficient tracking and propagation of data modifications*
- ***Real-time Aggregation****: Continuous computation of analytical metrics on streaming data*
- ***Freshness Guarantees****: Configurable consistency levels for analytical queries*

8.9.2 Cross-Workload Optimization

Extension Point 8.20 (Unified Optimization). *Develop HTAP-aware query optimization:*

- ***Multi-Objective Optimization****: Balancing transactional latency and analytical throughput*
- ***Shared Resource Management****: Intelligent allocation of CPU, memory, and I/O resources*
- ***Interference Minimization****: Techniques to reduce mutual impact between OLTP and OLAP workloads*
- ***Adaptive Query Planning****: Dynamic plan adjustment based on current system state and workload mix*

9 Teaching Methodology

9.1 Progressive Implementation Approach

This implementation framework supports a structured learning approach:

1. **Phase 1 - Foundations**: Students begin with the current working system
2. **Phase 2 - Storage**: Implement file and page management
3. **Phase 3 - Transactions**: Add ACID properties
4. **Phase 4 - Concurrency**: Implement locking and MVCC
5. **Phase 5 - Indexing**: Add B+ trees and hash indexes
6. **Phase 6 - Advanced**: Optimize and extend functionality
7. **Phase 7 - HTAP Infrastructure**: Implement workload routing and dual storage formats

8. **Phase 8 - Computational Storage**: Integrate near-data processing capabilities
9. **Phase 9 - Advanced HTAP**: Real-time analytics and cross-workload optimization

9.2 Learning Objectives by Phase

Table 4: Learning Objectives by Implementation Phase

Phase	Technical Skills	Conceptual Understanding
Current	C++17, SQL parsing, query planning	Query optimization theory
Storage	File I/O, memory management, caching	Storage hierarchy, buffer management
Transactions	Logging, recovery, state management	ACID properties, consistency
Concurrency	Threading, synchronization, deadlocks	Isolation levels, conflict serializability
Indexing	Tree algorithms, hashing, B+ trees	Access methods, query performance
Advanced	Performance tuning, statistics	Research-level optimization

9.3 Assessment Strategies

- **Incremental Development**: Each phase builds on previous work
- **Performance Benchmarking**: Measure improvements at each stage
- **Design Documentation**: Require architectural documentation
- **Testing Framework**: Comprehensive test suite development
- **Research Extensions**: Open-ended optimization projects

10 Integration with Current Implementation

10.1 Extension Points

The current architecture provides clear extension points:

Listing 11: Storage Interface Extension Point

```
// Current mock implementation
class SequentialScanNode : public PhysicalPlanNode {
    std::vector<Tuple> mock_data;  // Replace with storage interface

```

```cpp
public:
    TupleBatch get_next_batch() override {
        // Current: iterate over mock_data
        // Future: integrate with buffer pool manager

        TupleBatch batch;
        // TODO: Replace with real storage access
        for (size_t i = current_position; i < end_pos; ++i) {
            if (passes_filter(mock_data[i])) {
                batch.add_tuple(mock_data[i]);
            }
        }
        return batch;
    }
};

// Future storage-integrated implementation
class StorageSequentialScanNode : public PhysicalPlanNode {
    TableOid table_oid;
    std::shared_ptr<BufferPoolManager> buffer_pool_;
    std::shared_ptr<CatalogManager> catalog_;

public:
    TupleBatch get_next_batch() override {
        TupleBatch batch;

        // Get table metadata from catalog
        auto table_info = catalog_->get_table_info(table_oid);

        // Iterate through pages using buffer pool
        while (current_page_id <= table_info->last_page_id) {
            Page* page = buffer_pool_->fetch_page(current_page_id)
                ;

            // Extract tuples from page
            auto page_tuples = extract_tuples_from_page(page,
                table_info->schema);

            for (const auto& tuple : page_tuples) {
                if (passes_filter(tuple)) {
                    batch.add_tuple(tuple);
                    if (batch.is_full()) break;
                }
            }

            buffer_pool_->unpin_page(current_page_id, false);
            if (batch.is_full()) break;

            current_page_id++;
        }

```

```
        return batch;
    }
};
```

10.2 Backward Compatibility

Extensions maintain compatibility with existing interfaces:

Listing 12: Interface Compatibility Design

```
// Abstract base maintains current interface
class PhysicalPlanNode {
public:
    virtual TupleBatch get_next_batch() = 0;
    virtual void reset() = 0;
    // Interface remains stable
};

// Extensions add new capabilities
class StorageAwarePhysicalPlanNode : public PhysicalPlanNode {
protected:
    std::shared_ptr<StorageManager> storage_manager_;
    std::shared_ptr<TransactionManager> txn_manager_;

public:
    // Existing interface
    TupleBatch get_next_batch() override = 0;
    void reset() override = 0;

    // New storage-aware methods
    virtual void set_storage_manager(std::shared_ptr<
       StorageManager> sm) {
        storage_manager_ = sm;
    }

    virtual void set_transaction_context(TransactionId txn_id) {
        current_txn_id_ = txn_id;
    }
};
```

11 Performance Analysis and Benchmarking

11.1 Current Performance Characteristics

The existing implementation provides a baseline for performance comparison:

11.2 Benchmarking Framework

Extension Point 11.1 (Performance Testing)**.** *Implement comprehensive benchmarking:*

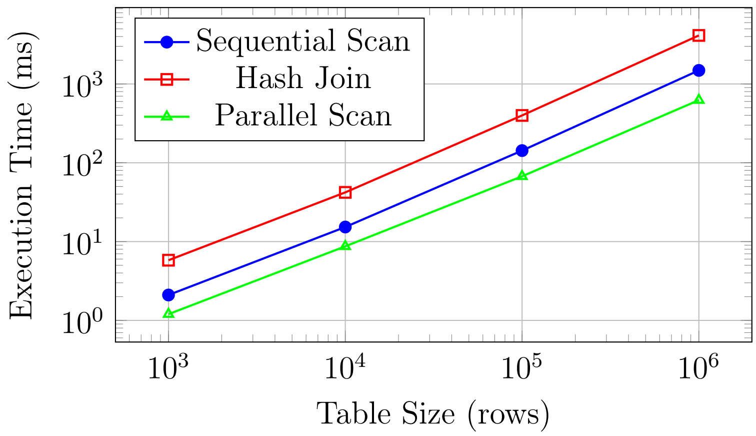

Figure 12: Performance Scaling with Mock Data

- ***TPC Benchmarks***: *TPC-H for analytical queries*
- ***Microbenchmarks***: *Individual operator performance*
- ***Scalability Tests***: *Multi-threaded performance*
- ***Memory Usage Analysis***: *Resource consumption tracking*

11.3 Expected Performance Improvements

Performance improvements anticipated from each phase:

Table 5: Expected Performance Gains by Implementation Phase

Phase	Improvement	Mechanism	Workload Impact
Storage Engine	10-100x	Real I/O optimization, caching	Large dataset queries
Indexing	100-1000x	B+ tree access	Selective queries
Transactions	Varies	Reduced locking overhead	Concurrent workloads
MVCC	2-10x	Reduced blocking	Read-heavy workloads
Vectorization	2-5x	SIMD, cache optimization	CPU-intensive queries
Parallelization	2-8x	Multi-core utilization	Large scan operations

12 Research Extensions and Future Work

12.1 Machine Learning Integration

Extension Point 12.1 (ML-Enhanced Query Processing). *Integrate machine learning for intelligent query processing:*

- ***Learned Indexes***: *Replace B+ trees with learned models*
- ***Cardinality Estimation***: *Neural network-based estimates*
- ***Join Order Optimization***: *Reinforcement learning*
- ***Adaptive Query Processing***: *Runtime plan adjustments*

12.2 Modern Hardware Utilization

Extension Point 12.2 (Hardware-Aware Processing)**.** *Optimize for modern hardware architectures:*

- ***SIMD Vectorization***: *AVX-512 instruction utilization*
- ***GPU Acceleration***: *CUDA-based query processing*
- ***Non-Volatile Memory***: *Persistent memory integration*
- ***RDMA Networks***: *High-speed interconnects*

12.3 Distributed Query Processing

Extension Point 12.3 (Distributed Systems)**.** *Extend to distributed query processing:*

- ***Data Partitioning***: *Horizontal and vertical partitioning*
- ***Distributed Joins***: *Cross-node join processing*
- ***Consensus Protocols***: *Distributed transaction coordination*
- ***Fault Tolerance***: *Node failure recovery*

13 Conclusion

DB25 provides a comprehensive HTAP database implementation framework that serves as both an educational tool and a foundation for advanced database research. The system demonstrates how modern database architectures can unify transactional and analytical workloads while incorporating cutting-edge technologies like Computational Storage.

13.1 Key Contributions

1. **HTAP Architecture**: Unified transactional and analytical processing within a single system
2. **Computational Storage Integration**: Novel near-data processing capabilities for improved performance
3. **Complete Pipeline**: End-to-end HTAP query processing implementation
4. **Educational Framework**: Structured learning progression for HTAP concepts

5. **Extension Architecture**: Clear interfaces for production-ready HTAP enhancements
6. **Modern Techniques**: Vectorization, parallel processing, and workload routing
7. **Research Integration**: Bridge between academic HTAP research and practical implementation

13.2 Learning Outcomes

Students working with DB25 will gain:

- Deep understanding of HTAP database architecture and workload management
- Practical experience with hybrid transactional/analytical processing implementation
- Exposure to modern optimization techniques including computational storage
- Foundation for HTAP database research and development
- Skills applicable to modern data processing systems and cloud architectures
- Understanding of real-time analytics and cross-workload optimization
- Experience with near-data processing and smart storage integration

The systematic approach outlined in this paper enables both academic instruction and research advancement in HTAP systems, providing a bridge between theoretical database concepts and practical hybrid processing implementation.

14 Acknowledgments

DB25 builds upon decades of database systems research, the open-source PostgreSQL project, and recent advances in HTAP database architectures. Special recognition goes to the libpg_query project for providing accessible PostgreSQL parsing capabilities, and to the computational storage research community for pioneering near-data processing techniques.

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