What's the relationship between databases and MapReduce? Can we combine their strengths?

What Do the Experts Say?

- Read what two DBMS luminaries thought about MapReduce and how readers reacted
  - http://databasecolumn.vertica.com/database-innovation/mapreduce-a-major-step-backwards/
  - http://databasecolumn.vertica.com/database-innovation/mapreduce-ii/
  - Links broken now, but a snapshot of their content will be on Blackboard or Piazza
- Active research area in databases to combine best of both worlds

DBMS Overview

- Some material obtained from Ramakrishnan/Gehrke book
- Relational databases have been around since the 1970s
- Parallel DBMS actively researched since 1980s
- Highly successful und ubiquitous
  - Relational technology also found in data warehousing
- Declarative programming
  - Specify WHAT you want, not HOW to get it
  - Optimizer finds efficient query plan
- Data independence
  - Write queries against logical schema
  - Create views to create illusion of different logical schema
- Designed for managing and analyzing large data

Strengths of the Relational Model

- Simple data structure: relations
  - "Flat" table with schema (attribute names and types defining the columns), containing tuples (rows)
  - No nesting or pointers
- Example
  - Students(sid, name, age, GPA)
  - Reservations(sid, bookID, date)
  - Books(bookID, topic, title)

Running Examples

SID	Name	Age	GPA
1	Alice	18	3.5
2	Bob	27	3.4
3	Carla	20	3.8

BookID	Topic	Title
B10	DB	Intro DB
B11	PL	More PL

SID	BookID	Date
2	B10	01/17/12
3	B11	01/18/12

More Strengths

- Specially designed query language
- Comparably simple operators that can be composed into complex queries
  - Enables automatic query optimization
- Not Turing-complete, e.g., not designed for complex calculations, but for easy efficient access to large data
- Relational calculus: basis for SQL
- Relational algebra: useful for representing query plans

Relational Algebra

- Basic operations:
  - Selection (σ): selects a subset of rows
  - Projection (π): selects a subset of columns
  - Cross-product (×): combines two relations
  - Set-difference (−): tuples in one relation but not the other
  - Union (∪): set union
- Additional operations: intersection, join, division, renaming (very useful)
- Algebra is closed, allowing composition
  - Each operation works on relations and returns a relation

Selection

- $\sigma_{\text{age}>25}(\text{Students})$

SID	Name	Age	GPA
1	Alice	18	3.5
2	Bob	27	3.4
3	Carla	20	3.8
4	Dan	20	3.9

SID	Name	Age	GPA
2	Bob	27	3.4

Projection

- $\pi_{\text{name,age}}(\text{Students})$

SID	Name	Age	GPA
1	Alice	18	3.5
2	Bob	27	3.4
3	Carla	20	3.8
4	Dan	20	3.9

Name	Age
Alice	18
Bob	27
Carla	20
Dan	20

Union, Intersection, Set-Difference

- Input relations have to be union-compatible

SID	Name	Age	GPA
1	Alice	18	3.5
2	Bob	27	3.4
3	Carla	20	3.8
4	Dan	20	3.9

SID	Name	Age	GPA
1	Alice	18	3.5
2	Bob	27	3.4
5	Erin	19	3.6
6	Frank	20	3.8

SID	Name	Age	GPA
1	Alice	18	3.5
2	Bob	27	3.4
3	Carla	20	3.8
4	Dan	20	3.9
5	Erin	19	3.6
6	Frank	20	3.8

$S1 \cup S2$

SID	Name	Age	GPA
3	Carla	20	3.8
4	Dan	20	3.9

$S1 - S2$

SID	Name	Age	GPA
1	Alice	18	3.5
2	Bob	27	3.4

$S1 \cap S2$

Cross-Product

- Pair each row from S with each row from Reservations
  - Rename those attributes occurring in both

SID	Name	Age	GPA
1	Alice	18	3.5
2	Bob	27	3.4
3	Carla	20	3.8

SID	BookID	Date
2	B10	01/17/12
3	B11	01/18/12

(SID)	Name	Age	GPA	(SID)	BookID	Date
1	Alice	18	3.5	2	B10	01/17/12
1	Alice	18	3.5	3	B11	01/18/12
2	Bob	27	3.4	2	B10	01/17/12
2	Bob	27	3.4	3	B11	01/18/12
3	Carla	20	3.8	2	B10	01/17/12
3	Carla	20	3.8	3	B11	01/18/12

$S \times R$

Joins

- Condition-join (aka theta-join)
  - $R \bowtie_C S = \sigma_C(R \times S)$
- Special cases
  - Equi-join: only equalities in C, no duplication of join columns
  - Natural join: equi-join on all common attributes

SID	Name	Age	GPA	BookID	Date
2	Bob	27	3.4	B10	01/17/12
3	Carla	20	3.8	B11	01/18/12

$R \bowtie_{R.SID=S.SID} S$

Example

- Find names of students who reserved a DB book

BookID	Topic	Title
B10	DB	Intro DB
B11	PL	More PL

- $\pi_{\text{name}}((\sigma_{\text{topic=DB}} B) \bowtie R \bowtie S)$
- $\pi_{\text{name}}(\pi_{\text{SID}}((\pi_{\text{BookID}} \sigma_{\text{topic=DB}} B) \bowtie R) \bowtie S)$

- Which one will be more efficient?
  – A query optimizer can find this automatically.

Relational Calculus

- Basis of SQL query language
- Algebra was not declarative, but calculus is
  – Many different algebra “implementations” possible for a calculus expression
- Tuple relational calculus (TRC)
  – Variables range over tuples
- Domain relational calculus (DRC)
  – Variables ranges over attribute values
- Calculus expressions are called formulas
  – Answer tuple = assignment of constants to variables that make the formula evaluate to *true*

Domain Relational Calculus

- Query: $\{\langle x_1, x_2, \dots, x_n\rangle \mid p(x_1, x_2, \dots, x_n)\}$

- Answer = all tuples $\langle x_1, x_2, \dots, x_n\rangle$ that make formula $p(x_1, x_2, \dots, x_n)$ true
- All variables $x_1, x_2, \dots, x_n$ must be free, i.e., not bound by quantifier, in formula $p(\dots)$
- No other variable in $p(\dots)$ is allowed to be free

DRC Formulas

- Atomic formula (op is one of $<, >, =, \neq, \leq, \geq$)
  – $\langle x_1, x_2, \dots, x_n\rangle \in$ Relation, or
  – x op y, or
  – x op const
- Formula (p, q are formulas)
  – Atomic formula, or
  – $\neg p, p \wedge q, p \vee q$, or
  – $\exists x(p(x))$ or $\forall x(p(x))$ where variable x is free in $p(x)$
    - Quantifiers $\exists x$ and $\forall x$ bind variable x; free variables are not bound

Example

- All students with GPA above 3.6
  – $\{\langle S, N, A, G\rangle \mid \langle S, N, A, G\rangle \in \text{Students} \wedge G > 3.6\}$
- First condition: domain variables S, N, A, G have to be attributes of the same student tuple
- Second condition: GPA selection

SID	Name	Age	GPA
1	Alice	18	3.5
2	Bob	27	3.4
3	Carla	20	3.8
4	Dan	20	3.9

Example

- Students with GPA above 3.6 who reserved book B10
  – $\{\langle S, N, A, G\rangle \mid \langle S, N, A, G\rangle \in \text{Students} \wedge G > 3.6$
  $\wedge \exists S_2, B, D(\langle S_2, B, D\rangle \in \text{Reservations} \wedge S = S_2$
  $\wedge B = \text{B10})\}$
- $\exists S_2, B, D$ is a shorthand for $\exists S_2\left(\exists B\left(\exists D(\dots)\right)\right)$
- Exists clause is used to find a tuple in Reservations that joins with the student tuple under consideration

SID	Name	Age	GPA
1	Alice	18	3.5
2	Bob	27	3.4
3	Carla	20	3.8

SID	BookID	Date
2	B10	01/17/12
3	B11	01/18/12

Safe Queries and Expressive Power

- Possible to write calculus queries with infinite number of answers—called unsafe queries
  - $\{\langle S, N, A, G\rangle \mid \neg(\langle S, N, A, G\rangle \in \text{Students})\}$
- Safe query: returns same result, no matter the attribute domains
- Every relational algebra query can be expressed as a safe query in DRC/TRC, and vice versa
- Relational completeness: query language, e.g., SQL, can express every relational algebra query

Basic SQL Query

```
SELECT   [DISTINCT] attribute-list
FROM     relation-list
WHERE    condition
```

```
SELECT   DISTINCT name
FROM     Students S, Reservations R
WHERE    S.SID = R.SID AND BookID = 'B10'
```

- Attribute-list: list of attributes from relation-list
- Relation-list: relation names, possibly with range-variable after the name
- Condition: comparisons of attributes or attribute against constant, using $<, >, =, \neq, \leq, \geq$
- DISTINCT: eliminate duplicates

Example

```
SELECT   S.age, S.age+1 AS age1, 2*S.age AS age2
FROM     Students S
WHERE    S.name LIKE 'J_%E'
```

- Can use arithmetic expressions in attribute-list and also in WHERE clause
- AS gives name to a result attribute
  - Could also use "=": age1 = S.age+1
- LIKE matches strings
  - "_" matches any single character
  - "%" matches 0 or more arbitrary characters

Students Who Reserved DB or PL Book

```
SELECT   S.SID
FROM     Students S, Reservations R, Books B
WHERE    S.SID = R.SID AND R.bookID = B.bookID
         AND (B.topic = 'DB' OR B.topic = 'PL')
```

- $\{\langle S, N, A, G\rangle \mid \langle S, N, A, G\rangle \in \text{Students} \wedge G > 3.6$
  $\wedge \exists S_2, B, D(\langle S_2, B, D\rangle \in \text{Reservations} \wedge S = S_2$
  $\wedge \exists B_2, O, I(\langle B_2, O, I\rangle \in \text{Books} \wedge B = B_2 \wedge (O = \text{DB} \vee O = \text{PL})))\}$
- What if we want those who reserved a DB *and* a PL book?
  - AND instead of OR would not work
  - Need to use INTERSECT
  - Careful: intersection needs to be on unique students, i.e., SID not just S.name

Nested Query with Correlation

```
SELECT   S.name
FROM     Students S
WHERE    EXISTS   (SELECT *
                   FROM Reservations R
                   WHERE R.bookID = 'B10' AND S.SID = R.SID)
```

- EXISTS tests is set is empty
- If sub-query depends on outside attributes, have to re-compute for every value of them
- UNIQUE (instead of EXISTS): checks if there is at most one reservation for the student
  - Choice of attribute-list in sub-query affects UNIQUE

Aggregate Operators

- COUNT(*), COUNT([DISTINCT] A)
- SUM([DISTINCT] A)
- AVG([DISTINCT] A)
- MAX(A), MIN(A)

```
SELECT   COUNT(*)
FROM     Students
```

```
SELECT   AVG(GPA)
FROM     Students
WHERE    age > 20
```

```
SELECT   S.name
FROM     Students S
WHERE    S.GPA =   (SELECT MAX(S2.GPA)
                    FROM Students S2)
```

GROUP BY and HAVING

SELECT	[DISTINCT] attribute-list
FROM	relation-list
WHERE	condition
GROUP BY	grouping-list
HAVING	group-condition

- Attribute-list contains attribute names and terms with aggregate operations
  - Attributes in attribute-list must appear in grouping-list
  - Reason: single attribute value per group!

Example

- Among all students with GPA > 3.4, find the lowest GPA for each age group with at least 2 students

SELECT	S.age, MIN(S.GPA) AS MinGPA
FROM	Students S
WHERE	S.GPA > 3.4
GROUP BY	S.age
HAVING	COUNT(*) >= 2

SID	Name	Age	GPA
1	Alice	18	3.5
2	Bob	27	3.4
3	Carla	20	3.8
4	Dan	20	3.9
6	Frank	20	3.8
7	Gina	27	3.8
8	Hal	18	3.5

Evaluation

SID	Name	Age	GPA
1	Alice	18	3.5
~~2~~	~~Bob~~	~~27~~	~~3.4~~
3	Carla	20	3.8
4	Dan	20	3.9
6	Frank	20	3.8
7	Gina	27	3.8
8	Hal	18	3.5

Age	GPA
18	3.5
20	3.8
20	3.9
20	3.8
27	3.8
18	3.5

Age	GPA
18	3.5
18	3.5

Age	GPA
20	3.8
20	3.9
20	3.8

Age	GPA
27	3.8

Age	GPA
20	3.8
20	3.9
20	3.8

Age	GPA
18	3.5
18	3.5

Age	MinGPA
18	3.5
20	3.8

What Is a Query Plan?

- DAG of relational operators and their implementations
  - Use index vs. scan entire relation
  - Data partitioning for divide-and-conquer strategy
- Pull interface: output "pulls" next tuple from upstream operators
  - Enables pipelining, avoids buffering

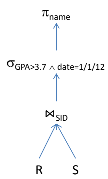
The System R Optimizer

- Most widely used optimizer style
- Transforms SQL query to initial plan (actually multiple query blocks)
- Considers alternative plans by leveraging relational algebra equivalences
- For each plan, combined CPU and I/O cost is estimated
  - Challenge: estimate size of intermediate results
- Search space too large, hence optimizer relies on heuristics to enumerate candidate plans

Plans Involving Joins

- Avoid Cartesian products
- Joins can be executed in any order
  - Exponential number of query plans
- Optimizer only considers left-deep plans
  - Allows pipelining of intermediate results
  - No need to materialize temporary relations
- Still many possible join orders…

Simple Example



Relational-algebra tree

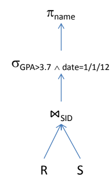
On-the-fly

On-the-fly

Block Nested Loops

Cost: 1000+1000·500 for join plus zero I/O for on-the-fly

Total: ~500,000 I/O



File scan File scan

Possible query plan

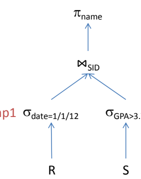
Alternative Plan: Push Selections

- Scan R, write Temp1: 1000+10
  - Assume 100 reservation days
- Scan S, write Temp2: 500+250
  - Assume 50% have GPA>3.7
- Join: 2·2·10 + 2·2·250 + 10+250
- Total: 3060 I/O

On-the-fly

Sort-merge join

Scan, write to Temp1



Scan, write to Temp2

Could lower cost further by also pushing projections and using other join implementation

Another Alternative: With Indexes

- Index on R: 100K/100=1000 tuples on 1000/100=10 pages
- Join: for each R-tuple, index lookup on S: 1000·1.2
- Total: 1210 I/O

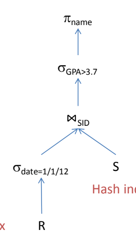
On-the-fly

On-the-fly

Index Nested Loops with pipelining

Use hash index, do not write result to Temp

Clustered hash index on date



Hash index on SID

Cannot push selection on GPA before the join, because that would prevent use of index

Parallel Databases

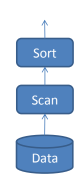
- Same SQL query, just replace the optimizer
  - Take data location and network cost into account
  - Optimize for latency or total cost
- Add new operators
  - Exchange: behaves like an iterator, but receives input via inter-process communication rather than iterator procedure calls
  - Split and Merge: create and join parallel dataflows
- Add new operator implementations
  - Semi-join to reduce network communication cost

Distributed Query Optimization

- Start: calculus query on global relations
- Transform into algebraic query on global relations
- Perform data localization, using fragment schema, to generate algebraic query on fragments
- Perform global optimization to create distributed query execution plan
- Run on local sites in parallel

Pipeline Parallelism

- Computation of one operator proceeds in parallel with another
- Model: output pulls from last operators, which pulls from its inputs and so on

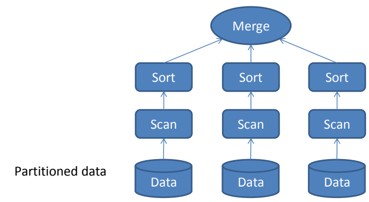


Limited Benefits of Pipeline Parallelism

- Relational pipelines are usually not very long
  - Ten or longer is rare
- Some operators are blocking and cannot be pipelined
  - Aggregates, sorting
- Execution cost of one operator might be much larger than the others
  - Limits speedup obtained by pipelining

Partitioned Parallelism

- Query performs batch-style computation on many input tuples



Data Partitioning

- Round-robin
  - Simple, but not helpful for associative access
- Hash partitioning
  - Assign tuples to partition using hash function
  - Good for associative access (equality-based)
  - Not good for range queries
- Range partitioning
  - Partition data into continuous ranges
  - Good for range queries, parallel sort
  - Risks data skew (uneven partitions) and execution skew (uneven access pattern)

Distributed Transactions?

- Transactions were crucial for the success of database systems
- Enable concurrent processing of multiple queries, but programmers could write them as if they executed in isolation

Transactions

- Transaction = user program, consisting of a sequence of DB reads and writes
- Let users write programs under the illusion that there is no concurrent access
- DBMS automatically takes care of scheduling
  - Interleaves transactions, but ensures result is identical to isolated execution
- Give programmer a simple mechanism for declaring all-or-nothing execution of a block of statements

ACID Properties

- Atomicity: Either all or none of the transaction's actions are executed
  - Even when a crash occurs mid-way
- Consistency: Transaction run *by itself* must preserve consistency of the database
  - User's responsibility
- Isolation: Transaction semantics do not depend on other concurrently executed transactions
- Durability: Effects of successfully committed transactions should persist, even when crashes occur

Example

T1: BEGIN A=A+100, B=B-100 END
T2: BEGIN A=1.01A, B=1.01B END

- Two bank accounts, A and B, owned by same user
- User transfers $100 from B to A
- Bank computes 1% interest on both
- Assume start state is A=500, B=500
- Correct serial executions: total interest = $10
  - T1, T2: A=606, B=404
  - T2, T1: A=605, B=405

Interleaving Scenarios

T1: A=A+100, B=B-100
T2: A=1.01A, B=1.01B

T1: A=A+100, B=B-100
T2: A=1.01A, B=1.01B

T1: R(A), W(A), R(B), W(B)
T2: R(B), W(B), R(A), W(A)

- First: ok, equivalent to T1, T2 order
- Second: not ok
  - A=606, B=505
- Abstract view shows the conflict

Scheduling Transactions

- Serial schedule: Schedule that does not interleave the actions of different transactions
  - Easy for programmer, easy to achieve consistency
  - Bad for performance
- Equivalent schedules: For any database state, the effect (on the objects in the database) of executing the first schedule is identical to the effect of executing the second schedule
- Serializable schedule: A schedule that is equivalent to some serial execution of the transactions
  - Retains advantages of serial schedule, but addresses performance issue
- Note: If each transaction preserves consistency, every serializable schedule preserves consistency

Anomalies: WR

T1: R(A), W(A), R(B), W(B), Abort
T2: R(A), W(A), C

- Reading uncommitted data (WR-conflict, "dirty read")
  - T2 reads value A written by T1 before T1 completed its changes
  - If T1 later aborts, T2 worked with invalid data
- Example: T1 deposits check to A, T2 credits interest to A

Problems With Dirty Reads

- Dirty read can result in unrecoverable schedule
  - T2 worked with invalid data and hence has to be aborted as well
  - But T2 already committed…
- Recoverable schedule: cannot allow T2 to commit until T1 has committed
  - Can still lead to cascading aborts

Anomalies: RW

T1: R(A), R(A), W(A), C
T2: R(A), W(A), C

- Unrepeatable read (RW conflict)
- T1 sees different values of A, even though it did not change it
- Example: online book store
  - Only one copy left; both T1 and T2 try to order it
  - One will get an error message
  - Could not have happened with serial execution

Anomalies: WW

T1: W(A), W(B), C
T2: W(A), W(B), C

- Overwriting uncommited data (WW conflict)
- T1's B and T2's A persist, which would not happen with serial execution
- Example: two employees with same salary
  - T1 sets both salaries to $4000, T2 to $4500
  - Above schedule results in A=4500, B=4000

Preventing Anomalies Through Locking

- Block problematic concurrent actions, but allow non-conflicting ones
  - Many transactions can read the same data concurrently
  - If T1 affects accounts A and B, while T2 works on X and Y, they can even perform updates concurrently
- Lock the right DB objects using appropriate locks to allow maximum concurrency without suffering from anomalies

Locking Basics

- Before being able to read an object, transaction needs to acquire a shared lock (S-lock) on it
- Before being able to modify an object, transaction needs to acquire an exclusive lock (X-lock) on it
- Multiple transactions can hold a shared lock on the same object
- At most one transaction can hold an exclusive lock on an object

Two-Phase Locking

- Phase 1: acquire locks
- Phase 2: release locks (cannot acquire new locks any more)
- Ensures serializable schedule, but does not necessarily prevent dirty reads
- Strict 2PL: all locks are released only when the transaction is completed
  - Prevents all anomalies shown earlier
- Problem: deadlocks

Deadlocks

- Ex: T1, T2 both want to read and write objects A and B
  - T1 acquires X-lock on A; T2 acquires X-lock on B
  - T1 wants to update B: waits for T2 to release its lock on B
  - T2 wants to read A: waits for T1 to release its lock on A
  - Strict 2PL does not allow either to release its locks before the transaction completed. Deadlock!
- DBMS can detect this
  - Cycle in waits-for graph (nodes = transactions, edges = objects they are waiting for)
  - Breaks deadlock by aborting one of the involved transactions
    - Which one to choose? Work performed is lost.

Aborting a Transaction

- All of T1's actions have to be undone
  - If another txn T2 has read an object last written by T1, T2 must be aborted as well!
  - Strict 2PL avoids such cascading aborts by releasing a transaction's locks only at commit time
- In order to undo the actions of an aborted transaction, the DBMS maintains a log in which every write is recorded
  - This mechanism is also used to recover from system crashes: all active txns at the time of the crash are aborted when the system comes back up

The Phantom Problem

- Assume initially the youngest student is 20 years old
- T1 contains twice: SELECT MIN(age) FROM Students
- T2 inserts a new student with age 18
- Consider the following schedule:
  - T1 runs query, T2 inserts new student, T1 runs query again
  - T1 sees two different results, i.e., an unrepeatable read
- Would Strict 2PL prevent this?
  - Assume T1 acquires S-lock on each existing Student tuple
  - T2 inserts a new tuple, which is not locked by T1
  - T2 releases its X-lock on the new student before T1 reads Students again
- What went wrong?

What Should We Lock?

- T1 cannot lock a tuple that T2 will insert
- …but T1 could lock the entire Students table
  - Now T2 cannot insert anything until T1 completed
- What if T1 computed a slightly different query:
  - SELECT MIN(age) FROM Students WHERE GPA > 3.5
- Now locking the entire Students table seems excessive, because inserting a new student with GPA $\leq$ 3.5 would not create a problem
  - T1 could lock the predicate [GPA > 3.5] on Students
- General challenge: DBMS needs to choose appropriate granularity for locking

Performance Of Locking

- Locks force transactions to wait
- Abort and restart due to deadlock wastes the work done by the aborted transaction
  - In practice, deadlocks are rare, e.g., due to lock downgrades approach
    - Request X-lock initially, then downgrade to S-lock when it becomes clear that only read access was needed
- More concurrent transactions => more lock contention
  - Allowing more concurrent transactions initially increases throughput, but at some point leads to thrashing
  - Solution: limit max number of concurrent transactions
  - Minimize lock contention by reducing time locks are held and by avoiding hotspots (objects frequently accessed)

Distributed Transactions

- Transactions take longer to access remote objects
  - Need to hold locks longer
  - Greater probability for waiting and deadlocks
- What if the network partitions?
  - Transaction cannot acquire/release some locks
- Even without partitions, the problem is hard
  - Need to coordinate commit between multiple nodes
  - What happens if some participating node crashes?
- Standard protocol: 2PC (2-phase commit)

2PC Basics

- Commit-request phase
  - Coordinator asks all participants to prepare for commit
  - Participants vote YES or NO to commit request
- Commit phase
  - Based on participants’ votes, coordinator decides to commit (if all voted YES) or abort
  - Coordinator notifies participants about decision
  - Participants apply corresponding action (commit or abort) locally

2PC Problems

- 2PC = blocking protocol
  - Nodes cannot make a decision without hearing from coordinator, e.g., might hold on to locks forever if coordinator is down and they answered YES to first request
- Expensive for many-worker transactions
- Some issues were addressed by later 2PC modifications, but the basic problems remain

NoSQL to the Rescue?

- Examples: MongoDB, CouchDB, HBase, Google's BigTable, Amazon's Dynamo
- Many driven by performance challenges
  - Inherent tradeoff: consistency, availability, and tolerance to network partitions (Eric Brewer, UC Berkeley)
    - Maintaining consistent state across 100s of machines requires expensive agreement
    - Failures reduce availability, unless consistency is weakened
- Solutions: weaker consistency guarantees, limited functionality, or tailored solution for specific workload

Bigtable

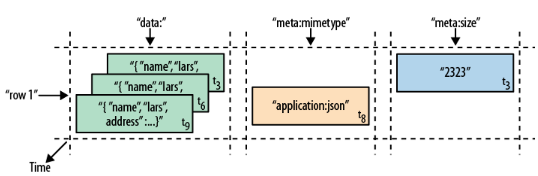
- Fay Chang, Jeffrey Dean, Sanjay Ghemawat, Wilson C. Hsieh, Deborah A. Wallach, Mike Burrows, Tushar Chandra, Andrew Fikes, and Robert E. Gruber. Bigtable: A Distributed Storage System for Structured Data. OSDI'06: Seventh Symposium on Operating System Design and Implementation, Seattle, WA, November, 2006

HBase

- Open-source implementation of BigTable
- Part of the Hadoop ecosystem
- Supports fast "random" reads and writes in Big Data
- Scales by adding more nodes
  - Scales to billions of rows, millions of columns
- Does not support SQL
- No transactions, but row-level atomicity
  - Explicit row locks can be set by client application

Data Model

- Data stored in tables
- Tables consist of rows and columns
  - Each table cell is versioned, e.g., html content of www.neu.edu on different dates
  - Cell content = un-interpreted array of bytes
- Row keys (=primary key) are byte arrays
  - Can use any serializable type
- Table is stored sorted by row key: byte-ordered
  - Choose key wisely according to query workload



Row Key	Time Stamp	Column "data:"	Column "meta:" "mimetype"	"size"	Column "counters:" "updates"
"row1"	t_3	"{ "name": "lars", "address": ...}"		"2323"	"1"
	t_6	"{ "name": "lars", "address": ...}"			"2"
	t_8		"application/json"		
	t_9	"{ "name": "lars", "address": ...}"			"3"

Source: HBase: The Definitive Guide, by Lars George

HBase Characteristics

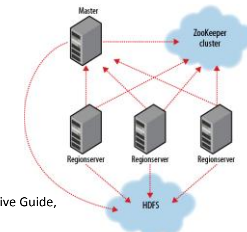
- All data accesses by row key or scanning
- No real indexes
  - Fast loading of data
  - No secondary indexes, but some projects exist for adding them
- No support for joins
  - Store wide de-normalized table
- When adding a node, some regions will be moved to it automatically

Column Families

- Columns are grouped into column families
  - E.g., *temperature* family contains columns *temperature:air* and *temperature:dew_point*
- Column families are stable
  - Specified as part of schema definition
- Individual columns can be added or removed easily
- All column family members are stored and managed together

Data Storage

- Table automatically partitioned into regions
  - Range of row keys
- Region managed by RegionServer, stored in HDFS or S3 etc.
- Small table -> single partition -> single-node database until it splits



Source:
Hadoop: The Definitive Guide,
by Tom White

Accessing HBase

- Clients connect to ZooKeeper to find Master
- Learn about RegionServer holding the requested data from Master
- Contact RegionServer for the actual data directly
  - Client caches region information it has learned for future accesses
- Write-ahead logging to HDFS ensures durability even if RegionServer crashes
  - Simplified DBMS-style redo of committed writes

HBase Clients

- **Java program**, e.g., from MapReduce
- Avro
- REST
- Thrift

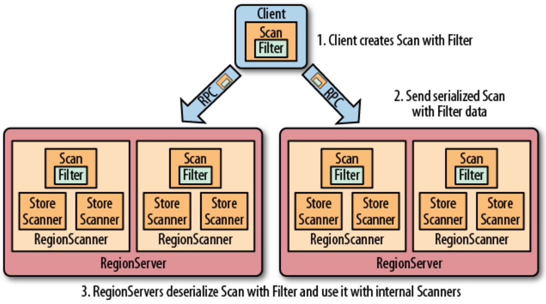
- Source for following examples: Hadoop: The Definitive Guide, by Tom White


```
public class ExampleClient {
 public static void main(String[] args) throws IOException {
  Configuration config = HBaseConfiguration.create();

  // Create table
  HBaseAdmin admin = new HBaseAdmin(config);
  HTableDescriptor htd = new HTableDescriptor("test");
  HColumnDescriptor hcd = new HColumnDescriptor("data");
  htd.addFamily(hcd);
  admin.createTable(htd);
  byte [] tablename = htd.getName();
  HTableDescriptor [] tables = admin.listTables();
  if (tables.length != 1 && Bytes.equals(tablename, tables[0].getName())) {
   throw new IOException("Failed create of table");
  }
```

- Creates table test with column family data
- Uses default table schema


```
  HTable table = new HTable(config, tablename);

  // Add new row named row1 to the table
  byte [] row1 = Bytes.toBytes("row1");
  Put p1 = new Put(row1);

  // Put value value1 into column data:1
  byte [] databytes = Bytes.toBytes("data");
  p1.add(databytes, Bytes.toBytes("1"), Bytes.toBytes("value1"));
  table.put(p1);

  // Read the contents of row row1
  Get g = new Get(row1);
  Result result = table.get(g);
  System.out.println("Get: " + result);

  // Scan the entire table
  Scan scan = new Scan();
  ResultScanner scanner = table.getScanner(scan);
  try {
   for (Result scannerResult: scanner) {
    System.out.println("Scan: " + scannerResult);
   }
  } finally { scanner.close(); }

  // Drop the table
  admin.disableTable(tablename);
  admin.deleteTable(tablename);
 }
}
```

Filters



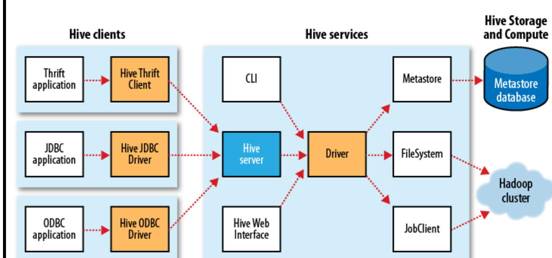
Source: HBase: The Definitive Guide, by Lars George

HBase and MapReduce

- Use org.apache.hadoop.hbase.mapreduce
- TableInputFormat makes sure each map task receives a single region
- TableOutputFormat allows reduce to write to an HBase table
- Look at the weather example in the Tom White book

Hive

- Initially developed by Facebook
- SQL-style data analysis on top of MapReduce
  - Write query in HiveQL
  - Automatically translated to plain MapReduce
- Integrates well with SQL tools, e.g., ODBC and JDBC
- Examples from Hadoop: The Definitive Guide, by Tom White



Source: Hadoop: The Definitive Guide, by Tom White

Hive vs. Relational DBMS

- Schema verified at query time
  - DBMS: schema enforced at data load time
- No updates or deletes, but insert is possible
- Rudimentary, but expanding, indexing support
  - Compact index: HDFS block numbers for each value
  - Bitmap index: compressed sets of rows where some value appears

Hive vs. Relational DBMS (cont.)

- Table- and partition-level locking
  - Locks managed by ZooKeeper
- Complex types ARRAY, MAP, and STRUCT
- Ongoing integration with HBase

Hive Storage

- Can use local file system, HDFS, S3 and so on
- Managed table: Hive copies files into its warehouse directory
- External table: location outside warehouse directory
- Row-oriented data layout: row 1, row 2, row 3
- Column-oriented layout: col 1 of some rows, col 2 of some rows, col 1 of next rows, col 2 of next rows

```
CREATE TABLE records (year STRING, temperature INT, quality INT)
ROW FORMAT DELIMITED
  FIELDS TERMINATED BY '\t';

LOAD DATA INPATH 'input/ncdc/micro-tab/sample.txt'
OVERWRITE INTO TABLE records;
```


Partitions

- Tables divided into partitions
  - Based on partition column(s), e.g., date
  - Partition attribute values determine directory structure
- Attributes used for partitioning do not appear in table schema any more

```
CREATE TABLE logs (ts BIGINT, line STRING)
PARTITIONED BY (dt STRING, country STRING);
```


Buckets

- Re-orders data in table
  - "Groups by" some attribute
  - Can sort within each group
- Very useful for equi-join
  - Hash-join style implementation

```
CREATE TABLE bucketed_users (id INT, name STRING)
CLUSTERED BY (id) SORTED BY (id ASC) INTO 4 BUCKETS;
```


Hive Query

```
SELECT year, MAX(temperature)
FROM records
WHERE temperature != 9999
  AND (quality = 0 OR quality = 1 OR quality = 4 OR quality = 5 OR quality = 9)
GROUP BY year;
```

- Plain SQL
- Executed as MapReduce job

Joins in Hive

- Inner join, outer join, semi join
- Hive uses rule-based optimizer
- Cost-based optimizer might be added in the future

```
SELECT sales.*, things.*
FROM sales JOIN things ON (sales.id = things.id);
```

```
SELECT sales.*, things.*
FROM sales LEFT OUTER JOIN things ON (sales.id = things.id);
```

```
SELECT * FROM things LEFT SEMI JOIN sales ON (sales.id = things.id);
```

Same as: `SELECT * FROM things WHERE things.id IN (SELECT id from sales);`

Advanced Features

- Subqueries
  - Limited compared to DBMS: only in FROM clause
- Views
  - Defined by HiveQL query
- User-defined functions: written in Java
- User-defined aggregate functions
  - Init() to reset internal state
  - Iterate() to update state
  - terminatePartial() to get partial result
  - Merge() to combine partial results
  - Terminate() to generate final result