6.5830 / 6.5831
Quiz 2 Review 🔍

November 27, 2023

Logistics

- **What:** Covers lectures 10 to 20 (inclusive)
- **When:** Wednesday during lecture (November 29, 2023 at 2:30 pm)
- **Where:** Lecture classroom (32-155)
- **Length:** 80 minutes
- **How:** Quiz will be on paper

- Open book/notes/laptop, but no Googling / LLMs please.
- Only class website is permitted.
- Email staff for special accommodation (6.5830-staff@mit.edu)

Topics

- Transactions
- Logging and recovery (ARIES)
- Parallel/distributed databases (analytics and transactions)
- Systems “potpourri”
  - High-performance transactional systems (H-Store / Calvin / Aurora)
  - Eventual consistency (DynamoDB)
  - Cluster computing (Spark)
  - Cloud analytics (Snowflake)
- Cardinality estimation

Transactions

- 🔑 Groups a sequence of operations into an all-or-nothing unit
  - A powerful abstraction!
- Desirable properties (ACID)
  - **Atomicity**: All or nothing
  - **Consistency**: Maintains application-specific invariants
  - ➡ **Isolation**: Transaction "appears" to run alone on the database
  - ➡ **Durability**: Committed transactions' writes persist even if the system crashes
- Transactions can be **aborted** by the user or DBMS

🔑 denotes a **key idea**

Transaction Isolation

- **Want:** Run transactions in parallel for performance reasons
- How to ensure “correctness”?
- 🔑 Create illusion of transactions running alone, one-by-one, on the database

Serial

Serializable

Conflict Serializability

A schedule is *conflict serializable* if it is possible to swap non-conflicting operations to derive a serial schedule.

Equivalently

For all pairs of conflicting operations {O1 in T1, O2 in T2} either

- O1 always precedes O2, or
- O2 always precedes O1.

Not conflict serializable:

T1	T2
RA	
	RA
	WA
WA	
RB	
WB	
	RB
	WB

Two Phase Locking (2PL) Protocol

- Before every read, acquire a shared lock
- Before every write, acquire an exclusive lock (or "upgrade") a shared to an exclusive lock
- 🔑 Release locks only after last lock has been acquired, and ops on that object are finished

T2 \ T1	S	X
S	✓	✗
X	✗	✗

Lock Compatibility Table

Problem: Cascading aborts

- If T1 aborts, T2, T3 and T4 also need to abort

- **Solution:** Just keep write locks until the end!

	T1	T2	T3	T4
Growing phase	WA			
		RA		
			RA	
				RA
	ABORT			
		ABORT		
			ABORT	
				ABORT

Strict Two-Phase Locking Protocol

- Before every read, acquire a shared lock
- Before every write, acquire an exclusive lock (or "upgrade") a shared to an exclusive lock
- Release *shared* locks only after last lock has been acquired, and ops on that object are finished
- Release *exclusive* locks only after the transaction commits
- Ensures cascadeless-ness

Rigorous Two-Phase Locking Protocol

- Before every read, acquire a shared lock
- Before every write, acquire an exclusive lock (or "upgrade") a shared to an exclusive lock
- 🔑 Release locks only after the transaction commits
- Ensures cascadeless-ness, and
- *Commit order = serialization order*

Example

- Permitted under strict 2PL but not rigorous 2PL:

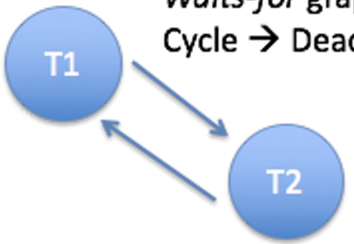
T1:	T2:
RA	
	WA
	COMMIT
COMMIT	

Deadlocks

- Possible for Ti to hold a lock Tj needs, and vice versa

	T1	T2	
	RA		
	WA		
		RB	
		WB	
T1 waits for T2 →	RB		
	WB		
		RA	← *T2 waits for T1*
		WA	

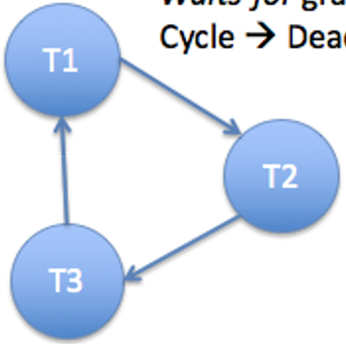
Waits-for graph
Cycle → Deadlock



Complex Deadlocks Are Possible

	T1	T2	T3
	RA		
	WA		
			RC
		RB	
		WB	
			RA ← *T3 waits for T1*
			WA
T1 waits for T2 →	RB		
	WB		
		RC ← *T2 waits for T3*	
		WC	

Waits-for graph
Cycle → Deadlock



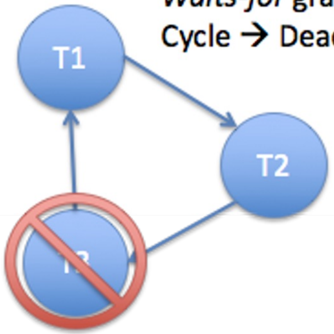
Resolving Deadlock

- Solution: abort one of the transactions
  - Recall: users can abort too

	T1	T2	
	RA		
	WA		
		RB	
		WB	
T1 waits for T2 →	RB		
	WB		
		RC	← ~~*T2 waits for T3*~~
		WC	

Equivalent to T2 - T1

Waits-for graph
Cycle → Deadlock



Final Wrinkle: Phantoms

- T1 scans a range; T2 later inserts into that range
- If T1 scans the range again, it will see a new value

<u>T1</u>
```
BEGIN
    SELECT * FROM emp WHERE SAL > 100
    …
    SELECT * FROM emp WHERE SAL > 200
END
```

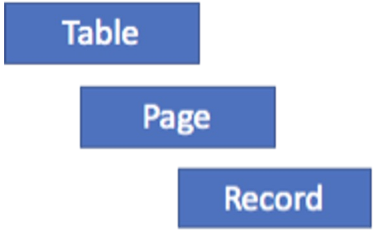
<u>T2</u>
```
BEGIN
    INSERT INTO EMP VALUES(…,sal=225)
END
```

If we are just locking, e.g., records, this insertion would be allowed in all 2PL algos we have studied, but is not serializable (since this couldn't happen in a serial execution).

Preventing phantom reads

- Easy way: Acquire table locks
- 🔑 But if we have a clustered index we don't need to scan the whole table for the range query. We can do better using "gap locks" / next key locking.
- Example:
  - DB Entries: 10, 11, 13, 20
  - T1: Scan entries > 18 → Also lock "gaps", i.e. lock gap 14 - 20 and 20 - ∞.
  - T2: Insert record 19 → Also needs to acquire the gap lock that T1 holds.
  - T1: Scan entries > 18 → No phantom read since T2 is waiting on the gap lock.

Locking Granularity / Intention Locks



T2 trying to acquire \ T1 holds	S (Reading / updating whole level)	X (Reading / updating whole level)	IX (Reading / updating lower level)	IS (Reading / updating lower level)
S	Y	N	N	Y
X	N	N	N	N
IX	N	N	Y	Y
IS	Y	N	Y	Y

- Suppose T1 wants to read record R1
- Needs to acquire *intention lock* on the Table and Page that T1 is in
- Intention lock marks higher levels with the fact that a transaction has a lock on a lower level
- Intention locks
  - Can be read intention or write intention locks
  - Prevent transactions from writing or reading the whole object when another transaction is working on a lower level
  - New *compatibility table*

Optimistic Concurrency Control (OCC)

- Alternative to locking for isolation
- Approach:
  - Store writes in a per-transaction buffer
  - Track read and write sets
  - At commit, check if transaction conflicted with earlier (concurrent) transactions
  - Abort transactions that conflict
  - Install writes at end of transaction
- 🔑 "Optimistic" in that it does not block, hopes to "get lucky" arrive in serial interleaving

OCC Implementation

- Divide transaction execution in 3 phases
  - **Read**: transaction executes on DB, stores local state
  - **Validate**: transaction checks if it can commit
  - **Write**: transaction writes state to DB

What If Serializability Isn't Needed?

- E.g., application only needs to read committed data
- Databases provide different isolation levels
  - READ UNCOMMITTED → 🔑 Do not acquire read locks.
    - Ok to read other transaction's dirty data
  - READ COMMITTED → 🔑 "Short" read locks.
    - Only read committed values
  - REPEATABLE READS → 🔑 No gap locks.
    - If R1 read A=x, R2 will read A=x ∀ A

- Many database systems default to READ COMMITTED

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Assumptions about crash

- Assume any data in memory is gone
- Data on disk is preserved
- → Recovery algorithms depend on when your system flushes pages

STEAL/NO FORCE ←→ UNDO/REDO

- If we STEAL pages, we will need to UNDO
- If we don't FORCE pages, we will need to REDO

Steal: Can write dirty pages to disk before the txn commits.

Force: Force writes to disk on txn commit. 🔑

	FORCE	NO FORCE
STEAL	UNDO	UNDO & REDO
NO STEAL	? UNDO	REDO

In GoDB, we do FORCE / NO STEAL and assume DB won't crash between FORCE and COMMIT

All commercial DBs do NO FORCE / STEAL for performance reasons

- If we FORCE pages, we will need to be able to UNDO if we crash between the FORCE and the COMMIT

Database State During Query Execution

Log records start and end of transactions, and contents of writes done to tables so we can solve both problems

Memory

Disk

🔑 **Write-ahead log!**

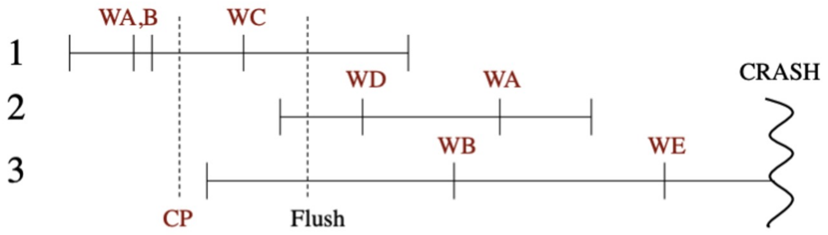
After crash, memory is gone!

🔑 **Problem 1**: Some transactions may have written their uncommitted state to tables – need to UNDO

Problem 2: Some transactions may not have flushed all of their state to tables prior to commit – need to REDO

Simplistic protocol

- Normal execution: Physical write-ahead-logging
- Recovery: Replay log from beginning. We can recover the exact state at the crash (physical logging)



LSN	Type	Tid	PrevLSN	Data
1	SOT	1		
2	UP	1	1	A
3	UP	1	2	B
[redacted]				
5	SOT	3		
6	UP	1	3	C
7	SOT	2		
8	UP	2	7	D
9	EOT	1	6	
10	UP	3	5	B
11	UP	2	8	A
12	EOT	2	11	
13	UP	3	10	E

Simplistic protocol: Problem #1

- We don't want to REDO things that are already reflected on disk (i.e. do an operation twice). That's a problem for escrows (e.g. record += 1).
  - Easy: Just keep a pageLSN field in the page header that tells you the last LSN that modified the page (at the time the page was flushed).

LSN	Type	Tid	PrevLSN	Data
1	SOT	1		
2	UP	1	1	A
3	UP	1	2	B
[redacted]				
5	SOT	3		
6	UP	1	3	C
7	SOT	2		
8	UP	2	7	D
9	EOT	1	6	
10	UP	3	5	B
11	UP	2	8	A
12	EOT	2	11	
13	UP	3	10	E

1. REDO

Disk

Page	pageLSN
A	2
B	3
C	6
D	0
E	0

🔑 Skip if LSN <= pageLSN

Simplistic protocol: Problem #2

- We want to recover to a state from which the user can resume normal operation (no pending transactions that were uncommitted at crash).
    - Easy: Just keep track of which transactions were not committed at crash and UNDO them. Can undo them logically (makes our life easier).

LSN	Type	Tid	PrevLSN	Data
1	SOT	1		
2	UP	1	1	A
3	UP	1	2	B
[redacted]				
5	SOT	3		
6	UP	1	3	C
7	SOT	2		
8	UP	2	7	D
9	EOT	1	6	
10	UP	3	5	B
11	UP	2	8	A
12	EOT	2	11	
13	UP	3	10	E

1. REDO

xactionTable

lastLSN	TID
13	3

Losers

2. UNDO 🔑

Simplistic protocol: Problem #3 (last one!)

- This is super slow! Imagine we need to replay a log containing months of transactions.
- 🔑 Only the last couple of log entries really need to be REDOne and UNDOne (with time pages get flushed & transactions commit)

LSN	Type	Tid	PrevLSN	Data
1	SOT	1		
2	UP	1	1	A
3	UP	1	2	B
[redacted]				
5	SOT	3		
6	UP	1	3	C
7	SOT	2		
8	UP	2	7	D
9	EOT	1	6	
10	UP	3	5	B
11	UP	2	8	A
12	EOT	2	11	
13	UP	3	10	E

1. REDO

Disk

Page	pageLSN
A	2
B	3
C	6
D	0
E	0

🔑 Skip if LSN <= pageLSN

Simplistic protocol: Problem #3 (last one!)

- This is super slow! Image we need to replay a log containing months of transactions.
- Only the last couple of log entries really need to be REDOne and UNDOne
- 🔑 For each dirty page in the buffer pool, we keep track which was the first LSN that dirtied it. → For this page, we only need to REDO the log from there.

LSN	Type	Tid	PrevLSN	Data
1	SOT	1		
2	UP	1	1	A
3	UP	1	2	B
[redacted]				
5	SOT	3		
6	UP	1	3	C
7	SOT	2		
8	UP	2	7	D
9	EOT	1	6	
10	UP	3	5	B
11	UP	2	8	A
12	EOT	2	11	
13	UP	3	10	E

dirtyPgTable

pgNo	recLSN
A	2
B	3
C	6
D	8

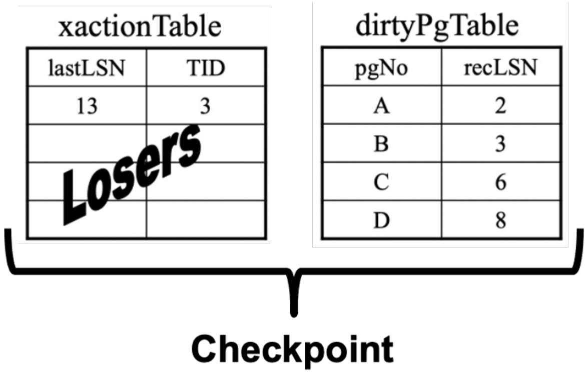
Simplistic protocol: Problem #3 (last one!)

- For each dirty page in the buffer pool, we keep track which was the first LSN that dirtied it. → For this page, we only need to REDO the log from there.
    - But where to keep this “dirty page table”?
    - Persist: Lots of logging and we need to force these writes to disk.
    - Memory: It will be lost at crash, so we need to start scanning the log from beginning again to build it.

    - 🔑 Solution: Checkpoints: Keep in memory but periodically write to disk.
    - You will need to scan some of the log to rebuild the dirty pages table, but not all of it!
    - At the same time you avoid doing a lot of forced writes!

Simplistic protocol: Problem #3 (last one!)

- What do we need to checkpoint to only re-scan some of the log?
  - Dirty page table
  - Transaction table



xactionTable

lastLSN	TID
13	3

dirtyPgTable

pgNo	recLSN
A	2
B	3
C	6
D	8

Simplistic protocol: Problem #3 (last one!)

- What do we need to checkpoint to only re-scan some of the log?
  - Dirty page table
  - Transaction table

"UNDO table"

xactionTable

lastLSN	TID
13	3

Losers

"REDO table"

dirtyPgTable

pgNo	recLSN
A	2
B	3
C	6
D	8

Checkpoint

Summary / ARIES

- Normal operation:
  - Physical write-ahead-logging
  - Include LSN of last update in page headers (pageLSN)
  - Keep track of active transactions (for UNDO) and LSNs that first dirtied a page (for REDO) → checkpoint that periodically.
- Recovery:
  - **Analysis phase**: Start from last checkpoint in log and reconstruct transaction table and dirty page table at time of crash.
  - **REDO phase**: Physically REDO log records that haven't been flushed before crash. After that, your system will be in the state at the crash.
  - **UNDO phase**: UNDO transactions that weren't committed at the time of the crash ("losers").

Redo

- Where to begin?
  - Min(recLSN)! – earliest unflushed update
- Redo an update UNLESS:
  - Page is not in dirtyPgTable
    - Page flushed prior to checkpoint, didn't re-dirty
  - LSN < recLSN
    - Page flushed & re-dirtied prior to checkpoint
  - LSN <= pageLSN
    - Page flushed after checkpoint
    - *Only step that requires going to disk*

dirtyPgTable

pgNo	recLSN
A	$\boxed{2}$
B	3
C	6
D	8
E	13

Disk

Page	pageLSN
A	2
B	3
C	6
D	0
E	0

UNDO

- 🔑 We need to log UNDOs
  - If we crash during recovery
  - If we crash while rolling back an aborted transaction
  - These log records are called Compensation Log Records (CLRs)
- Check where to start UNDO (lastLSN in Transaction Table) and UNDO each update going backwards using the prevLSN field in log

LSN	Type	Tid	PrevLSN	Data
10	UP	3	5	B
11	UP	2	8	A
12	EOT	2	11	
13	UP	3	**10**	E

xactionTable

lastLSN	TID
13	3

Losers

UNDO

- 🔑 We need to log UNDOs
  - If we crash during recovery
  - If we crash while rolling back an aborted transaction
  - These log records are called Compensation Log Records (CLRs)
- Check where to start UNDO (lastLSN in Transaction Table) and UNDO each update going backwards using the prevLSN field in log

LSN	Type	Tid	PrevLSN	Data
10	UP	3	5	B
11	UP	2	8	A
12	EOT	2	11	
13	UP	3	**10**	E
14	CLR	3	13	E, 10

xactionTable

lastLSN	TID
10	3

Losers

V ARIES

10. [10 points]: Which of the following statements about ARIES recovery are true?

A. True / False If a CLR (Compensation Log Record) is found in the log, the system must have crashed during the REDO phase of the ARIES Algorithm.

B. True / False In theory, if the recovery algorithm keeps crashing during recovery forever, then due to the CLR logs being added the size of the log can keep on increasing forever.

C. True / False Dirty pages are flushed to the disk at checkpoints.

D. True / False We can always get rid of the log before the second last checkpoint.

E. True / False PrevLSN is used to determine where to start the REDO phase from.

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Distributed and Parallel Databases

- 🔑 Same semantics as a single-node ACID SQL database, but on multiple cores/machines

- Distributed databases must deal with node failures

Ways to Partition the Data

- **Round-robin**
  - Perfect load-balancing (data-wise)
  - Often all nodes need to participate in a query
- **Hash**
  - Pretty good load balancing (unless many duplicates)
  - Bad at range analytical queries (cannot easily skip partitions)
- **Range**
  - Good at range / localized analytical queries
  - Can be bad at load-balancing (data skew)

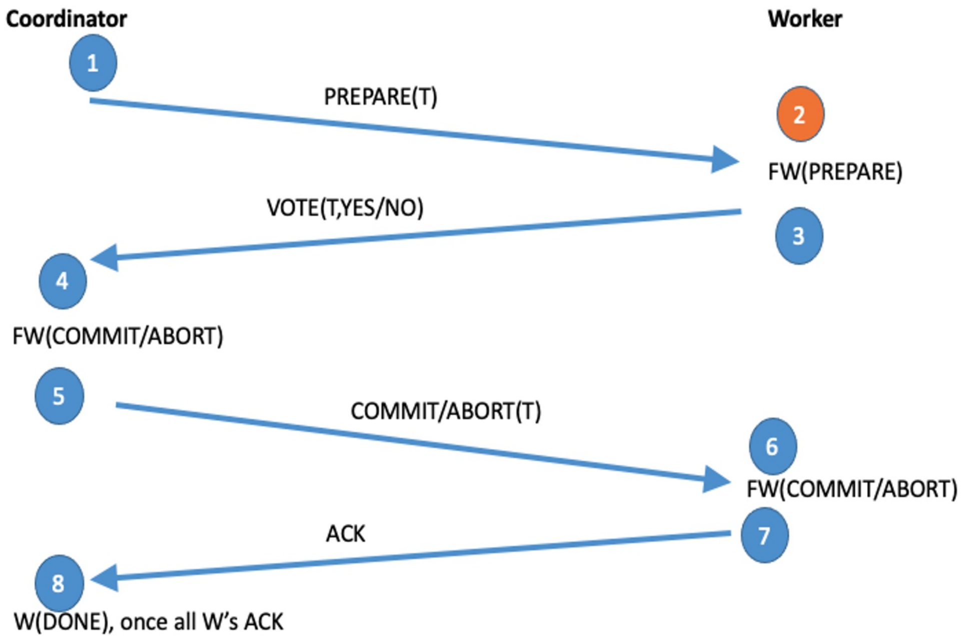
Parallel Joins (Hash Partitioning and Equijoins)

- **Partitioned on join attributes?** Run join locally on each partition.
- Otherwise, two options (non-exhaustive):
- **Re-partition (one or both tables): “shuffle join”**
  - Each node transmits and receives (|T| / n) / n * (n - 1) bytes per repartitioned table
- **Replicate table across all nodes**
  - Each node transmits and receives (|T| / n) * (n - 1) bytes

Distributed Transactions: Two Phase Commit

- 🔑 Distributed algorithm used to make a commit/abort decision **for multiple “sites”**
    - “Commit only if **all** participants agree to commit”
- Requires a coordinator
- Often considered a performance bottleneck

Two Phase Commit



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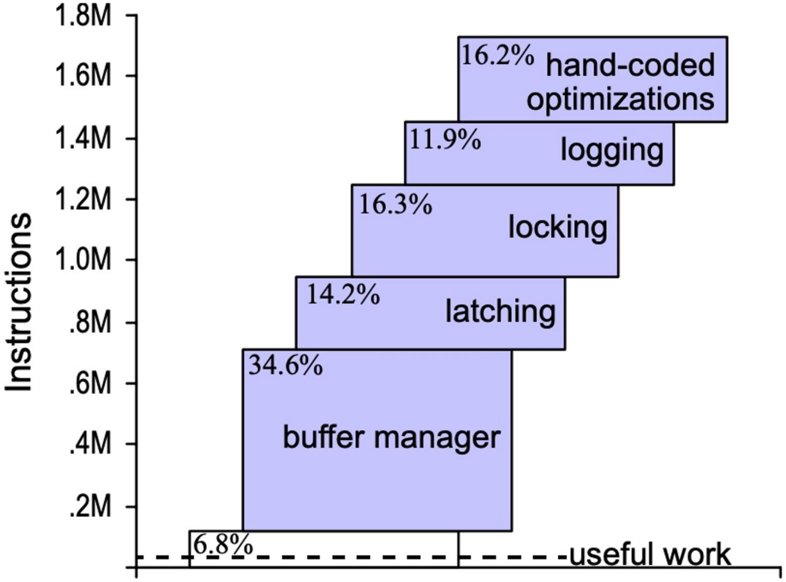
High-Performance Transactions

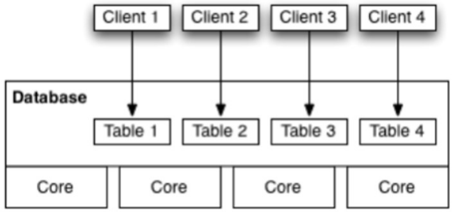
- Running old code on new hardware $\nRightarrow$ speed-up
- New performance bottlenecks
- 2PC is slow
- Consider new architectures!



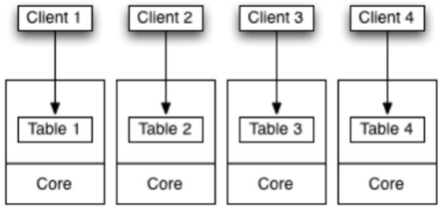
Stavros Harizopoulos, Daniel J. Abadi, Samuel Madden, and Michael Stonebraker. OLTP through the looking glass, and what we found there. SIGMOD 2008

H-Store

- **Distributed <u>in-memory</u> DBMS**
  - Often enough memory to store the entire dataset
- 🔑 **Partition the data; single-thread per partition**
  - Eliminate coordination overhead within a partition
- **Stored-procedure transactions**
  - Optimize partitioning for the workload
  - Avoid waiting for the client
- **Weaknesses**
  - Stored-procedure assumption
  - Multi-partition transactions?



“Classical” design



Thread-per-partition

Diagrams courtesy of Prof. Andy Pavlo

Calvin

- **Distributed DBMS**
- 🔑 **Deterministic execution**
  - Avoid distributed coordination (2PC) during transaction execution by determining a non-conflicting, deterministic execution order up front!
  - Ordering performed in batches
- **Weaknesses**
  - Need to know transactions & read/write sets up front
  - Stored-procedure assumption
  - If lot of contention (e.g. all txns contend for one record) you can only issue them one at a time (no other way to avoid conflicts)

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CAP theorem

- Consistency, availability, partition-tolerance: You can have 2, not all 3 🔑

- ACID has strong consistency but will appear down if machines go down or network becomes partitioned

- Many systems choose availability over consistency (e.g. NoSQL)

Dynamo

- Availability
- Partitioning
    - for scaling
    - consistent hashing 🔑
- Replication
    - for fault tolerance and performance
    - ‘N’ successors in the ring stores the key
- Vector clocks for detecting conflicting writes

Vector Clock Updates

- Each coordinator maintains a version counter for **each data item** that increments for every write it coordinates
  - If a node stores m objects, it stores m vector clocks along with them
  - Each vector clock has n entries, which denote the number of writes done by each of n coordinators

- Clock for one data item A at coordinator i
  - before: V_A[1], …, V_A[i], …, V_A[n]
  - after: : V_A[1], …, $\boldsymbol{V_A}$**[i]+1**, …, V_A[n]

Vector Clock

- Read - Read from the quorums
- E.g.: Read V1, V2, V3 - If one of these, say V1, is greater than the others for every component, V1 is the latest value and we can reconcile based on vector clocks
- What if they are incomparable? ---> i.e., can't decide which is the latest version of the data
  - V1 = [1, **1**], V2 = [**2**, 0]
  - Return both data versions, and use application-specific reconciliation 🔑

Dynamo Question (2015)

Which of the following statements are true?

V1 =< R1 : 0, R2 : 3, R3 : 2 >

V2 =< R1 : **1**, R2 : 3, R3 : **2** >

V3 =< R1 : **0**, R2 : 0, R3 : **3** >

A) The writer that produced V1 observed V2
B) The writer that produced V2 observed V1
C) V2 and V3 are :”concurrent writes” (cannot be reconciled)

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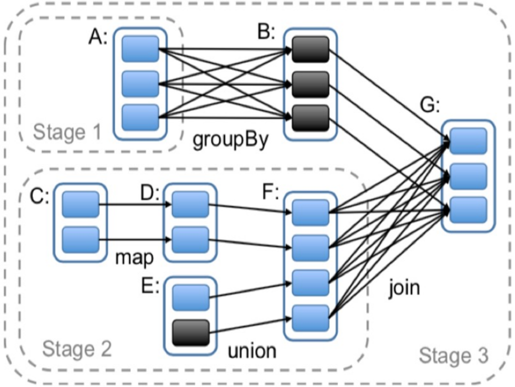
Spark

- Distributed “dataflow” language
- Resilient Distributed Dataset (RDD) which you can perform operations on
- Programs operate on partitions of data in parallel



Spark: Memory use

🔑 ● Intermediate results are kept in-memory (e.g. in contrast to MapReduce)
● Very useful for interactive or iterative workloads, e.g., ML tasks that train over same data periodically

Spark: Lineage

- Limit operations to coarse-grained transformations and only log the transformations instead of replicating data for recovering ---> **Lineages**

Use cases to recover from failure:

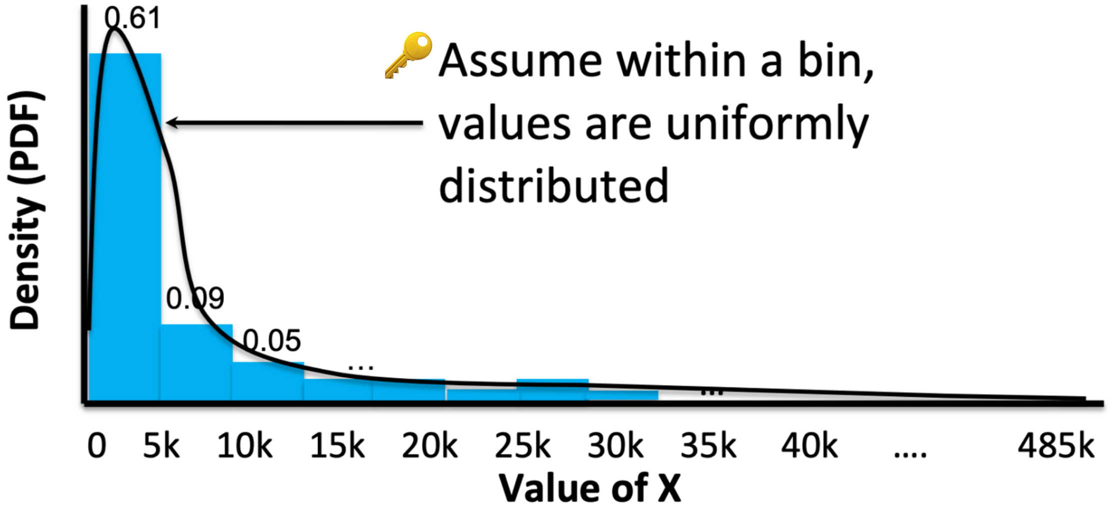
- Short lineage chain? 🔑
  - Just recompute from lineage
- Long lineage chain?
  - Checkpoint intermediate results to stable storage!

Topics

- Transactions
- Logging and recovery (ARIES)
- Parallel/distributed databases (analytics and transactions)
- Systems “potpourri”
  - High-performance transactional systems (H-Store / Calvin / Aurora)
  - Eventual consistency (DynamoDB)
  - Cluster computing (Spark)
  - Cloud analytics (Snowflake)
- Cardinality estimation

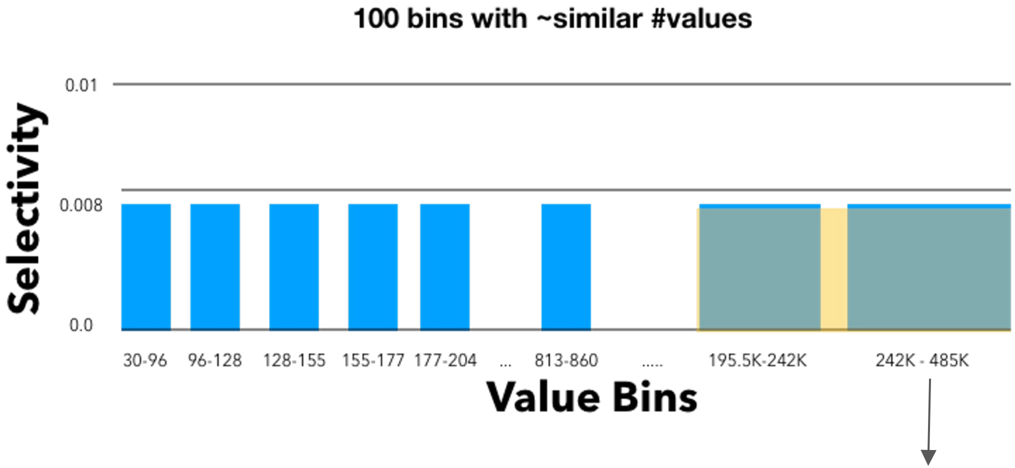
Equal-width histograms

- Histograms can approximate any distribution (pdf) for a single attribute.
- Easy to build (ANALYZE): scan (sample of) one table.



Cardinality Estimation for one column

Equal width vs **Equal depth histograms**



Source of error: Within this large bucket, assume **uniformity**

Pros

- More detail where there is more data ---> uniformity assumption more accurate
- Fast to compute

Cons

- Less detail in other regions (e.g., in the large bins)

Cardinality Estimation for 2 columns

- Take selectivity estimates for single columns, and assume they are 🔑 **independent,** i.e. multiply selectivities.

Pros
- Fast to compute
- Don't need to store 2d distributions etc.

Cons
- Columns are often correlated (might severely misestimate then)
- Errors will accumulate as more columns / joins added

Main Assumptions

- Uniformity
  - Within a bin of histogram; (or when computing joins)
- Independence
  - When combining selectivities for multiple columns