EECS 262a
Advanced Topics in Computer Systems
Lecture 10

Transactions and Isolation Levels 2
February 24th, 2016

Alan Fekete

Slides by Alan Fekete (University of Sydney), Anthony D. Joseph and John Kubiatowicz (UC Berkeley)

http://www.eecs.berkeley.edu/~kubitron/cs262

Today's Papers

- **The Notions of Consistency and Predicate Locks in a Database System**
  K.P. Eswaran, J.N. Gray, R.A. Lorie, and I.L. Traiger. Appears in *Communications of the ACM*, Vol. 19, No. 11, 1976
- **Key Range Locking Strategies for Improved Concurrency**
  David Lomet. Appears in *Proceedings of the 19th VLDB Conference*, 1993
- Thoughts?

Overview

- Serializability
- The Phantom Issue
- Predicate Locking
- Key-Range Locks
- Next-Key Locking techniques
- Index Management and Transactions
- Multi-level reasoning

Theory and reality

- Traditional serializability theory treats database as a set of items (Eswaran et al '76 says "entities") which are read and written
- Two phase locking is proved correct in this model
  – We now say "serializable"
- But, database has a richer set of operations than just read/write
  – Declarative selects
  – Insert
  – Delete

Review: Goals of Transaction Scheduling

- Maximize system utilization, i.e., concurrency
  - Interleave operations from different transactions
- Preserve transaction semantics
  - Semantically equivalent to a serial schedule, i.e., one transaction runs at a time

T1: R, W, R, W **T2:** R, W, R, R, W

Serial schedule (T1, then T2):
R, W, R, W, R, W, R, R, W

Serial schedule (T2, then T1):
R, W, R, R, W, R, W, R, W

Two Key Questions

1) Is a given schedule equivalent to a serial execution of transactions?

Schedule: R, R, W, W, R, R, R, W, W

≡ ? ≡ ?

Serial schedule (T1, then T2):
R, W, R, W, R, W, R, R, W

Serial schedule (T2, then T1):
R, W, R, R, W, R, W, R, W

2) How do you come up with a schedule equivalent to a serial schedule?

Transaction Scheduling

- **Serial schedule:** A schedule that does not interleave the operations of different transactions
  - Transactions run serially (one at a time)
- **Equivalent schedules:** For any storage/database state, the effect (on storage/database) and output 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
  - Intuitively: with a serializable schedule you only see things that could happen in situations where you were running transactions one-at-a-time

Anomalies with Interleaved Execution

- May violate transaction semantics, e.g., some data read by the transaction changes before committing
- Inconsistent database state, e.g., some updates are lost
- Anomalies always involves a “write”; Why?

Anomalies with Interleaved Execution

- Read-Write conflict (Unrepeatable reads)

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

- Violates transaction semantics
- Example: Mary and John want to buy a TV set on Amazon but there is only one left in stock
  - (T1) John logs first, but waits…
  - (T2) Mary logs second and buys the TV set right away
  - (T1) John decides to buy, but it is too late…

Anomalies with Interleaved Execution

- Write-read conflict (reading uncommitted data)

```
T1:R(A),W(A),     W(A)
T2:          R(A),    …
```

- Example:
  - (T1) A user updates value of A in two steps
  - (T2) Another user reads the intermediate value of A, which can be inconsistent
  - Violates transaction semantics since T2 is not supposed to see intermediate state of T1

Anomalies with Interleaved Execution

- Write-write conflict (overwriting uncommitted data)

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

- Get T1's update of B and T2's update of A
- Violates transaction serializability
- If transactions were serial, you'd get either:
  - T1's updates of A and B
  - T2's updates of A and B

Conflict Serializable Schedules

- Two operations **conflict** if they
  - Belong to different transactions
  - Are on the same data
  - At least one of them is a write
- Two schedules are **conflict equivalent** iff:
  - Involve same operations of same transactions
  - Every pair of **conflicting** operations is ordered the same way
- Schedule S is **conflict serializable** if S is conflict equivalent to some serial schedule

Conflict Equivalence – Intuition

- If you can transform an interleaved schedule by swapping *consecutive non-conflicting* operations of *different transactions* into a serial schedule, then the original schedule is **conflict serializable**
- Example:

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

⇩

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

⇩

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


Conflict Equivalence – Intuition (cont’d)

- If you can transform an interleaved schedule by swapping *consecutive non-conflicting* operations of *different transactions* into a serial schedule, then the original schedule is **conflict serializable**
- Example:

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

⇩

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

⇩

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


Conflict Equivalence – Intuition (cont’d)

- If you can transform an interleaved schedule by swapping *consecutive non-conflicting* operations of *different transactions* into a serial schedule, then the original schedule is **conflict serializable**

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

- Is this schedule serializable?

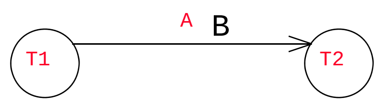
Dependency Graph

- **Dependency graph:**
  - Transactions represented as nodes
  - Edge from Ti to Tj:
    - » an operation of Ti conflicts with an operation of Tj
    - » Ti appears earlier than Tj in the schedule
- **Theorem:** Schedule is conflict serializable if and only if its dependency graph is acyclic

Example

- Conflict serializable schedule:

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



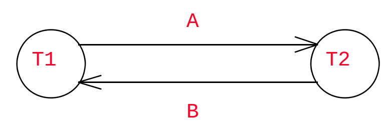
Dependency graph

- No cycle!

Example

- Conflict that is *not* serializable:

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



Dependency graph

- Cycle: The output of T1 depends on T2, and vice-versa

Notes on Conflict Serializability

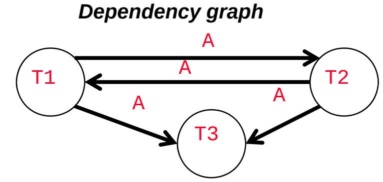
- Conflict Serializability doesn't allow all schedules that you would consider correct
  - This is because it is strictly *syntactic* - it doesn't consider the meanings of the operations or the data
- In practice, Conflict Serializability is what gets used, because it can be done efficiently
  - Note: in order to allow more concurrency, some special cases do get implemented, such as for travel reservations, …
- Two-phase locking (2PL) is how we implement it

Serializability ≠ Conflict Serializability

- Following schedule is **not** conflict serializable

```
T1:R(A),     W(A),
T2:     W(A),
T3:                 WA
```

Dependency graph



- However, the schedule is serializable since its output is equivalent with the following serial schedule

```
T1:R(A),W(A),
T2:          W(A),
T3:               WA
```

- Note: deciding whether a schedule is serializable (not conflict-serializable) is NP-complete

Locks (Simplistic View)

- Use *locks* to control access to data

- Two types of locks:
  - shared (S) lock – multiple concurrent transactions allowed to operate on data
  - exclusive (X) lock – only one transaction can operate on data at a time

Lock Compatibility Matrix

	S	X
S	√	–
X	–	–

Two-Phase Locking (2PL)

1) Each transaction must obtain:
   - S (*shared*) or X (*exclusive*) lock on data before reading,
   - X (*exclusive*) lock on data before writing

2) A transaction can not request additional locks once it releases any locks

Thus, each transaction has a "growing phase" followed by a "shrinking phase"

Avoid deadlock by acquiring locks in some lexicographic order

Two-Phase Locking (2PL)

- 2PL guarantees conflict serializability

- Doesn't allow dependency cycles. Why?

- Answer: a dependency cycle leads to deadlock
  - Assume there is a cycle between Ti and Tj
  - Edge from Ti to Tj: Ti acquires lock first and Tj needs to wait
  - Edge from Tj to Ti: Tj acquires lock first and Ti needs to wait
  - Thus, both Ti and Tj wait for each other
  - Since with 2PL neither Ti nor Tj release locks before acquiring all locks they need → deadlock

- Schedule of conflicting transactions is conflict equivalent to a serial schedule ordered by "lock point"

Example

- T1 transfers $50 from account A to account B

```
T1:Read(A),A:=A-50,Write(A),Read(B),B:=B+50,Write(B)
```

- T2 outputs the total of accounts A and B

```
T2:Read(A),Read(B),PRINT(A+B)
```

- Initially, A = $1000 and B = $2000

- What are the possible output values?
  - 3000, 2950, 3050

Is this a 2PL Schedule?

1	Lock_X(A) <granted>	
2	Read(A)	Lock_S(A)
3	A: = A-50	
4	Write(A)	
5	Unlock(A)	<granted>
6		Read(A)
7		Unlock(A)
8		Lock_S(B) <granted>
9	Lock_X(B)	
10		Read(B)
11	<granted>	Unlock(B)
12		PRINT(A+B)
13	Read(B)	
14	B := B +50	
15	Write(B)	
16	Unlock(B)	

No, and it is not serializable

Is this a 2PL Schedule?

1	Lock_X(A) <granted>	
2	Read(A)	Lock_S(A)
3	A: = A-50	
4	Write(A)	
5	Lock_X(B) <granted>	
6	Unlock(A)	<granted>
7		Read(A)
8		Lock_S(B)
9	Read(B)	
10	B := B +50	
11	Write(B)	
12	Unlock(B)	<granted>
13		Unlock(A)
14		Read(B)
15		Unlock(B)
16		PRINT(A+B)

Yes, so it is serializable

Cascading Aborts

- Example: T1 aborts
  - Note: this is a 2PL schedule

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

- Rollback of T1 requires rollback of T2, since T2 reads a value written by T1
- Solution: **Strict Two-phase Locking (Strict 2PL)**: same as 2PL except
  - All locks held by a transaction are released only when the transaction completes

Strict 2PL (cont'd)

- All locks held by a transaction are released only when the transaction completes
- In effect, "shrinking phase" is delayed until:
  a) Transaction has committed (commit log record on disk), or
  b) Decision has been made to abort the transaction (then locks can be released after rollback)

Is this a Strict 2PL schedule?

1	Lock_X(A) <granted>	
2	Read(A)	Lock_S(A)
3	A: = A-50	
4	Write(A)	
5	Lock_X(B) <granted>	
6	Unlock(A)	<granted>
7		Read(A)
8		Lock_S(B)
9	Read(B)	
10	B := B +50	
11	Write(B)	
12	Unlock(B)	<granted>
13		Unlock(A)
14		Read(B)
15	No: Cascading Abort	Unlock(B)
16	Possible	PRINT(A+B)

Is this a Strict 2PL schedule?

1	Lock_X(A) <granted>	
2	Read(A)	Lock_S(A)
3	A: = A-50	
4	Write(A)	
5	Lock_X(B) <granted>	
6	Read(B)	
7	B := B +50	
8	Write(B)	
9	Unlock(A)	
10	Unlock(B)	<granted>
11		Read(A)
12		Lock_S(B) <granted>
13		Read(B)
14		PRINT(A+B)
15		Unlock(A)
16		Unlock(B)

Overview

- Serializability
- The Phantom Issue
- Predicate Locking
- Key-Range Locks
- Next-Key Locking techniques
- Index Management and Transactions
- Multi-level reasoning

Phantom

T1

```
Select count(*)
where dept = “Acct”
//find and S-lock (“Sue”,
  “Acct”, 3500) and (“Tim”,
  “Acct, 2400)
```

T2

```
Insert (“Joe”,”Acct”, 2000)
//X-lock the new record
Commit
//release locks
```

```
Select sum(salary)
where dept = “Acct”
//find and S-lock (“Sue”,
  “Acct”, 3500) and (“Tim”,
  “Acct, 2400) and (“Joe”,
  “Acct”, 2000)
```

Phantoms and Commutativity

- A predicate-based select doesn't commute with the insert of a record that meets the select's where clause
- We need to have some lock to protect the correctness of the result of the where clause
  - Not just the records that are the result!
  - Eswaran et al '76 describe (conceptually) locking the records that might exist but don't do so yet

Page-level locking

- The traditional concurrency control in the 1970s was page-level locking
- If all locks are at page granularity or above, phantoms can't arise
  - Lock every page read or written (even when page is scanned and no records are found/returned)
  - There are no queries to find a set of pages
- But performance is often poor
  - Lots of false conflicts, low concurrency obtained

Overview

- Serializability
- The Phantom Issue
- Predicate Locking
- Key-Range Locks
- Next-Key Locking techniques
- Index Management and Transactions
- Multi-level reasoning

Predicate Locking

- Solution proposed by Eswaran et al in the 1976 journal paper where they identified and explained the phantom issue
  - And also gave a proof of correctness of 2PL!
  - Context: transactions and serializability were new ideas!
- Never implemented in any system I know of

Locking Predicates

- S-Lock the predicate in a where-clause of a SELECT
  - Or a simpler predicate that "covers" this
- X-lock the predicate in a where clause of an UPDATE, INSERT or DELETE

Conflict decision

- A lock can't be granted if a conflicting lock is held already
- For predicates, a Lock on P by T conflicts with Lock on Q by U if
  - Locks are not both S-mode
  - T different from U
  - P and Q are mutually satisfiable
    - » Some record r could exist in the schema such that P(r) and Q(r)

An Effective Test for Conflict

- In general, satisfiability of predicates is undecidable
- Eswaran et al suggest using covering predicates that are boolean combinations of atomic equality/inequalities

$$P = (\text{Location} = \text{'Napa'} \vee \text{Location} = \text{'Santa Rosa'}) \wedge (\text{Balance} < 500 \wedge \text{Balance} > 10)$$
$$P' = \text{Location} = \text{'Napa'} \wedge \text{Balance} = 700.$$

Then the disjunctive normal form of $P \wedge P'$ is

$$\text{Location} = (\text{'Napa'} \wedge \text{Balance} < 500 \wedge \text{Balance} > 10 \wedge \text{Balance} = 700) \vee (\text{Location} = \text{'Santa Rosa'} \wedge \text{Location} = \text{'Napa'} \wedge \text{Balance} < 500 \wedge \text{Balance} > 10 \wedge \text{Balance} = 700).$$

- Satisfiability is a decidable problem, but not efficient

Implementation Issues

- Note the contrast to traditional lock manager implementations
  - Conflict is only on lock for same lockname
  - Can be tested by quick hashtable lookup!

Overview

- Serializability
- The Phantom Issue
- Predicate Locking
- Key-Range Locks
- Next-Key Locking techniques
- Index Management and Transactions
- Multi-level reasoning

BREAK

CS262a Project Proposals

- Two People from this class
  - Projects can overlap with other classes
  - Exceptions to the two person requirement need to be OK'd
- Should be a miniature research project
  - State of the art (can't redo something that others have done)
  - Should be "systems related", i.e. dealing with large numbers of elements, big data, parallelism, etc…
  - Should be publishable work (but won't quite polish it off by end of term)
  - Must have solid methodology!
- Metric of success/base case for measurements
  - Figure out what your "metrics of success" are going to be…
  - What is the base case you are measuring against?
- Project proposals due Friday at midnight – should have:
  - Motivation and problem domain
  - Description of what you are going to do and what is new about it
  - How you are going to do the evaluation (what is methodology, base case, etc.)
  - If you need resources, you need to tell us NOW exactly what they are…
  - List of ALL participants

Key-Range Locks (Lomet'93)

- A collection of varying algorithms/implementation ideas for dealing with phantoms with a lock manager which only considers conflicts on the same named lock
  - Some variants use traditional Multi-Granularity Locking (MGL) modes: IX, IS, SIX, etc.
  - Other dimensions of variation: whether to merge locks on keys, ranges, records
    - » Are deleted records removed, or just marked deleted
    - » Are keys unique, or duplicatable

Main Ideas

- Avoid phantoms by checking for conflicts on dynamically chosen ranges in key space
  - –Each range is from one key that appears in the relation, to the next that appears
- Define lock modes so conflict table will capture commutativity of the operations available
- Conservative approximations: simpler set of modes, that may conflict more often

Range

- If *k0* is one key and *k* is the next, that appear in the relation contents
  - –(*k0*,*k*] is the semi-open interval that starts immediately above *k0* and then includes *k*
- Name this range by something connected to *k* (but distinguish it from the key lock for *k*)
  - –Example: *k* with marker for range
  - –Or use *k* for range, Record ID for key itself
- Note: insert or delete will change the set of ranges!

Operations of the storage layer

- Read at *k*
- Update at *k*
- Insert
- Delete
- Scan from *k* to *k'* (or fetch next after *k*, as far as *k'*)
  - –Note that higher query processing converts complex predicates into operations like these
    - » Locks on scan ranges will automatically cover the predicate in the query

Overview

- Serializability
- The Phantom Issue
- Predicate Locking
- Key-Range Locks
- Next-Key Locking techniques
- Index Management and Transactions
- Multi-level reasoning

Current Practice

- Implementations do not use the full flexibility of Lomet's modes
- Common practice is to use MGL modes, and to merge lock on range with lock on upper key
  - A S-lock on key *k* implicitly is also locking the range (*k0*,*k*] where *k0* is the previous key
  - This is basis of ARIES/KVL

Insertion

- As well as locking the new record's key, take instant duration IX lock on the next key
  - Make sure no scan has happened that would have showed the non-existence of key just being inserted
  - No need to prevent future scans of this range, because they will see the new record!

Gap Locks

- A refinement S-locks a range (*k0*,*k*] by S-locking the key *k*, and separately it gets a lock on *k* with a special mode G, that represents the gap – the open interval (*k0*,*k*)
- This is used in InnoDB

Overview

- Serializability
- The Phantom Issue
- Predicate Locking
- Key-Range Locks
- Next-Key Locking techniques
- Index Management and Transactions
- Multi-level reasoning

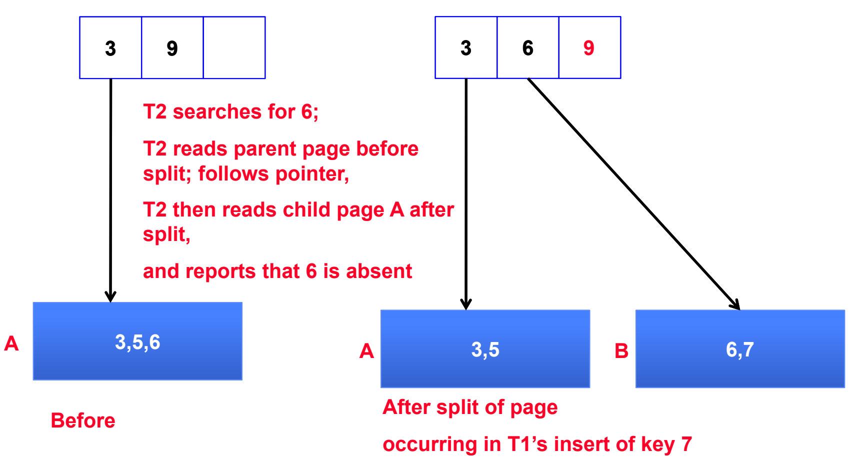
Indices

- Primary index
  - Leaves contain all records with data from table
  - Higher levels contain some records that point to leaf pages or other index pages, with keys to work out which pointer to follow
- Secondary index
  - Leaves contain value of some attribute, and some way to access the records of the data that contain that value in the attribute
    - » Eg primary key value, rowid, etc

Problems

- Suppose we don't do concurrency control on the index structure, but just on the data records (in the leaves)
- Two problems can arise
  - Impossible structure
    - » Transaction executes an operation that sees a structure that violates data structure properties
  - Phantom: query with where clause sees the wrong set of values
    - » Access through an index must protect against insertion of future matching data record

Mangled Data Structure



Logical Locks and Physical Latches

	Locks	*Latches*
Separate …	User transactions	Threads
Protect …	Database contents	In-memory data structures
During …	Entire transactions	Critical sections
Modes …	Shared, exclusive, update, intention, escrow, schema, etc.	Read, writes, (perhaps) update
Deadlock …	Detection & resolution	Avoidance
… by …	Analysis of the waits-for graph, timeout, transaction abort, partial rollback, lock de-escalation	Coding discipline, "lock leveling"
Kept in …	Lock manager's hash table	Protected data structure

From Graefe, TODS 35(3):16

Lock: logical level, held for transaction duration

Latch: physical level, held for operation duration

Latch Coupling

- When descending a tree
  - Hold latch on parent until after latch on child is obtained
- Exception: if child is not in buffer (it must be fetched from disk)
  - Release latch on parent
  - Return to root, traverse tree again

Avoiding Undos for Structural Modifications

- Use System Transactions
  - To ensure recoverability, but avoid lots of unneeded data movement during transaction rollback
- Perform structure modification as separate transaction, outside the scope of the user transaction that caused it
  - Structure modification is logical no-op
  - Eg insert is done by system transaction that splits page; then record is inserted by user transaction into the now-available space

Overview

- Serializability
- The Phantom Issue
- Predicate Locking
- Key-Range Locks
- Next-Key Locking techniques
- Index Management and Transactions
- Multi-level reasoning

Abstraction

- Data structures can be considered as abstract data types with mathematical values, or as a complex arrangement of objects-with-references
- Example: compare a hash table abstractly as a Map (relating keys and values), or concretely as an array of linked lists

Abstraction

- An operation that changes the logical abstract content is realized by a complex sequence of changes to the objects and references
- The same abstract state can be represented by many different detailed arrangements

Abstraction

- Both concurrency control and recovery can be designed in different ways, depending on what level of abstraction is being considered
- For a DBMS, we can think of a relational table in different levels

Logical View

- Treat the relation as a set of records
- Order not important
- Layout not important
- Example:
  - –We log that we executed INSERT (7, fred) into Table57

Physical View

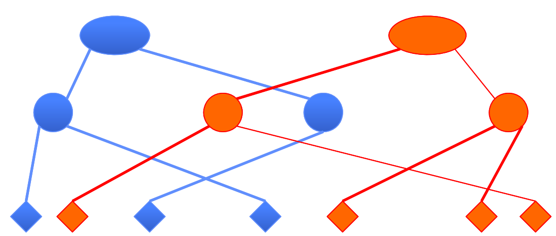
- Treat the relation as a collection of pages whose bits are described
- Example:
  - –We log that bytes 18 to 32 in page 17, and bytes 4 to 64 in page 19, were changed as follows…

Physiological View

- Treat the relation as a collection of pages each of which contains a set of records
- Example:
  - We log that in page 17 record (7, fred) was inserted
- “Logical within a page, but physical pages are noticed”
- Enables placing the LSN of relevant log entry into each page

Multi-level Execution

- Top level is a set of transactions
- Next level shows how each transaction is made of logical operations on relations
- Then we see how each logical operation is made up of page changes, each described physiologically
- Lowest level shows operations, each of which has physical changes on the bits of a page



Lowest level operations happen in time order as shown

Multi-level Execution

- Lowest level operations are in a total order of real-time
- Higher levels may have concurrency between the operations
  - Deduce this from whether their lowest-level descendants form overlapping ranges in time

Multi-level Reasoning

- Each level can be rearranged to separate completely the operations of the level above, provided appropriate policies are used
  - Once rearranged, forget there was a lower layer
- If an operation contains a set of children whose combined effect is no-op (at that level), then remove the operation entirely

Multilevel Transaction Management

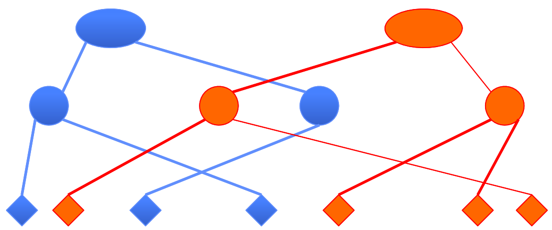
- Obtain a suitable-mode lock when performing an operation at a level
  - Hold the lock until the parent operation completes
- To abort an operation that is in-progress, perform (and log) compensating operations for each completed child operation, in reverse order

Necessary Properties

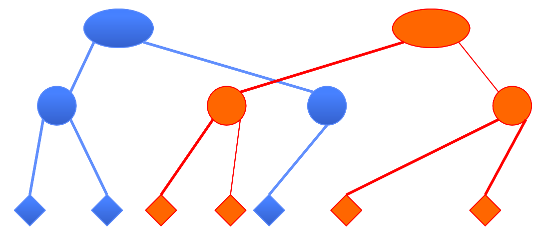
- Lock modes
  - If operations at a level are not commutative, then their lock-modes must conflict
- Recovery
  - Performing an operation from a log record must be idempotent
    - » Use LSNs etc to restrict whether changes will occur
- Compensators
  - Compensator for an operation must act as its inverse

Defined Properties

- Commutativity
  - O1 and O2 commute if their effect is the same in either order
- Idempotence
  - O1 is idempotent if O1 followed by O1 has the same effect as O1 by itself
- Inverse
  - Q1 is inverse to O1 if (O1 then Q1) has no effect



Lowest level operations happen in time order as shown



Rearrange lowest level, to make next level non-concurrent

Then remove lowest level,

and think about level above as single steps

Were these good papers?

- What were the authors' goals?
- What about the evaluation / metrics?
- Did they convince you that this was a good system /approach?
- Were there any red-flags?
- What mistakes did they make?
- Does the system/approach meet the "Test of Time" challenge?
- How would you review this paper today?

References and Further Reading

- Transactional Information Systems, by G. Weikum and G. Vossen, 2002
- A Survey of B-Tree Locking Techniques, by G. Graefe. ACM TODS 35(3):16, July 2010