CompSci 516

Data Intensive Computing Systems

Lecture 11

Intro to Transactions

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Announcements

- HW2 deadline extended to Monday, Oct 17, 11:55 pm
- Keep working on your proposed project too
  - 2 * weight of each homework
- Midterm next Wednesday, 10/12 in class
  - Lecture 1 – 10
  - Any question – ask on piazza!

Where are we now?

We learnt

- ✓ Relational Model and Query Languages
  - ✓ SQL, RA, RC
  - ✓ Postgres (DBMS)
  - HW1
- ✓ Map-reduce and spark
  - HW2
- ✓ DBMS Internals
  - ✓ Storage
  - ✓ Indexing
  - ✓ Query Evaluation
  - ✓ Operator Algorithms
  - ✓ External sort
  - ✓ Query Optimization
- ✓ Database Normalization

Next

- Transactions
  - Basic concepts
  - Concurrency control
  - Recovery
  - (for the next 4-5 lectures)

Reading Material

- [RG]
  - Chapter 16.1-16.3, 16.4.1
  - 17.1-17.4
  - 17.5.1, 17.5.3

Acknowledgement:
The following slides have been created adapting the instructor material of the [RG] book provided by the authors Dr. Ramakrishnan and Dr. Gehrke.

Motivation: Concurrent Execution

- Concurrent execution of user programs is essential for good DBMS performance.
  - Disk accesses are frequent, and relatively slow
  - it is important to keep the CPU busy by working on several user programs concurrently
  - short transactions may finish early if interleaved with long ones
  - may increase system throughput (avg. #transactions per unit time) and response time (avg time to complete a transaction)
- A user's program may carry out many operations on the data retrieved from the database
  - but the DBMS is only concerned about what data is read/written from/to the database

Transactions

```
T1:  BEGIN   A=A+100,   B=B-100   END
T2:  BEGIN   A=1.06*A,   B=1.06*B   END
```

- A transaction is the DBMS's abstract view of a user program
  - a sequence of reads and write
  - the same program executed multiple times would be considered as different transactions
  - DBMS will enforce some ICs, depending on the ICs declared in CREATE TABLE statements
  - Beyond this, the DBMS does not really understand the semantics of the data. (e.g., it does not understand how the interest on a bank account is computed)

Example

- Consider two transactions:

```
T1:  BEGIN   A=A+100,   B=B-100   END
T2:  BEGIN   A=1.06*A,   B=1.06*B   END
```

- Intuitively, the first transaction is transferring $100 from B's account to A's account. The second is crediting both accounts with a 6% interest payment
- There is no guarantee that T1 will execute before T2 or vice-versa, if both are submitted together.
- However, the net effect *must* be equivalent to these two transactions running serially in some order

Example

```
T1:  BEGIN  A=A+100,  B=B-100  END
T2:  BEGIN  A=1.06*A,  B=1.06*B  END
```

- Consider a possible interleaving (schedule):

```
T1:  A=A+100,             B=B-100
T2:            A=1.06*A,            B=1.06*B
```

- ❖ This is OK. But what about:

```
T1:  A=A+100,                       B=B-100
T2:            A=1.06*A, B=1.06*B
```

- ❖ The DBMS's view of the second schedule:

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

Commit and Abort

```
T1:  BEGIN   A=A+100,   B=B-100   END
T2:  BEGIN   A=1.06*A,  B=1.06*B  END
```

- A transaction might commit after completing all its actions
- or it could abort (or be aborted by the DBMS) after executing some actions

Concurrency Control and Recovery

```
T1:  BEGIN   A=A+100,   B=B-100   END
T2:  BEGIN   A=1.06*A,   B=1.06*B   END
```

- Concurrency Control
  - (Multiple) users submit (multiple) transactions
  - Concurrency is achieved by the DBMS, which interleaves actions (reads/writes of DB objects) of various transactions
  - user should think of each transaction as executing by itself one-at-a-time
  - The DBMS needs to handle concurrent executions
- Recovery
  - Due to crashes, there can be partial transactions
  - DBMS needs to ensure that they are not visible to other transactions

ACID Properties

- Atomicity
- Consistency
- Isolation
- Durability

Atomicity

```
T1:  BEGIN   A=A+100,   B=B-100   END
T2:  BEGIN   A=1.06*A,   B=1.06*B   END
```

- A user can think of a transaction as always executing all its actions in one step, or not executing any actions at all
  - Users do not have to worry about the effect of incomplete transactions
  - DBMS logs all actions so that it can undo the actions of aborted transactions.

Consistency

```
T1:  BEGIN   A=A+100,   B=B-100   END
T2:  BEGIN   A=1.06*A,  B=1.06*B   END
```

- Each transaction, when run by itself with no concurrent execution of other actions, must preserve the consistency of the database
  - e.g. if you transfer money from the savings account to the checking account, the total amount still remains the same
  - ensuring this property is the responsibility of the user

Isolation

```
T1:   BEGIN   A=A+100,   B=B-100   END
T2:   BEGIN   A=1.06*A,   B=1.06*B   END
```

- A user should be able to understand a transaction without considering the effect of any other concurrently running transaction
  - even if the DBMS interleaves their actions
  - transaction are “isolated or protected” from other transactions

Durability

```
T1:  BEGIN   A=A+100,   B=B-100   END
T2:  BEGIN   A=1.06*A,   B=1.06*B   END
```

- Once the DBMS informs the user that a transaction has been successfully completed, its effect should persist
  - even if the system crashes before all its changes are reflected on disk

Next, how we maintain all these four properties
But, in detail later

Ensuring Consistency

- e.g. Money debit and credit between accounts
- User's responsibility to maintain the integrity constraints
- DBMS may not be able to catch such errors in user program's logic
  - e.g. if the credit is (debit – 1)
- However, the DBMS may be in inconsistent state "during a transaction" between actions
  - which is ok, but it should leave the database at a consistent state when it commits or aborts
- Database consistency follows from transaction consistency, isolation, and atomicity

Ensuring Isolation

- DBMS guarantees isolation (later, how)
- If T1 and T2 are executed concurrently, either the effect would be T1->T2 or T2->T1 (and from a consistent state to a consistent state)
- But DBMS provides no guarantee on which of these order is chosen

Ensuring Atomicity

- Transactions can be incomplete due to several reasons
  - Aborted (terminated) by the DBMS because of some anomalies during execution
    - in that case automatically restarted and executed anew
  - The system may crash (say no power supply)
  - A transaction may decide to abort itself encountering an unexpected situation
    - e.g. read an unexpected data value or unable to access disks

Ensuring Atomicity

- A transaction interrupted in the middle can leave the database in an inconsistent state
- DBMS has to remove the effects of partial transactions from the database
- DBMS ensures atomicity by "undoing" the actions of incomplete transactions
- DBMS maintains a "log" of all changes to do so

Ensuring Durability

- The log also ensures durability
- If the system crashes before the changes made by a completed transactions are written to the disk, the log is used to remember and restore these changes when the system restarts
- "recovery manager" will be discussed later
  - takes care of atomicity and durability

Notations

```
T1:  BEGIN   A=A+100,   B=B-100   END
T2:  BEGIN   A=1.06*A,   B=1.06*B   END
```

- Transaction is a list of "actions" to the DBMS
  - includes "reads" and "writes"
  - $R_T(O)$: Reading an object O by transaction T
  - $W_T(O)$: Writing an object O by transaction T
  - also should specify $Commit_T$ and $Abort_T$
  - T is omitted if the transaction is clear from the context

Assumptions

- Transactions communicate only through READ and WRITE
  - i.e. no exchange of message among them
- A database is a fixed collection of independent objects
  - i.e. objects are not added to or deleted from the database
  - this assumption can be relaxed
    - (dynamic db/phantom problem later)

Schedule

- An actual or potential sequence for executing actions as seen by the DBMS
- A list of actions from a set of transactions
  – includes READ, WRITE, ABORT, COMMIT
- Two actions from the same transaction T MUST appear in the schedule in the same order that they appear in T
  – cannot reorder actions from a given transaction

Serial Schedule

T1	T2
R(A)	
W(A)	
R(B)	
W(B)	
COMMIT	
	R(A)
	W(A)
	R(B)
	W(B)
	COMMIT

- If the actions of different transactions are not interleaved
  - transactions are executed from start to finish one by one

Problems with a serial schedule

- The same motivation for concurrent executions, e.g.
  - while one transaction is waiting for page I/O from disk, another transaction could use the CPU
  - reduces the time disks and processors are idle
- Increases system throughput
  - average #transactions computed in a given time
- Also improves response time
  - average time taken to complete a transaction
  - since short transactions can be completed with long ones and do not have to wait for them to finish

Scheduling Transactions

- Serial schedule: Schedule that does not interleave the actions of different transactions

- Equivalent schedules: For any database state, the effect (on the set of 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 committed transactions
  - Note: If each transaction preserves consistency, every serializable schedule preserves consistency

Serializable Schedule

- If the effect on any consistent database instance is guaranteed to be identical that of “some” complete serial schedule for a set of “committed transactions”
- However, no guarantee on T1-> T2 or T2 -> T1

T1	T2
R(A)	
W(A)	
R(B)	
W(B)	
COMMIT	
	R(A)
	W(A)
	R(B)
	W(B)
	COMMIT

serial schedule

T1	T2
R(A)	
W(A)	
	R(A)
	W(A)
R(B)	
W(B)	
	R(B)
	W(B)
	COMMIT
COMMIT	

T1	T2
	R(A)
	W(A)
R(A)	
	R(B)
	W(B)
W(A)	
R(B)	
W(B)	
	COMMIT
COMMIT	

serializable schedules

Anomalies with Interleaved Execution

- If two consistency-preserving transactions when run interleaved on a consistent database might leave it in inconsistent state

- Write-Read (WR)
- Read-Write (RW)
- Write-Write (WW)

- No conflict with RR if no write is involved

WR Conflict

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

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

- Reading Uncommitted Data (WR Conflicts, “dirty reads”):
  - transaction T2 reads an object that has been modified by T1 but not yet committed
  - or T2 reads an object from an inconsistent database state (like fund is being transferred between two accounts by T1 while T2 adds interests to both)

RW Conflict

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

- Unrepeatable Reads (RW Conflicts):
  - T2 changes the value of an object A that has been read by transaction T1, which is still in progress
  - If T1 tries to read A again, it will get a different result
  - Suppose two customers are trying to buy the last copy of a book simultaneously

WW conflict

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

- Overwriting Uncommitted Data (WW Conflicts, "lost update"):
  - T2 overwrites the value of A, which has been modified by T1, still in progress
  - Suppose we need the salaries of two employees (A and B) to be the same
    - T1 sets them to $1000
    - T2 sets them to $2000

Schedules with Aborts

T1:	R(A), W(A),		Abort
T2:		R(A), W(A) Commit	

- Actions of aborted transactions have to be undone completely
  - may be impossible in some situations
    - say T2 reads the fund from an account and adds interest
    - T1 aims to deposit money but aborts
  - if T2 has not committed, we can "cascade" aborts by aborting T2 as well
  - if T2 has committed, we have an "unrecoverable schedule"

Recoverable Schedule

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

- Transaction commit if and only after all transactions they read have committed
  - avoids cascading aborts

Conflict Equivalent Schedules

- Two schedules are conflict equivalent if:
  - Involve the same actions of the same transactions
  - Every pair of conflicting actions of two committed transactions is ordered the same way
- Conflicting actions:
  - both by the same transaction T_i
    - $R_i(X)$, $W_i(Y)$
  - both on the same object by two transactions T_i and T_j, at least one action is a write
    - $R_i(X)$, $W_j(X)$
    - $W_i(X)$, $R_j(X)$
    - $W_i(X)$, $W_j(X)$

Conflict Equivalent Schedules

- Two conflict equivalent schedules have the same effect on a database
  - all pairs of conflicting actions are in same order
  - one schedule can be obtained from the other by swapping "non-conflicting" actions
    - either on two different objects
    - or both are read on the same object

Conflict Serializable Schedules

- Schedule S is conflict serializable if S is conflict equivalent to some serial schedule

- In class:
- $r_1(A); w_1(A); r_2(A); w_2(A); r_1(B); w_1(B); r_2(B); w_2(B)$
- to
- $r_1(A); w_1(A); r_1(B); w_1(B); r_2(A); w_2(A); r_2(B); w_2(B)$

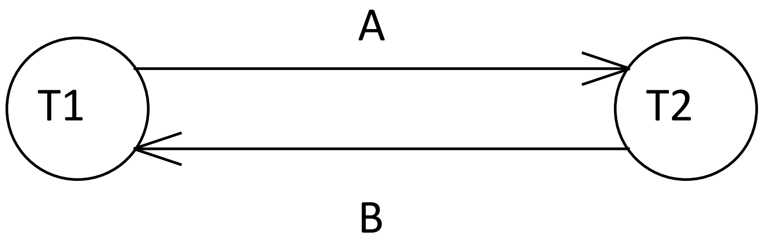
Example

- A schedule that is not conflict serializable:

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

can write it in this equivalent way as well

$R_1(A)$, $W_1(A)$, $R_2(A)$, $W_2(A)$, $R_2(B)$, $W_2(B)$, $R_1(B)$, $W_1(B)$



Precedence graph

- The cycle in the graph reveals the problem. The output of T1 depends on T2, and vice-versa.

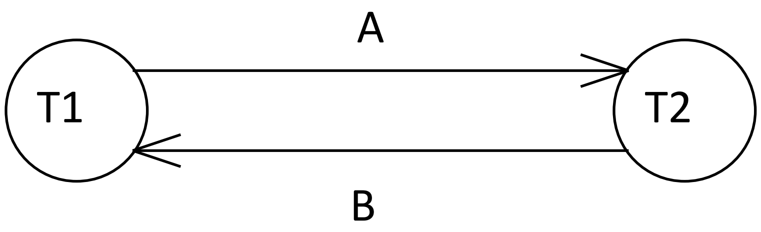
Precedence Graph

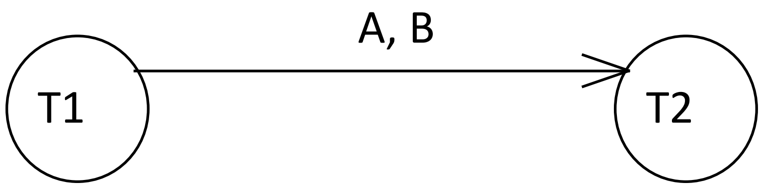
- Also called dependency graph, conflict graph, or serializability graph
- One node per committed transaction
- Edge from T_i to T_j if an action of T_i precedes and conflicts with one of T_j's actions
  - $W_i(A)$ --- $R_j(A)$, or
  - $R_i(A)$ --- $W_j(A)$, or
  - $W_i(A)$ --- $W_j(A)$
- T_i must precede T_j in any serial schedule

Conflict Serializability

- Theorem: Schedule is conflict serializable if and only if its precedence graph is acyclic

$R_1(A), W_1(A), R_2(A), W_2(A), R_2(B), W_2(B), R_1(B), W_1(B)$





$r_1(A); w_1(A); r_2(A); w_2(A); r_1(B); w_1(B); r_2(B); w_2(B)$

Lock-Based Concurrency Control

- DBMS should ensure that only serializable and recoverable schedules are allowed
  - No actions of committed transactions are lost while undoing aborted transactions

- Uses a locking protocol

- Lock: a bookkeeping object associated with each "object"
  - different granularity

- Locking protocol:
  - a set of rules to be followed by each transaction

Strict two-phase locking (Strict 2PL)

Two rules

1. Each transaction must obtain
   - a S (shared) lock on object before reading
   - and an X (exclusive) lock on object before writing
   - exclusive locks also allow reading an object, additional shared lock is not required
   - If a transaction holds an X lock on an object, no other transaction can get a lock (S or X) on that object
   - transaction is suspended until it acquires the required lock

2. All locks held by a transaction are released when the transaction completes

Example: Strict 2PL

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

- WR conflict (dirty read)
- Strict 2PL does not allow this

T1:	X(A), R(A), W(A),	
T2:		HAS TO WAIT FOR LOCK ON A

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

Example: Strict 2PL

T1:	S(A), R(A),		X(C), R(C), W(C), C
T2:		S(A), R(A), X(B), R(B), W(B), C	

- Strict 2PL allows interleaving

More on Strict 2PL

- Every transaction has
  - a growing phase of acquiring locks, and
  - a shrinking phase of releasing locks
- Strict 2PL allows only serializable schedules
  - precedence graphs will be acyclic (check yourself)
  - Additionally, allows recoverable schedules and simplifies transaction aborts
  - two transactions can acquire locks on different objects independently

2PL vs. strict 2PL

- 2PL:
  - first, acquire all locks, release none
  - second, release locks, cannot acquire any other lock
- Strict 2PL:
  - release write (X) lock, only after it has ended (committed or aborted)
- (Non-strict) 2PL also allows only serializable schedules like strict 2PL, but involves more complex abort processing

Strict 2PL and Conflict Serializability

- Strict 2PL allows only schedules whose precedence graph is acyclic
- Can never allow cycles as the X locks are being held by one transaction
- However, it is sufficient but not necessary for serializability
- Relaxed solution: View serializability

View Serializability

- Schedules S1 and S2 are view equivalent if:
  - If T_i reads initial value of A in S_1, then T_i also reads initial value of A in S_2
  - If T_i reads value of A written by T_j in S_1, then T_i also reads value of A written by T_j in S_2,
  - For all data object A, if T_i writes final value of A in S_1, then T_i also writes final value of A in S_2
- S is view serializable, if it is view equivalent to some serial schedule

S1 (view seriaizable,
not conflict serializable)

T1:	R(A)		W(A) C	
T2:		W(A) C		
T3:				W(A) C

S2 (serial)

T1:	R(A),W(A) C		
T2:		W(A) C	
T3:			W(A) C

More on View Serializability

- Every conflict serializable schedule is view serializable (check it yourself)
- But the converse may not be true
- If VS but not CS, would contain a “blind write” (see below)
- Verifying and enforcing VS is more expensive than CS, so less popular than CS

S1 (view seriaizable, not conflict serializable)

T1:	R(A)		W(A) C	
T2:		W(A) C		
T3:				W(A) C

S2 (serial)

T1:	R(A),W(A) C		
T2:		W(A) C	
T3:			W(A) C

Lock Management

- Lock and unlock requests are handled by the lock manager
- Lock table entry:
  - Number of transactions currently holding a lock
  - Type of lock held (shared or exclusive)
  - Pointer to queue of lock requests (if the shared or exclusive lock cannot be granted immediately)
- Locking and unlocking have to be atomic operations
- Lock upgrade: transaction that holds a shared lock can be upgraded to hold an exclusive lock
- Transaction commits or aborts
  - all locks released

Deadlocks

- Deadlock: Cycle of transactions waiting for locks to be released by each other
  - database systems periodically check for deadlocks

- Two ways of dealing with deadlocks:
  - Deadlock detection
  - Deadlock prevention

Deadlock Detection

1. Create a waits-for graph: (example on next slide)
   - Nodes are transactions
   - There is an edge from T_i to T_j if T_i is waiting for T_j to release a lock

- Periodically check for cycles in the waits-for graph
- Abort a transaction on a cycle and release its locks, proceed with the other transactions
  - several choices
  - one with the fewest locks
  - one has done the least work/farthest from completion
  - if being repeatedly restarted, should be favored at some point

2. Use timeout, if long delay, assume (pessimistically) a deadlock

Deadlock Detection

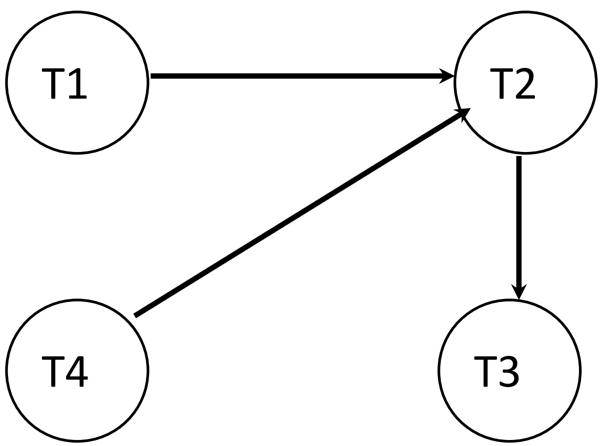
Example:

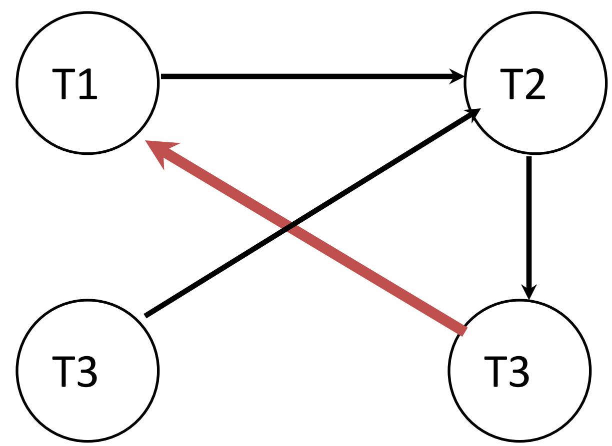
T1: S(A), R(A), S(B)

T2: X(B),W(B) X(C)

T3: S(C), R(C) X(A)

T4: X(B)





Deadlock Prevention

- Assign priorities based on timestamps
- Assume T_i wants a lock that T_j holds. Two policies are possible:
  - Wait-Die: It T_i has higher priority, T_i waits for T_j; otherwise T_i aborts
  - Wound-wait: If T_i has higher priority, T_j aborts; otherwise T_i waits
- Convince yourself that no cycle is possible
- If a transaction re-starts, make sure it has its original timestamp
  - each transaction will be the oldest one and have the highest priority at some point

- A variant of strict 2PL, conservative 2PL, works too
  - acquire all locks it ever needs before a transaction starts
  - no deadlock but high overhead and poor performance, so not used in practice

Dynamic Databases

- If we relax the assumption that the DB is a fixed collection of objects
- Then even Strict 2PL will not assure serializability
- causes ”Phantom Problem” in dynamic databases

Example: Phantom Problem

- T1 wants to find oldest sailors in rating levels 1 and 2
  - Suppose the oldest at rating 1 has age 71
  - Suppose the oldest at rating 2 has age 80
  - Suppose the second oldest at rating 2 has age 63

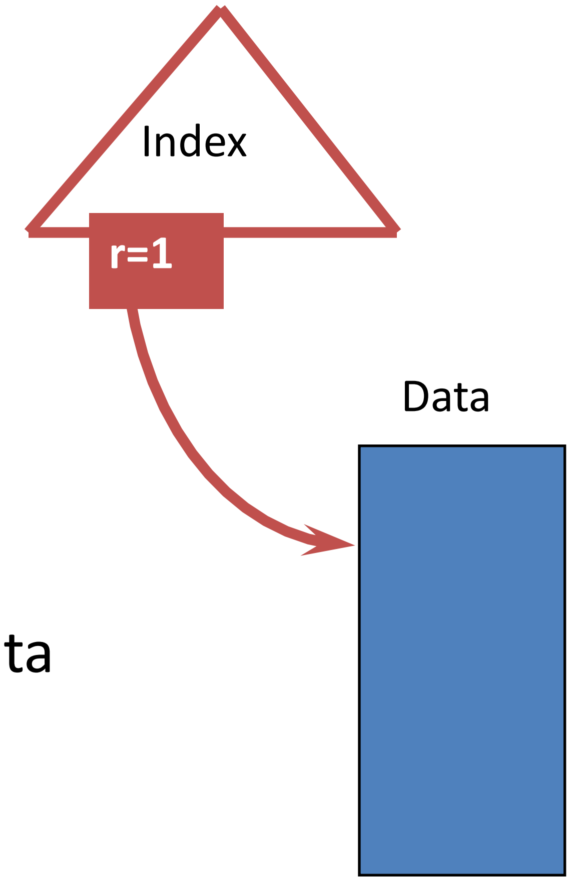
- Another transaction T2 intervenes:
  - Step 1: T1 locks all pages containing sailor records with rating = 1, and finds oldest sailor (age = 71)
  - Step 2: Next, T2 inserts a new sailor onto a new page (rating = 1, age = 96)
  - Step 3: T2 locks pages with rating = 2, deletes oldest sailor with rating = 2 (age = 80), commits, releases all locks
  - Step 4: T1 now locks all pages with rating = 2, and finds oldest sailor (age = 63)

- No consistent DB state where T1 is "correct"
  - T1 found oldest sailor with rating = 1 before modification by T2
  - T1 found oldest sailor with rating = 2 after modification by T2

What was the problem?

- Conflict serializability guarantees serializability only if the set of objects is fixed
- Problem:
  - T1 implicitly assumed that it has locked the set of all sailor records with rating = 1
  - Assumption only holds if no sailor records are added while T1 is executing
  - Need some mechanism to enforce this assumption
- Index locking and predicate locking

Index Locking



- If there is a dense index on the rating field using Alt. (2), T1 should lock the index page containing the data entries with rating = 1
  - If there are no records with rating = 1, T1 must lock the index page where such a data entry would be, if it existed
- If there is no suitable index, T1 must lock all pages, and lock the file/table to prevent new pages from being added
  - to ensure that no new records with rating = 1 are added

Predicate Locking

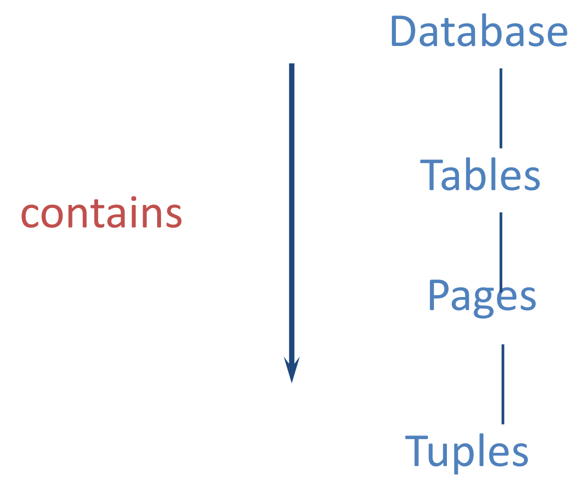
- Grant lock on all records that satisfy some logical predicate, e.g. rating = 1 or, age > 2*salary

- Index locking is a special case and an efficient implementation of predicate locking
  - e.g. Lock on the index pages for records satisfying rating = 1

- The general predicate locking has a lot of locking overhead and so not commonly used

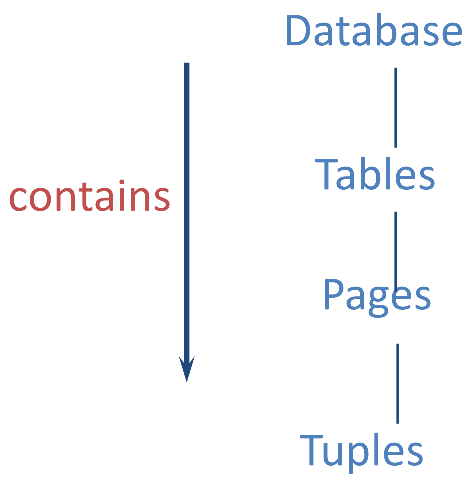
DB Objects may contain other objects

- A DB contains several files
- A file is a collection of pages
- A page is a collection of records/tuples



Carefully choose lock granularity

- If a transaction needs most of the pages
  - set a lock on the entire file
  - reduces locking overhead
- If only a few pages are needed
  - lock only those pages
- Need to efficiently ensure no conflicts
  - e.g. a page should not be locked by T1 if T2 already holds the lock on the file



New Lock Modes & Protocol

- Allow transactions to lock at each level, but with a special protocol using new "intention locks":

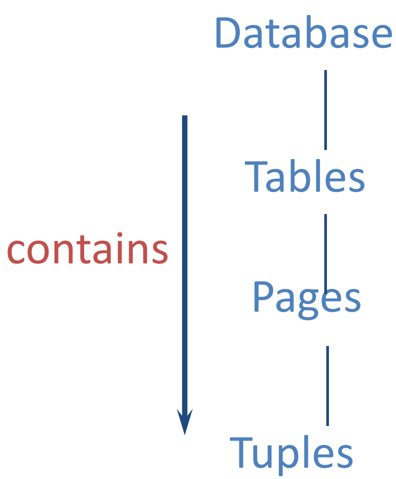
- Before locking an item (S or X), transaction must set "intention locks" (IS or IX) on all its ancestors
- For unlock, go from specific to general (i.e., bottom-up)
  - otherwise conflicting lock possible at root

conflicting locks

	--	IS	IX	S	X
--	√	√	√	√	√
IS	√	√	√	√	
IX	√	√	√		
S	√	√		√	
X	√				

other tr. cannot have IX or X

other tr. cannot have any other lock



SIX mode = S + IX

- Common situation: a transaction needs to read an entire file and modify a few records
  - S lock
  - IX lock (to subsequently lock)

  some containing objects in X mode

- Obtain a SIX lock
  - conflict with either S or IX

conflicting locks

	--	IS	IX	S	X
--	√	√	√	√	√
IS	√	√	√	√	
IX	√	√	√		
S	√	√		√	
X	√				

other tr. cannot have IX or X

other tr. cannot have any other lock

Transaction in SQL

- BEGIN TRANSACTION
- <…. SQL STATEMENTS>
- COMMIT or ROLLBACK

Summary

- Transaction
  - $R_1(A)$, $W_2(A)$, ….
  - Commit C_1, abort A_1
  - Lock/unlock: $S_1(A)$, $X_1(A)$, $US_1(A)$, $UX_1(A)$
- ACID properties
  - what they mean, whose responsibility to maintain each of them
- Conflicts: RW, WR, WW
- 2PL/Strict 2PL
  - all lock acquires have to precede all lock releases
  - Strict 2PL: release X locks only after commit or abort

Summary

- Schedule
  - Serial schedule
  - Serializable schedule (why do we need them?)
  - Conflicting actions
  - Conflict-equivalent schedules
  - Conflict-serializable schedule
  - View-serializable schedule (relaxation)
  - Conflict Serializability => View Serializability => Serializability
  - Recoverable schedules
- Dependency (or Precedence) graphs
  - their relation to conflict serializability (by acyclicity)
  - their relation to Strict 2PL

Summary

- Lock management basics
- Deadlocks
  - detection
    - waits-for graph has cycle, or timeout
    - what to do if deadlock is detected
  - prevention
    - wait-die and wound-wait
- Phantom problem and dynamic db
  - index and predicate lock
- Multiple granularity lock