CompSci 516
Database Systems

Lecture 14
Transactions
– Concurrency Control

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Announcements (Tues 2/22)

- Midterm grades and exams on gradescope
  - Sample solution on sakai
  - Contact us if you have questions
- HW2-part 1 due next week 3/1
  - One group submission per pair is needed
  - Part 2 (on cloud) will be released later if we have time due to change in AWS setups

Reading Material

- [RG]
  - Chapter 17.5.1, 17.5.3, 17.6
- [GUW]
  - Chapter 18.8, 18.9
  - Today's examples are from GUW (lecture slides will be sufficient for this class and exams)

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

Today's topics

- Optimistic concurrency control (17.6.1) Timestamp-based concurrency control (17.6.2)
- Multi-version concurrency control (17.6.3)
- Dynamic databases and Phantom problem (17.5.1)
- Multiple—granularity locking (17.5.3)

Approaches to CC other than locking

Approaches to Concurrency Control (CC)

- Lock-based CC
  - (so far)
- Optimistic CC
  - Today
  - overview only
- Time-stamp-based CC
  - today
- Multi-version CC
  - today

uses “timestamps” in some way

Timestamp

- Each transaction gets a unique timestamp

- e.g.
  - system's clock value when it is issued by the scheduler (assume one transactions issued on one tick of the clock)
  - or a unique number given by a counter (incremented after each transaction)
- Basic idea:
  - Timestamps should enforce the <u>unique</u> equivalent serial schedule
  - If TS(T1) > TS(T2), in the equivalent serial schedule T1 should appear after T2
  - Whenever violated, ABORT

Locking is a "pessimistic or conservative" approach to CC

- Locking is a conservative approach in which conflicts are prevented
- Either uses "blocking" (delay) or abort
  - note the several usages of a "block"!
- Disadvantages of locking:
  - Lock management overhead
  - Deadlock detection/resolution
  - Lock contention for heavily used objects
- If only light contention for data objects, still the overhead of following a locking protocol is paid

(1) Optimistic CC

Optimistic CC (or Kung-Robinson approach)

- If conflicts are rare, we might be able to gain concurrency by not locking, and instead checking for conflicts before transactions commit

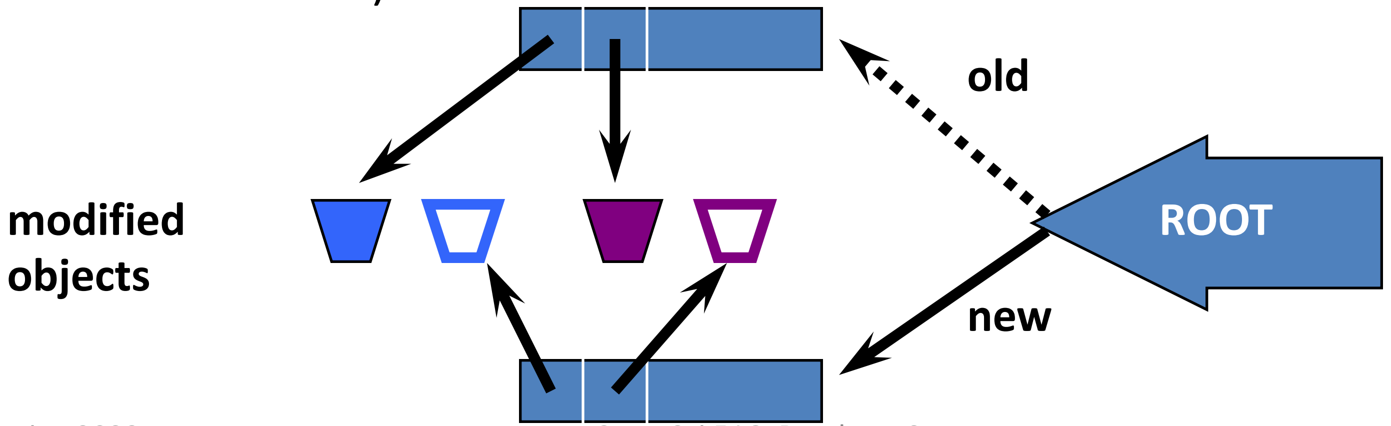
Optimistic CC

Overview only

- Transactions have three phases:
  1. **READ (R):** Read from the database, but make changes to ”private copies” of objects (assume private workspace)

  2. **VALIDATE (V):** When decide to commit, also check for conflicts with concurrently executing transactions
     - if a possible conflict, abort, clear private workspace, restart

  3. **WRITE (W):** If no conflict, make local copies of changes public (copy them into the database)



What does Validation do?

- To validate T_2 , for each committed transactions T_1 such that $TS(T_1) < TS(T_2)$, one of the validation tests must be satisfied

- Validation ensures no RW, WR, WW conflicts, e.g.,
  - T1 completes all R, V, W before T2 starts
  - Or, T1 completes before W of T2 starts, and T2 does not read anything that T1 writes
  - Or, T1 completes its R before T2 starts its R, and T2 does not read/write anything that T1 writes

R = READ V = Validation W = WRITE

- Overhead:
  - Some parts have to be in "critical section" without other transactions
  - Need to maintain objects that are read/written by each transactions
  - If validation fails, need to restart, lost work

End of Lecture 14

Optimistic CC vs locking

- If there are few conflicts and validation is efficient
  - optimistic CC is better than locking

- If many conflicts
  - cost of repeatedly restarting transactions hurts performance significantly

Start of Lecture 15

(2) Timestamp-based CC

Timestamp CC

Main Idea:

- Give each transaction T
  - a unique timestamp TS(T) when it begins
  - Later transactions get higher timestamps

- Give each object O
  - a read-timestamp RT(O) -- largest timestamp of the transactions that read O
  - a write-timestamp WT(O) -- largest timestamp of the transactions that wrote to O
  - a Commit bit C(O): whether the last transaction writing O has committed
    - RG uses RTS/WTS, GUW uses RT/WT, either of these is fine

- If
  - action ai of Ti conflicts with action aj of Tj,
  - and TS(Ti) < TS(Tj)
- then
  - ai must occur before aj
- Otherwise, abort and restart violating transaction

Request for a read: $R_T(X)$

See example first
And read yourself

1. If TS(T) >= WT(X)
   - last written by a previous transaction –- *OK (i.e., "physically realizable")*
   - If C(X) is true –- *check if previous transaction has committed*
     - Grant the read request by T
     - if TS(T) > RT(X)
       - set RT(X) = TS(T)
   - If C(X) is false
     - Delay T until C(X) becomes true, or the transaction that wrote X aborts
2. If TS(T) < WT(X)
   - write is not realizable -- already *written by a later trans.*
   - Abort (or, Rollback) T *--i.e., abort and restart with a larger timestamp*

Request for a write: $W_T(X)$

See example first
And read yourself

1. If TS(T) >= RT(X) and TS(T) >= WT(X)
   - last written/read by a previous transaction – *OK*
   - Grant the write request by T
     - write the new value of X
   - Set WT(X) = TS(T)
   - Set C(X) = false *-- T not committed yet, set to true when T commits*
2. If TS(T) >= RT(X) but TS(T)< WT(X)
   - write is still realizable *–-but already a later value in X*
   - If C(X) is true
     - previous writer of X has committed
     - simply ignore the write request by T
     - but allow T to proceed without making changes to the database
   - If C(X) is false
     - Delay T until C(X) becomes true, or the transaction that wrote X aborts

- If TS(T) < RT(X)
  - write is not realizable *-- already read by a later transaction*
  - Abort (or, Rollback) T

Example

Example from GUW book

- Three transactions T1 (TS = 200), T2 (TS = 150), T3 (TS = 175)
- Three objects A, B, D
  - initially all have RT = WT = 0, C = 1 (i.e., true)
- Sequence of actions
  - $R_1(B)$, $R_2(A)$, $R_3(D)$, $W_1(B)$, $W_1(A)$, $W_2(D)$, $W_3(A)$
- Q. What is the state of the database at the end if the timestamp-based CC protocol is followed
  - i.e. report the RT, WT, C

Initial condition and Steps

Step	T1	T2	T3	A	B	D
	200	150	175	RT = 0, WT = 0, C = 1	RT = 0, WT = 0, C = 1	RT = 0, WT = 0, C = 1
1	$R_1(B)$					
2		$R_2(A)$				
3			$R_3(D)$			
4	$W_1(B)$					
5	$W_1(A)$					
6		$W_2(D)$				
7			$W_3(A)$			

After Step 1

WT of B is <= $TS(T_1)$
C = 1
Read OK.

Step	T1	T2	T3	A	B	D
	200	150	175	RT = 0, WT = 0, C = 1	RT = 200, WT = 0, C = 1	RT = 0, WT = 0, C = 1
1	$R_1(B)$				RT=200	
2		$R_2(A)$				
3			$R_3(D)$			
4	$W_1(B)$					
5	$W_1(A)$					
6		$W_2(D)$				
7			$W_3(A)$			

After Step 2

WT of A is <= TS(T_2)
C = 1
Read OK.

Step	T1	T2	T3	A	B	D
	200	150	175	RT = 150, WT = 0, C = 1	RT = 200, WT = 0, C = 1	RT = 0, WT = 0, C = 1
1	$R_1(B)$				RT=200	
2		$R_2(A)$		RT=150		
3			$R_3(D)$			
4	$W_1(B)$					
5	$W_1(A)$					
6		$W_2(D)$				
7			$W_3(A)$			

After Step 3

WT of D is <= TS(T_3)
C = 1
Read OK.

Step	T1	T2	T3	A	B	D
	200	150	175	RT = 150, WT = 0, C = 1	RT = 200, WT = 0, C = 1	RT = 175, WT = 0, C = 1
1	$R_1(B)$				RT=200	
2		$R_2(A)$		RT=150		
3			$R_3(D)$			RT=175
4	$W_1(B)$					
5	$W_1(A)$					
6		$W_2(D)$				
7			$W_3(A)$			

After Step 4

Note the change in C bit as T2 has not committed yet

WT & RT of B is <= $TS(T_1)$
Write OK.

Step	T1	T2	T3	A	B	D
	200	150	175	RT = 150, WT = 0, C = 1	RT = 200, WT = 200 C = 0	RT = 175, WT = 0, C = 1
1	$R_1(B)$				RT=200	
2		$R_2(A)$		RT=150		
3			$R_3(D)$			RT=175
4	$W_1(B)$				WT=200 C=0	
5	$W_1(A)$					
6		$W_2(D)$				
7			$W_3(A)$			

After Step 5

Note the change in C bit as T1 has not committed yet

RT & WT of A <= TS(T_1)
Write ok.

Step	T1	T2	T3	A	B	D
	200	150	175	RT = 150 WT = 200 C = 0	RT = 200 WT = 200 C = 0	RT = 175 WT = 0 C = 1
1	$R_1(B)$				RT=200	
2		$R_2(A)$		RT=150		
3			$R_3(D)$			RT=175
4	$W_1(B)$				WT=200 C=0	
5	$W_1(A)$			WT=200 C=0		
6		$W_2(D)$				
7			$W_3(A)$			

After Step 6

Object D has been read by a later transaction - abort

$RT(D) = 175 < 150 = TS(T_2)$

Abort T_2

Step	T1	T2	T3	A	B	D
	200	150	175	RT = 150 WT = 200 C = 0	RT = 200 WT = 200 C = 0	RT = 175 WT = 0 C = 1
1	$R_1(B)$				RT=200	
2		$R_2(A)$		RT=150		
3			$R_3(D)$			RT=175
4	$W_1(B)$				WT=200 C=0	
5	$W_1(A)$			WT=200 C=0		
6		$W_2(D)$ Abort				
7			$W_3(A)$			

After Step 7

Delay until T1 commits or aborts

$RT(A) <= TS(T_3)$ – write ok

$WT(A) > TS(T_3)$ and $C(A) = 0$

Delay T_3

Step	T1	T2	T3	A	B	D
	200	150	175	RT = 150 WT = 200 C = 0	RT = 200 WT = 200 C = 0	RT = 175 WT = 0 C = 1
1	$R_1(B)$				RT=200	
2		$R_2(A)$		RT=150		
3			$R_3(D)$			RT=175
4	$W_1(B)$				WT=200 C=0	
5	$W_1(A)$			WT=200 C=0		
6		$W_2(D)$ Abort				
7			$W_3(A)$ Delay			

Thomas Write Rule

- If a write request comes from T on O, TS(T) < WT(O), and TS(T) >= RT(O)
  – violates timestamp order of T w.r.t. writer of O
  – i.e., O has been written by a later transaction T2

Thomas Write Rule:

- If C(O) = true, we can safely ignore such outdated writes by T
  – Otherwise ”delay/block” to check whether T2 commits eventually
- no need to restart T
  – T’s write is effectively followed by another write with no intervening reads
- Allows some serializable, but not conflict serializable schedules (see example in Lec 13 slides)

(3) Multiversion CC

Another approach to CC

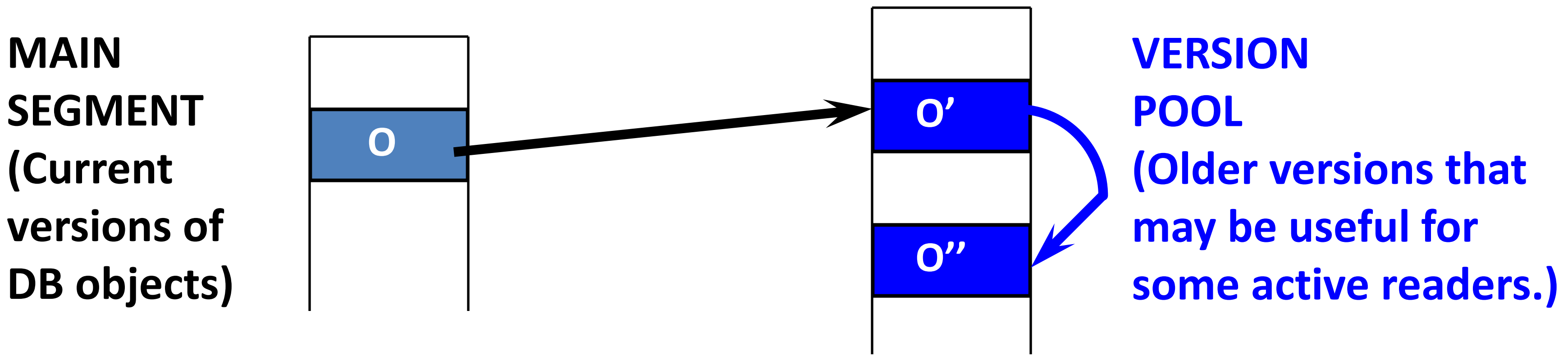
- Multiversion CC
  - another way of using timestamps
  - ensures that a transaction never has to be restarted (aborted) to read an object
    - unlike timestamp-based CC

- The idea is to make several copies of each DB object
  - each copy of each object has a write timestamp

- Ti reads the most recent version whose timestamp precedes TS(Ti)

Multiversion CC

- Idea: Let "writers" make a "new" copy while "readers" use an appropriate "old" copy:



Readers are always allowed to proceed

– But may be "blocked" until writer commits.

Multiversion CC (Contd.)

See example first
And read yourself

- Each version of an object has
  - its writer's TS as its WT, and
  - the timestamp of the transaction that most recently read this version as its RT

- Versions are chained backward
  - we can discard versions that are "too old to be of interest"

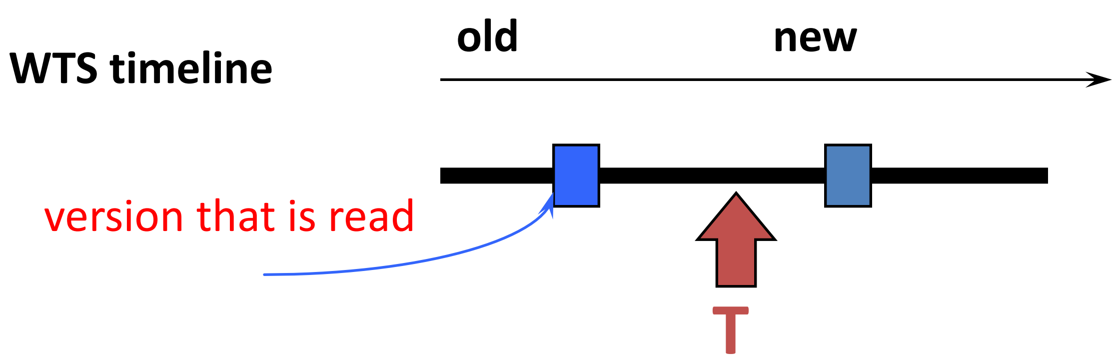
- Each transaction is classified as Reader or Writer.
  - Writer may write some object; Reader never will
  - Transaction declares whether it is a Reader when it begins

Reader Transaction

See example first
And read yourself

- For each object to be read:
  - Finds newest version with WT < TS(T)
  - Starts with current version in the main segment and chains backward through earlier versions
  - Update RT if necessary (i.e., if TS(T) > RT, then RT = TS(T))

- Assuming that some version of every object exists from the beginning of time, Reader transactions are never restarted
  - However, might block until writer of the appropriate version commits



Writer Transaction

See example first
And read yourself

- To read an object, follows reader protocol
- To write an object:
  - must make sure that the object has not been read by a "later" transaction
  - Finds newest version V s.t. WT(V) <= TS(T).
- If RT(V) <= TS(T)
  - T makes a copy CV of V, with a pointer to V,
    with WT(CV) = TS(T), RT(CV) = TS(T)
  - Write is buffered until T commits; other transactions can see TS values but can't read version CV
- Else
  - reject write

Example

- Four transactions T1 (TS = 150), T2 (TS = 200), T3 (TS = 175), T4(TS = 225)

- One object A
  - Initial version is A_0

- Sequence of actions
  - $R_1(A)$, $W_1(A)$, $R_2(A)$, $W_2(A)$, $R_3(A)$, $R_4(A)$

- Q. What is the state of the database at the end if the multiversion CC protocol is followed

Initial condition and Steps

A_0 existed before the transactions started

Step	T1	T2	T3	T4	A_0		
	150	200	175	225	RT=0, WT=0		
1	$R_1(A)$						
2	$W_1(A)$						
3		$R_2(A)$					
4		$W_2(A)$					
5			$R_3(A)$				
6				$R_4(A)$			

After Step 1

A_0 is the newest version with WT <= $TS(T_1)$
Read A_0

Step	T1	T2	T3	T4	A_0		
	150	200	175	225	RT=0, WT=0		
1	$R_1(A)$				Read RT = 150		
2	$W_1(A)$						
3		$R_2(A)$					
4		$W_2(A)$					
5			$R_3(A)$				
6				$R_4(A)$			

After Step 2

- A_0 is the newest version with WT <= TS(T_1)
- RT(A_0) <= TS(T_1)
- Create a new version A_{150}
- Set its WT, RT to TS(T_1) = 150 (A_{150} named accordingly)

Step	T1	T2	T3	T4	A_0	A_{150}	
	150	200	175	225	RT=150 WT=0	RT=150 WT=150	
1	$R_1(A)$				Read RT = 150		
2	$W_1(A)$					Create RT=150 WT=150	
3		$R_2(A)$					
4		$W_2(A)$					
5			$R_3(A)$				
6				$R_4(A)$			

After Step 3

- A_{150} is the newest version with WT <= $TS(T_2)$
- Read A_{150}
- Update RT

Step	T1	T2	T3	T4	A_0	A_{150}	
	150	200	175	225	RT=150 WT=0	RT=200 WT=150	
1	$R_1(A)$				Read		
2	$W_1(A)$					Create RT=150 WT=150	
3		$R_2(A)$				Read RT=200	
4		$W_2(A)$					
5			$R_3(A)$				
6				$R_4(A)$			

After Step 4

- A_{150} is the newest version with WT <= TS(T_2)
- RT(A_{150}) <= TS(T_2)
- Create a new version A_{200}
- Set its WT, RT to TS(T_2) = 200 (A_{200} named accordingly)

Step	T1	T2	T3	T4	A_0	A_{150}	A_{200}
	150	200	175	225	RT=150 WT=0	RT=200 WT=150	RT=200 WT=200
1	$R_1(A)$				Read		
2	$W_1(A)$					Create RT=150 WT=150	
3		$R_2(A)$				Read RT=200	
4		$W_2(A)$					Create RT=200 WT=200
5			$R_3(A)$				
6				$R_4(A)$			

After Step 5

- A_{150} is the newest version with WT <= TS(T_3)
- Read A_{150}
- DO NOT Update RT

Step	T1	T2	T3	T4	A_0	A_{150}	A_{200}
	150	200	175	225	RT=150 WT=0	RT=200 WT=150	RT=200 WT=200
1	$R_1(A)$				Read		
2	$W_1(A)$					Create RT=150 WT=150	
3		$R_2(A)$				Read RT=200	
4		$W_2(A)$					Create RT=200 WT=200
5			$R_3(A)$			Read	
6				$R_4(A)$			

After Step 6

- A_{200} is the newest version with WT <= TS(T_4)
- Read A_{200}
- Update RT

Step	T1	T2	T3	T4	A_0	A_{150}	A_{200}
	150	200	175	225	RT=150 WT=0	RT=200 WT=150	RT=225 WT=200
1	$R_1(A)$				Read		
2	$W_1(A)$					Create RT=150 WT=150	
3		$R_2(A)$				Read RT=200	
4		$W_2(A)$					Create RT=200 WT=200
5			$R_3(A)$			Read	
6				$R_4(A)$			Read RT=225

Dynamic Database and Phantom Problem

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

Sailors(sid, name, age, rating)

S4, Bob, 71, 1

S7, Mary, 80, 2 — Removed by T2
S3, Alice, 63, 2

S5, Ken, 96, 1 — New by T2

- 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?

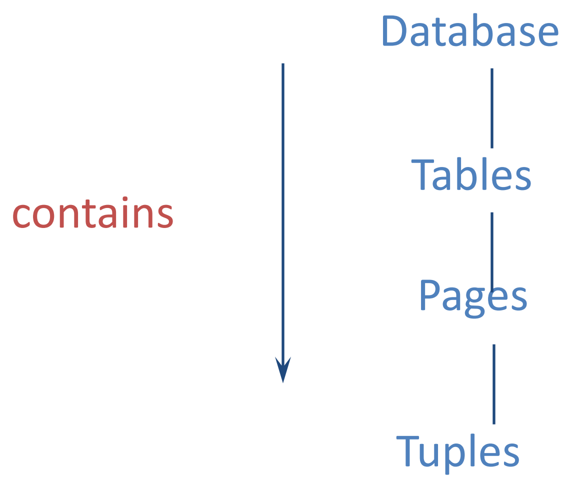
- Conflict serializability guarantees serializability only if the set of objects is fixed
  - T1 implicitly and incorrectly assumed that it has locked the set of all sailor records with rating = 1

- Solution to Phantom Problem
  - Index locking: Lock the index, no new rating = 1 records can be inserted
  - predicate locking: Lock on "predicate" (any condition) like "rating = 1" – more flexible but more expensive than index locking

Multiple-granularity Locking

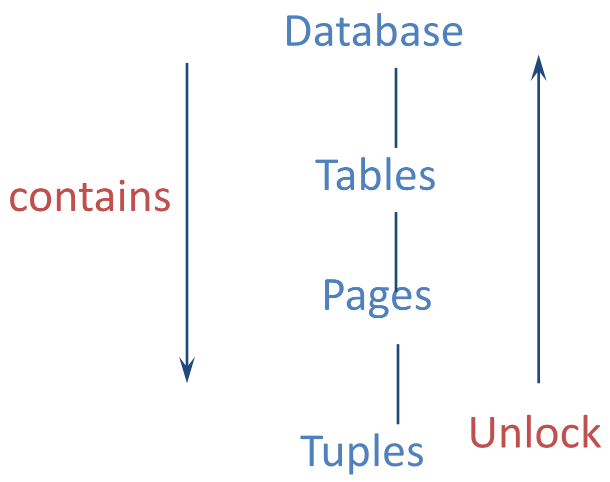
DB "Objects" may contain other objects

- 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
- Acquire “intention locks” on all the ancestors before locking an item
  - Conflicts with lock requests
  - Unlock bottom-up (tuple-> pages->..)



Transaction in SQL

- SET TRANSACTION ISOLATION LEVEL READ UNCOMMITTED [;]
- BEGIN TRANSACTION
- <…. SQL STATEMENTS>
- COMMIT or ROLLBACK

- Four isolation levels : performance and serializability

	Dirty Read	Unrepeatable Read	Phantom
READ UNCOMMITTED	Maybe	Maybe	Maybe
READ COMMITTED	No	Maybe	Maybe
REPEATABLE READS	No	No	Maybe
SERIALIZABLE	No	No	No

Summary

- Note the key ideas for three timestamp-based alternative approaches (to Lock-based approaches) to CC
  - Optimistic: validation tests
  - Timestamp: RT(O) & WT(O) on each object O
  - Multiversion: multiple versions of each object O with different WT and RT
- Note: a new action (block or delay) in addition to commit or abort
- “Phantom Problem” and why serializability/2PL fails
- New requirements and mechanisms for multiple-granularity locks