Transactions Intro & Concurrency Control

R & G Chaps. 16/17

There are three side effects of acid.
Enhanced long term memory,
decreased short term memory,
and I forget the third.
- Timothy Leary

Learning Transactions: A Plan

- This is a big topic in many senses
  - Foundational ideas, much material to master
- Plan of attack
  - Start with overview of the key issues and solutions
  - Deep dive on the key areas: concurrency, recovery

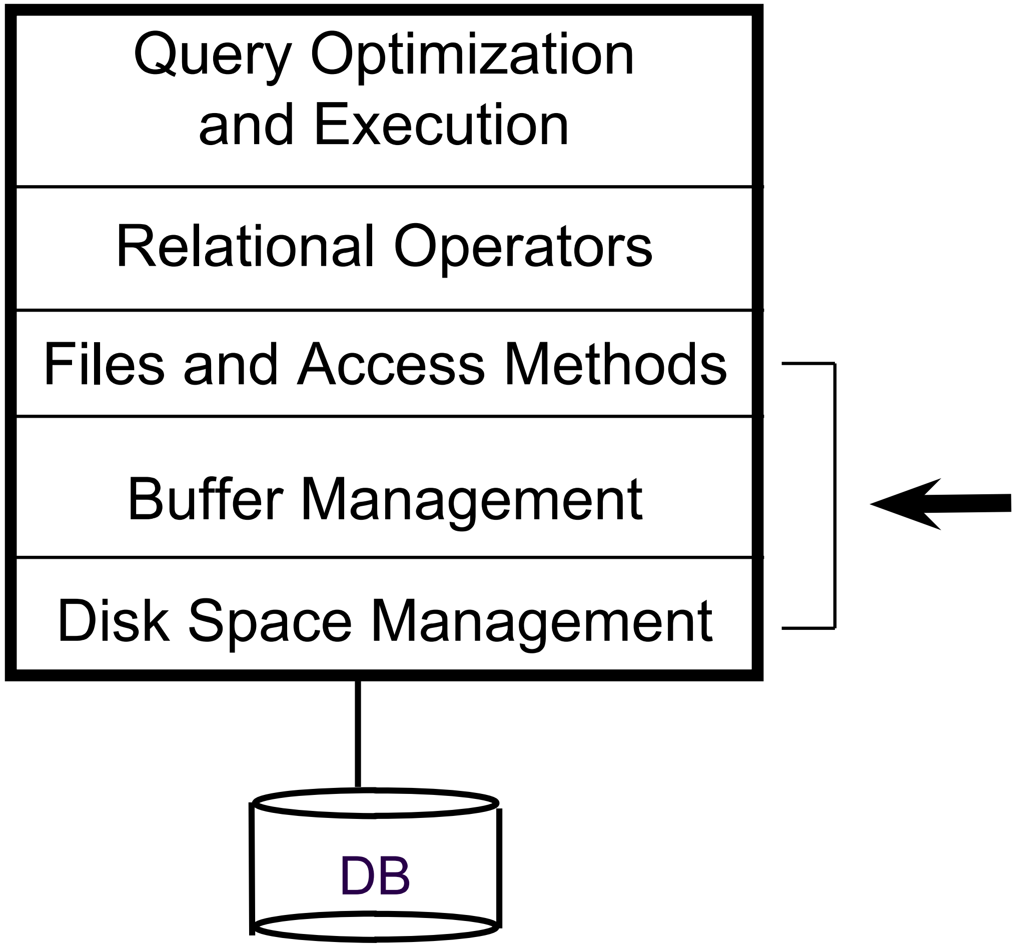
Learning Transactions: A Plan (cont)

- You will learn one concrete solution for each
  - Concurrent: Two-Phase Locking (2PL)
  - Recovery: Write-Ahead Logging (WAL)
  - Both are widely-used, mature solutions with rich guarantees
- We'll discuss some alternatives, but in less detail
  - Additional clever solutions for transactional guarantees
  - More relaxed guarantees enabling even better performance
- This space is still being aggressively explored
  - In research and industry

Concurrency Control & Recovery

- **Part 1: Concurrency Control**
  - Provide correct and fast data access in the presence of concurrent work by many users
- **Part 2: Recovery**
  - Ensures database is fault tolerant, and not corrupted by software, system or media failure
  - Storage guarantees for mission-critical data
- **It's all about the programmer!**
  - Systems provide guarantees
  - These guarantees lighten the load of app writers

Structure of a DBMS



These layers must consider concurrency control and recovery (Transaction, Lock, Recovery Managers)

Motivation: Transactions and Concurrent Execution

- **Transaction ("xact"):**
  DBMS's abstract view of a user program (or activity)
  - A sequence of reads and writes of database objects.
  - Batch of work that must commit or abort as an atomic unit
- **Transaction Manager controls execution of transactions.**
- **User's program logic is invisible to DBMS!**
  - Arbitrary computation possible on data fetched from the DB
  - The DBMS only sees data read/written from/to the DB.
- **Challenge: provide atomic xacts to concurrent users!**
  - Provide programmers the illusion of an isolated, reliable computer
  - Knowing only the programmer's reads and writes

Concurrency: Why bother?

- **The *latency* argument**
- **The *throughput* argument**
- **Both are critical!**

What does a Transaction guarantee? The ACID properties

- **A tomicity:** **All** actions in the Xact happen, **or none** happen.
- **C onsistency:** If the DB **starts consistent**, it **ends** up **consistent** at end of Xact.
- **I solation:** Execution of **one** Xact **is isolated from** that of **other** Xacts.
- **D urability:** If a Xact **commits**, its effects **persist**.

Atomicity and Durability

A.C.I
.D.

- **A transaction ends in one of two ways:**
  - *commit* after completing all its actions
    - "commit" is a contract with the caller of the DB
  - *abort* (or be aborted by the DBMS) after executing some actions.
    - Or *system crash* while the xact is in progress; treat as abort.

- **Two important properties for a transaction:**
  - *Atomicity* : Either execute all its actions, or none of them
  - *Durability* : The effects of a committed xact must survive failures.

- **DBMS ensures the above by *logging* all actions:**
  - *Undo* the actions of aborted/failed transactions.
  - *Redo* actions of committed transactions not yet propagated to disk when system crashes.

Transaction Consistency

A.C.I
.D.

- **Transactions preserve DB *consistency***
  - Given a consistent DB state, produce another consistent DB state
- **DB Consistency expressed as a set of declarative Integrity Constraints**
  - CREATE TABLE/ASSERTION statements
- **Transactions that violate ICs are aborted**
  - That's all the DBMS can automatically check!

Isolation (Concurrency)

A.C.I
.D.

- **DBMS interleaves actions of many xacts**
  - Actions = reads/writes of DB objects
- **DBMS ensures xacts do not “interfere”.**
- **Each xact executes as if it ran by itself.**
  - Concurrent accesses have no effect on a xact’s behavior
  - Net effect must be identical to executing all transactions *in some serial order*.
  - Users & programmers think about transactions in isolation
    - Without considering effects of other concurrent transactions!

Checkpoint

- **Review**
  - ACID Transactions make guarantees that
    - Improve performance (via concurrency)
    - Relieve programmers of correctness concerns
      - Hide concurrency and failure handling!
  - Two key issues to consider, and mechanisms
    - Concurrency Control (via two-phase locking)
    - Recovery (via write-ahead logging)
  - We'll do Concurrency Control first.

Concurrency: Providing Isolation

- **Serial schedules**
  - one transaction runs at a time
  - safe but slow
- **Try to find schedules *equivalent* to serial …**
  - but *interleaved* for better performance

Serializable Schedules

- **We need a "touchstone" concept for correct behavior**
- **Definition: Serial schedule**
  - Each transaction runs from start to finish without any intervening actions from other transactions
- **Definition: 2 schedules are equivalent if they:**
  - involve same actions of same transactions, and
  - leave the DB in the same final state
- **Definition: Schedule S is serializable if:**
  - S is equivalent to any serial schedule

Conflicting Operations

- **We need an easier check for equivalence than "guarantees the same outcome in any DB state"**
- **Use notion of "conflicting" operations (read/write)**
- **Definition: Two operations conflict if they:**
  - are by different transactions,
  - are on the same object,
  - at least one of them is a write.

Conflict Serializable Schedules

- **Definition: Two schedules are conflict equivalent iff:**
  - They involve the same actions of the same transactions, and
  - every pair of conflicting actions is ordered the same way
- **Definition: Schedule S is conflict serializable if:**
  - S is conflict equivalent to some serial schedule.
- **Note, some serializable schedules are NOT conflict serializable**
  - A price we pay to achieve efficient enforcement.

Conflict Serializability – Intuition

- **A schedule S is conflict serializable if:**
  - You are able to transform S into a serial schedule by swapping **consecutive non-conflicting** operations of different transactions.
- ***Example:***

R(A) W(A) R(B W(B)

R(A) W(A) R(B W(B)

Conflict Serializability (Continued)

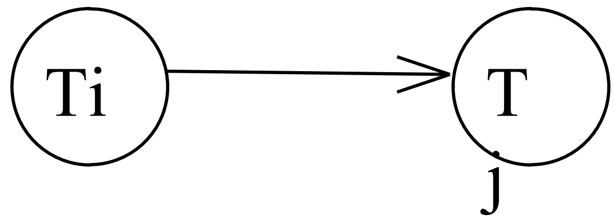
- **Here's another example:**

R(A)			W(A)
	R(A)	W(A)	

- **Conflict Serializable or not????**

NOT!

Dependency Graph



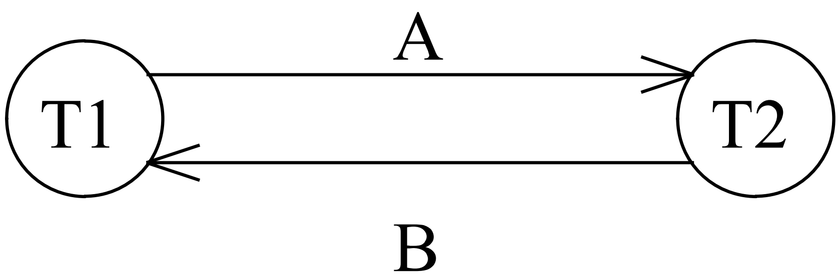
- ***Dependency graph***:
  - One node per Xact
  - Edge from Ti to Tj if:
    - An operation Oi of Ti conflicts with an operation Oj of Tj and
    - Oi appears earlier in the schedule than Oj.

- **Theorem: Schedule is conflict serializable *if and only if* its dependency graph is acyclic.**

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)	



Dependency graph

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

An Aside: View Serializability

- **Alternative (weaker!) notion of serializability.**
- **Schedules S1 and S2 are view equivalent if:**
  1. *same initial reads*: If Ti reads initial value of A in S1, then Ti also reads initial value of A in S2
  2. *same dependent reads:* If Ti reads value of A written by Tj in S1, then Ti also reads value of A written by Tj in S2
  3. *same winning writes:* If Ti writes final value of A in S1, then Ti also writes final value of A in S2
- **Basically, allows *all* conflict serializable schedules + "blind writes"**

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

view ≡

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

Notes on Serializability Definitions

- **View Serializability allows (slightly) more schedules than Conflict Serializability does.**
  - But V.S. is difficult to enforce efficiently.

- **Neither definition allows *all* schedules that are actually "serializable".**
  - Because they don't understand the meanings of the operations or the data.
    - Keep favorite examples that are Serializable but not C.S.

- **In practice, Conflict Serializability is what gets used, because it can be enforced efficiently.**
  - To allow more concurrency, some special cases do get handled separately. (Search the web for "Escrow Transactions" for example)

Two-Phase Locking (2PL)

- **The most common scheme for enforcing conflict serializability**
- **A bit "pessimistic"**
  - Sets locks for fear of conflict.. Some cost here.
  - Alternative schemes "optimistically" let transactions move forward, and aborting them when conflicts are detected.
    - Not today

Two-Phase Locking (2PL)

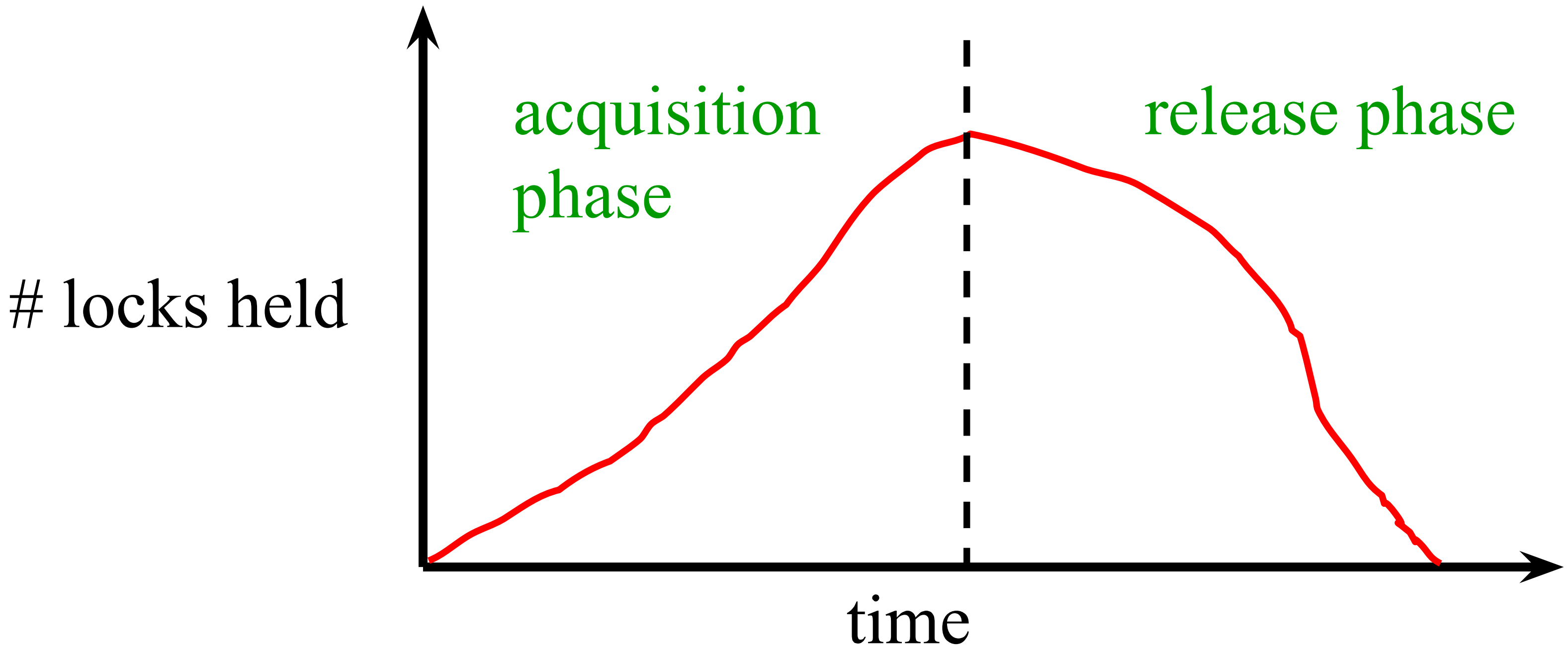
Lock Compatibility Matrix

	S	X
S	√	–
X	–	–

rules:

- Xact must obtain a **S** (*shared*) lock before reading, and an **X** (*exclusive*) lock before writing.
- Xact cannot get new locks after releasing any locks.

Two-Phase Locking (2PL), cont.



2PL guarantees conflict serializability ☺

But, does *<u>not</u>* prevent **Cascading Aborts.** ☹

Strict 2PL

- ***Problem:*** **Cascading Aborts**
- ***Example:*** **rollback of T1 requires rollback of T2!**

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

- **Strict Two-phase Locking (Strict 2PL) protocol:**

  Same as 2PL, except:

  <u>Locks released only when transaction completes</u>

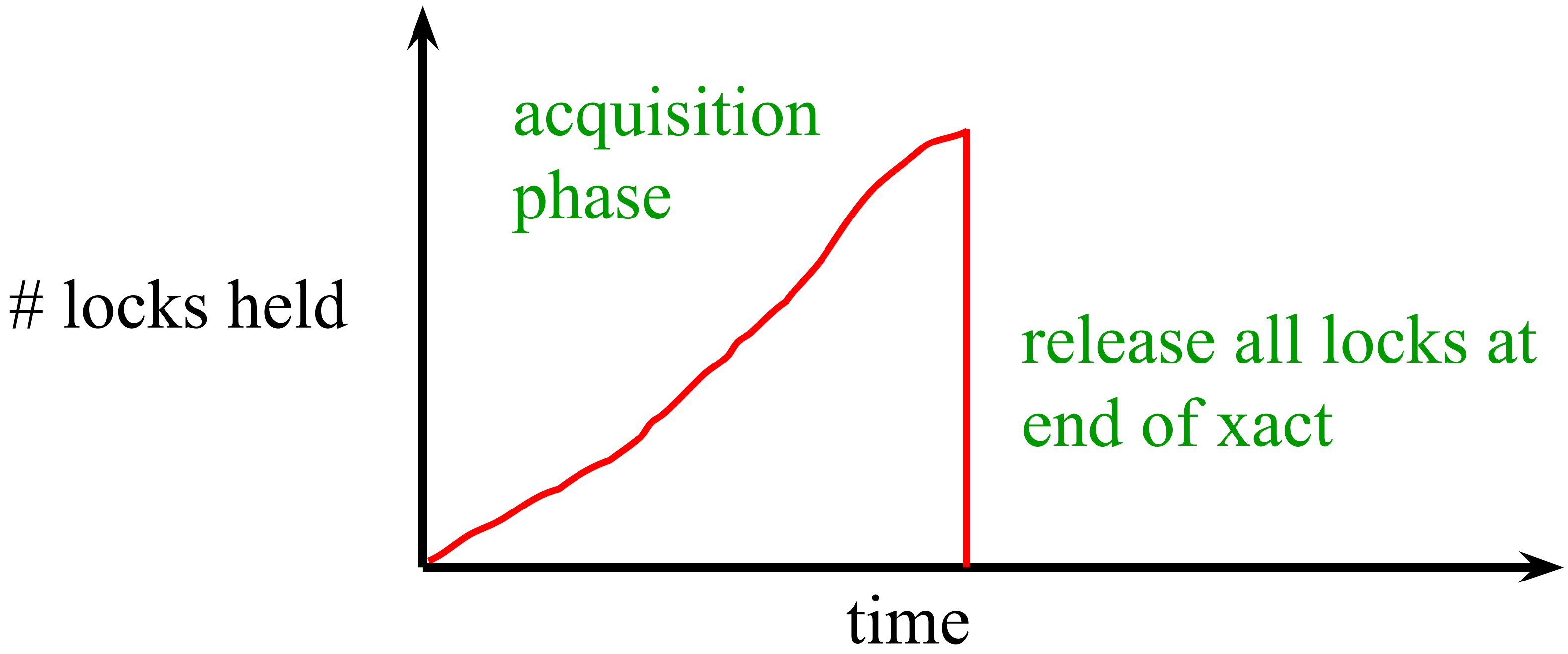
  i.e., either:

  (a) transaction has committed (commit record on disk),

  or

  (b) transaction has aborted and rollback is complete.

Strict 2PL (continued)



Next ...

- **A few examples**

Non-2PL, A= 1000, B=2000, Output =?

T1	T2
Lock_X(A)	
Read(A)	
	Lock_S(A)
A: = A-50	
Write(A)	
Unlock(A)	
	Read(A)
	Unlock(A)
	Lock_S(B)
Lock_X(B)	
	Read(B)
	Unlock(B)
	PRINT(A+B)
Read(B)	
B := B +50	
Write(B)	
Unlock(B)	

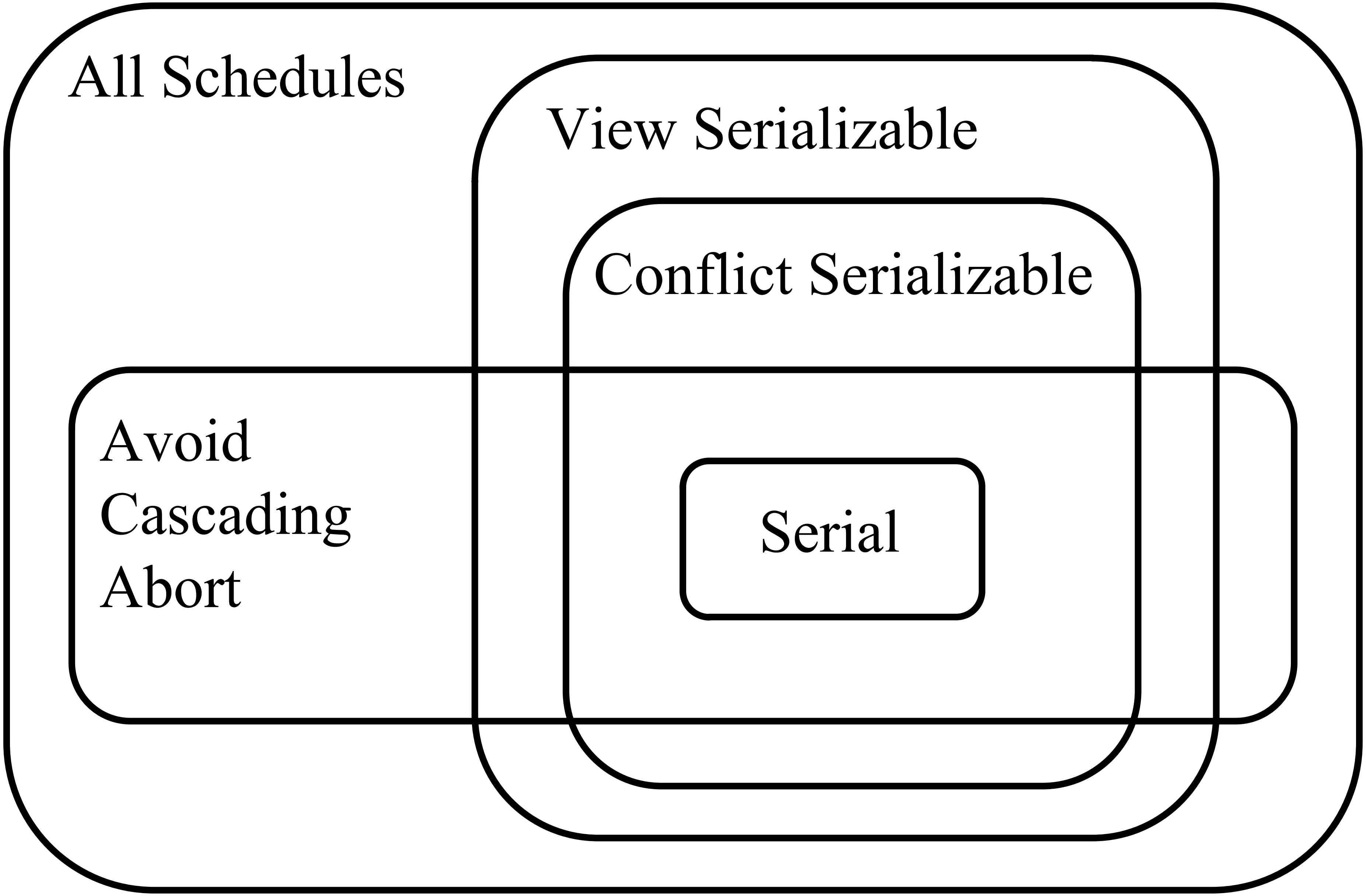
2PL, A= 1000, B=2000, Output =?

T1	T2
Lock_X(A)	
Read(A)	
	Lock_S(A)
A: = A-50	
Write(A)	
Lock_X(B)	
Unlock(A)	
	Read(A)
	Lock_S(B)
Read(B)	
B := B +50	
Write(B)	
Unlock(B)	
	Unlock(A)
	Read(B)
	Unlock(B)
	PRINT(A+B)

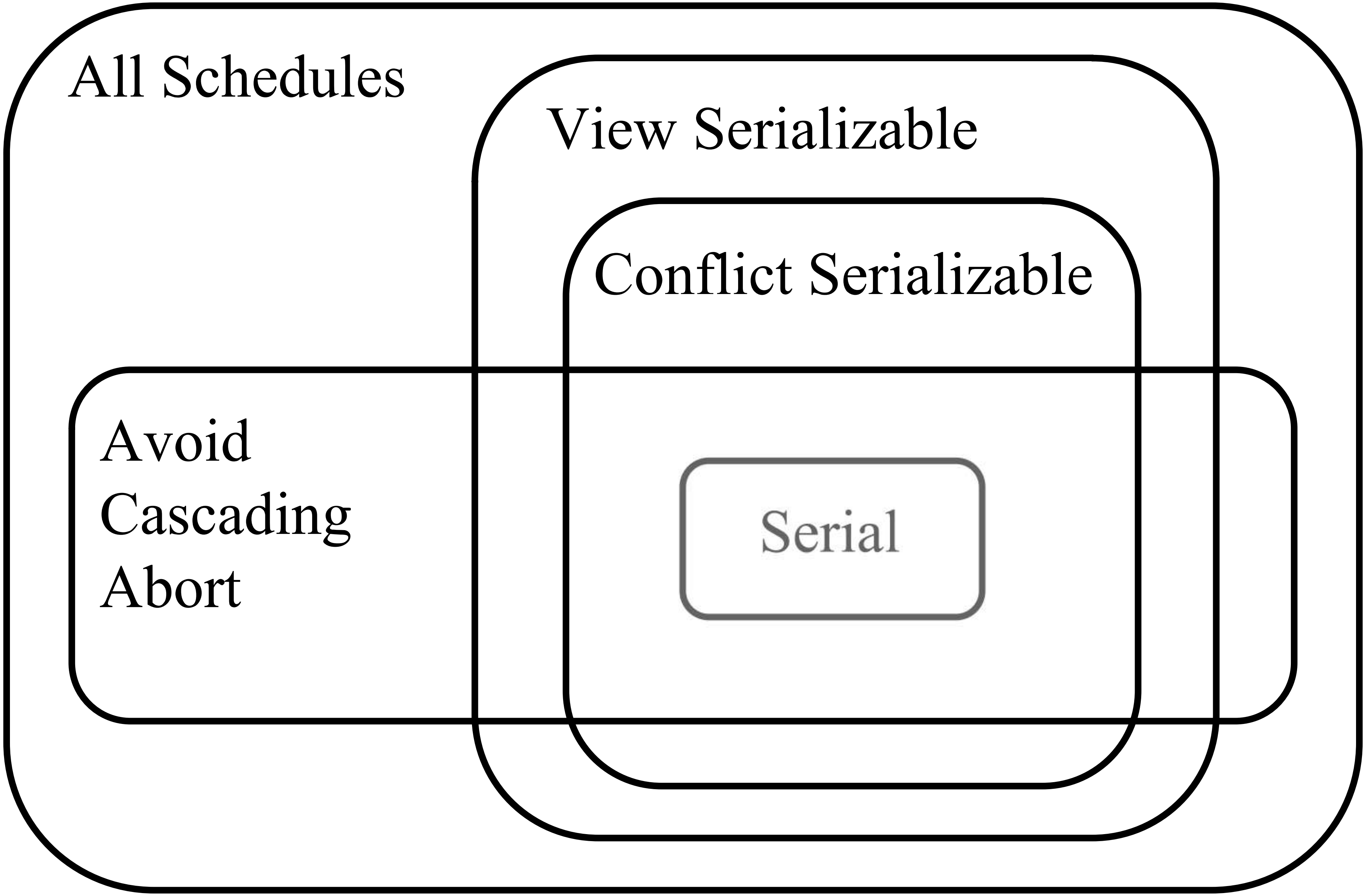
Strict 2PL, A= 1000, B=2000, Output =?

T1	T2
Lock_X(A)	
Read(A)	
	Lock_S(A)
A: = A-50	
Write(A)	
Lock_X(B)	
Read(B)	
B := B +50	
Write(B)	
Unlock(A)	
Unlock(B)	
	Read(A)
	Lock_S(B)
	Read(B)
	PRINT(A+B)
	Unlock(A)
	Unlock(B)

Venn Diagram for Schedules



Which schedules does Strict 2PL allow?



Lock Management

- Lock and unlock requests handled by Lock Manager

- LM is a hashtable, keyed on names of objects being locked.

- LM keeps an entry for each currently held lock.

- Entry contains:
  - Set of xacts currently granted access to the lock
  - Type of lock held (shared or exclusive)
  - Queue of lock requests

Lock Management, cont.

- **When lock request arrives:**
  - Does any other xact hold a conflicting lock?
    - If no, put the requester into the “granted set” and let them proceed.
    - If yes, put requestor into wait queue.

- **Lock upgrade:**
  - xact with shared lock can request to upgrade to exclusive

Example (Work out the lock table!)

Lock_X(A)	
	Lock_S(B)
	Read(B)
	Lock_S(A)
Read(A)	
A: = A-50	
Write(A)	
Lock_X(B)	

Deadlocks

- **Deadlock: Cycle of transactions waiting for locks to be released by each other.**
- **Two ways of dealing with deadlocks:**
  - prevention (a non-starter)
  - avoidance
  - detection
- **Many systems just punt and use Timeouts**
  - What are the dangers with this approach?

Deadlock Prevention

- **Common technique in operating systems**
- **Standard approach: resource ordering**
  - Screen < Network Card < Printer
- **Why is this problematic for Xacts in a DBMS?**

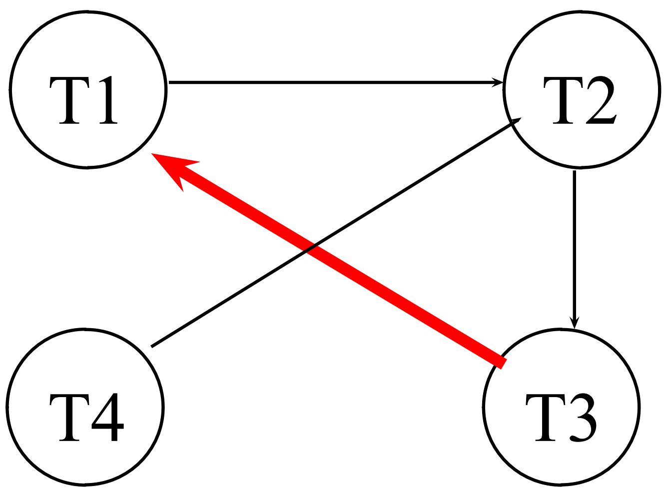
Deadlock Detection

- **Create and maintain a "waits-for" graph**
- **Periodically check for cycles in graph**

Deadlock Detection (Continued)

Example:

T1:	**S(A), S(D),**		**S(B)**			
T2:		**X(B)**			**X(C)**	
T3:			**S(D), S(C),**			**X(A)**
T4:				**X(B)**		



Deadlock!

- **T1, T2, T3 are deadlocked**
  - Doing no good, and holding locks
- **T4 still cruising**
- **In the background, run a deadlock detector**
  - Periodically extract the waits-for graph
  - Find cycles
  - "Shoot" a transaction on the cycle
- **Empirical fact**
  - Most deadlock cycles are small (2-3 transactions)

Deadlock Avoidance

- **Assign priorities based on timestamps.**
- **Say Ti wants a lock that Tj holds**

Two possible policies:

Read the names like a "ternary predicate" on priorities, with the form:

(Ti > Tj) ? X : Y;

Wait-Die: if Ti has higher priority, Ti waits for Tj;
else Ti aborts

Wound-wait: if Ti has higher priority, Tj aborts;
else Ti waits

- **Why do these schemes guarantee no deadlocks?**
- **Priority usually based on transaction's *age* (now - timestamp)**

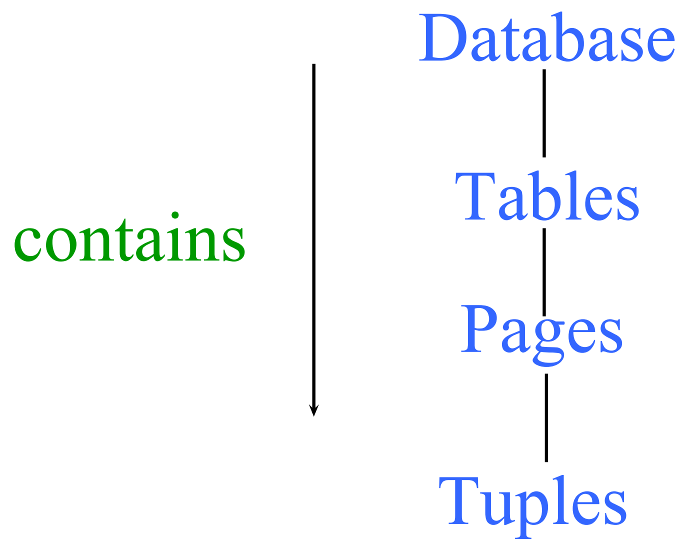
- **Important detail: If a transaction re-starts, make sure it gets its original timestamp. Why?**

Locking Granularity

- **Hard to decide what granularity to lock (tuples vs. pages vs. tables).**
- ***why?***

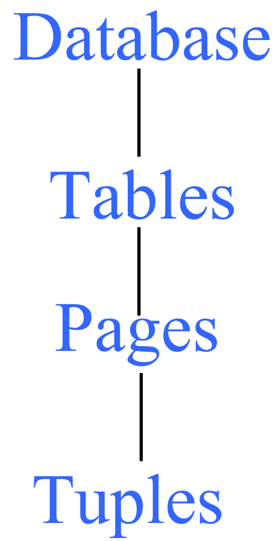
Multiple-Granularity Locks

- **Shouldn't have to make same decision for all transactions!**
- **Data "containers" are nested:**

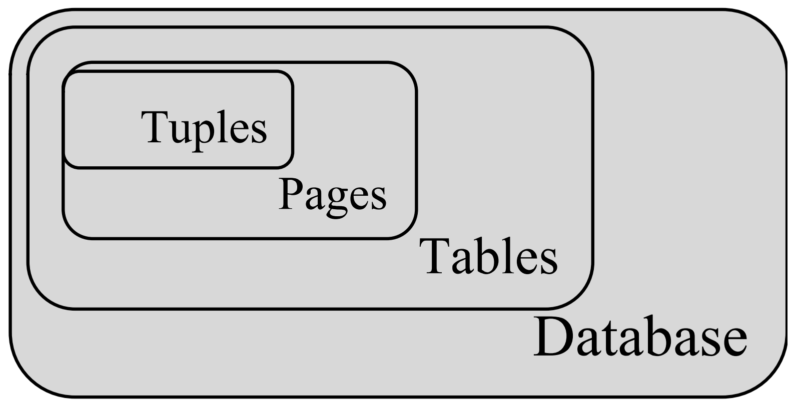


Solution: New Lock Modes, Protocol

- Allow Xacts to lock at each level, but with a special protocol using new "intent" locks:
- Still need S and X locks, but before locking an item, Xact must have proper intent locks on all its ancestors in the granularity hierarchy.



- IS – Intent to get S lock(s) at finer granularity.
- IX – Intent to get X lock(s) at finer granularity.
- SIX mode: Like S & IX at the same time. Why useful?



Multiple Granularity Lock Protocol

Database
Tables
Pages
Tuples

- Each Xact starts from the root of the hierarchy.
- To get S or IS lock on a node, must hold IS or IX on parent node.
  - What if Xact holds S on parent? SIX on parent?
- To get X or IX or SIX on a node, must hold IX or SIX on parent node.
- Must release locks in bottom-up order.

Protocol is correct in that it is equivalent to directly setting locks at the leaf levels of the hierarchy.

Lock Compatibility Matrix

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

Database
Tables
Pages
Tuples

- IS – Intent to get S lock(s) at finer granularity.
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Lock Compatibility Matrix

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

Database

Tables

Pages

Tuples

- IS – Intent to get S lock(s) at finer granularity.
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- SIX mode: Like S & IX at the same time.

Just so you're aware: Indexes

- **2PL on B+-tree pages is a rotten idea.**
  - Why?
- **Instead, do short locks (latches) in a clever way**
  - Idea: Upper levels of B+-tree just need to direct traffic correctly. Don't need serializability!
  - Different tricks to exploit this
    - The *B-link* tree is very elegant
    - The *Bw-tree* is a recent variant for main-memory DBs
- **Note: this is pretty complicated!**

Just so you're aware: Phantoms

- **Suppose you query for sailors with rating between 10 and 20, using a B+-tree**
  - Tuple-level locks in the Heap File
- **I insert "Dread Pirate Roberts", with rating 12**
- **You do your query again**
  - Yikes! A phantom!
  - Problem: Serializability assumed a static DB!
- **What we want: lock the *logical* range 10-20**
  - Imagine that lock table!
- **What is done: set locks in indexes cleverly**
  - So-called "next key locking"

Summary

- **Correctness criterion for isolation is "serializability".**
  - In practice, we use "conflict serializability," which is somewhat more restrictive but easy to enforce.
- **Two Phase Locking and Strict 2PL: Locks implement the notions of conflict directly.**
  - The lock manager keeps track of the locks issued.
  - **Deadlocks** may arise; can either be prevented or detected.
- **Multi-Granularity Locking:**
  - Allows flexible tradeoff between lock "scope" in DB, and locking overhead in RAM and CPU
- **More to the story**
  - Optimistic/Multi-version/Timestamp CC
  - Index "latching", phantoms