SCIENCE
PASSION
TECHNOLOGY

Database Systems
09 Transaction Processing

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Last update: May 13, 2019

Announcements/Org

- **#1 Video Recording**
  - Since lecture 03, video/audio recording
  - Link in TeachCenter & TUbe
- **#2 Exercises**
  - Exercise 1 graded, feedback in TC in next days
  - **Exercise 2 still open** until May 14 11.50pm (incl. 7 late days, **no submission is a mistake**)
  - Exercise 3 published and introduced today

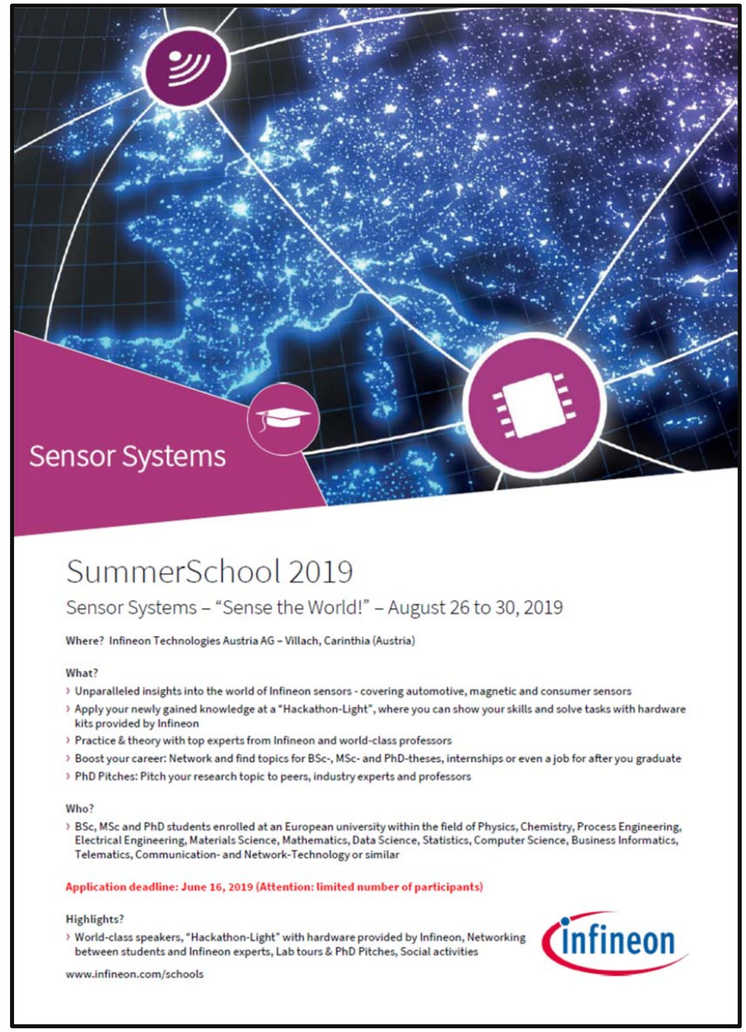
77.4%

53.7%

- **#3 CS Talks x4** (Jun 17 2019, 5pm, Aula Alte Technik)
  - Claudia Wagner (University Koblenz-Landau, Leibnitz Institute for the Social Sciences)
  - Title: Minorities in Social and Information Networks
  - **Dinner opportunity for interested female students!**

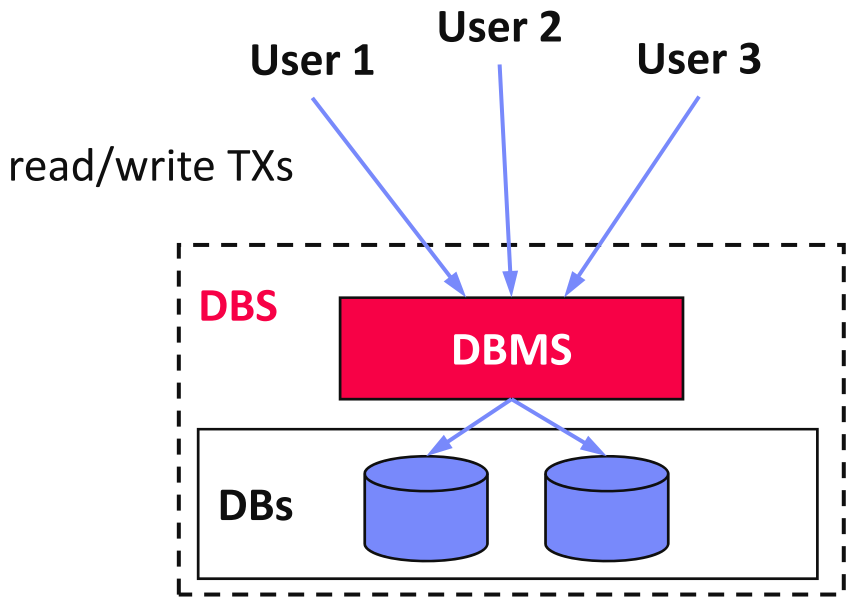
Announcements/Org, cont.

- **#4 Infineon Summer School 2019**
  Sensor Systems
  - **Where:** Infineon Technologies Austria, Villach Carinthia, Austria
  - **Who:** BSc, MSc, PhD students from different fields including business informatics, computer science, and electrical engineering
  - **When:** Aug 26 through 30, 2019
  - **Application deadline: Jun 16, 2019**



- **#5 Poll: Date of Final Exam**
  - We'll move Exercise 4 to Jun 25
  - Current date: **Jun 24, 6pm**
  - Alternatives: **Jun 27, 4pm** / **7.30pm**, or week starting Jul 8 (Erasmus?)

Transaction (TX) Processing



#1 Multiple users
➔ **Correctness?**

#2 Various failures
(TX, system, media)
➔ **Reliability?**

Deadlocks
Constraint violations
Network failure
Crash/power failure
Disk failure

- **Goal: Basic Understanding of Transaction Processing**
  - Transaction processing from user perspective
  - Locking and concurrency control to ensure **#1 correctness**
  - Logging and recovery to ensure **#2 reliability**

Agenda

- **Overview Transaction Processing**
- **Locking and Concurrency Control**
- **Logging and Recovery**
- **Exercise 3: Tuning and Transactions**

Additional Literature:

[**Jim Gray**, Andreas Reuter: Transaction Processing: Concepts and Techniques. **Morgan Kaufmann 1993**]

[Gerhard Weikum, Gottfried Vossen: Transactional Information Systems: Theory, Algorithms, and the Practice of Concurrency Control and Recovery. **Morgan Kaufmann 2002**]

Overview Transaction Processing

Terminology of Transactions

- **Database Transaction**
  - A transaction (TX) is a **series of steps** that brings a database from a **consistent state** into another (not necessarily different) **consistent state**
  - **ACID properties** (atomicity, consistency, isolation, durability)

- **Terminology by Example**

#2 Start/**begin of TX** (BOT)

#1 Isolation level (defined by addressed anomalies)

```
START TRANSACTION ISOLATION LEVEL SERIALIZABLE;
  UPDATE Account SET Balance=Balance-100
     WHERE AID = 107;
  UPDATE Account SET Balance=Balance+100
     WHERE AID = 999;

  SELECT Balance INTO lbalance
     FROM Account WHERE AID=107;
  IF lbalance < 0 THEN
     ROLLBACK TRANSACTION;
  END IF
COMMIT TRANSACTION;
```

#3 Reads and writes of data objects

#4 Abort/rollback TX (unsuccessful end of transaction, EOT)

#5 Commit TX (successful end of transaction, EOT)

#6 Savepoints (checkpoint for partial rollback)

Example OLTP Benchmarks

- **Online Transaction Processing (OLTP)**
  - Write-heavy database workloads, primarily with point lookups/accesses
  - **Applications:** financial, commercial, travel, medical, and governmental ops
  - **Benchmarks:** e.g., **TPC-C**, **TPC-E**, AuctionMark, SEATS (Airline), **Voter**

- **Example TPC-C**
  - 45% New-Order
  - 43% Payment
  - 4% Order Status
  - 4% Delivery
  - 4% Stock Level

New Order Transaction:

1) Get records describing a warehouse (tax), customer, district
2) Update the district to increment next available order number
3) Insert record into Order and NewOrder
4) For All Items
   a) Get item record (and price)
   b) Get/update stock record
   c) Insert OrderLine record
5) Update total amount of order

[http://www.tpc.org/tpc_documents_current_versions/pdf/tpc-c_v5.11.0.pdf]

ACID Properties

- **Atomicity**
  - A transaction is executed atomically (**completely or not at all**)
  - If the transaction fails/aborts no changes are made to the database (**UNDO**)
- **Consistency**
  - A successful transaction ensures that all **consistency constraints are met** (referential integrity, semantic/domain constraints)
- **Isolation**
  - Concurrent transactions are executed in isolation of each other
  - **Appearance of serial transaction execution**
- **Durability**
  - **Guaranteed persistence** of all changes made by a successful transaction
  - In case of system failures, the database is recoverable (**REDO**)

Anomalies – Lost Update

TA1 updates points for Exercise 1

```
SELECT Pts INTO :points
   FROM Students WHERE Sid=789;

points += 23.5;

UPDATE Students SET Pts=:points
   WHERE Sid=789;
COMMIT TRANSACTION;
```

TA2 updates points for Exercise 2

```
SELECT Pts INTO :points
   FROM Students WHERE Sid=789;

points += 24.0;

UPDATE Students SET Pts=:points
   WHERE Sid=789;
COMMIT TRANSACTION;
```

Time

Student received 24 instead of 47.5 points
(lost update 23.5)

- **Problem: Write-write dependency**
- **Solution: Exclusive lock on write**

Anomalies – Dirty Read

TA1 updates points for Exercise 1

```
UPDATE Students SET Pts=100
   WHERE Sid=789;

ROLLBACK TRANSACTION;
```

TA2 updates points for Exercise 2

```
SELECT Pts INTO :points
   FROM Students WHERE Sid=789;

points += 24.0;

UPDATE Students SET Pts=:points
   WHERE Sid=789;
COMMIT TRANSACTION;
```

Time

Student received 124 instead of 24 points

- **Problem: Write-read dependency**
- **Solution: Read only committed changes; otherwise, cascading abort**

Anomalies – Unrepeatable Read

TA1 updates points for Exercise 1	TA2 runs statistics for Exercise 1
	`SELECT Pts INTO :p1 FROM Students WHERE Sid=789;`
`START TRANSACTION; UPDATE Students SET Pts=Pts+23.5 WHERE Sid=789; COMMIT TRANSACTION;`	`...`
modified value →	`SELECT Pts INTO :p2 FROM Students WHERE Sid=789; ... COMMIT TRANSACTION;`

Time

TA2 sees only committed data but analysis corrupted as p1!=p2

- **Problem: Read-write dependency**
- **Solution: TA works on consistent snapshot of touched records**

Anomalies – Phantom

TA1 inserts missing student

TA2 runs statistics for Exercise 1

```
                                  | SELECT Avg(Pts) INTO :p1
                                  |    FROM Students WHERE Sid<1000;
----------------------------------+----------------------------------
START TRANSACTION;                |
  INSERT INTO Students            | ...
    VALUES (999, ..., 0);         |
COMMIT TRANSACTION;               |
----------------------------------+----------------------------------
                                  | SELECT Avg(Pts) INTO :p2
                                  |    FROM Students WHERE Sid<1000;
                                  | ...
                                  | COMMIT TRANSACTION;
```

added row (harder to track because new database object)

Time

TA2 sees only committed data but analysis corrupted as p1!=p2

- **Similar to non-repeatable read but at set level** (snapshot of accessed data objects not sufficient)

Isolation Levels

- **Different Isolation Levels**
  - **Tradeoff Isolation vs performance** per session/TX
  - SQL standard requires **guarantee against lost updates** for all

```
SET TRANSACTION
    ISOLATION LEVEL
    READ COMMITTED
```

- **SQL Standard Isolation Levels**

Isolation Level	Lost Update	Dirty Read	Unrepeatable Read	Phantom Read
READ UNCOMMITTED	No	Yes	Yes	Yes
READ COMMITTED	No	No	Yes	Yes
REPEATABLE READ	No	No	No	Yes
[SERIALIZABLE]	No	No	No	No

  - Serializable w/ highest guarantees (**pseudo-serial execution**)

- **How can we enforce these isolation levels?**
  - **User:** set default/transaction isolation level (mixed TX workloads possible)
  - **System:** dedicated concurrency control strategies + scheduler

Excursus: A Critique of SQL Isolation Levels

[Hal Berenson, Philip A. Bernstein, Jim Gray, Jim Melton, Elizabeth J. O'Neil, Patrick E. O'Neil: A Critique of ANSI SQL Isolation Levels. **SIGMOD 1995**]

- **Summary**
  - **Critique:** SQL standard isolation levels are ambiguous (strict/broad interpretations)
  - Additional anomalies: dirty write, cursor lost update, fuzzy read, read skew, write skew
  - Additional isolation levels: **cursor stability** and **snapshot isolation**

- **Snapshot Isolation (< Serializable)**
  - **Type of optimistic concurrency control** via multi-version concurrency control
  - TXs reads data from a snapshot of committed data when TX started
  - **TXs never blocked on reads**, other TXs data invisible
  - TX **T1 only commits if no other TX wrote the same data items** in the time interval of T1

Excursus: Isolation Levels in Practice

- **Default and Maximum Isolation Levels for "ACID" and "NewSQL" DBs** [as of 2013]
  - 3/18 `SERIALIZABLE` by default
  - 8/18 did not provide `SERIALIZABLE` at all

[Peter Bailis, Alan Fekete, Ali Ghodsi, Joseph M. Hellerstein, Ion Stoica: HAT, Not CAP: Towards Highly Available Transactions. **HotOS 2013**]

Beware of defaults, even though the SQL standard says **`SERIALIZABLE`** is the default

Database	Default	Maximum
Actian Ingres 10.0/10S [1]	S	S
Aerospike [2]	RC	RC
Akiban Persistit [3]	SI	SI
Clustrix CLX 4100 [4]	RR	RR
Greenplum 4.1 [8]	RC	S
IBM DB2 10 for z/OS [5]	CS	S
IBM Informix 11.50 [9]	Depends	S
MySQL 5.6 [12]	RR	S
MemSQL 1b [10]	RC	RC
MS SQL Server 2012 [11]	RC	S
NuoDB [13]	CR	CR
Oracle 11g [14]	RC	SI
Oracle Berkeley DB [7]	S	S
Oracle Berkeley DB JE [6]	RR	S
Postgres 9.2.2 [15]	RC	S
SAP HANA [16]	RC	SI
ScaleDB 1.02 [17]	RC	RC
VoltDB [18]	S	S

RC: read committed, RR: repeatable read, SI: snapshot isolation, S: serializability, CS: cursor stability, CR: consistent read

Locking and Concurrency Control

(Consistency and Isolation)

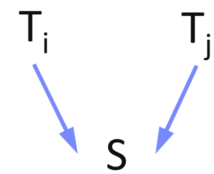
Overview Concurrency Control

- **Terminology**
  - **Lock:** logical synchronization of TXs access to database objects (row, table, etc)
  - **Latch:** physical synchronization of access to shared data structures
- **#1 Pessimistic Concurrency Control**
  - Locking schemes (lock-based database scheduler)
  - Full serialization of transactions
- **#2 Optimistic Concurrency Control (OCC)**
  - Optimistic execution of operations, check of conflicts (validation)
  - Optimistic and timestamp-based database schedulers
- **#3 Mixed Concurrency Control (e.g., PostgreSQL)**
  - Combines locking and OCC
  - Might return **synchronization errors**

```
ERROR: could not serialize access
       due to concurrent update
ERROR: deadlock detected
```

Serializability Theory

- **Operations of Transaction T_j**
  - Read and write operations of A by T_j: **$r_j(A)$ $w_j(A)$**
  - Abort of transaction T_j: **a_j** (unsuccessful termination of T_j)
  - Commit of transaction T_j: **c_j** (successful termination of T_j)
- **Schedule S**
  - Operations of a transaction **T_j are executed in order**
  - Multiple transactions may be executed concurrently
  - ➔ **Schedule describes the total ordering of operations**



- **Equivalence of Schedules S1 and S2**
  - Read-write, write-read, and write-write dependencies on data object A executed in same order:

$$r_i(A) <_{S1} w_j(A) \Leftrightarrow r_i(A) <_{S2} w_j(A)$$
$$w_i(A) <_{S1} r_j(A) \Leftrightarrow w_i(A) <_{S2} r_j(A)$$
$$w_i(A) <_{S1} w_j(A) \Leftrightarrow w_i(A) <_{S2} w_j(A)$$

Serializability Theory, cont.

- **Example Serializable Schedules**
  - Input TXs
    T1: BOT $r_1(A)$ $w_1(A)$ $r_1(B)$ $w_1(B)$ c_1
    T2: BOT $r_2(C)$ $w_2(C)$ $r_2(A)$ $w_2(A)$ c_2
  - Serial execution
    $r_1(A)$ $w_1(A)$ $r_1(B)$ $w_1(B)$ c_1 $r_2(C)$ $w_2(C)$ $r_2(A)$ $w_2(A)$ c_2
  - Equivalent schedules
    $r_1(A)$ $r_2(C)$ $w_1(A)$ $w_2(C)$ $r_1(B)$ $r_2(A)$ $w_1(B)$ $w_2(A)$ c_1 c_2
    $r_1(A)$ $w_1(A)$ $r_2(C)$ $w_2(C)$ $r_1(B)$ $w_1(B)$ $r_2(A)$ $w_2(A)$ c_1 c_2

- **Serializability Graph (conflict graph)**
  - Operation dependencies (read-write, write-read, write-write) aggregated
  - **Nodes:** transactions; **edges:** transaction dependencies
  - **Transactions are serializable** (via topological sort) **if the graph is acyclic**
  - **Beware:** In < SERIALIZABLE, many equivalent schedules that give different results than true serial execution (dirty read, unrepeatable read, phantom)

Locking Schemes

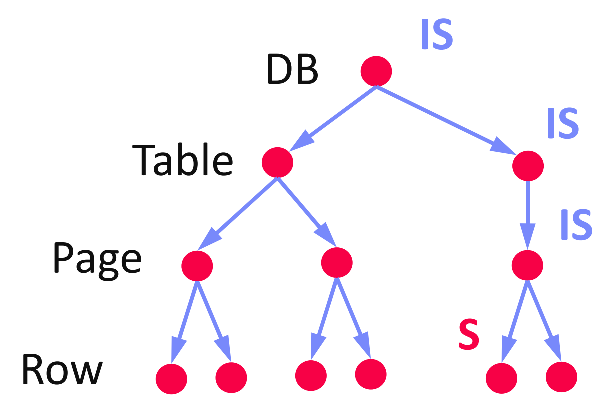
- **Compatibility of Locks**
  - X-Lock (exclusive/write lock)
  - S-Lock (shared/read lock)

Existing Lock / Requested Lock

	None	S	X
S	Yes	Yes	No
X	Yes	No	No

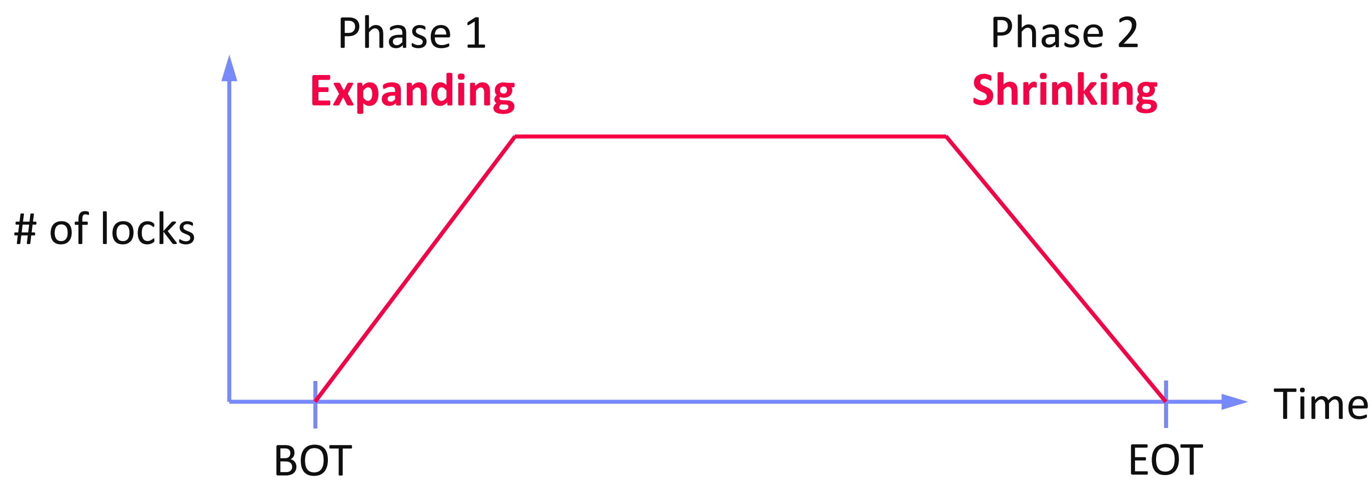
- **Multi-Granularity Locking**
  - Hierarchy of DB objects
  - Additional intentional **IX and IS locks**

	None	S	X	IS	IX
S	Yes	Yes	No	Yes	No
X	Yes	No	No	No	No
IS	Yes	Yes	No	Yes	Yes
IX	Yes	No	No	Yes	Yes



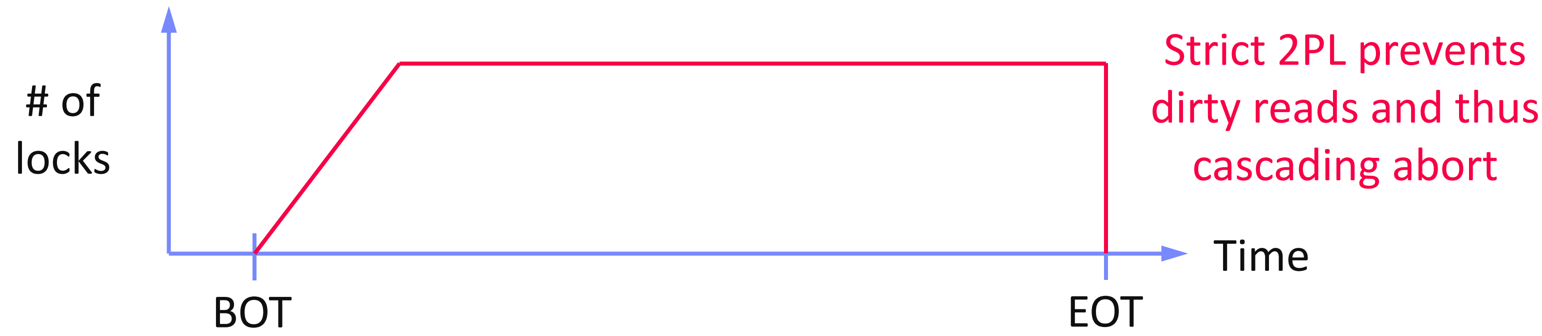
Two-Phase Locking (2PL)

- **Overview**
  - 2PL is a concurrency protocol that guarantees **SERIALIZABLE**
  - **Expanding phase:** acquire locks needed by the TX
  - **Shrinking phase:** release locks acquired by the TX (can only start if all needed locks acquired)

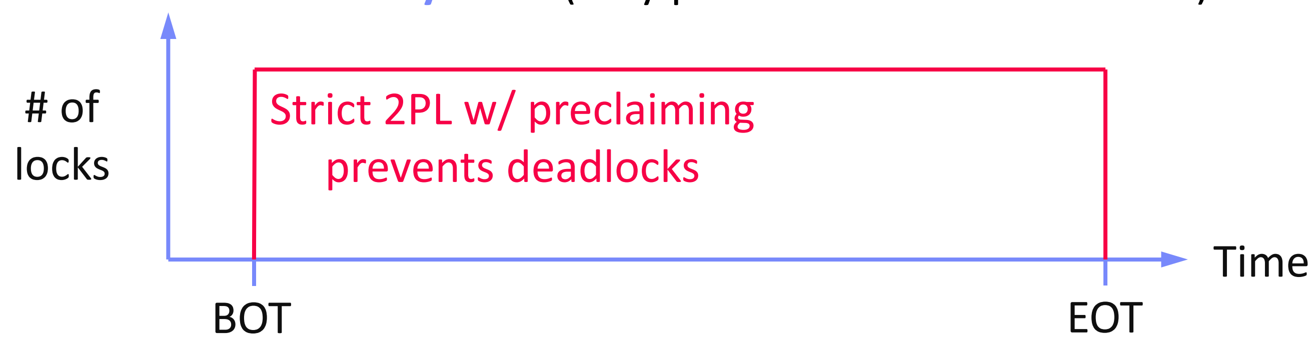


Two-Phase Locking, cont.

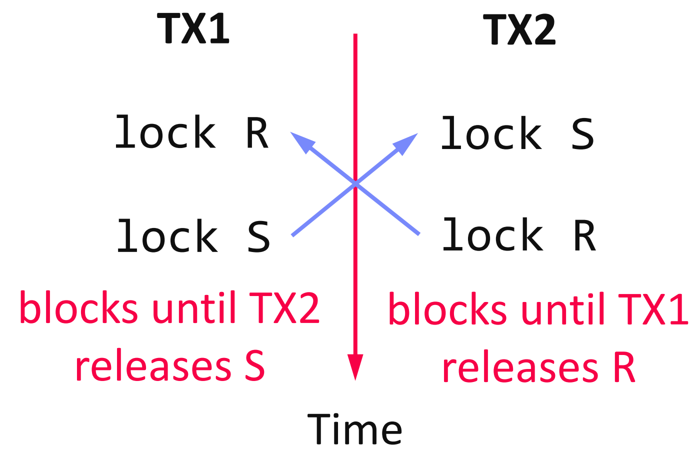
- **Strict 2PL (S2PL) and Strong Strict 2PL (SS2PL)**
  - **Problem:** Transaction rollback can cause (**Dirty Read**)
  - Release all X-locks (S2PL) or X/S-locks (SSPL) **at end of transaction (EOT)**



- **Strict 2PL w/ pre-claiming (aka conservative 2PL)**
  - Problem: incremental expanding can cause deadlocks for interleaved TXs
  - **Pre-claim all necessary locks** (only possible if entire TX known)



Deadlocks



DEADLOCK, as this will never happen

- **Deadlock Scenario**
  - Deadlocks of concurrent transactions
  - Deadlocks happen due to **cyclic dependencies without pre-claiming** (wait for exclusive locks)
- **#1 Deadlock Prevention**
  - Guarantee that deadlocks can't happen
  - E.g., **via pre-claiming** (but overhead and not always possible)
- **#2 Deadlock Avoidance**
  - Attempts to avoid deadlocks before acquiring locks via timestamps per TX
  - **Wound-wait** (T1 locks something hold by T2 → if T1<T2, restart T2)
  - **Wait-die** (T1 locks something hold by T2 → if T1>T2, abort T1 but keep TS)
- **#3 Deadlock Detection**
  - Maintain a wait-for graph of blocked TX (similar to serializability graph)
  - Detection of cycles in graph (on timeout) → abort one or many TXs

Timestamp Ordering

Great, **low overhead scheme if conflicts are rare** (no hot spots)

- **Synchronization Scheme**
  - Transactions get timestamp (or version number) **$TS(T_j)$** at BOT
  - Each data object A has **readTS(A)** and **writeTS(A)**
  - Use timestamp comparison to validate access, otherwise abort
  - No locks but latches (physical synchronization)
- **Read Protocol $T_j(A)$**
  - If $TS(T_j)$ >= writeTS(A): **allow read**, set readTS(A) = max($TS(T_j)$, readTS(A))
  - If $TS(T_j)$ < writeTS(A): **abort T_j** (older than last modifying TX)
- **Write Protocol $T_j(A)$**
  - If $TS(T_j)$ >= readTS(A) AND $TS(T_j)$ >= writeTS(A): **allow write**, set writeTS(A)=$TS(T_j)$
  - If $TS(T_j)$ < readTS(A): **abort T_j** (older than last reading TX)
  - If $TS(T_j)$ < writeTS(A): **abort T_j** (older than last modifying TX)

Optimistic Concurrency Control (OCC)

- **Read Phase**
  - Initial reads from DB, **repeated reads and writes into TX-local buffer**
  - Maintain **ReadSet(T_j)** and **WriteSet(T_j)** per transaction T_j
  - TX seen as read-only transaction on database
- **Validation Phase**
  - Check read/write and write/write conflicts, **abort on conflicts**
  - BOCC (Backward-oriented concurrency control) – check all older TXs Ti
    - **Serializable:** if $EOT(T_i) < BOT(T_j)$ or $WSet(T_i) \cap RSet(T_j) = \emptyset$
    - **Snapshot isolation:** $EOT(T_i) < BOT(T_j)$ or $WSet(T_i) \cap WSet(T_j) = \emptyset$
  - FOCC (Forward-oriented concurrency control) – check running TXs
- **Write Phase**
  - Successful TXs with write operations propagate their local buffer into the database and log

Logging and Recovery

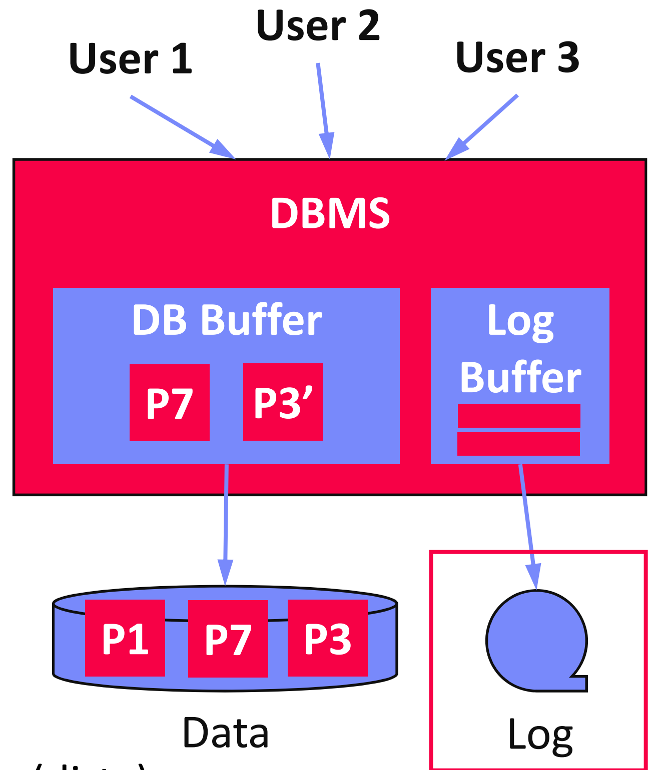
(Atomicity and Durability)

Failure Types and Recovery

- **Transaction Failures**
  - E.g., Violated integrity constraints, abort
  - → **R1-Recovery: partial UNDO** of this uncommitted TX
- **System Failures** (soft crash)
  - E.g., HW or operating system crash, power outage
  - Kills all in-flight transactions, but does not lose persistent data
  - → **R2-Reovery: partial REDO** of all committed TXs
  - → **R3-Recovery: global UNDO** of all uncommitted TXs
- **Media Failures** (hard crash)
  - E.g., disk hard errors (non-restorable)
  - Loses persistent data → need backup data (checkpoint)
  - → **R4-Recovery: global REDO** of all committed TXs

Database (Transaction) Log

- **Database Architecture**
  - Page-oriented storage on disk and in memory (DB buffer)
  - Dedicated **eviction algorithms**
  - Modified in-memory pages marked as dirty, flushed by cleaner thread
  - Log: append-only TX changes
  - Data/log often placed on different devices and periodically archived (backup + truncate)



- **Write-Ahead Logging (WAL)**
  - The log records representing changes to some (dirty) data page must be on **stable storage before the data page** (UNDO - atomicity)
  - **Force-log on commit** or full buffer (REDO - durability)
  - **Recovery:** forward (REDO) and backward (UNDO) processing of the log records

[C. Mohan, Donald J. Haderle, Bruce G. Lindsay, Hamid Pirahesh, Peter M. Schwarz: ARIES: A Transaction Recovery Method Supporting Fine-Granularity Locking and Partial Rollbacks Using Write-Ahead Logging. **TODS 1992**]

Logging Types and Recovery

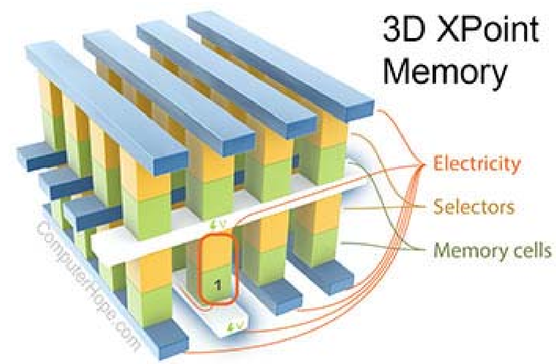
- **#1 Logical (Operation) Logging**
  - REDO: **log operation (not data)** to construct after state
  - UNDO: **inverse operations** (e.g., increment/decrement), not stored
  - **Non-determinism** cannot be handled, more flexibility on locking
- **#2 Physical (Value) Logging**
  - REDO: **log REDO (after) image** of record or page
  - UNDO: **log UNDO (before) image** of record or page
  - **Larger space overhead** (despite page diff) for set-oriented updates

```
UPDATE Emp
  SET Salary=Salary+100
  WHERE Dep='R&D';
```

- **Restart Recovery (ARIES)**
  - Conceptually: take database checkpoint and replay log since checkpoint
  - **Operation and value locking**; stores log seq. number (LSN, PageID, PrevLSN)
  - **Phase 1 Analysis:** determine winner and loser transactions
  - **Phase 2 Redo:** replay all TXs in order **[repeating history]** → **state at crash**
  - **Phase 3 Undo:** replay uncommitted TXs (losers) in reverse order

Excursus: Recovery on Storage Class Memory

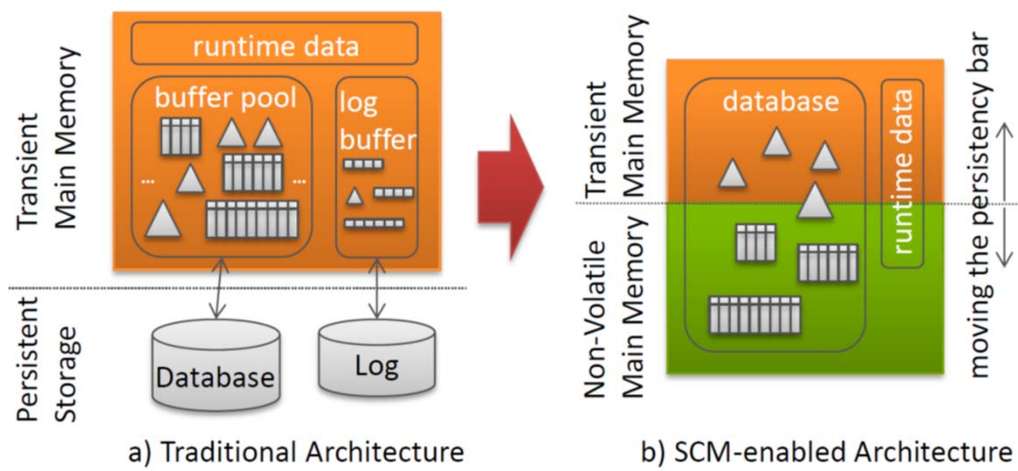
- **Background: Storage Class Memory (SCM)**
  - **Byte-addressable, persistent memory** with higher capacity, but latency close to DRAM
  - **Examples:** Resistive RAM, Magnetic RAM, Phase-Change Memory (e.g., **Intel 3D XPoint**)



[**Credit:** https://computerhope.com]

- **SOFORT: DB Recovery on SCM**
  - Simulated DBMS prototype on SCM
  - Instant recovery by trading TX throughput vs recovery time
  - Configured: **% of transient data structures on SCM**

[Ismail Oukid, Wolfgang Lehner, Thomas Kissinger, Thomas Willhalm, Peter Bumbulis: Instant Recovery for Main Memory Databases. **CIDR 2015**]



Exercise 3:
Tuning and Transactions

Published: May 13

Deadline: Jun 4

Task 3.1 Indexing and Materialized Views

5/25 points

- **Setup** (help by **end of this week**)
  - We'll provide csv files for individual tables
  - We'll provide the query for Q10

- **#1 Indexing** (Q: distinct club names for players w/ jnum<=3)
  - Create and run the SQL query, obtain the text explain
  - Create a secondary index on jersey number
  - Re-run the SQL query, obtain the text explain, and describe the difference

- **#2 Materialized Views** (Q10)
  - Create a materialized view that could speed up Q10
  - Rewrite the SQL query to use the materialized view, obtain text explain, and describe difference

See lecture 07 Physical Design

Task 3.2 B-Tree Insertion and Deletion

6/25 points

- **Setup**
  - ```
    SET seed TO 0.0<student_id>
    SELECT * FROM generateseries(1,16) ORDER BY random();
    ```

- **#3 B-Tree Insertion**
  - Draw the final b-tree after inserting your sequence in order (e.g., with you favorite tool, by hand, or ASCI art)

- **#4 B-Tree Deletion**
  - Draw the final b-tree after taking #3 and deleting the sequence [8,14) in order of their values

See lecture 07 Physical Design
    ```

Task 3.3 Join Implementation

10/25 points

- **Setup**
  - Pick your favorite programming language
  - Use existing/your own Tuple representation (int ID, other attributes)
- **#5 Table Scan**
  - Created via `Collection<Tuple>` (or similar) as input
  - Implements a simple table scan via open(), next(), close()
- **#6 Hash Join**
  - Created via two iterators (left and right) as input
  - Implement a hash join for multisets via open(), next(), close()
- **#7 Nested Loop Join**
  - Created via two iterators (left and right) as input
  - Implement a nested loop join for multisets via open(), next(), close()

See lecture 08 Query Processing

Task 3.4 Transaction Processing

4/25 points

- **Setup**
  - Create tables `R(a INT, b INT)` and `S(a INT, b INT)`
- **#8 Simple Transaction**
  - Create a SQL transaction that atomically inserts two tuples into R and three tuples into S
- **#9 Deadlock**
  - Create two SQL transactions that can be execute interactively to create a deadlock; annotate the order as comments
  - Explain the reason for the deadlock

See lecture 09 Transaction Processing

Conclusions and Q&A

- **Summary 09 Transaction Processing**
  - Overview transaction processing
  - Locking and concurrency control
  - Logging and recovery
- **Summary Part A: Database Systems**
  - Databases systems primarily from user perspective
  - End of lectures for Databases 1 (but +1 ECTS if you attend entire course)
  - **Exercise 3** published, submission deadline **June 4, 11.59pm**
- **Next Lectures (Part B: Modern Data Management)**
  - **10 NoSQL (key-value, document, graph)** [May 20]
  - **11 Distributed file systems and object storage** [May 27]
  - **12 Data-parallel computation (MapReduce, Spark)** [Jun 03]
  - **13 Data stream processing systems** [Jun 17]