

Data Management

09 Transaction Processing

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Announcements/Org

■ #1 Video Recording

- Link in **TeachCenter** & **TUbe** (lectures will be public)
- <https://tugraz.webex.com/meet/m.boehm>
- Corona traffic light **RED** → May 17: **ORANGE** (but tests required)



■ #2 Reminder Communication

- **Newsgroup:** <news://news.tugraz.at/tu-graz.lv.dbase>
- **Office hours:** Mo 12.30-1.30pm (<https://tugraz.webex.com/meet/m.boehm>)

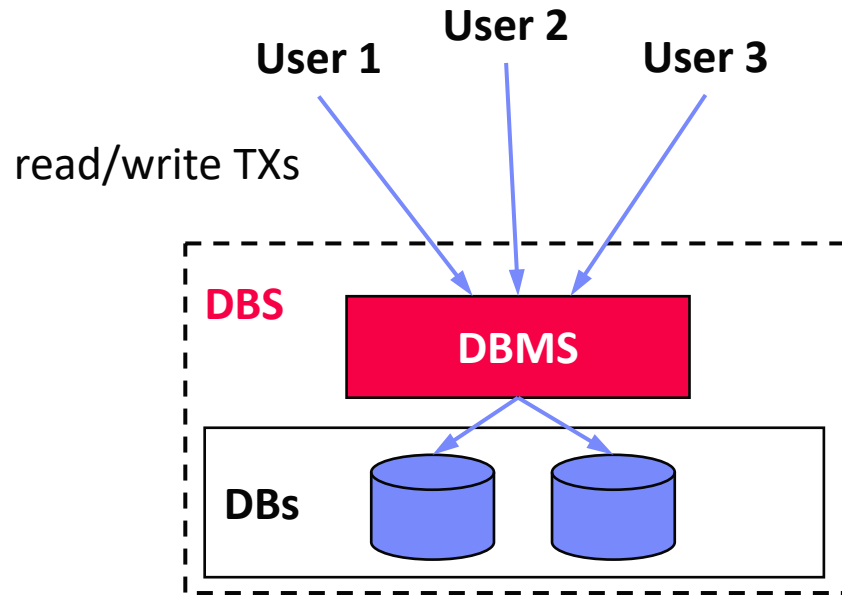
■ #3 Exercise Submissions

- **Grading:** Exercise 1 - done, Exercise 2 - end of May
- **Exercise 3:** published May 4, updated May 7 discussed today, deadline May 25

■ #4 Exams Dates

- Requested for **Jun 28 4pm**, **Jun 28 6.30pm**, **Jul 5 4pm** (waiting for approval)
- HS i11, i12, i13 (start 10min past, 90min working time)

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**]

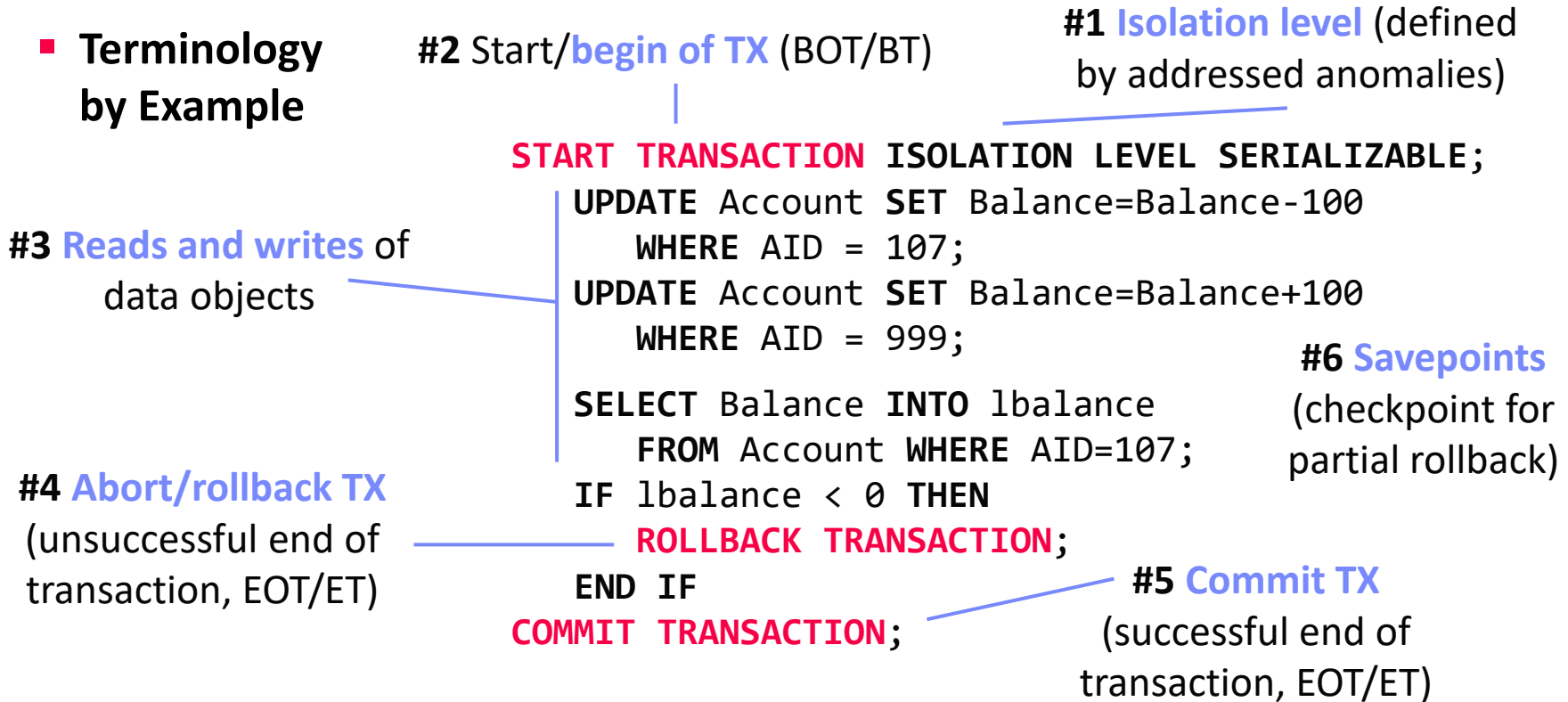
Overview Transaction Processing

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



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

[Theo Härder, Andreas Reuter: Principles of Transaction-Oriented Database Recovery. **ACM Comput. Surv.** 15(4) 1983]



■ 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;
```



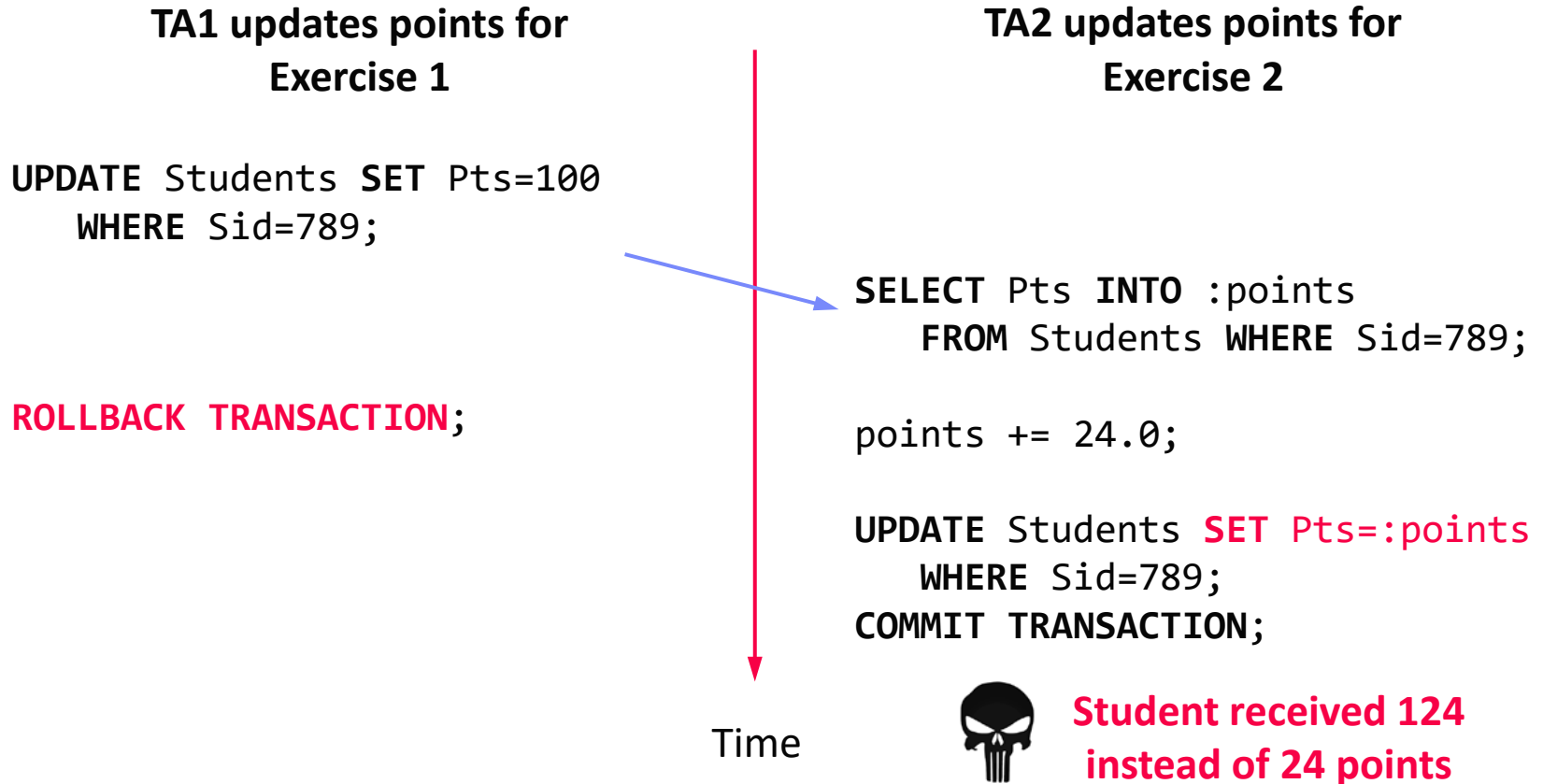
Time



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

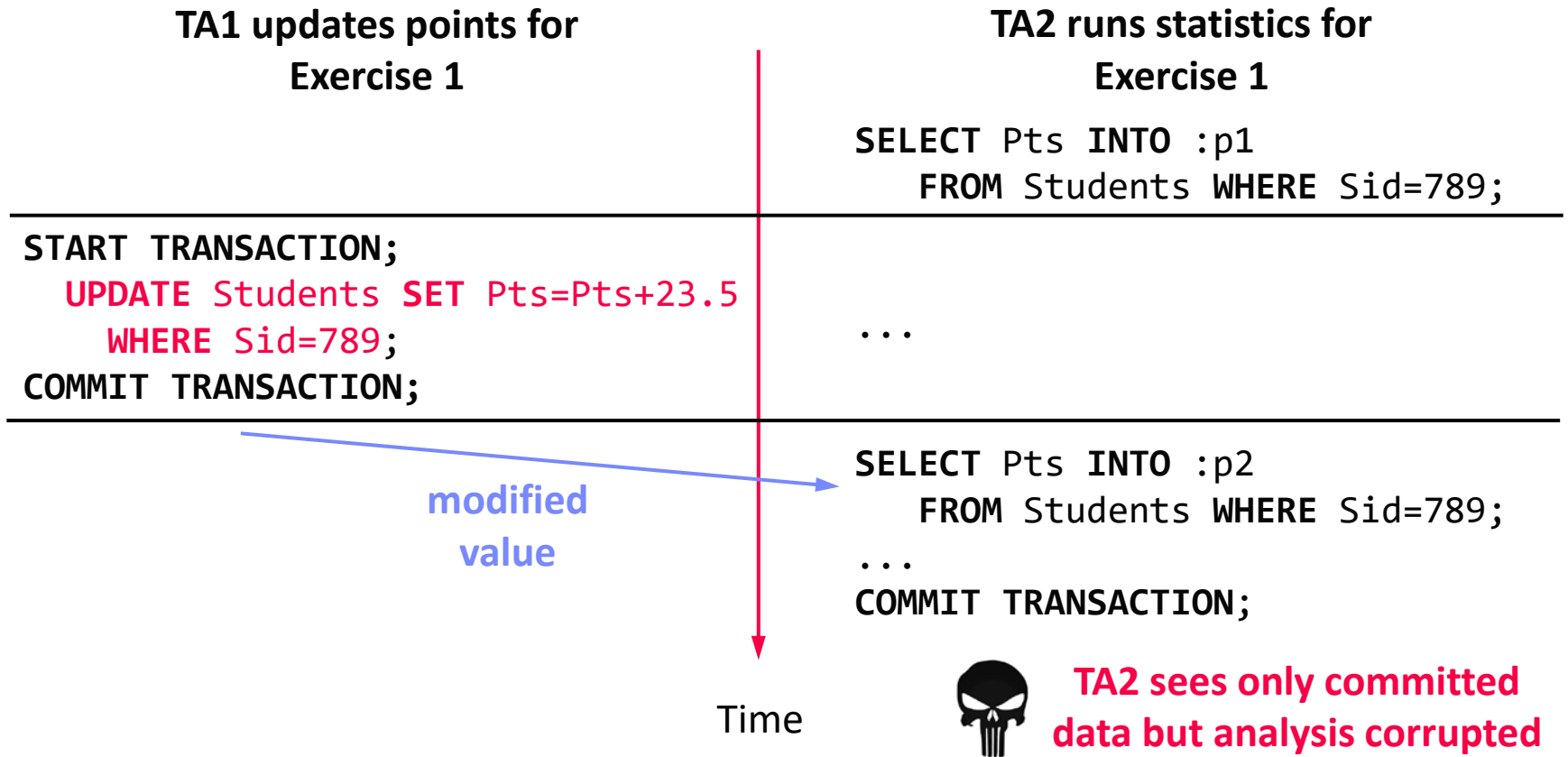
- **Problem:** Write-write dependency
- **Solution:** Exclusive lock on write

Anomalies – Dirty Read



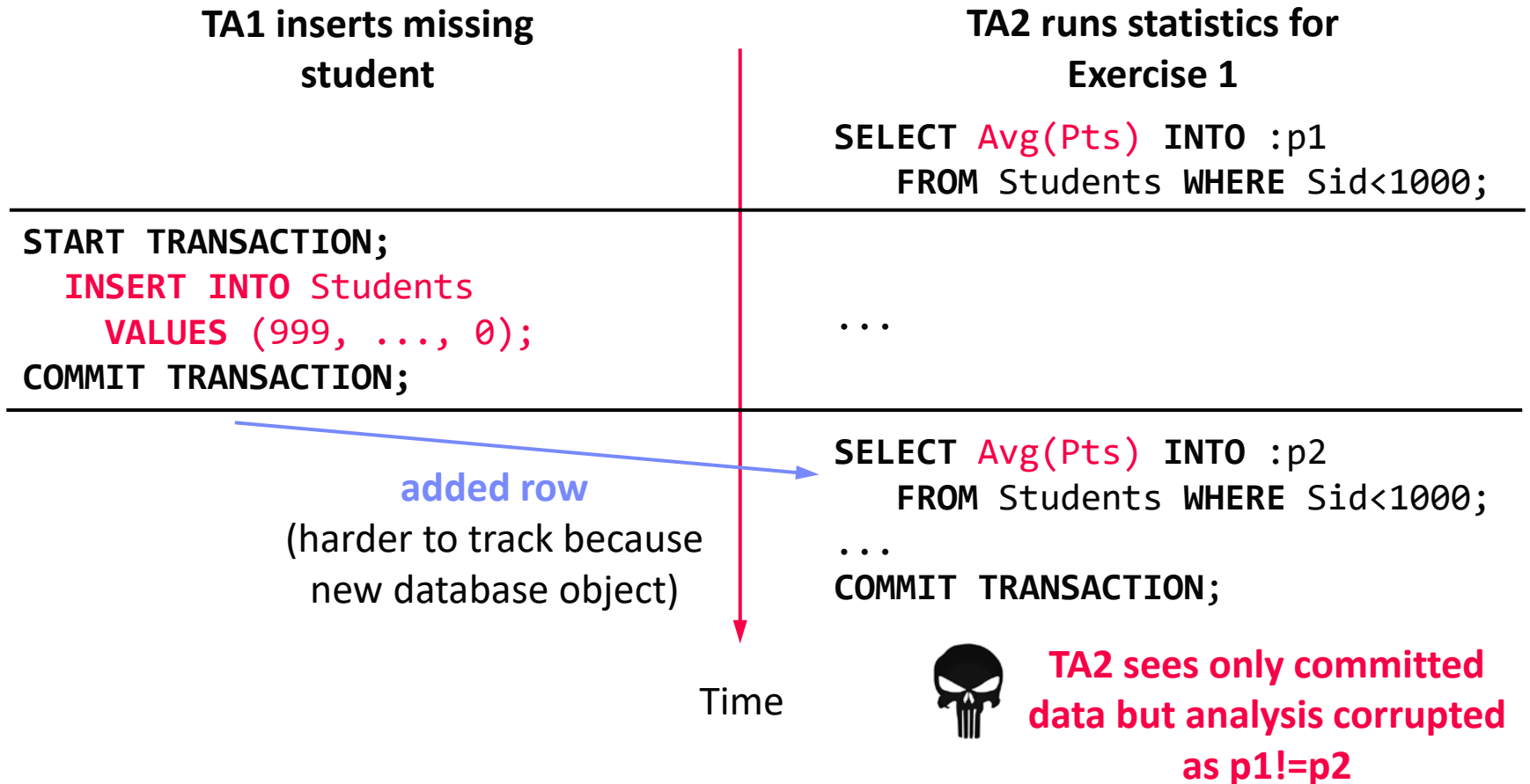
- **Problem:** Write-read dependency
- **Solution:** Read only committed changes; otherwise, cascading abort

Anomalies – Unrepeatable Read



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

Anomalies – Phantom



- **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 (P1)	Unrepeatable Read (P2)	Phantom Read (P3)
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**)

* Lost update potentially w/ different semantics in standard

- **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

■ Summary

- **Criticism:** 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**

[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**]



■ 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

[<http://dbmsmusings.blogspot.com/2019/05/introduction-to-transaction-isolation.html>]

■ Current Status?

- “SQL standard that **fails to accurately define database isolation levels** and database vendors that attach liberal and non-standard semantics”

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 **ERROR:** could not serialize access due to concurrent update
- Might return **synchronization errors** **ERROR:** deadlock detected

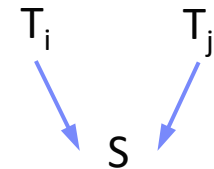
Serializability Theory

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

- Wrong schedule

$r_1(A)$ $r_2(C)$ $w_2(C)$ $r_2(A)$ $w_1(A)$ $r_1(B)$ $w_1(B)$ $w_2(A)$ 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:** Serializability Theory considers only successful transactions, which disregards anomalies like dirty read that might happen in practice

BREAK (and Test Yourself)

- Given two transactions T_1 and T_2 , which pairs of the following three schedules are equivalent? Explain for each pair (S_1 - S_2 , S_1 - S_3 , S_2 - S_3) why they are equivalent or non-equivalent. [5 points]

- $T_1 = \{r_1(a), r_1(c), w_1(a), w_1(c)\}$
- $T_2 = \{r_2(b), w_2(b), r_2(c), w_2(c)\}$

Schedules

- $S_1 = \{r_1(a), r_1(c), w_1(a), w_1(c), r_2(b), w_2(b), r_2(c), w_2(c)\} = \{T_1, T_2\}$

→ $S_1 \equiv S_2$ (equivalent, because $r_2(b), w_2(b)$ independent of T_1)

- $S_2 = \{r_1(a), r_2(b), r_1(c), w_1(a), w_2(b), w_1(c), r_2(c), w_2(c)\}$

→ $S_1 \not\equiv S_3$
(transitive)

→ $S_2 \not\equiv S_3$ (non-equivalent, because $w_1(c), r_2(c)$ of c in different order)

- $S_3 = \{r_1(a), r_2(b), r_1(c), w_1(a), w_2(b), r_2(c), w_1(c), w_2(c)\}$

Locking Schemes

Compatibility of Locks

- X-Lock (exclusive/write lock)
- S-Lock (shared/read lock)

Requested Lock

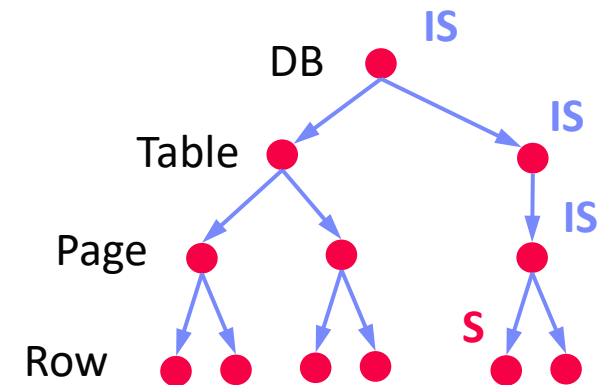
Existing Lock

	None	S	X
S	Yes	Yes	No
X	Yes	No	No

Multi-Granularity Locking

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

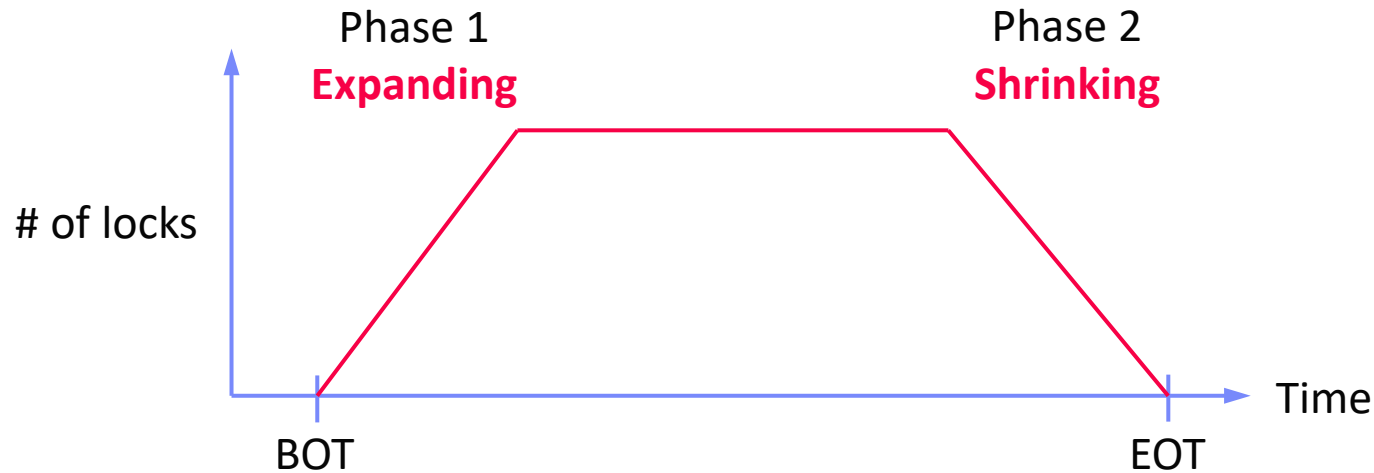
	None	S	X	IS	IX
S	Yes	Yes	No	Yes	No
X	Yes	No	No	No	No
IS	Yes	Yes	No	Yes	Yes
IX	Yes	No	No	Yes	Yes



Two-Phase Locking (2PL)

Overview

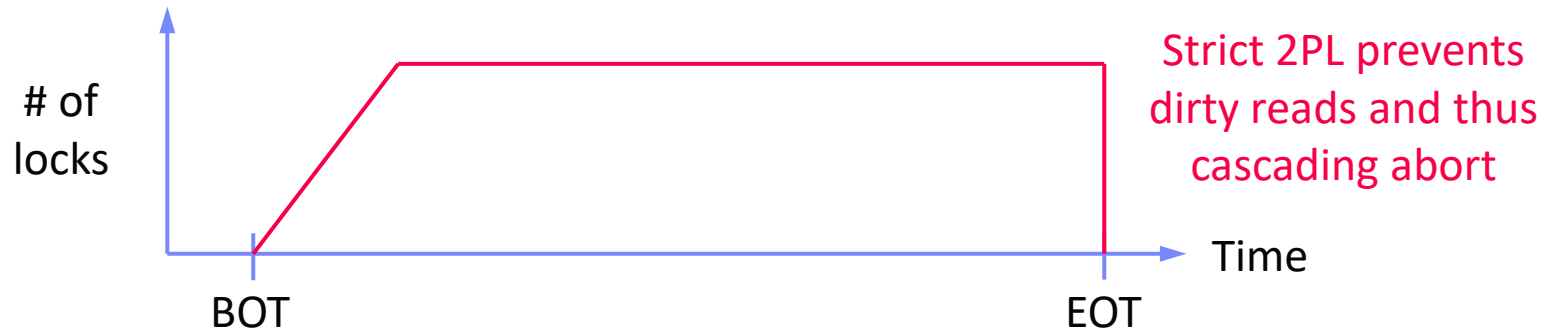
- 2PL is a concurrency protocol that guarantees **SERIALIZABLE**
- **Expanding phase**: acquire locks needed by the TX
- **Shrinking phase**: release locks acquired by the TX
(can only start if all needed locks acquired)



Two-Phase Locking, cont.

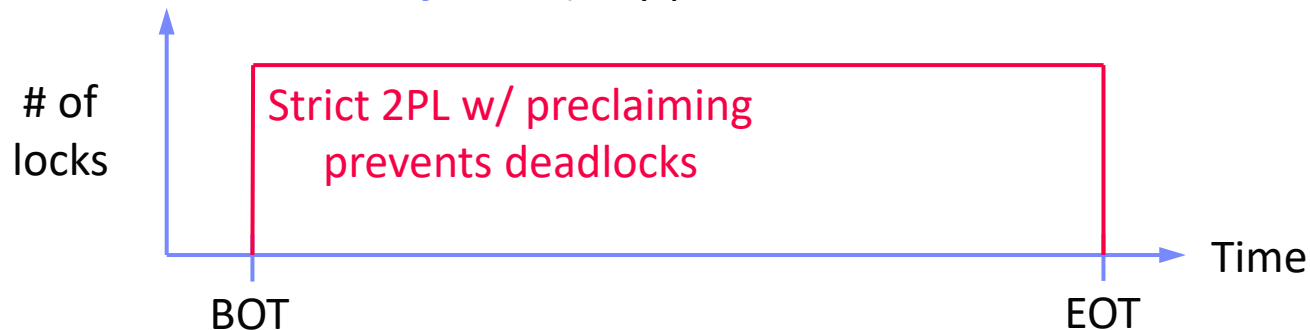
- **Strict 2PL (S2PL) and Strong Strict 2PL (SS2PL)**

- **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 + **latches**)



Deadlocks

Deadlock Scenario

- Deadlocks of concurrent transactions
- Deadlocks happen due to **cyclic dependencies without pre-claiming** (wait for exclusive locks)

#1 Deadlock Prevention

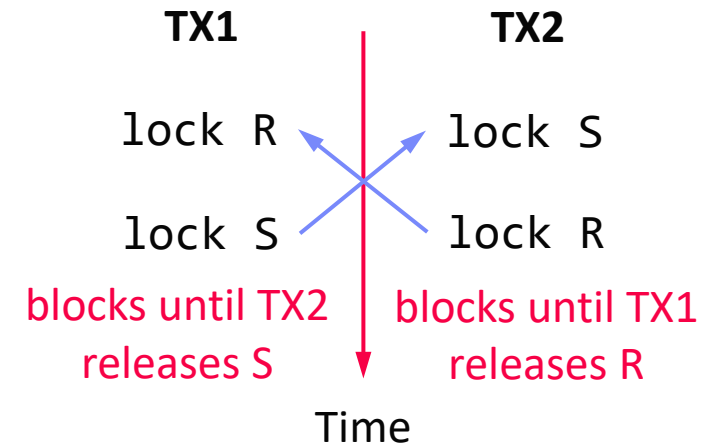
- Guarantee that deadlocks can't happen
- E.g., **via pre-claiming** (but overhead and not always possible)

#2 Deadlock Avoidance

- Attempts to avoid deadlocks before acquiring locks via timestamps per TX
- Wound-wait** (T1 locks something held by T2 → if $T1 < T2$, restart T2)
- Wait-die** (T1 locks something held 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



DEADLOCK, as this will never happen



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 $TS(T_j) \geq \text{writeTS}(A)$: **allow read**, set $\text{readTS}(A) = \max(TS(T_j), \text{readTS}(A))$
- If $TS(T_j) < \text{writeTS}(A)$: **abort T_j** (older than last modifying TX)

▪ Write Protocol $T_j(A)$

- If $TS(T_j) \geq \text{readTS}(A)$ AND $TS(T_j) \geq \text{writeTS}(A)$: **allow write**, set $\text{writeTS}(A) = TS(T_j)$
- If $TS(T_j) < \text{readTS}(A)$: **abort T_j** (older than last reading TX)
- If $TS(T_j) < \text{writeTS}(A)$: **abort T_j** (older than last modifying TX)

- **BEWARE:** Timestamp Ordering requires additional handling of dirty reads, and concurrent transactions in general (e.g., via abort or versions)

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 T_i that finished (EOT) while T_j was running ($EOT(T_i) \geq BOT(T_j)$)
 - **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: propagate TX-local buffer into the database and log
- Unsuccessful TXs: discard the TX-local buffer

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-Recovery: 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

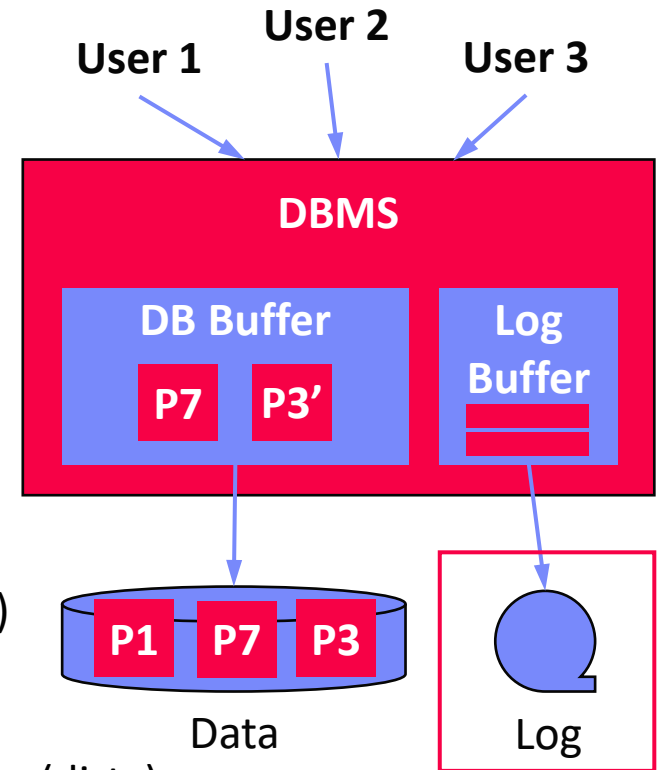
Database (Transaction) Log

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
- Log sequence number (LSN)



[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

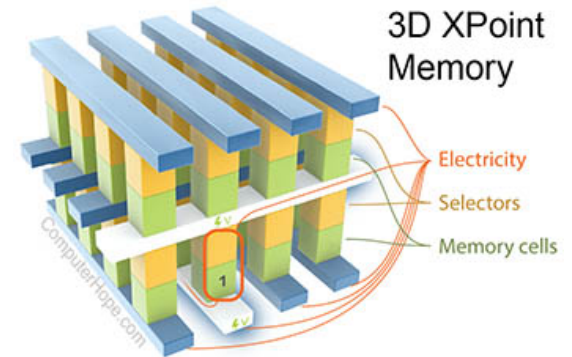
```
UPDATE Emp
SET Salary=Salary+100
WHERE Dep='R&D';
```

■ 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**)

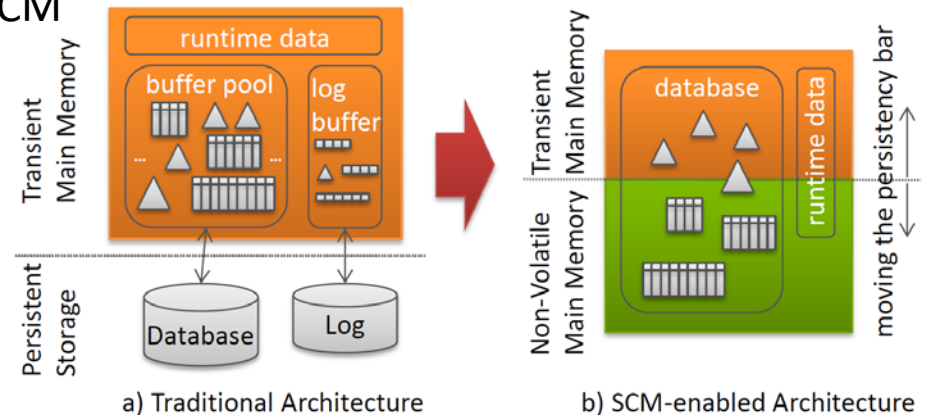


[Credit: <https://computerhope.com>]

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



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



- Write-Behind Logging** (for hybrid SCM)
 - Update persistent data (SCM) on commit, log change metadata + timestamps → **1.3x**

[Joy Arulraj, Matthew Perron, Andrew Pavlo: Write-Behind Logging. **PVLDB 2016**]



Exercise 3: Tuning and Transactions

Published: **May 04, 2021**

Deadline: **May 25, 2021**

Task 3.1 Query Rewriting and Tuning

6/25
points

■ a) Query Processing

- **Q09:** List the top 10 athletes by the number of Olympic games they participated in. (return athlete key, athlete name, number of games; sorted descending by number of games, ascending by athlete name)

■ b) Materialized Views (MV)

- Create a MatView that speeds up reoccurring queries such as Q09 w/ arbitrary length of the top-k list
- Obtain plan (in JSON) with and without manually used MatView.

■ c) Indexing

- **Q10** Computes the average BMI of athletes with a weight <50 Kg.
- Obtain the plan for Q10 (in JSON) with and without a secondary index

```
SELECT round(avg(A.Weight / (A.Height/100.0 * A.Height/100.0)), 2)
FROM Athletes A
WHERE A.Weight < 50
```

Task 3.2 B-Tree Insertion and Deletion

6/25
points

Setup

- Generated a sequence S of numbers as follows and materialize as Input.txt

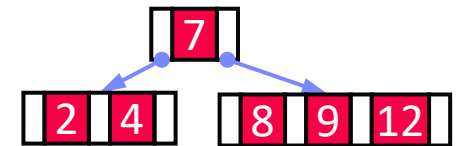
```
SELECT SETSEED(1.0/(SELECT MOD(X,8)+1));
SELECT * FROM generate_series(1,16) ORDER BY random();
```

B-Tree Insertion (k=2)

- Draw a B-tree after sequentially inserting S in the defined order

B-Tree Deletion

- Draw the B-tree again after deleting the sequence [8,14) in order of keys (del 8, del 9, ..., del 13)



a: (b) 7 (c)
 b: 2 () 4
 c: 8 () 9 () 12

Note: Text Format

node_id: (child_node_id 1) key (child_node_id 2) ... (child_node_id n)

Task 3.3 Transaction Processing

4/25
points

■ a) Setup

- Create the following tables w/ meaningful data types → TXSetup.sql

Customers(CID, Name, Debt)

Products(PID, Name, Price, Stock)

Orders(ODate, CID, PID, Quantity)

- Insert the following tuples

(7, 'C1', 0.0) into Customer

(1, 'P1', 25, 100) into Products

■ b) Atomic Transaction

- Write a SQL transaction a placing a new order → TXNewOrder.sql
 - Add order for customer C1, 15 x product P1, as of 2021-05-25
 - Modify product stock / customer debt accordingly

Task 3.4 Iterator Model and Operators

9/25
points

- **a) Operator Implementations** (**Extra Credit** for ICE course ‘Databases’)
 - Pick your favorite programming language (e.g., Python, Java, C# or C++)
 - **open()**, **next()**, **close()** iterator model (base class)
 - Implement **table scan**, **equi selection**, **hash join**, and **hash count aggregate**
- **b) Implement Query Q11** (on new provided data)

```
SELECT R.Medal, count(R.EKey)
FROM Athletes A, Results R
WHERE A.AKey = R.Akey
      AND A.Gender = 'F'
GROUP BY R.Medal
```



```
A = new TblScan(args[1]) //Athletes
R = new TblScan(args[2]) //Results
A2 = new EqSelect(A, attr=3, value=F))
AR = new HashJoin(A2, R, 1, 3)
q = new HashCountAgg(AR, 9, 7)

q.open()
while( (t = q.next()) != EOF )
    out.write(t)
q.close()
```

[\[https://mboehm7.github.io/teaching/ss21_dbs/data.zip\]](https://mboehm7.github.io/teaching/ss21_dbs/data.zip)

```
./runQuery11.sh ./Athletes.csv ./Results.csv ./output.csv
```

Summary 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 (but +1 ECTS if you attend entire course)

- **Next Lectures (Part B: Modern Data Management)**
 - **10 NoSQL (key-value, document, graph)** [May 31]
 - **11 Distributed Storage and Data Analysis** [Jun 07]
 - **12 Data Stream Processing Systems and Q&A** [Jun 14]