# IN3020/4020 – Database Systems
# Spring 2021, Week 8.1
### (second half Continued from 8. March 2021)

# Serialization and Concurrency Control
# Part 1

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Based upon slides by E. Thorstensen from Spring 2019

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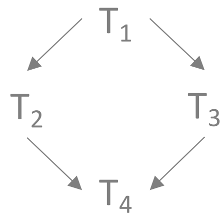
# Precedence graphs

A precedence graph




- Let S be an execution plan, and let $p_i(A)$ and $q_k(B)$ be two (arbitrary) operations in S. The notation $p_i(A) <_S q_k(B)$ means that $p_i(A)$ is to be executed before $q_k(B)$ in S. Then the precedent graph P of S, defined as P(S), is as follows:
  - Nodes: The transactions in S
  - Edges: The precedents in S
    - $T_i \rightarrow T_k$ (where $i \neq k$) if
      1. $p_i(A) <_S q_k(A)$ and
      2. at least one of $p_i$ or $q_k$ is a write operation

**Exercise (group):** Draw P(S) for S = $w_3(A)$; $w_2(C)$; $r_1(A)$; $w_1(B)$; $r_1$ (C); $w_2(A)$; $r_4(A)$; $w_4(D)$

Note: There are 4 transactions ($T_1$, $T_2$, $T_3$, $T_4$ ), and not all data elements A, B, C and D are in every transaction. Is S serializable?

# Precedence graphs - Lemma

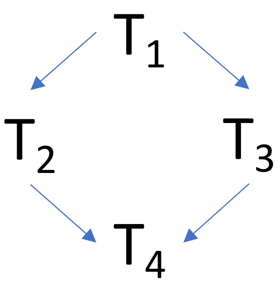
**Reminder**
S is an **execution plan** and P(S) is a **precedence graph** for the execution plan S

- Lemma: $S_1$ and $S_2$ are conflict equivalent plans $\Longrightarrow$ $P(S_1) = P(S_2)$
- Proof: We show that $P(S_1) \neq P(S_2)$ $\Longrightarrow$ $S_1$ and $S_2$ are not conflict equivalent.
  - Assume that $S_1$ and $S_2$ are both merging/interweaving of transactions $\{T_1, ..., T_n\}$, but that $P(S_1) \neq P(S_2)$.
  - Then i and k ($i \neq k$) exist such that $T_i \rightarrow T_k$ is an edge in $P(S_1)$, but not in $P(S_2)$.
  - This means that there are operations $p_i$ and $q_k$ that conflict with a data element A such that
    - $S_1 = ... p_i(A) ... q_k(A) ...$ (hence the edge $T_i \rightarrow T_k$ in $P(S_1)$)
    - $S_2 = ... q_k(A) ... p_i(A) ...$ (so there is also an edge $T_k \rightarrow$ Ti in $P(S_2)$)
  - This shows that $S_1$ and $S_2$ are not conflict equivalent.

# Precedence graphs - continued

- Note: We cannot conclude the opposite, i.e., from $P(S_1) = P(S_2)$ that $S_1$ and $S_2$ are conflict equivalents.
- Proof (case example):
  - $S_1 = w_1(A); r_2(A); w_2(B); r_1(B)$
  - $S_2 = r_2(A); w_1(A); r_1(B); w_2(B)$
- $S_1$ and $S_2$ are obviously not conflict equivalent (why?)
- But $P(S_1)$ and $P(S_2)$ both have the two nodes $T_1$ and $T_2$ and the two edges $T_1 \rightarrow T_2$ and $T_2 \rightarrow T_1$, so $P(S_1) = P(S_2)$.

# Precedence graphs - Theorem




- Theorem:
  P(S) is acyclic $\Leftrightarrow$ S is conflict serializable
- Proof ($\Longrightarrow$)
  Suppose that P(S) is acyclic. Restructure S as follows:
  1. Choose a transaction $T_1$ that has no incoming edges in P(S)
  2. Move all operations in $T_1$ to the start of S
     (in the order they occur in $T_1$), i.e., S = .... $q_k(B)$ .... $p_1(A)$ ....
  3. Now we have $S_1$ = [the operations in $T_1$] [the rest of S>]
  4. Repeat 1-3 to serialize the rest of S.

# Enforcement of serializability and serializability protocols

- Method 1:
  Run the system and register P(S)
  "At the end of the day" we check if P(S) is acyclic, i.e., if everything went well
- Method 2:
  Check in advance that the execution plan can never cause cycles in P(S)
- A framework that supports method 2 is called a serialization protocol

# Locking protocols

- We introduce two new types of operation:
  - **Lock:** $l_i$(A) – $T_i$ puts (an exclusive) lock on A
  - **Unlock:** $u_i$(A) – $T_i$ releases the lock on A
- In addition, we require that DBMS must maintain a lock table that shows which data elements are locked by which transactions
- Most DBMS´ have their own lock manager modules that keep track of the lock table

# Execution plan $S_D$ with locks

| T1 | T2 | A | B |
|---|---|---|---|
| | | 25 | 25 |
| $l_1(A)$; Read(A) | | | |
| A←A+100; Write(A); $u_1(A)$ | | 125 | |
| | $l_2(A)$; Read(A) | | |
| | A←Ax2; Write(A); $u_2(A)$ | 250 | |
| | $l_2(B)$; Read(B) | | |
| | B←Bx2; Write(B); $u_2(B)$ | | 50 |
| $l_1(B)$; Read(B) | | | |
| B←B+100; Write(B); $u_1(B)$ | | | 150 |
| | | 250 | 150 |

Note that Locks alone do <u>NOT</u> guarantee serializability!

# Locking rules – 2 Phase Locking (2PL)

- **Rule 1** - Well-formed transactions:
  Before $T_i$ performs operation $p_i(A)$, $T_i$ must have performed $l_i(A)$, and it should perform $u_i(A)$ after $p_i(A)$
  Example: $T_i$: ... $l_i(A)$ ... $r_i(A)$ ... $w_i(A)$ ... $u_i(A)$ ...
- **Rule 2** - Allowed ("Legal") Execution Plans: Execution plans cannot allow two transactions to lock on the same data element at the same time

  i.e.,: S: ... $l_i(A)$ ................ $u_i(A)$ ...

  No $l_k(A)$ (for $k \neq i$)

# Locking rules – 2 Phase Locking (2PL)

- **Rule 3 –** 2 phase locking
- A transaction that has performed an unlock operation is not allowed to perform other lock operations
  $T_i$ = ............ $l_i(A)$ ...... $u_i(A)$ ......
  No $u_i(B)$ No $l_i(B)$
- The time leading up to the transaction's first unlock operation is called the transaction's <u>growing phase</u>
- The time from the transaction's first unlock operation is called the transaction <u>shrinking phase</u>

# Conflict rules for lock/unlock

- $l_i$(A), $l_k$(A) leads to conflict
- $l_i$(A), $u_k$(A) leads to conflict

- Note that the following two situations do not lead to conflict:
  - $u_i$(A), $u_k$(A)
  - $l_i$(A), $r_k$(A)

# Start of the shrinking phase

**Reminder:**

- The time leading up to the transaction's first unlock operation is called the transaction's growing phase
- The time from the transaction's first unlock operation is called the transaction shrinking phase

- **Rule 1:** Well formed transactions
- **Rule 2:** Allowed or "legal" execution plans
- **Rule 3:** 2 phase locking (2PL)

- A helping definition:
  $Sh(T_i)$ = first unlock operation that $T_i$ performs
- **Lemma:** If $T_i \rightarrow T_k$ in P(S), then $Sh(T_i) <_S Sh(T_k)$
- **Proof:** Ti → Tk means that
  S = … $p_i(A)$ … $q_k(A)$ …; where $p_i$ and $q_k$ are in conflict
  - **Rule 1** states that $u_i(A)$ must come after $p_i(A)$ and $l_k(A)$ before $q_k(A)$
  - **Rule 2** states that $l_k(A)$ must come after $u_i(A)$.
    Thus, we have S = … $p_i(A)$ … $u_i(A)$ … $l_k(A)$ … $q_k(A)$ …;
  - **Rule 3** states that $Sh(T_i)$ cannot come after $u_i(A)$ and that $Sh(T_k)$ must come after $l_k(A)$
- Q.E.D. We have proved that $Sh(T_i)$ must come before $Sh(T_k)$ in S

# 2PL ensures conflict serializability

- **THEOREM:** If a plan S complies with rules 1, 2 and 3,
  then S is conflict serializable

- **Proof:** According to the earlier theorem (see earlier slides from slide 28), it is sufficient to show that if a plan S complies with rules 1, 2 and 3, then the precedence graph P(S) is acyclic
- Thus, assume (ad absurdum) that P(S) has a cycle T1 → T2 → ... → Tn → T1
- According to the lemma, then
  $Sh(T_1) <_S Sh(T_2) <_S ... <_S Sh(T_n) <_S Sh(T_1)$
- But this is impossible, so P(S) is acyclic!

Reminder:
$Sh(T_i)$ = first unlock operation that $T_i$ performs

# Deadlock

| T1 | T2 |
|---|---|
| $l_1(A)$; Read(A); | |
| $A \leftarrow A+100$; Write(A); | |
| | $l_2(B)$; Read(B); |
| | $B \leftarrow B \times 2$; Write(B); |
| Must wait for T2 | |
| $l_1(B)$; | |
| | Must wait for T1 |
| | $l_2(A)$; |

This demonstrates that 2PL is NOT a guarantee against deadlock!

# Read and write locks

- For improved concurrency, we can use two different types of locks:
  - **Shared lock** (**sl**) that allows other transactions to read the data element but not write it
  - **Write lock** (eXclusive lock, **xl**) that does not allow other transactions to read or write the data element
- Notation:
  - $sl_k(A)$ : $T_k$ puts a read lock (shared lock) on A
  - $xl_k(A)$ : $T_k$ puts a write lock (eXclusive lock) on A
  - $u_k(A)$ : $T_k$ deletes its lock(s) on A (both read and write)
- $sl_k(A)$ is not executed if any transaction other than $T_k$ has write lock on A
- $xl_k(A)$ is not executed if a transaction other than $T_k$ has locked A (it does not matter whether it is a read or write lock)

# Rules for read and write locks

- For **Well-formed transactions** (rule 1)
  Any transaction $T_k$ must comply with the following three rules:
  - An $r_k(A)$ must come after an $sl_k(A)$ or $xl_k(A)$ without any $u_k(A)$ in between
  - A $w_k(A)$ must come after an $xl_k(A)$ without any $u_k(A)$ in between
  - There must be a $u_k(A)$ after an $sl_k(A)$ or $xl_k(A)$
- For **2-phase lock** (rule 3)
  In addition, any 2PL transaction $T_k$ must comply with the following:
  - No $sl_k(A)$ or $xl_k(A)$ can come after an $u_k(B)$ regardless of what A and B are

# Rules for read and write locks (continued)

- **Allowed execution plans** (rule 2)
  Each data element is either unlocked, or has one write lock, or has one or more read locks.
  This is ensured by all plans S following these rules:
  - If $xl_i(A)$ occurs in S, it must be followed by a $u_i(A)$ before an $xl_k(A)$ or $sl_k(A)$ with $k \neq i$
  - If $sl_i(A)$ occurs in S, it must be followed by a $u_i(A)$ before there can be an $xl_k(A)$, where $k \neq i$

# Conflict serializability of SL / XL plans

**THEOREM:** If a plan S complies with the rules for read and write locks on the two previous slides, then S is conflict serializable.

**PROOF:** Almost identical to the **proof that plans using only exclusive locks ensure conflict serializability** (slide 39), but with the only difference being that we need that neither

$sl_i(A)$ followed by $sl_k(A)$

nor

$sl_i(A)$ followed by $u_k(A)$

is a conflict.

# Compatibility matrices

- Compatibility matrices are used to store the lock allocation rules when using multiple lock types
- The matrices have one row and one column for each lock type
- Compatibility matrices are interpreted as follows:
  - If $T_i$ asks to put a type K lock on data element A, it only gets it if there is a 'Yes' in column K in all rows R of the matrix where some other $T_k$ has a type R lock on A
- Example: Compatibility matrix for S / X locks

**Lock that T is asking to get on A ↓**

| Lock that A has ↓ | S | X |
|---|---|---|
| **S** | Yes | No |
| **X** | No | No |

# Upgrading the locks

- For better (more efficient) concurrency, we can allow T to first set read lock and then upgrade it to write lock if needed
- Example:

| $T_1$ | $T_2$ |
|---|---|
| $sl_1(A); r_1(A);$ | |
| | $sl_2(A); r_2(A);$ |
| | $sl_2(B); r_2(B);$ |
| $sl_1(B); r_1(B);$ | |
| $xl_1(B);$ **Rejected!** | |
| | $u_2(A); u_2(B);$ |
| $xl_1(B); w_1(B);$ | |
| $u_1(A); u_1(B);$ | |

# Upgrading the locks (continued)

- One disadvantage is that upgrading locks increases the risk of deadlock!
- Example:

| $T_1$ | $T_2$ |
|---|---|
| $sl_1(A); r_1(A);$ | |
| | $sl_2(A); r_2(A);$ |
| $xl_1(A);$ **Rejected!** | |
| | $xl_2(A);$ **Rejected!** |

- The example illustrates that protocols that use lock upgrades are only suitable if there are many more read than write transactions

# Update locks

- An update lock is a read lock that will later be upgraded to a write lock
- Update locks are denoted by U (Update lock)
- The compatibility matrix for S / X / U locks comes in two variants (where the asymmetric is most common):
  - an asymmetric ('N') that prioritizes writing transactions
  - a symmetric (‘Y') that prioritizes reading transactions

**Requests lock ↓**

| Has lock ↓ | **S** | **X** | **U** |
|---:|:---:|:---:|:---:|
| **S** | Yes | No | Yes |
| **X** | No | No | No |
| **U** | Yes/No | No | No |

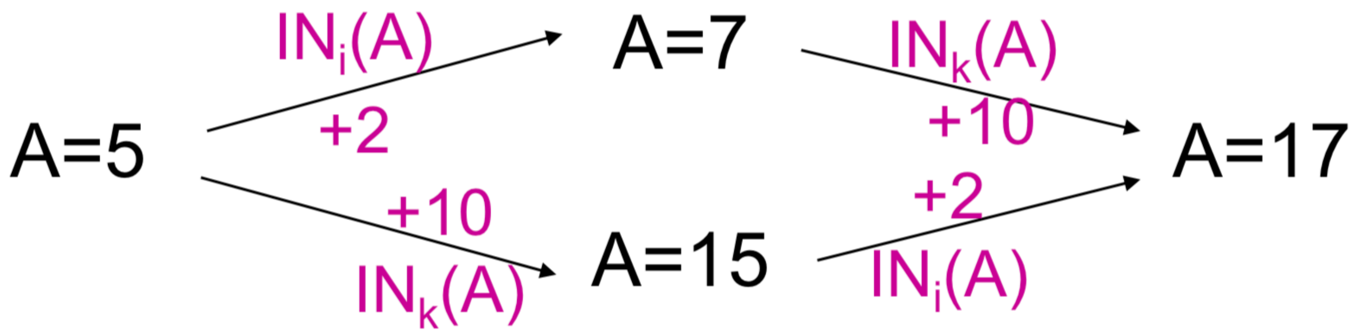
# Update locks (continued)

- Plans that earlier resulted in deadlock due to read-to-write lock upgrades do not do so with the use of update locks.
  (BUT **NOTE!** There may be other causes of deadlock!)
- Example (which was a deadlock earlier):

| $T_1$ | $T_2$ |
|---|---|
| $ul_1(A)$; $r_1(A)$; | |
| | $ul_2(A)$; **Rejected!** |
| $xl_1(A)$; $w_1(A)$; $u_1(A)$; | |
| | $ul_2(A)$; $r_2(A)$; |
| | $xl_2(A)$; $w_2(A)$; $u_2(A)$; |

# Incremental locks

- Atomic increment operation: $IN_i(A)$
  {Read (A); A ← A + v; Write (A)}
- $IN_i(A)$ and $IN_k(A)$ are not in conflict!



# Incremental locks (continued)

- The purpose is to streamline bookkeeping transactions
- Increment locks are denoted by I (looks sure like *l*, so be careful!)
- Increment locks conflict with both read and write locks, but not with other increment locks
- Here is the compatibility matrix for S / X / I locks:

| | **Requests lock ↓** | | |
|---|---|---|---|
| Has lock ↓ | **S** | **X** | **I** |
| **S** | Yes | No | No |
| **X** | No | No | No |
| **I** | No | No | Yes |

# We continue with the challenges of concurrency…

For that, we will be looking at

**new types of locks (alerts), lock management**

and then **isolation**

# Lock scheduling

- In practice, no DBMS will allow the transactions to set or release any locks themselves
- Transactions perform only the read, write, commit and abort operations, and optionally update and increment
- The locks are entered into the transactions and are set and released by a separate module in DBMS called the lock manager (Lock Scheduler)
- Lock manager uses its own internal data structure, the lock table, to manage the locks
- The lock table is not part of the buffer area; (depending upon the DBMS) it is (usually) unavailable for the transactions

# Lock scheduling, lock management

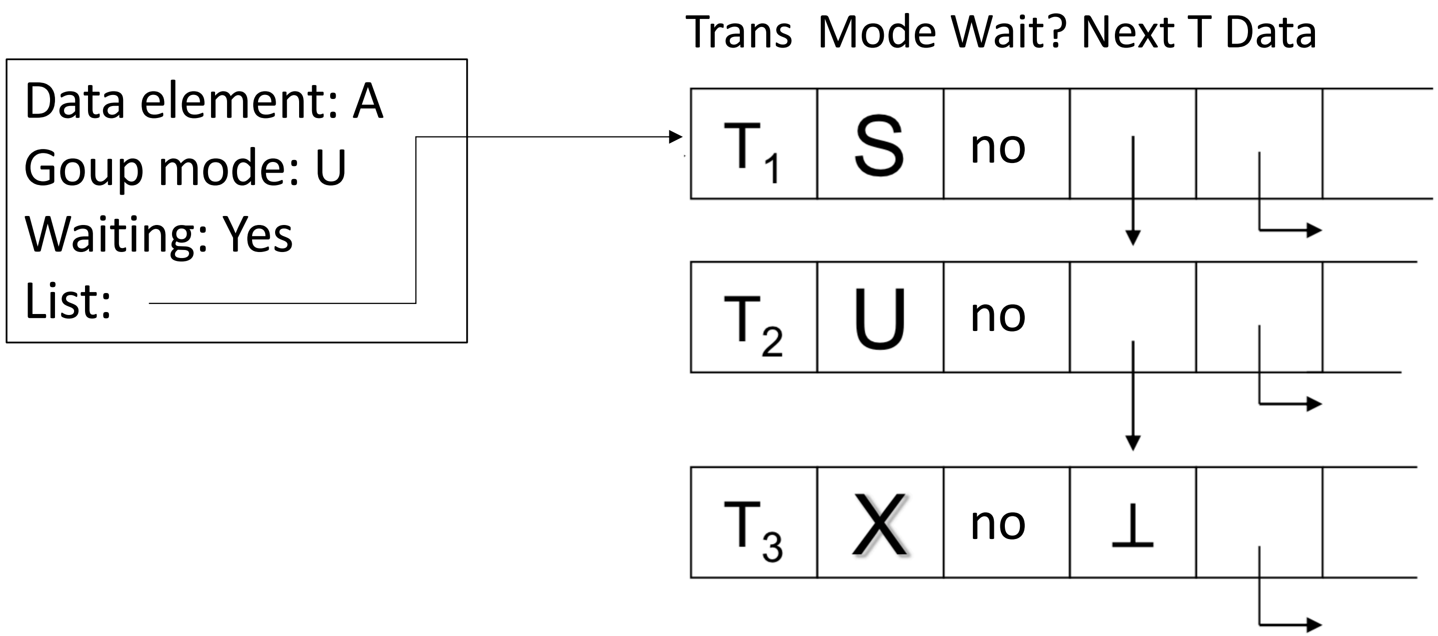
The lock manager consists of two parts:

- **Part I** analyzes each transaction T and inserts “correct” lock requirements prior to operations in T and sets the requirements in the lock table. The requirements it selects depend on which lock types are available.
- **Part II** controls whether the operations and lock requirements it receives from Part I can be performed. Those that cannot be realized are placed in a queue to wait for the lock that prevents execution to be removed (which also means that there is a queue for each lock)
- When T does commit (or abort), Part I deletes all locks set by T and notifies Part II, which checks the queues for these locks and allows the transactions that can continue

# Lock table

- Logically, the lock table is a table that contains all lock information for each data item in the database
- In practice, the lock table is organized as a hash table with the address of the data element´s address as the key
- Unlocked data elements are not included in the lock table
- The lock table is therefore proportional to the number of requested and granted locks, and not to the number of data elements
- For each A in the lock table, the following information is stored:
  - Group mode (strictest lock held on A)
  - A waiting flag that indicates whether someone is waiting to lock A
  - A list of those T that are waiting for lock on A

# Example of lock info for a data element A




To other data elements $T_3$ has (pending) lock on (useful for commit / abort)

# Granularity and alert (warning) locks

- The concept of a data element is intentionally undefined. Three natural granularities on data elements are:
  - **a relation:** the naturally largest (lockable) data element
  - **a block:** a relation consists of one or more blocks
  - **a tuple:** a block can contain one or more tuples
- Different transactions may require locks at all these levels at the same time
- To achieve this, we introduce alert (warning) locks, **IS** and **IX**, which state that we intend to put a read or write lock further down in the hierarchy, respectively. Note: Read "I" as "Intended lock".

# Alert (warning) locks (continued)

**Requests lock ↓**

| Has lock ↓ | IS | IX | S | X |
|---|---|---|---|---|
| **IS** | Yes | Yes | Yes | No |
| **IX** | Yes | Yes | No | No |
| **S** | Yes | No | Yes | No |
| **X** | No | No | No | No |

**Example:** T wants to write tuple A in block B in relation R

- If R has neither S-lock nor X-lock, T sets IX-lock on R
- If T gets IX-lock on R, it checks if B has S or X lock. If B does not have those, T puts IX-lock on B
- If T gets IX-lock on B, it checks if A has any locks. If A does not have any, T puts X-lock on A and then can write A

Note that if a transaction T has a write lock on R, no one else can write a tuple in R until T clears the lock

# Managing phantom tuples

**Example:**

- We shall sum a field for all the tuples in a relation R
- Before summing, we put a read-lock on all the R tuples to ensure a consistent answer
- During the addition operation, another transaction inserts a new tuple in R, which makes the sum become wrong
- This is possible because the tuple did not exist when we put our reading locks. Such a tuple is called a phantom tuple!
- The solution is to put an IS (intended Shared Lock) lock on the relation. Then, no one can enter any new tuples until the lock is deleted.