Transaction Management

Air-line Reservation

- 10 available seats vs 15 travel agents.
- How do you design a robust and fair reservation system?
  - Do not enough resources
  - Fair policy to every body
  - Robustness

Failures

Number of factors might cause failures in user requirements processing.

1. System failure:
   - Disk failure - e.g. head crash, media fault.
   - System crash - unexpected failure requiring a reboot.
2. Program error - e.g. a divide by zero.
3. Exception conditions - e.g. no seats for your reservation.
4. Concurrency control - e.g. deadlock, expired locks.

To handle failures correctly and efficiently

Each database user must express his requirements as a set of program units.

Each program unit is a *transaction* that either

- accesses the contents of the database, or
- changes the state of the database, from one consistent state to another.

- Sydney → Tokyo → LA → N.Y
- It does not make sense only partial trip has tickets

Example transaction: buy a ticket from Sydney to N.Y. by JAL.

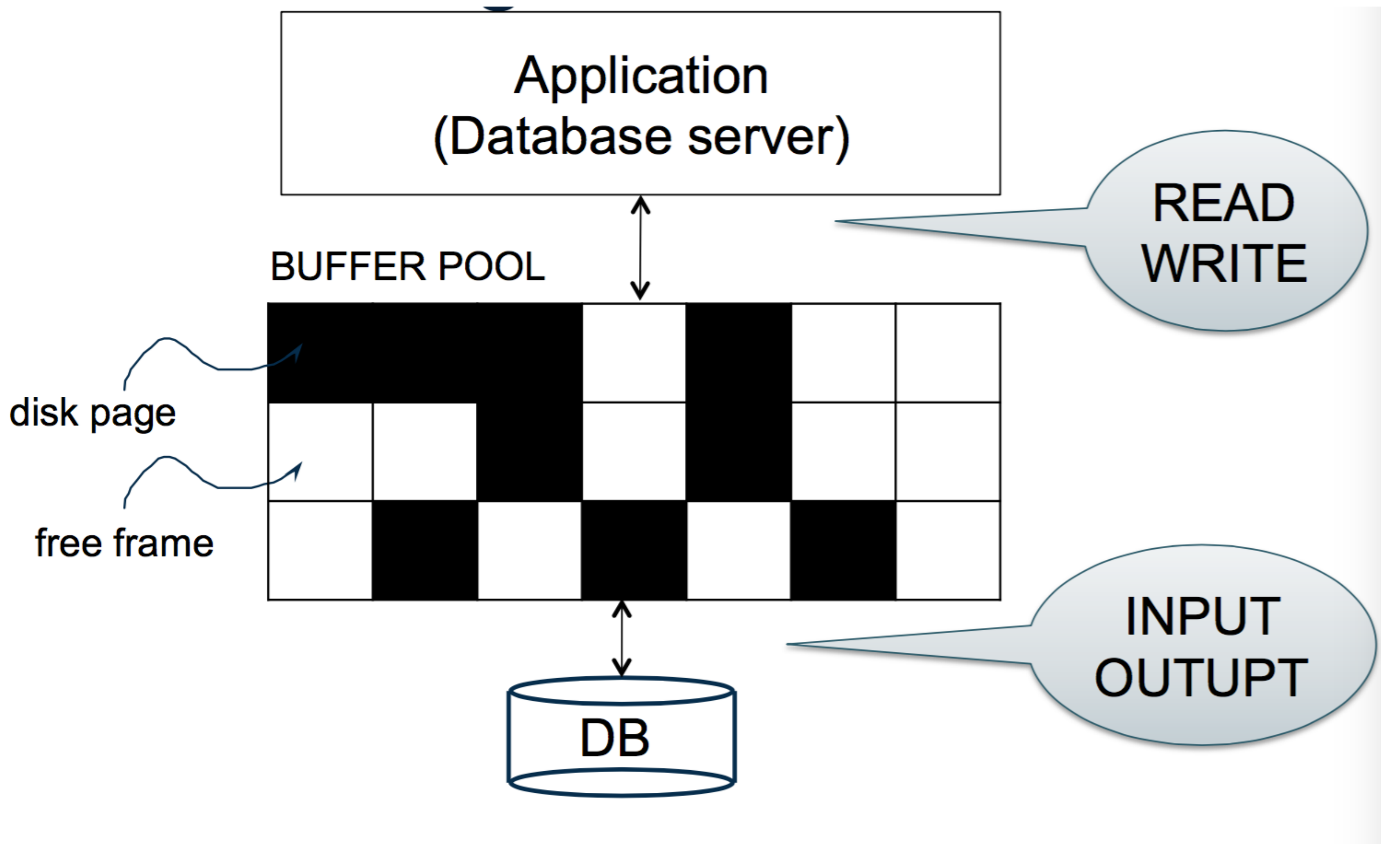
A transaction must be treated as an *atomic* unit.

Transaction Processing

Three kinds of operations may be used in a transaction:

- *Read*.
- *Write*.
- Computation.

Buffer Management in a DBMS



Read

1. Compute the data block that contains the item to be read

2. Either
   - find a buffer containing the block, or
   - read from disk into a buffer

3. Copy the value from the buffer.

Write

1. Compute the disk block containing the item to be written,

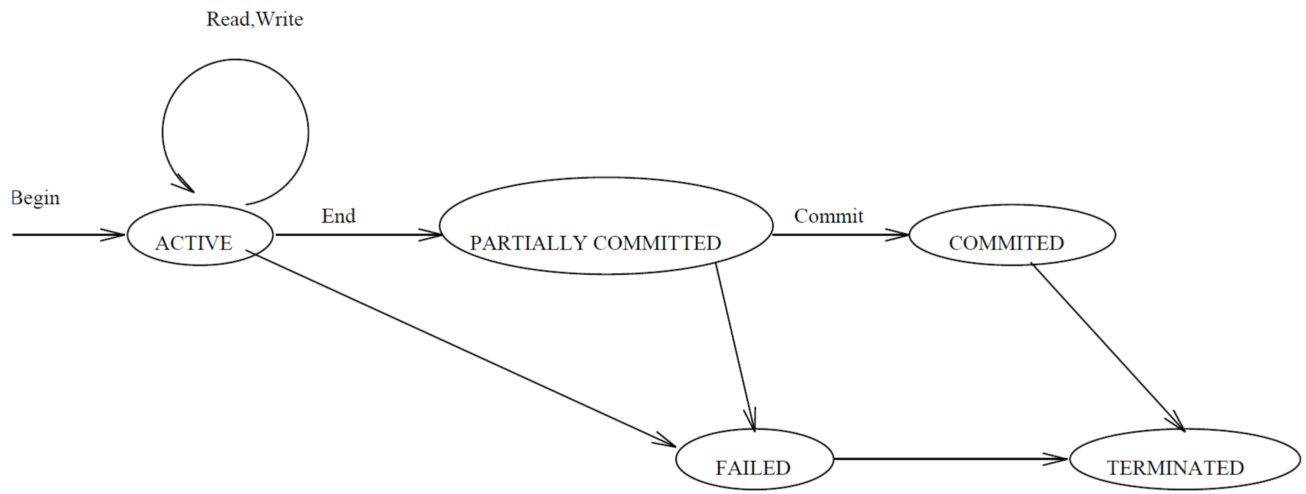
2. Either
   – find a buffer containing the block, or
   – read from disk into a buffer,

3. Copy the new value into the buffer,

4. At some point (maybe later), write the buffer back to disk.

Processing States of a Transaction

- The typical processing states are illustrated in the figure below (E/N Fig 17.4):



- ***Partially committed point:*** At this point, check and enforce the correctness of the concurrent execution.
- ***Committed state:*** Once a transaction enters the committed state, it has concluded its execution successfully.

Desirable Properties of Transaction Processing **ACID**

- ***Atomicity:*** A transaction is either performed in its entirety or not performed at all.

- ***Consistency preservation:*** A correct execution of the transaction must take the database from one consistent state to another.

- ***Isolation:*** A transaction should not make its updates visible to other transactions until it is committed.

- ***Durability or permanency:*** Once a transaction changes the database and the changes are committed, these changes must never be lost because of subsequent failure.

Problems without Enforcing ACID

- For a banking system,
  - If durability is not enforced, then a customer may lose a deposit.
  - If consistency preservation is not enforced, then the bank runs a high risk of bankrupt. E.g., run-over upper-limit.
- Below are the problems if atomicity and isolation are not enforced in a concurrent execution of transactions.

Lost Update Problem (Isolation is not enforced)

- Suppose we have these two transactions, T_1 and T_2:

T_1:

read(X)
$X \leftarrow X + N$
write(X)
read(Y)
$Y \leftarrow Y - N$
write(Y)

T_2:

read(X)
$X \leftarrow X + M$
write(X)

- Let us see what may happen if T_1 and T_2 are executed concurrently in an uncontrolled way:

Suppose initially that $X = 100; Y = 50; N = 5$ and $M = 8$.

Database	T_1	T_2
$X = 100, Y = 50$	$X = ?, Y = ?$	$X = ?$
$X = 100, Y = 50$	read(X) $X = 100, Y = ?$	$X = ?$
$X = 100, Y = 50$	$X \leftarrow X + N$ $X = 105, Y = ?$	$X = ?$
$X = 100, Y = 50$	$X = 105, Y = ?$	read(X) $X = 100$
$X = 100, Y = 50$	$X = 105, Y = ?$	$X \leftarrow X + M$ $X = 108$
$X = 105, Y = 50$	write(X) $X = 105, Y = ?$	$X = 108$
$X = 105, Y = 50$	read(Y) $X = 105, Y = 50$	$X = 108$
$X = 108, Y = 50$	$X = 105, Y = 50$	write(X) $X = 108$
$X = 108, Y = 50$	$Y \leftarrow Y - N$ $X = 105, Y = 45$	$X = 108$
$X = 108, Y = 45$	write(Y) $X = 105, Y = 45$	$X = 108$

- At the end of T_1 and T_2, X should be 113, Y should be 45.
- The update $X \leftarrow X + N$ has been lost.

The Temporary Update Problem

Database	T_1	T_2
$X = 100, Y = 50$	$X = ?, Y = ?$	$X = ?$
$X = 100, Y = 50$	read(X) $X = 100, Y = ?$	$X = ?$
$X = 100, Y = 50$	$X \leftarrow X + N$ $X = 105, Y = ?$	$X = ?$
$X = 105, Y = 50$	write(X) $X = 105, Y = ?$	$X = ?$
$X = 105, Y = 50$	**FAILS**	read(X) $X = 105$
$X = 105, Y = 50$		$X \leftarrow X + M$ $X = 113$

Recover from the disk

Several possibilities for what might happen next:

Database	T_1	T_2
X = 105, Y = 50		X = 113
X= 100, Y = 50	Case 1: DBMS undoes T_1	X = 113
X=113, Y=50		Write (X) X= 113

Database	T_1	T_2
X = 105, Y = 50		X = 113
X= 105, Y = 50	Case 2: DBMS does nothing to T_1	X = 113
X=113, Y=50		Write (X) X= 113

Database	T_1	T_2
X = 105, Y = 50		X = 113
X= 105, Y = 50		X = 113
X=100, Y=50	Case 3: DBMS undoes T_1	Write (X), X= 113 X = 100

Case 1:

Database	T_1	T_2
$X = 105, Y = 50$		$X = 113$
DBMS undoes T_1		
$X = 100, Y = 50$		$X = 113$
		write(X)
$X = 113, Y = 50$		$X = 113$

Case 2:

Database	T_1	T_2
$X = 105, Y = 50$		$X = 113$
DBMS does nothing about T_1		
$X = 105, Y = 50$		$X = 113$
		write(X)
$X = 113, Y = 50$		$X = 113$

Case 3:

Database	T_1	T_2
$X = 105, Y = 50$		$X = 113$
$X = 113, Y = 50$		write(X) $X = 113$
DBMS undoes T_1		
$X = 100, Y = 50$		$X = 113$

- In case 1 and 2, only half of T_1 has been executed.
- In case 3, T_2 has been lost.

The Incorrect Summary Problem

T_1	T_3
	$sum \leftarrow 0$
	read(A)
	$sum \leftarrow sum + A$
	$\vdots$
read(X)	
$X \leftarrow X - N$	
write(X)	
	$\vdots$
	read(X)
	$sum \leftarrow sum + X$
	read(Y)
	$sum \leftarrow sum + Y$
	$\vdots$
read(Y)	
$Y \leftarrow Y + N$	
write(Y)	
	$\vdots$

- Here the sum calculated by T_3 will be wrong by N.

Recover from Failures

- Ensure the A in ACID

- Log-based Recovery
  - Undo logging
  - Redo logging
  - Undo/Redo logging

System Log

- System Log
  - The system needs to record the states information to recover failures correctly.
  - The information is maintained in a log (also called journal or audit trail).
  - The system log is kept in hard disk but maintains its current contents in main memory.

System Log

- Start transaction marker [start transaction, *T*]: Records that transaction *T* has started execution.
- [read item, *T*, *X*]: Records that transaction *T* has read the value of database item *X*.
- [write item, *T*, *X*, old value, new value]: Records that *T* has changed the value of database item *X* from old value to new value.
- Commit transaction marker [commit, *T*]: Records that transaction *T* has completed successfully, and arms that its effect can be committed (recorded permanently) to the database.
- [abort, *T*]: Records that transaction *T* has been aborted.

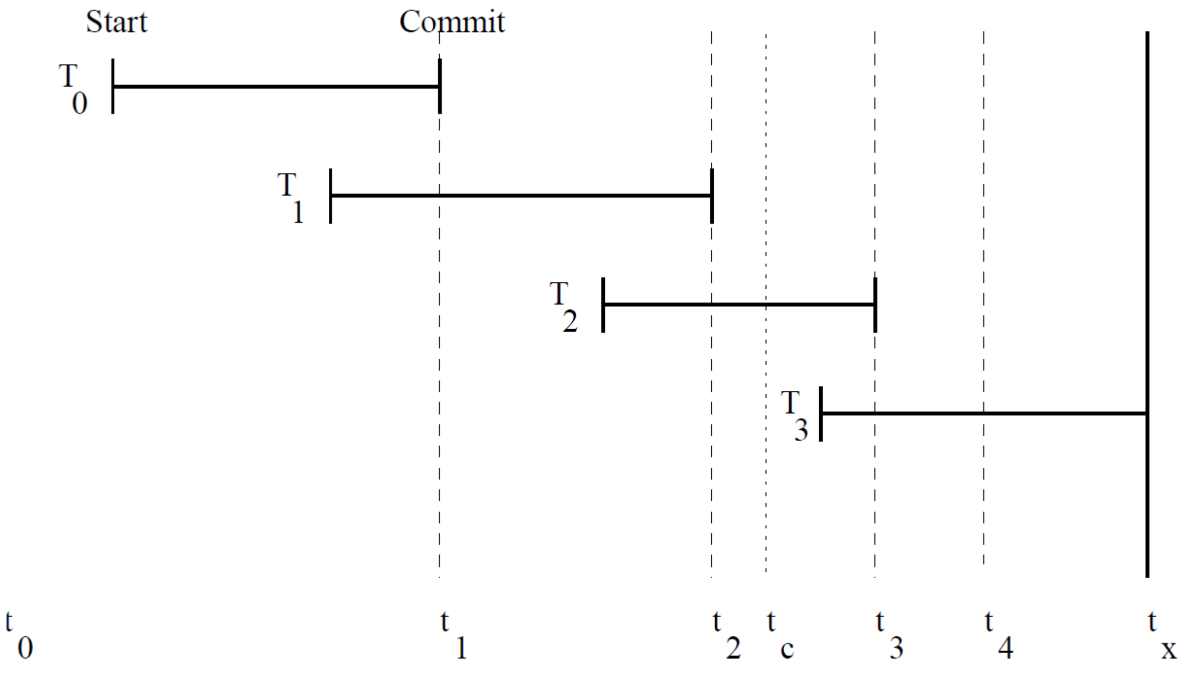
System Log (Cont’d)

- In fact some other entries (rollback, undo, redo) are also required for a recovery method.

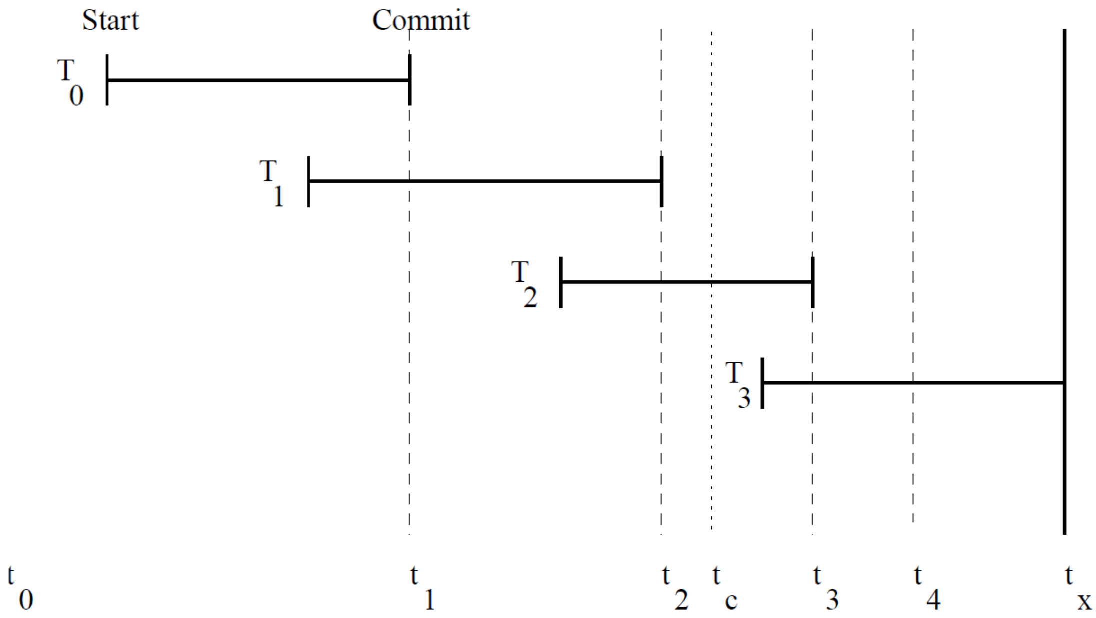
- These entries allow the recovery manager to *rollback* an unsuccessful transaction (undo any partial updates).

Recovery

- Let us see how the log might be used to recover from a system crash.
- The diagram below shows transactions between the last system backup and a crash.



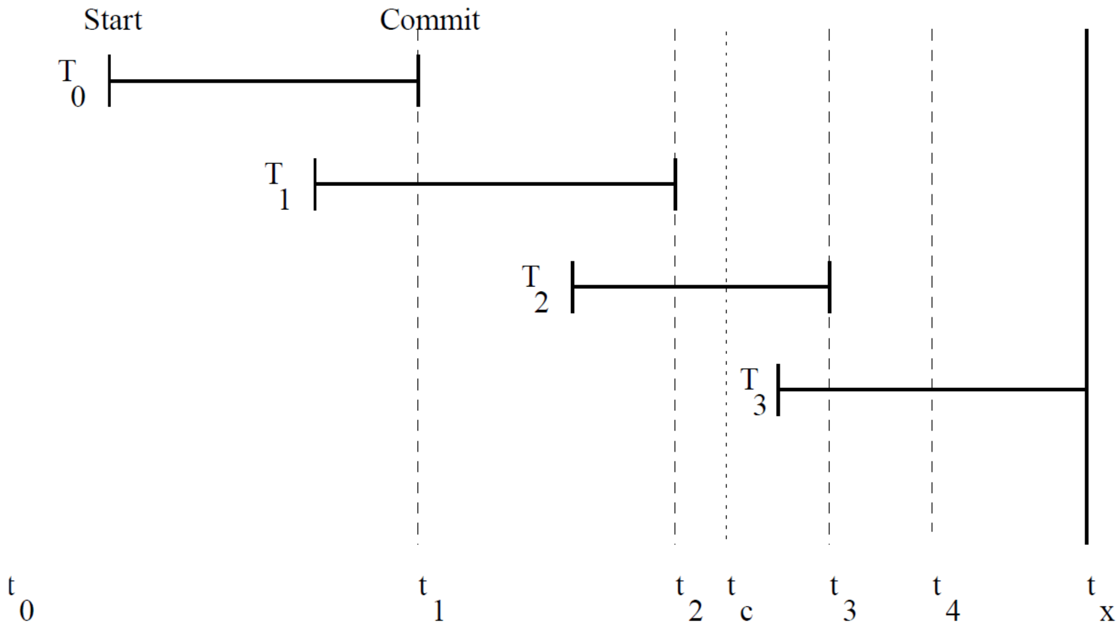
Recovery (Cont'd)



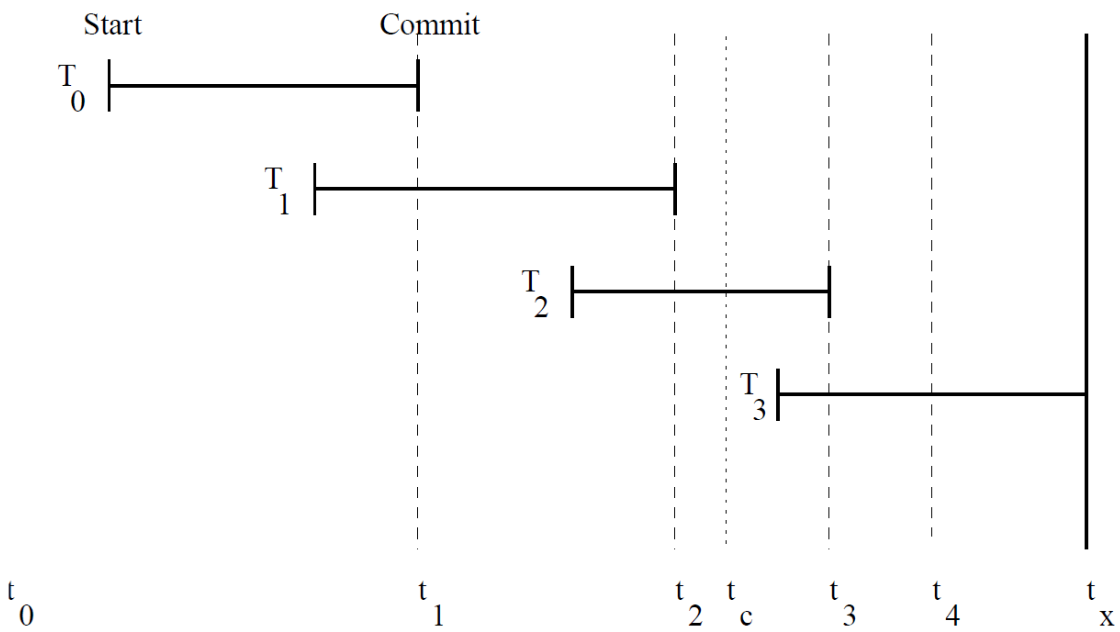
- The database on disk will be in a state somewhere between that at t_0 and the state at t_x.
- The same is also true for log entries.

Recovery (Cont'd)

- We will assume that the *write-ahead log strategy* is used. This means that
  - old data values must be force-written to the log (i.e. the buffer must be copied to disk) before any change can be made to the database, and
  - the transaction is regarded as committed when the new data values and the commit marker have been force-written to the log.
- Thus the log is force-written at least at t_1, t_2 and t_3 in the above.



- Suppose the log was last written to disk at t_4.
- By examining the log:
  1. We know that T_0, T_1 and T_2 have committed and their effects should be reflected in the database after recovery.
  2. But we do not know whether the effects of T_0, T_1 and T_2 were reflected at the time of the crash.
  3. We also know that T_3 has started, may have modified some data, but is not committed. Thus T_3 should be undone.



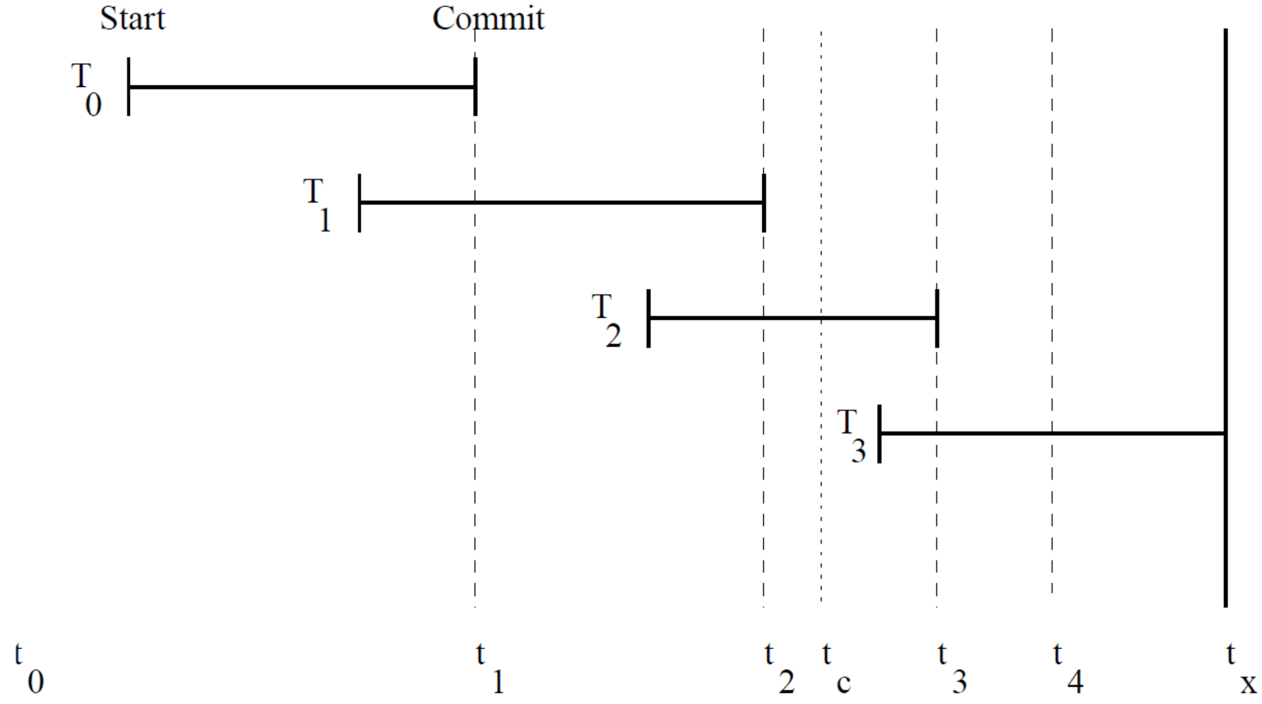
- The database can be recovered by rolling back T_3 using the old data values from the log, and redoing the changes made by T_0 ... T_2 using the new data values (for these committed transactions) from the log.
- Notice that instead of rolling back, the database could have been restored from the backup. This might be necessary in the event of a disk crash for example (for this reason, the log should be stored on an independent disk pack).

Checkpoints

- Notice also that using this system, the longer the time between crashes, the longer recovery may take.

- To avoid this problem, the system may take *checkpoints* at regular intervals.

- To do this:
  - a *start of checkpoint* marker is written to the log, then
  - the database updates in buffers are force-written, then
  - an *end of checkpoint* marker is written to the log.



- In our example, suppose a checkpoint is taken at time t_c. Then on recovery we only need redo T_2.

Recall: Desirable Properties of Transaction Processing: **ACID**

- *Atomicity:* A transaction is either performed in its entirety or not performed at all.

- *Consistency preservation:* A correct execution of the transaction must take the database from one consistent state to another.

- *Isolation:* A transaction should not make its updates visible to other transactions until it is committed.

- *Durability or permanency:* Once a transaction changes the database and the changes are committed, these changes must never be lost because of subsequent failure.

Concurrency Control

- Multiple concurrent transactions T_1, T_2, …

- They read/write common elements A_1, A_2, …

- How can we prevent unwanted interference?

The Scheduler is responsible for that

Schedules of Transactions

- To fully utilise resources, desirable to interleave the operations of transactions in an appropriate way.

- For example, if one transaction is waiting for I/O to complete, another transaction can use the CPU.

- A *schedule S* of the transactions $T_1, \ldots, T_n$
  - is a sequential ordering of the operations of $T_1, \ldots, T_n$, and
  - preserves the ordering of operations in each transaction T_i.

Example Schedules

(a)

T_1	T_2
read(X)	
$X \leftarrow X + N$	
write(X)	
read(Y)	
$Y \leftarrow Y - N$	
write(Y)	
	read(X)
	$X \leftarrow X + M$
	write(X)

(b)

T_1	T_2
	read(X)
	$X \leftarrow X + M$
	write(X)
read(X)	
$X \leftarrow X + N$	
write(X)	
read(Y)	
$Y \leftarrow Y - N$	
write(Y)	

Example Schedules (Cont.)

(c)

T_1	T_2
read(X)	
$X \leftarrow X + N$	
	read(X)
	$X \leftarrow X + M$
write(X)	
read(Y)	
	write(X)
$Y \leftarrow Y - N$	
write(Y)	

(d)

T_1	T_2
read(X)	
$X \leftarrow X + N$	
write(X)	
	read(X)
	$X \leftarrow X + M$
	write(X)
read(Y)	
$Y \leftarrow Y - N$	
write(Y)	

Serial Schedule

- As we have seen, if operations are interleaved arbitrarily, incorrect results may occur.
- However, it is reasonable to assume that schedules (a) and (b) in the figure will give correct results (as long as the transactions are independent).
- (a) and (b) are called *serial* schedules, and we will assume that *any serial schedule is correct*.

(a)

T_1	T_2
read(X)	
$X \leftarrow X + N$	
write(X)	
read(Y)	
$Y \leftarrow Y - N$	
write(Y)	
	read(X)
	$X \leftarrow X + M$
	write(X)

(b)

T_1	T_2
	read(X)
	$X \leftarrow X + M$
	write(X)
read(X)	
$X \leftarrow X + N$	
write(X)	
read(Y)	
$Y \leftarrow Y - N$	
write(Y)	

Serializable Schedule

- Notice that schedule (d) always produces the same result as schedules (a) and (b), so it should also give correct results.
- A schedule is *serializable* if it always produces the same result as some serial schedule.
- Notice that schedule (c) is not serializable.

(c)

T_1	T_2
read(X)	
$X \leftarrow X + N$	
	read(X)
	$X \leftarrow X + M$
write(X)	
read(Y)	
	write(X)
$Y \leftarrow Y - N$	
write(Y)	

(d)

T_1	T_2
read(X)	
$X \leftarrow X + N$	
write(X)	
	read(X)
	$X \leftarrow X + M$
	write(X)
read(Y)	
$Y \leftarrow Y - N$	
write(Y)	

Scheduling Transactions

- Serial schedule: Schedule that does not interleave the actions of different transactions.

- Equivalent schedules: For any database state, the effect (on the set of objects in the database) of executing the first schedule is identical to the effect of executing the second schedule.

- Serializable schedule: A schedule over a set S of transactions is equivalent to some serial execution of the set of committed transactions in S.

Serializability

Note: If each transaction preserves consistency, every serializable schedule preserves consistency.

Conflict Serializable Schedules

- Two schedules are *conflict equivalent* if:
  - Involve the same actions of the same transactions
  - Every pair of conflicting actions is ordered the same way

- Schedule S is *conflict serializable* if S is conflict equivalent to some serial schedule

Conflict Serializability

- Any conflict serializable schedule is also a serializable schedule (why ?)

- The inverse is not true.

$w_1(Y); w_2(Y); w_2(X); w_1(X); w_3(X);$

Lost write

Equivalent, but not conflict equivalent

$w_1(Y); w_1(X); w_2(Y); w_2(X); w_3(X);$

Testing Conflict Serializable

- Why not run only serial schedules? That is, run one transaction after the other?

Because of very poor throughput due to disk latency

- When there are only two transactions, there are only two serial schedules - for *n* transactions there will be *n*!.

- Fortunately there is an efficient algorithm to check whether a schedule is conflict serializable without checking all these possibilities.

Check Conflict Serializability

- *Algorithm*

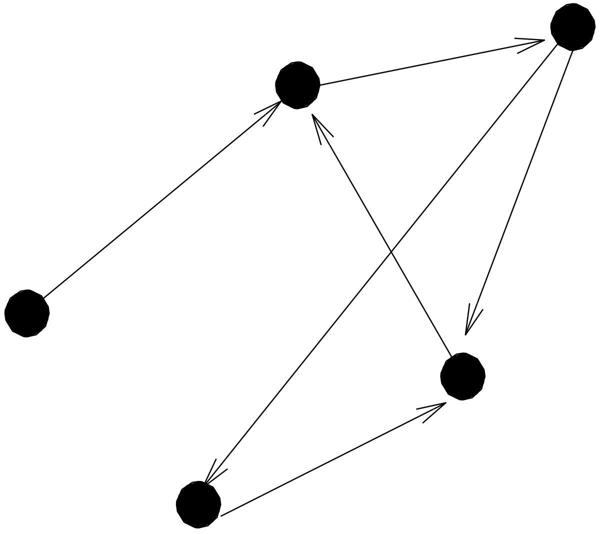
  Step 1: Construct a *schedule* (or *precedence*) graph – a *directed graph*.

  Step 2: Check if the graph is *cyclic*:

  - Cyclic: non-serializable.
  - Acyclic: serializable.

- A *directed graph* $G = (V, A)$ consists of
  - a vertex set V, and
  - an arc set A such that each arc connects two vertices.

- G is *cyclic* if G contains a directed cycle.



Cyclic Graph

Construct a Schedule Graph $G_S = (V, A)$ for a schedule S

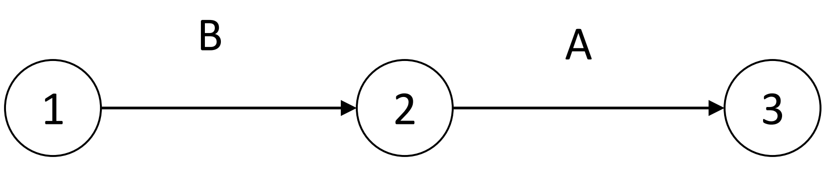
1. A vertex in V represents a transaction.

2. For two vertices T_i and T_j, an arc $T_i \rightarrow T_j$ is added to A if
   - there are two *conflicting* operations $O_1 \in T_i$ and $O_2 \in T_j$,
   - in S, O_1 is before O_2.

Two operations O_1 and O_2 are *conflicting* if
- they are in different transactions but on the same data item,
- one of them must be a write.

Example 1

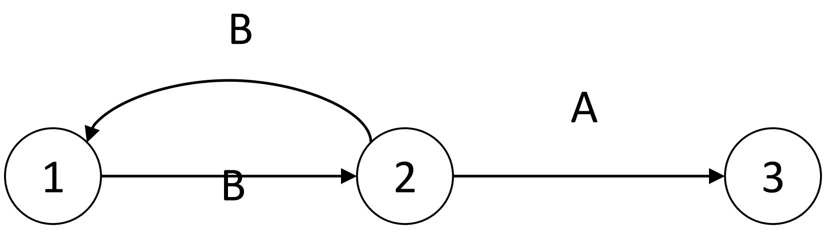
$r_2(A); r_1(B); w_2(A); r_3(A); w_1(B); w_3(A); r_2(B); w_2(B)$



This schedule is conflict-serializable

Example 2

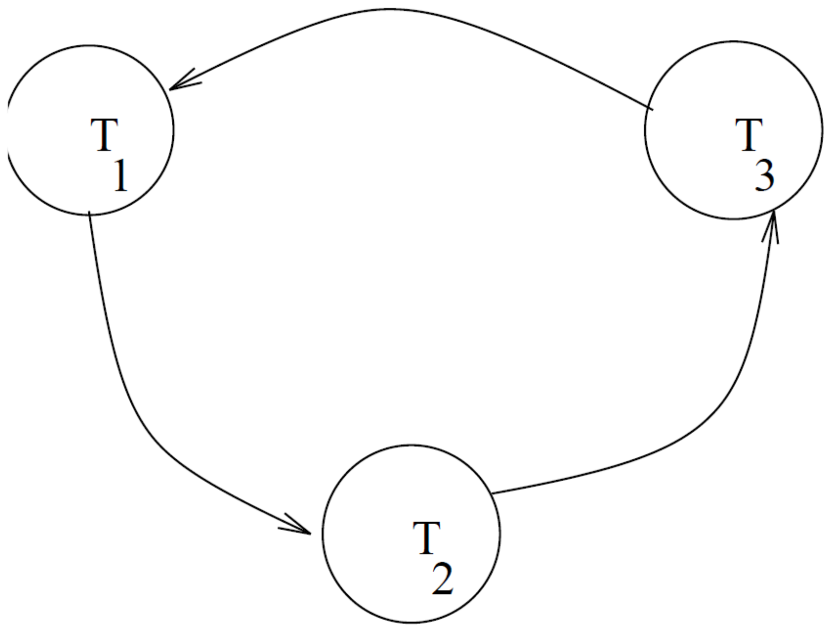
$r_2(A); r_1(B); w_2(A); r_2(B); r_3(A); w_1(B); w_3(A); w_2(B)$



This schedule is NOT conflict-serializable

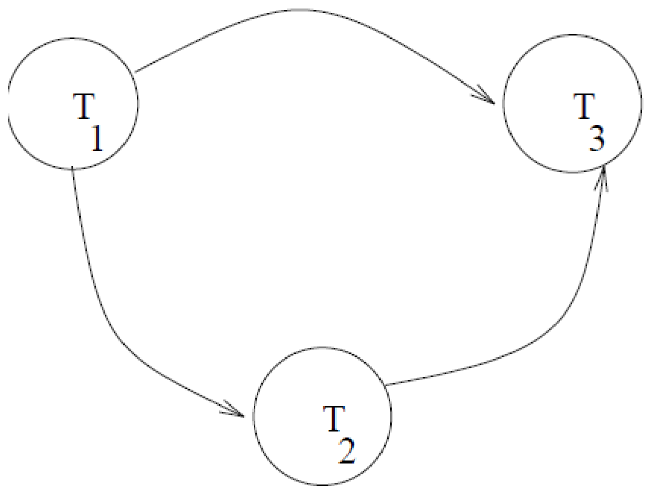
Example 1:

Schedule	T_1	T_2	T_3
read(A)	read(A)		
read(B)		read(B)	
$A \leftarrow f_1(A)$	$A \leftarrow f_1(A)$		
read(C)			read(C)
$B \leftarrow f_2(B)$		$B \leftarrow f_2(B)$	
write(B)		write(B)	
$C \leftarrow f_3(C)$			$C \leftarrow f_3(C)$
write(C)			write(C)
write(A)	write(A)		
read(B)			read(B)
read(A)		read(A)	
$A \leftarrow f_4(A)$		$A \leftarrow f_4(A)$	
read(C)	read(C)		
write(A)		write(A)	
$C \leftarrow f_5(C)$	$C \leftarrow f_5(C)$		
write(C)	write(C)		
$B \leftarrow f_6(B)$			$B \leftarrow f_6(B)$
write(B)			write(B)


T_1
T_3
T_2

Example 2:

Schedule	T_1	T_2	T_3
read(A)	read(A)		
$A \leftarrow f_1(A)$	$A \leftarrow f_1(A)$		
read(C)	read(C)		
write(A)	write(A)		
$A \leftarrow f_2(C)$	$A \leftarrow f_2(C)$		
read(B)		read(B)	
write(C)	write(C)		
read(A)		read(A)	
read(C)			read(C)
$B \leftarrow f_3(B)$		$B \leftarrow f_3(B)$	
write(B)		write(B)	
$C \leftarrow f_4(C)$			$C \leftarrow f_4(C)$
read(B)			read(B)
write(C)			write(C)
$A \leftarrow f_5(A)$		$A \leftarrow f_5(A)$	
write(A)		write(A)	
$B \leftarrow f_6(B)$			$B \leftarrow f_6(B)$
write(B)			write(B)



- Unfortunately, testing for serializability on the fly is not practical.

- Instead, a number of protocols have been developed which ensure that if every transaction obeys the rules, then *every* schedule will be serializable, and thus correct.

Concurrency Control Methods

- **Locking Mechanism**

  The idea of locking some data item *X* is to:
  - give a transaction exclusive use of the data item *X*,
  - do not restrict the access of other data items.

  This prevents one transaction from changing a data item currently being used in another transaction.

- We will discuss a simple locking scheme which locks individual items, using read and write locks

Locking Rules

- In this schema, every transaction *T* must obey the following rules.

- 1) If *T* has only one operation (read/write) manipulating an item *X*:
  - obtain a read lock on *X* before reading it,
  - obtain a write lock on *X* before writing it,
  - unlock *X* when done with it.

- 2) If *T* has several operations manipulating *X*:
  - obtain one proper lock only on *X*:

  a read lock if all operations on *X* are reads;

  a write lock if one of these operations on *X* is a write.
  - unlock *X* after the last operation on *X* in *T* has been executed.

Locking Rules (cont.)

- In this scheme,
  - Several read locks can be issued on the same data item at the same time.
  - A read lock and a write lock cannot be issued on the same data item at the same time, neither two write locks.
- This still does not guarantee serializability.

Example: Based on E/N Fig 18.3.

T_1	T_2
read_lock(Y)	
read(Y)	
unlock(Y)	
	read_lock(X)
	read(X)
	unlock(X)
	write_lock(Y)
	read(Y)
	$Y \leftarrow X + Y$
	write(Y)
	unlock(Y)
write_lock(X)	
read(X)	
$X \leftarrow X + Y$	
write(X)	
unlock(X)	

Two Phase Locking (2PL)

- To guarantee serializability, transactions must also obey the *two-phase locking protocol*:

  - *Growing Phase*: all locks for a transaction must be obtained before any locks are released, and

  - *Shrinking Phase*: gradually release all locks (once a lock is released no new locks may be requested).

Two Phase Locking (2PL) (Cont.)

Example: Based on E/N Fig 18.4.

T_1
read_lock(Y)
read(Y)
write_lock(X)
unlock(Y)
read(X)
$X \leftarrow X + Y$
write(X)
unlock(X)

- Locking thus provides a solution to the problem of correctness of schedules.

Two phase locking ensures conflict serializability

Deadlock

- A problem that arises with locking is **deadlock**.
- Deadlock occurs when two transactions are each waiting for a lock on an item held by the other.

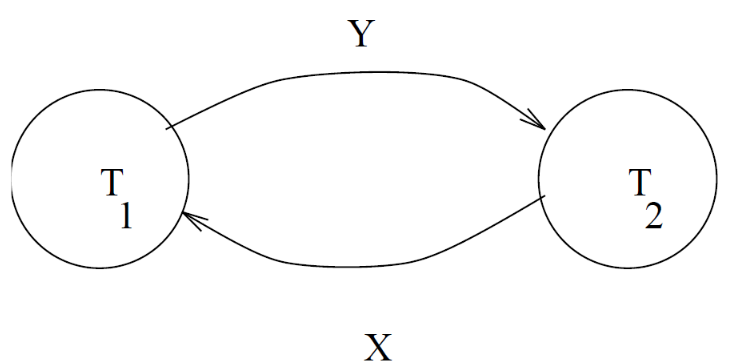
T_1	T_2
write_lock(X)	
read(X)	
	write_lock(Y)
	read(Y)
write_lock(Y)	
waiting for Y*	write_lock(X)
waiting for Y*	***waiting for X***

Deadlock Check

- Create the *wait-for graph* for currently active transactions:
  - create a vertex for each transaction; and
  - an arc from T_i to T_j if T_i is waiting for an item locked by T_j.

- If the graph has a cycle, then a *deadlock* has occurred.

Example:



Several methods to deal with deadlocks

- *deadlock detection*
  - periodically check for deadlocks, abort and rollback some transactions (restart them later). This is a good choice if transactions are very short or very independent.

Several methods to deal with deadlocks (Cont.)

- *deadlock prevention* - Assign priorities based on timestamps. Assume Ti wants a lock that Tj holds. Two policies are possible:
  - Wait-Die: If Ti has higher priority, Ti waits for Tj; otherwise Ti aborts
  - Wound-wait: If Ti has higher priority, Tj aborts; otherwise Ti waits
- If a transaction re-starts, make sure it has its original timestamp

Timestamp ordering

- The idea here is:
  - to assign each transaction a timestamp (e.g. start time of transaction), and
  - to ensure that the schedule used is equivalent to executing the transactions in timestamp order

- Each data item, X, is assigned
  - a read timestamp, *read TS*(*X*) - the latest timestamp of a transaction that read X, and
  - a write timestamp, *write TS*(*X*) - the latest timestamp of a transaction that write X.

- These are used in read and write operations as follows. Suppose the transaction timestamp is *T*.

$read(X)$:

```
If T >= write_TS(X) then
    { execute read(X);
    if T >= read_TS(X) then
          read_TS(X) <- T }
else
   rollback the transaction and restart
```

$write(X)$:

```
If T >= read_TS(X) and T >= write_TS(X) then
   { execute write(X); write_TS(X) <- T }
else
   rollback and restart
```

- **Thomas' write rule:**

$write(X)$:

```
If T < read_TS(X) then
   rollback and restart
else if T < write_TS(X) then
        ignore the write
      else
         { execute write(X);
           write_TS(X) <- T }
```

- Some problems:
  - Cyclic restart: There is no deadlock, but a kind of livelock can occur - some transactions may be constantly aborted and restarted.

  - Cascading rollback: When a transaction is rolled back, so are any transactions which read a value written by it, and any transactions which read a value written by them . . . etc. This can be avoided by not allowing transactions to read values written by uncommitted transactions (make them wait).

Multiversioning

- Similar to the timestamp ordering approach; but is allowed to access “old” versions of a table.
- A history of the values and timestamps (versions) of each item is kept.
- When the value of an item is needed, the system chooses a **proper** version of the item that maintains serializability.
- This results in fewer aborted transactions at the cost of greater complexity to maintain more versions of each item.

- We will look at a scheme, several versions $X_1, \ldots, X_k$ of each data item are kept. For each X_i we also keep
  - *read TS*(X_i) - as for timestamp ordering.
  - *write TS*(X_i) - as for timestamp ordering.

- Read and write are done as follows for a transaction *P* with timestamp T.

$read(X)$:

```
Find Xi s.t. write_TS(Xi) is the
   highest write timestamp but <= T
update read_TS(Xi) (and do read(Xi))
return Xi as the value for X
```

$write(X)$:

```
Find Xi s.t. write_TS(Xi) is the
   highest write timestamp but <= T
if T < read_TS(Xi) then
   rollback and restart
else
   { create a new version X(k+1) of X;
     set read_TS(X(k+1)) to T;
     set write_TS(X(k+1)) to T}
```

- *Note:* Cascading rollback and cyclic restart problems can still occur, but should be reduced.

- However, there is an increased overhead in maintaining multiple versions of items.

Optimistic scheduling

- In two-phase locking, timestamp ordering, and multiversioning concurrency control techniques, a certain degree of checking is done **before** a database operation can be executed.

- The idea here is to push on and hope for the best!

- No checking is done while the transaction is executing.

- The protocol has three phases.
  - *read phase* - A transaction can read data items from the database into local variables. However, updates are applied only to local copies of the data items kept in the transaction workspace.
  - *validation phase* - checks are made to ensure that serializability is not violated,
  - *write phase* -if validation succeeds, updates are applied and the transaction is committed. Otherwise, the updates are discarded and the transaction is restarted.

- A scheme uses timestamps and keeps each transaction's
  - read-set - the set of items read by the transaction,
  - write-set - the set of items written by the transaction.
- During validation, we check that the transaction does not interfere with any transaction that is committed or currently validating.

- Each transaction T is assigned 3 timestamps:

  Start(T), *Validation*(T), *Finish*(T).

- To pass the validation test for T, one of the following must be true:
  - 1. *Finish*(S) < *Start*(T); or
  - 2. for S s.t. *Start*(T) < *Finish*(S), then
    a) write set of S is disjoint from the read set of T, and
    b) *Finish*(S) < *Validation*(T).

Optimistic control is a good option if there is not much interaction between transactions.

2PL vs. TSO vs. MV vs. OP

- A Comparison among two-phase locking (2PL), timestamp ordering (TSO), multiversioning (MV), optimistic (OP) concurrency control techniques.

- MV should provide the greatest concurrency degree (in average). However, we need to maintain multiversions for each data item.

- 2PL can offer the second greatest concurrency degree (in average); but will result in deadlocks. To resolve the deadlocks, either
  - need additional computation to detect deadlocks and to resolve the deadlocks, or
  - reduce the concurrency degree to prevent deadlocks by adding other restrictions.

2PL vs. TSO vs. MV vs. OP (cont.)

- If most transactions are very short, we can use 2PL + deadlock detection and resolution.

- TSO has a less concurrency degree than that of 2PL if a proper deadlock resolution is found. However, TSO does not cause deadlocks. Other problems, such as cyclic restart and cascading rollback, will appear in TSO.

- If there are not much interaction between transactions, OP is a very good choice. Otherwise, OP is a bad choice.