Concurrency Control

- The problem of synchronizing concurrent transactions such that the consistency of the database is maintained while, at the same time, maximum degree of concurrency is achieved.
- Principles:
  - We want to interleave the execution of transactions for performance reasons
    - E.g., execute operations of another transaction when the first one starts doing I/O.
  - However, we want the results of interleaved executions to be equivalent to non-interleaved execution for correctness
    - We need to be able to reason about the execution order of transactions.

Potential Anomalies Due to Concurrent Execution

- Lost updates
  - The effects of some transactions are not reflected in the database.
  - Transaction T_2 reading uncommitted changes to data made by transaction T_1.
    - Write-Read conflicts
  - Transaction T_2 overwriting uncommitted changes of transaction T_1.
    - Write-Write conflicts
- Inconsistent retrievals (unrepeatable reads)
  - A transaction, if it reads the same data item more than once, should always read the same value.
  - Transaction T_2 modifies data that is being accessed by transaction T_1.
    - Read-Write conflicts

Execution Schedule (or History)

- An order in which the operations of a set of transactions are executed.
- A schedule (history) can be defined as a partial order over the operations of a set of transactions.

T_1:	T_2:	T_3:
Read(x)	Write(x)	Read(x)
Write(x)	Write(y)	Read(y)
Commit	Read(z)	Read(z)
	Commit	Commit

$$H_1=W_2(x)\ R_1(x)\ R_3(x)\ W_1(x)\ C_1 W_2(y)\ R_3(y)\ R_2(z)\ C_2\ R_3(z)\ C_3\}$$

Formalization of Schedule

A complete schedule $SC(T)$ over a set of transactions $T=\{T_1, \ldots, T_n\}$ is a partial order $SC(T)=\{\Sigma_T, <_T\}$ where

❶ $\Sigma_T = \cup_i \Sigma_i$, for $i = 1, 2, \ldots, n$

❷ $<_T \supseteq \cup_i <_i$, for $i = 1, 2, \ldots, n$

❸ For any two conflicting operations $o_{ij}, o_{kl} \in \Sigma_T$, either $o_{ij} <_T o_{kl}$ or $o_{kl} <_T o_{ij}$

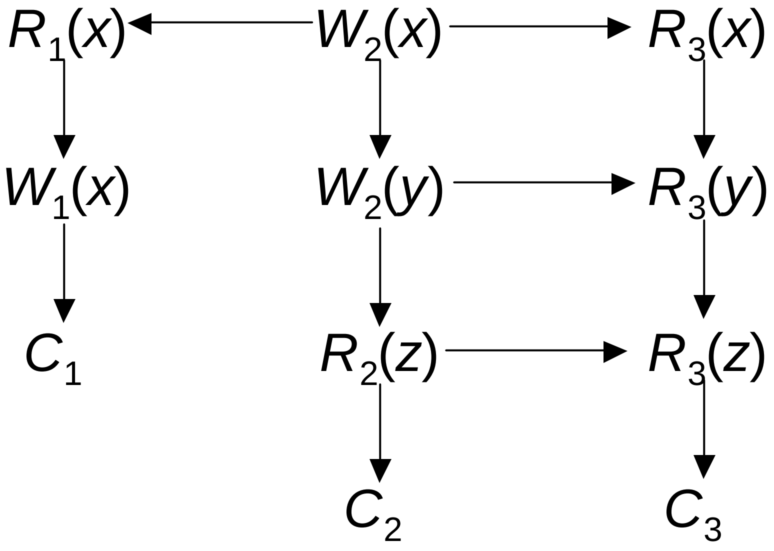
(Remember: o_{ij} is an operation of transaction T_i)

Complete Schedule – Example

Given three transactions

T_1:	T_2:	T_3:
Read(x)	Write(x)	Read(x)
Write(x)	Write(y)	Read(y)
Commit	Read(z)	Read(z)
	Commit	Commit

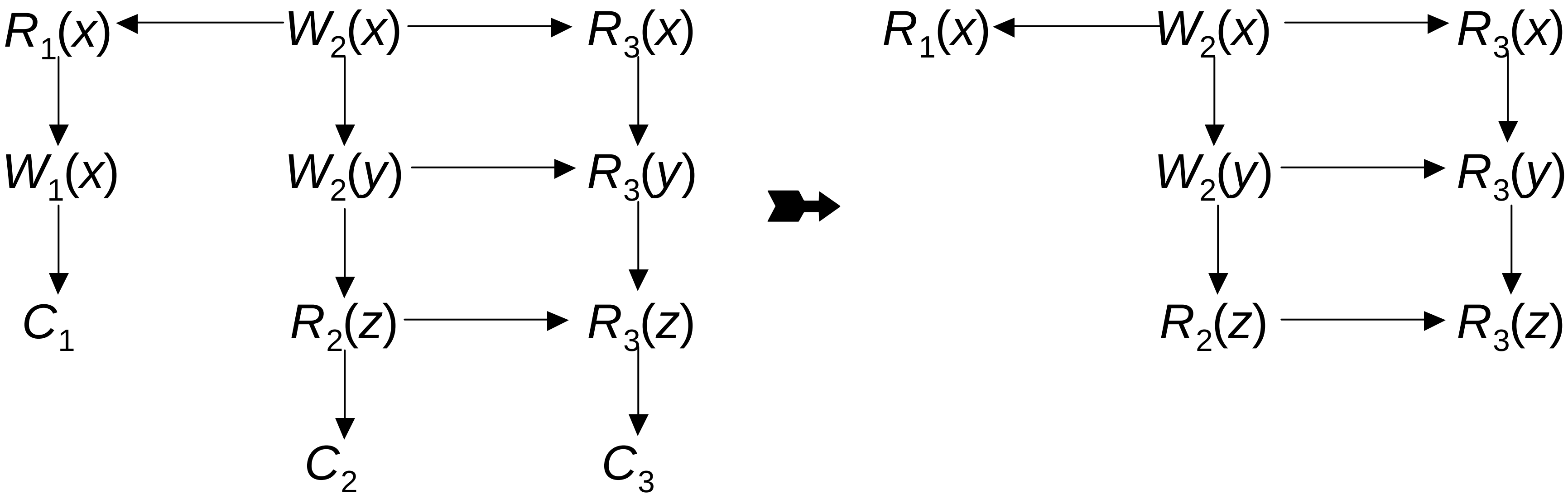
A possible complete schedule is given as the DAG



Schedule Definition

A schedule is a prefix of a complete schedule such that only some of the operations and only some of the ordering relationships are included.

T_1:	T_2:	T_3:
Read(x)	Write(x)	Read(x)
Write(x)	Write(y)	Read(y)
Commit	Read(z)	Read(z)
	Commit	Commit



Serial Schedule

- All the actions of a transaction occur consecutively.
- No interleaving of transaction operations.
- If each transaction is consistent (obeys integrity rules), then the database is guaranteed to be consistent at the end of executing a serial schedule.

T_1:	T_2:	T_3:
Read(x)	Write(x)	Read(x)
Write(x)	Write(y)	Read(y)
Commit	Read(z)	Read(z)
	Commit	Commit

$$H_s = \underbrace{W_2(x)\ W_2(y)\ R_2(z)\ C_2}_{T_2}\ \underbrace{R_1(x)\ W_1(x)\ C_1}_{T_1}\ \underbrace{R_3(x)\ R_3(y)\ R_3(z)\ C_3}_{T_3}\}$$

$$T_2 \rightarrow T_1 \rightarrow T_3$$

Serializable Schedule

- Transactions execute concurrently, but the net effect of the resulting schedule upon the database is *equivalent* to some *serial* schedule.
- Equivalent with respect to what?
  - *Conflict equivalence*: the relative order of execution of the conflicting operations belonging to committed transactions in two schedules are the same.
  - *Conflicting operations*: two incompatible operations (e.g., Read and Write) conflict if they both access the same data item.
    - Incompatible operations of each transaction is assumed to conflict; do not change their execution orders.
    - If two operations from two different transactions conflict, the corresponding transactions are also said to conflict.

Serializable Schedule

T_1:	T_2:	$T3$:
Read(x)	Write(x)	Read(x)
Write(x)	Write(y)	Read(y)
Commit	Read(z)	Read(z)
	Commit	Commit

The following are not conflict equivalent

$H_s = W_2(x)\ W_2(y)\ R_2(z)\ C_2\ R_1(x)\ W_1(x)\ C_1\ R_3(x)\ R_3(y)\ R_3(z)\ C_3$

$H_1 = W_2(x)\ R_1(x)\ R_3(x)\ W_1(x)\ C_1\ W_2(y)\ R_3(y)\ R_2(z)\ C_2\ R_3(z)\ C_3$

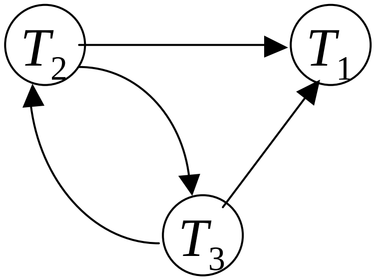
The following are conflict equivalent; therefore H_2 is *serializable*.

$H_s = W_2(x)\ W_2(y)\ R_2(z)\ C_2\ R_1(x)\ W_1(x)\ C_1\ R_3(x)\ R_3(y)\ R_3(z)\ C_3$

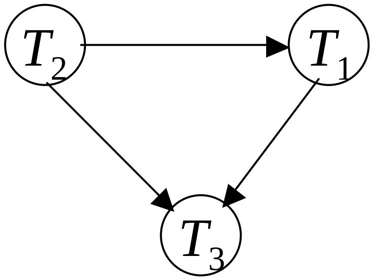
$H_2 = W_2(x)\ R_1(x)\ W_1(x)\ C_1\ R_3(x)\ W_2(y)\ R_3(y)\ R_2(z)\ C_2\ R_3(z)\ C_3$

Serializability Graph

- Serializability graph $SG_H=\{V,E\}$ for schedule H:
  - $V=\{T \mid T$ is a committed transaction in $H\}$
  - $E=\{T_i \rightarrow T_j$ if $o_{ij} \in T_i$ and $o_{kl} \in T_k$ conflict and $o_{ij} <_H o_{kl}\}$



H_1



H_2

- Theorem: Schedule H is serializable iff SG_H does not contain any cycles.

Concurrency Control Algorithms

- Pessimistic
  - Two-Phase Locking-based (2PL)
  - Timestamp Ordering (TO)
- Optimistic

Locking-Based Algorithms

- Transactions indicate their intentions by requesting locks from the scheduler (called lock manager).
- Locks are either read lock (*rl*) [also called shared lock] or write lock (*wl*) [also called exclusive lock]
- Read locks and write locks conflict (because Read and Write operations are incompatible

	rl	*wl*
rl	yes	no
wl	no	no

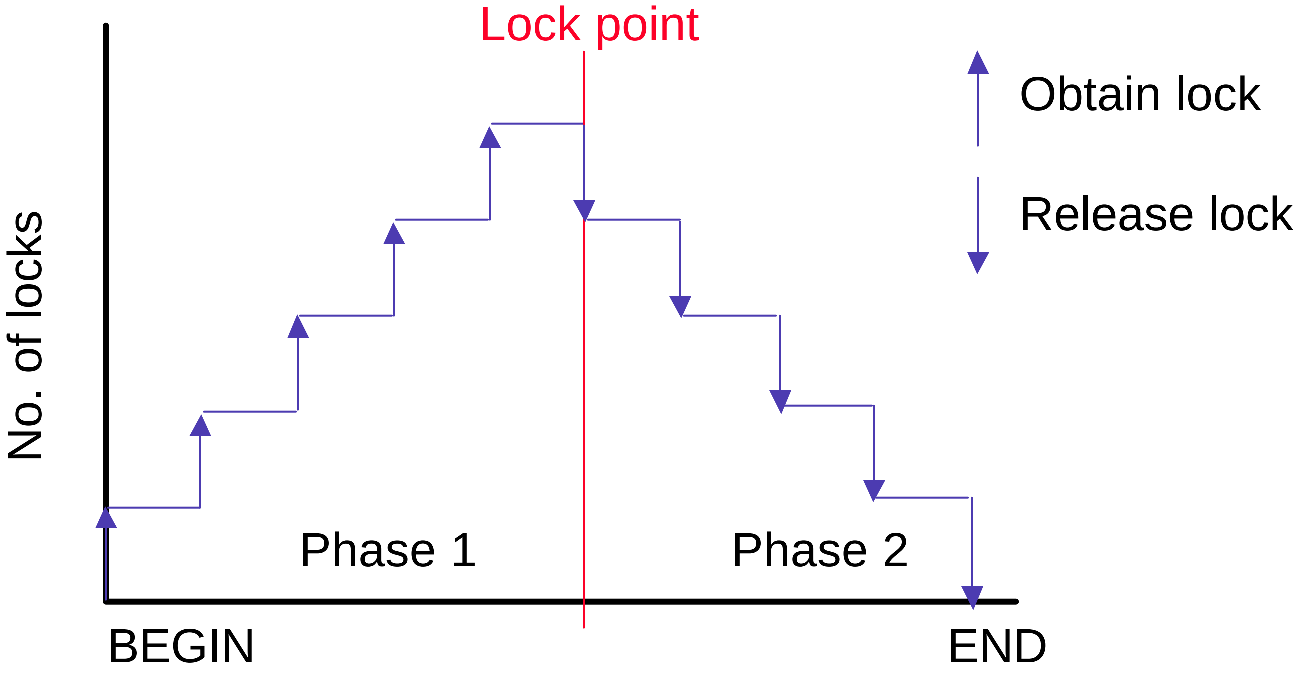
- Locking works nicely to allow concurrent processing of transactions.

Two-Phase Locking (2PL)

❶ A Transaction locks an object before using it.

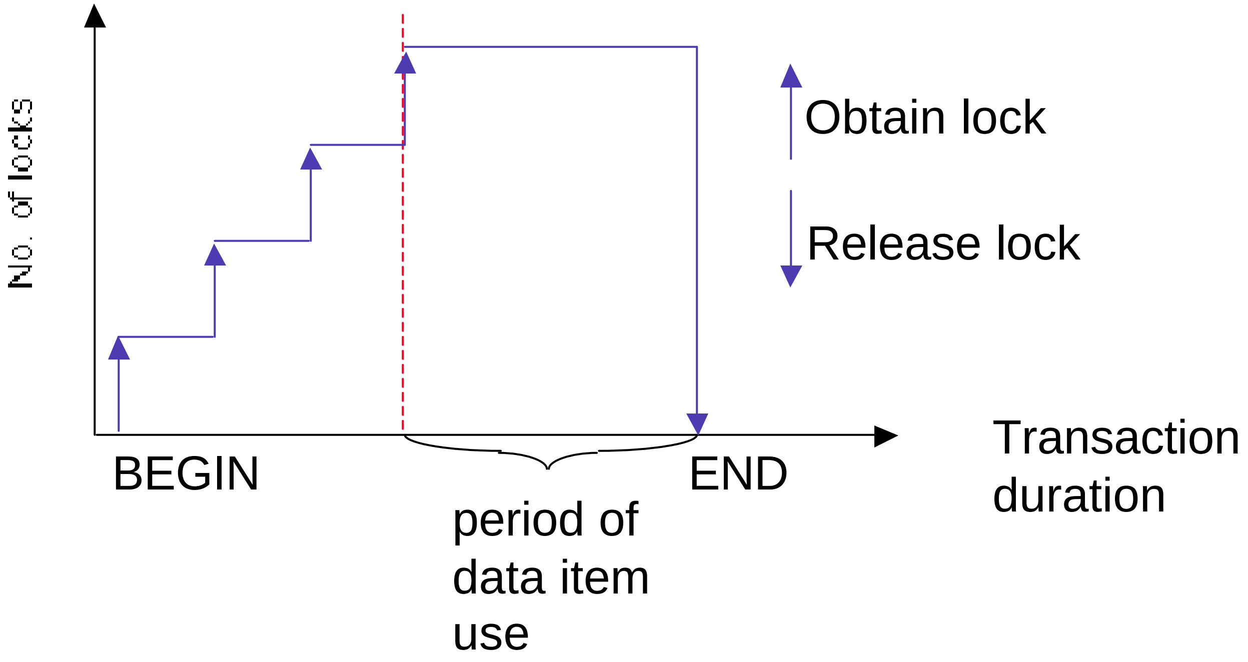
❷ When an object is locked by another transaction, the requesting transaction must wait.

❸ When a transaction releases a lock, it may not request another lock.



Strict 2PL

Hold locks until the end.



Timestamp Ordering

❶ Transaction (T_i) is assigned a globally unique timestamp $ts(T_i)$.

❷ Transaction manager attaches the timestamp to all operations issued by the transaction.

❸ Each data item is assigned a write timestamp (*wts*) and a read timestamp (*rts*):

- $rts(x)$ = largest timestamp of any read on x
- $wts(x)$ = largest timestamp of any write on x

❹ Conflicting operations are resolved by timestamp order.

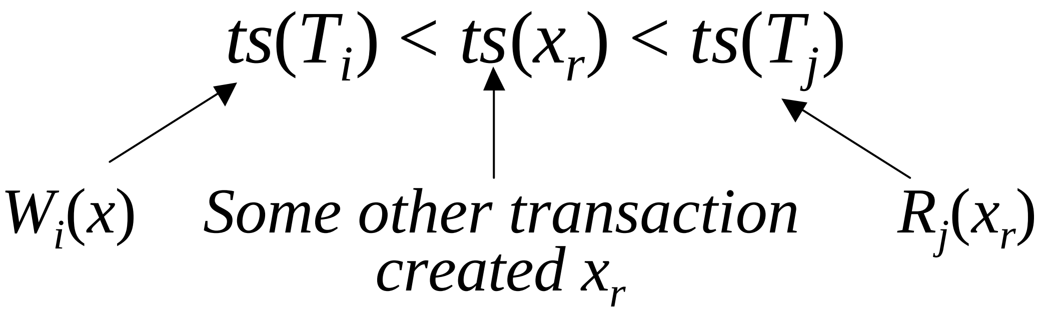
Basic T/O:

```
for $R_i(x)$:
if $ts(T_i) < wts(x)$
then reject $R_i(x)$
else {accept $R_i(x)$
        $rts(x) \leftarrow ts(T_i)$ }
```

```
for $W_i(x)$:
if $ts(T_i) < rts(x)$ or $ts(T_i) < wts(x)$
then reject $W_i(x)$
else {accept $W_i(x)$
        $wts(x) \leftarrow ts(T_i)$ }
```

Multiversion Timestamp Ordering

- Do not modify the values in the database, create new values.
- A $R_i(x)$ is translated into a read on one version of x.
  - Find a version of x (say x_v) such that $ts(x_v)$ is the largest timestamp less than $ts(T_i)$.
- A $W_i(x)$ is translated into $W_i(x_w)$ and accepted if the scheduler has not yet processed any $R_j(x_r)$ such that



$$ts(T_i) < ts(x_r) < ts(T_j)$$

$W_i(x)$

Some other transaction created x_r

$R_j(x_r)$

Optimistic Concurrency Control Algorithms

Pessimistic execution

Validate Read Compute Write

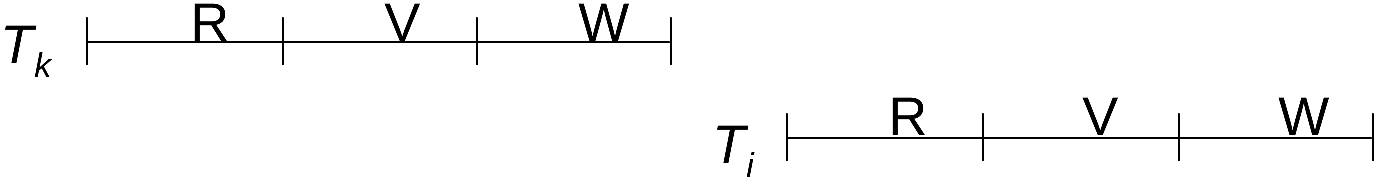
Optimistic execution

Read Compute Validate Write

Optimistic CC Validation Test

❶ If all transactions T_k where $ts(T_k) < ts(T_i)$ have completed their write phase before T_i has started its read phase, then validation succeeds

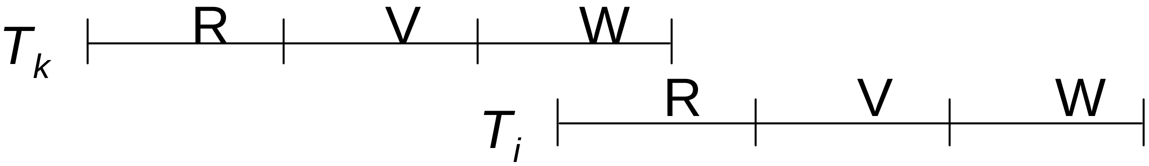
- Transaction executions in serial order



Optimistic CC Validation Test

❷ If there is any transaction T_k such that $ts(T_k)<ts(T_i)$ and which completes its write phase while T_i is in its read phase, then validation succeeds if $WS(T_k) \cap RS(T_i) = \emptyset$

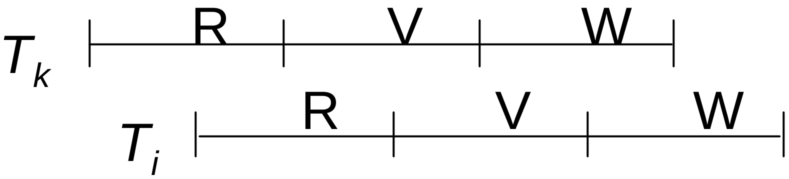
- Read and write phases overlap, but T_i does not read data items written by T_k



Optimistic CC Validation Test

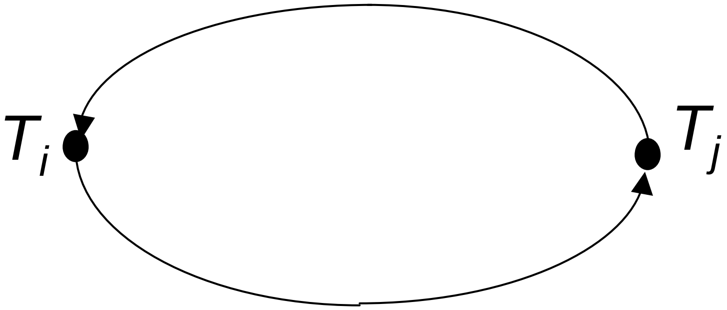
❸ If there is any transaction T_k such that $ts(T_k) < ts(T_i)$ and which completes its read phase before T_i completes its read phase, then validation succeeds if $WS(T_k) \cap RS(T_i) = \emptyset$ and $WS(T_k) \cap WS(T_i) = \emptyset$

- They overlap, but don't access any common data items.



Deadlock

- A transaction is deadlocked if it is blocked and will remain blocked until there is intervention.
- Locking-based CC algorithms may cause deadlocks.
- Wait-for graph
  - If transaction T_i waits for another transaction T_j to release a lock on an entity, then $T_i \rightarrow T_j$ in WFG.



Deadlock Management

- Prevention
  - Guaranteeing that deadlocks can never occur in the first place. Check transaction when it is initiated. Requires no run time support.
- Avoidance
  - Detecting potential deadlocks in advance and taking action to insure that deadlock will not occur. Requires run time support.
- Detection and Recovery
  - Allowing deadlocks to form and then finding and breaking them. As in the avoidance scheme, this requires run time support.

Deadlock Prevention

- All resources that may be needed by a transaction must be predeclared.
  - The system must guarantee that none of the resources will be needed by an ongoing transaction.
  - Resources must only be reserved, but not necessarily allocated a priori
  - Unsuitable in database environment
  - Suitable for systems that have no provisions for undoing processes.
- Evaluation:
  - – Reduced concurrency due to pre-allocation
  - – Evaluating whether an allocation is safe leads to added overhead.
  - – Difficult to determine (partial order)
  - \+ No transaction rollback or restart is caused.

Deadlock Avoidance

- Transactions are not required to request resources a priori.
- Transactions are allowed to proceed unless a requested resource is unavailable.
- In case of conflict, transactions may be allowed to wait for a fixed time interval.
- Order the data items and always request locks in that order.
- More attractive than prevention in a database environment.

Deadlock Avoidance – Wait-Die & Wound-Wait Algorithms

WAIT-DIE Rule: If T_i requests a lock on a data item which is already locked by T_j, then T_i is permitted to wait iff $ts(T_i)<ts(T_j)$. If $ts(T_i)>ts(T_j)$, then T_i is aborted and restarted with the same timestamp.

- **if** $ts(T_i)<ts(T_j)$ **then** T_i waits **else** T_i dies
- non-preemptive: T_i never preempts T_j

WOUND-WAIT Rule: If T_i requests a lock on a data item which is already locked by T_j , then T_i is permitted to wait iff $ts(T_i)>ts(T_j)$. If $ts(T_i)<ts(T_j)$, then T_j is aborted and the lock is granted to T_i.

- **if** $ts(T_i)<ts(T_j)$ **then** T_j is wounded **else** T_i waits
- preemptive: T_i preempts T_j if it is younger

Deadlock Detection

- Transactions are allowed to wait freely.
- Wait-for graphs and cycles.