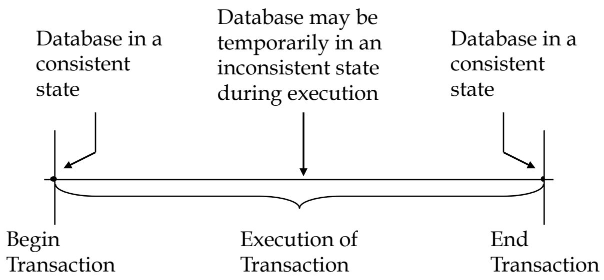
Outline

- Introduction & architectural issues
- Data distribution
- Distributed query processing
- Distributed query optimization
- ❑Distributed transactions & concurrency control
  - ❑ Transaction models and concepts
  - ❑ Distributed concurrency control
- ❑Distributed reliability
- ❑Data replication
- ❑Parallel database systems
- ❑Database integration & querying
- ❑Peer-to-Peer data management
- ❑Stream data management
- ❑MapReduce-based distributed data management

Transaction

A transaction is a collection of actions that make consistent transformations of system states while preserving system consistency.

- concurrency transparency
- failure transparency



Transaction Example – A Simple SQL Query

```
Transaction   BUDGET_UPDATE
begin
    EXEC SQL   UPDATE   PROJ
               SET      BUDGET = BUDGET∗1.1
               WHERE    PNAME = “CAD/CAM”
end.
```

Example Database

Consider an airline reservation example with the relations:

FLIGHT(FNO, DATE, SRC, DEST, STSOLD, CAP)
CUST(CNAME, ADDR, BAL)
FC(FNO, DATE, CNAME,SPECIAL)

Example Transaction – SQL Version

```
Begin_transaction Reservation
begin
    input(flight_no, date, customer_name);
    EXEC SQL  UPDATE     FLIGHT
              SET        STSOLD = STSOLD + 1
              WHERE      FNO = flight_no AND DATE = date;
    EXEC SQL  INSERT
              INTO       FC(FNO, DATE, CNAME, SPECIAL);
              VALUES     (flight_no, date, customer_name, null);
    output("reservation completed")
end . {Reservation}
```

Termination of Transactions

```
Begin_transaction Reservation
begin
    input(flight_no, date, customer_name);
    EXEC SQL   SELECT      STSOLD,CAP
               INTO        temp1,temp2
               FROM        FLIGHT
               WHERE       FNO = flight_no AND DATE =  date;
    if temp1 = temp2 then
        output("no free seats");
        Abort
    else
        EXEC SQL     UPDATE FLIGHT
                     SET    STSOLD = STSOLD + 1
                     WHERE  FNO = flight_no AND DATE = date;
        EXEC SQL     INSERT
                     INTO   FC(FNO, DATE, CNAME, SPECIAL);
                     VALUES (flight_no, date, customer_name, null);
       Commit
       output("reservation completed")
     endif
end . {Reservation}
```

Example Transaction – Reads & Writes

```
Begin_transaction Reservation
begin
        input(flight_no, date, customer_name);
        temp ← Read(flight_no(date).stsold);
        if temp = flight(date).cap then
        begin
            output("no free seats");
            Abort
        end
        else begin
            Write(flight(date).stsold, temp + 1);
            Write(flight(date).cname, customer_name);
            Write(flight(date).special, null);
            Commit;
            output("reservation completed")
        end
end. {Reservation}
```

Characterization

- Read set (RS)
  - The set of data items that are read by a transaction
- Write set (WS)
  - The set of data items whose values are changed by this transaction
- Base set (BS)
  - RS ∪ WS

Principles of Transactions

ATOMICITY
- all or nothing

CONSISTENCY
- no violation of integrity constraints

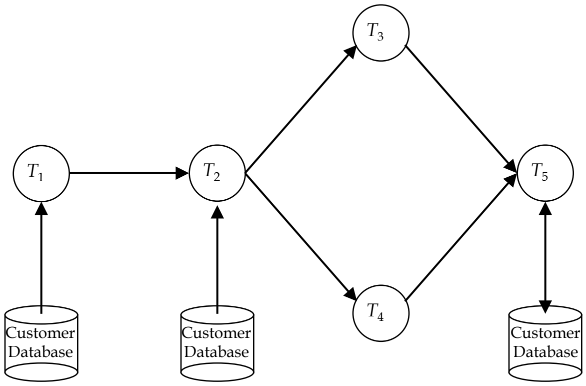
ISOLATION
- concurrent changes invisible ⇒ serializable

DURABILITY
- committed updates persist

Workflows

- "A collection of tasks organized to accomplish some business process."
- Types
  - Human-oriented workflows
    - Involve humans in performing the tasks.
    - System support for collaboration and coordination; but no system-wide consistency definition
  - System-oriented workflows
    - Computation-intensive & specialized tasks that can be executed by a computer
    - System support for concurrency control and recovery, automatic task execution, notification, etc.
  - Transactional workflows
    - In between the previous two; may involve humans, require access to heterogeneous, autonomous and/or distributed systems, and support selective use of ACID properties

Workflow Example



T_1: Customer request obtained
T_2: Airline reservation performed
T_3: Hotel reservation performed
T_4: Auto reservation performed
T_5: Bill generated

Transactions Provide…

- *Atomic* and *reliable* execution in the presence of failures
- *Correct* execution in the presence of multiple user accesses
- Correct management of *replicas* (if they support it)

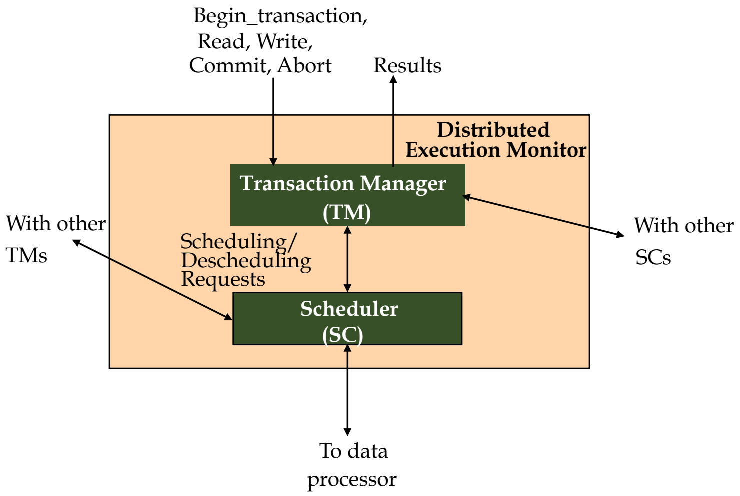
Transaction Processing Issues

- Transaction structure (usually called transaction model)
  - Flat (simple), nested
- Internal database consistency
  - Semantic data control (integrity enforcement) algorithms
- Reliability protocols
  - Atomicity & Durability
  - Local recovery protocols
  - Global commit protocols

Transaction Processing Issues

- Concurrency control algorithms
  - How to synchronize concurrent transaction executions (correctness criterion)
  - Intra-transaction consistency, isolation
- Reliability protocols
  - Atomicity & Durability
  - Local recovery protocols
  - Global commit protocols
- Replica control protocols
  - How to control the mutual consistency of replicated data
  - One copy equivalence and ROWA

Architecture Revisited



Begin_transaction,
Read, Write,
Commit, Abort

Results

Distributed
Execution Monitor

Transaction Manager
(TM)

With other
TMs

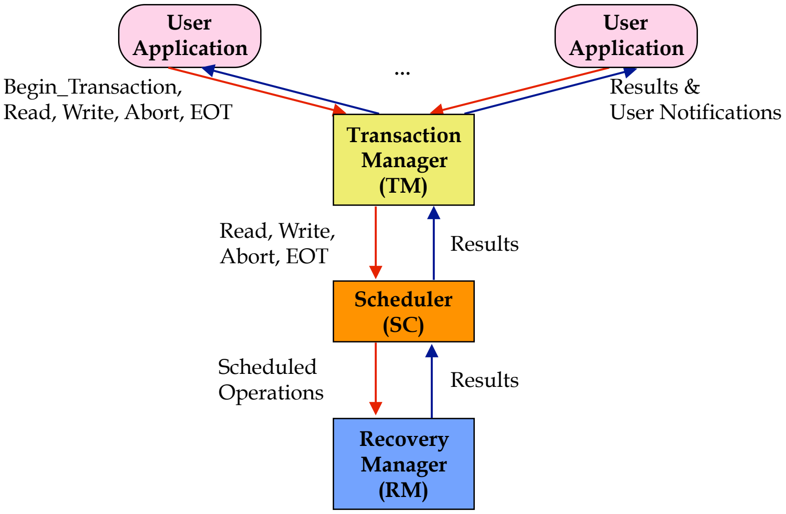
Scheduling/
Descheduling
Requests

With other
SCs

Scheduler
(SC)

To data
processor

Centralized Transaction Execution



User
Application

...

User
Application

Begin_Transaction,
Read, Write, Abort, EOT

Results &
User Notifications

Transaction
Manager
(TM)

Read, Write,
Abort, EOT

Results

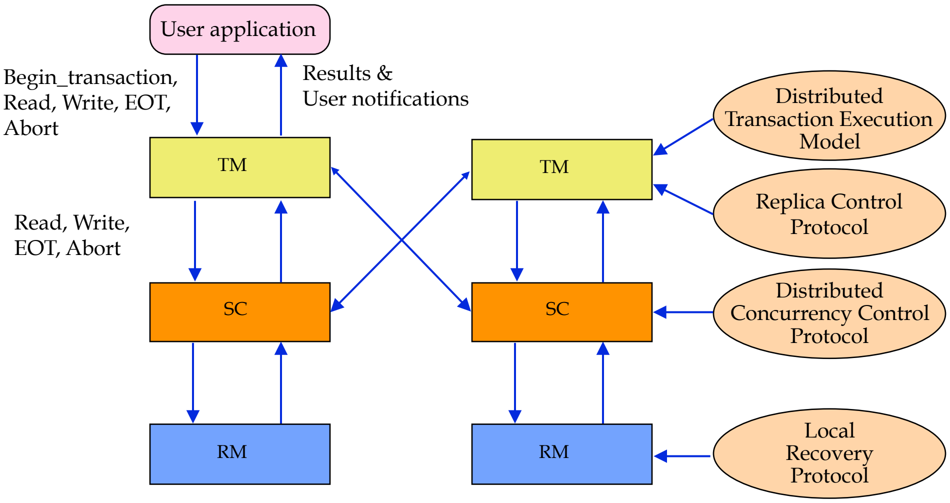
Scheduler
(SC)

Scheduled
Operations

Results

Recovery
Manager
(RM)

Distributed Transaction Execution



User application

Begin_transaction,
Read, Write, EOT,
Abort

Results &
User notifications

TM

TM

Read, Write,
EOT, Abort

SC

SC

RM

RM

Distributed
Transaction Execution
Model

Replica Control
Protocol

Distributed
Concurrency Control
Protocol

Local
Recovery
Protocol

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.
- Anomalies:
  - Lost updates
    - The effects of some transactions are not reflected on the database.
  - Inconsistent retrievals
    - A transaction, if it reads the same data item more than once, should always read the same value.

Isolation Example

- Consider the following two transactions:

T_1:	T_2:
Read(x)	Read(x)
$x \leftarrow x+1$	$x \leftarrow x+1$
Write(x)	Write(x)
Commit	Commit

- Possible execution sequences:

T_1: Read(x)	T_1: Read(x)
T_1: $x \leftarrow x+1$	T_1: $x \leftarrow x+1$
T_1: Write(x)	T_2: Read(x)
T_1: Commit	T_1: Write(x)
T_2: Read(x)	T_2: $x \leftarrow x+1$
T_2: $x \leftarrow x+1$	T_2: Write(x)
T_2: Write(x)	T_1: Commit
T_2: Commit	T_2: Commit

Execution History (or Schedule)

- An order in which the operations of a set of transactions are executed.
- A history (schedule) 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

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

Serial History

- 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 history.

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

$$H = \{\underbrace{W_2(x), W_2(y), R_2(z)}_{T_2}, \underbrace{R_1(x), W_1(x)}_{T_1}, \underbrace{R_3(x), R_3(y), R_3(z)}_{T_3}\}$$

Serializable History

- Transactions execute concurrently, but the net effect of the resulting history upon the database is equivalent to some serial history.
- Equivalent with respect to what?
  - ***Conflict equivalence***: the relative order of execution of the conflicting operations belonging to unaborted transactions in two histories 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 History

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

The following are not conflict equivalent

$H_s=\{W_2(x),W_2(y),R_2(z),R_1(x),W_1(x),R_3(x),R_3(y),R_3(z)\}$

$H_1=\{W_2(x),R_1(x), R_3(x),W_1(x),W_2(y),R_3(y),R_2(z),R_3(z)\}$

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

$H_s=\{W_2(x),W_2(y),R_2(z),R_1(x),W_1(x),R_3(x),R_3(y),R_3(z)\}$

$H_2=\{W_2(x),R_1(x),W_1(x),R_3(x),W_2(y),R_3(y),R_2(z),R_3(z)\}$

Serializability in Distributed DBMS

- Somewhat more involved. Two histories have to be considered:
  - local histories
  - global history
- For global transactions (i.e., global history) to be serializable, two conditions are necessary:
  - Each local history should be serializable.
  - Two conflicting operations should be in the same relative order in all of the local histories where they appear together.

Global Non-serializability

T_1:		T_2:	
	Read(x)		Read(x)
	$x \leftarrow x$-100		Read(y)
	Write(x)		Commit
	Read(y)		
	$y \leftarrow y$+100		
	Write(y)		
	Commit		

- x stored at Site 1, y stored at Site 2
- LH_1, LH_2 are individually serializable (in fact serial), but the two transactions are not globally serializable.

$$LH_1=\{R_1(x),W_1(x), R_2(x)\}$$

$$LH_2=\{R_2(y), R_1(y),W_1(y)\}$$

Concurrency Control Algorithms

- Pessimistic
  - Two-Phase Locking-based (2PL)
    - Centralized (primary site) 2PL
    - Primary copy 2PL
    - Distributed 2PL
  - Timestamp Ordering (TO)
    - Basic TO
    - Multiversion TO
    - Conservative TO
  - Hybrid
- Optimistic
  - Locking-based
  - Timestamp ordering-based

Locking-Based Algorithms

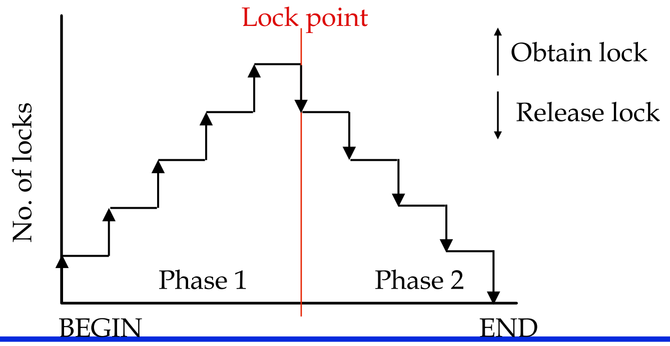
- Transactions indicate their intentions by requesting locks from the scheduler (called lock manager).
- Locks are either read lock (*rl*) [also called shared lock] or write lock (*wl*) [also called exclusive lock]
- Read locks and write locks conflict (because Read and Write operations are incompatible

	rl	*wl*
rl	yes	no
wl	no	no

- Locking works nicely to allow concurrent processing of transactions.

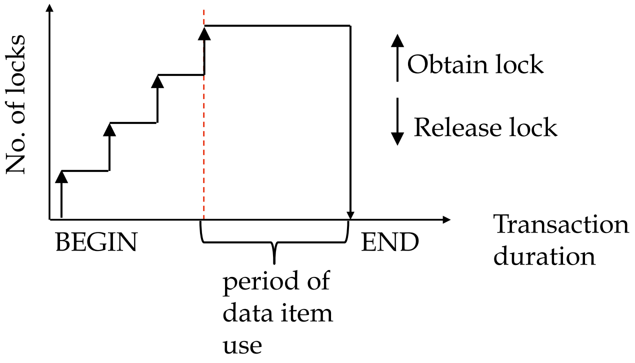
Two-Phase Locking (2PL)

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.



No. of locks

Obtain lock

Release lock

BEGIN

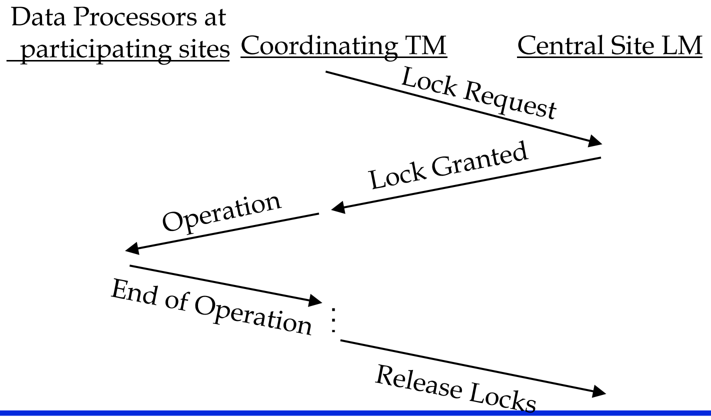
END

Transaction duration

period of data item use

Centralized 2PL

- There is only one 2PL scheduler in the distributed system.
- Lock requests are issued to the central scheduler.



Data Processors at participating sites

Coordinating TM

Central Site LM

Lock Request

Lock Granted

Operation

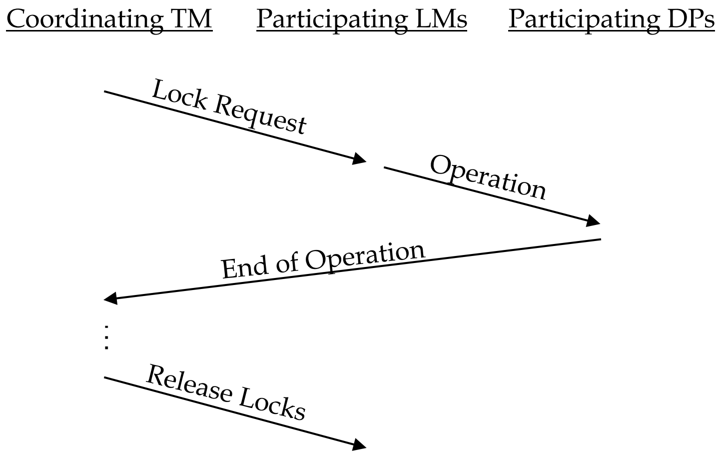
End of Operation

Release Locks

Distributed 2PL

- 2PL schedulers are placed at each site. Each scheduler handles lock requests for data at that site.
- A transaction may read any of the replicated copies of item x, by obtaining a read lock on one of the copies of x. Writing into x requires obtaining write locks for all copies of x.

Distributed 2PL Execution



Coordinating TM Participating LMs Participating DPs

Lock Request

Operation

End of Operation

⋮

Release Locks

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 read on x

❹ Conflicting operations are resolved by timestamp order.

Basic T/O:

<u>for $R_i(x)$</u>

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

<u>for $W_i(x)$</u>

```
if $ts(T_i) < rts(x)$ and $ts(T_i) < wts(x)$
then reject $W_i(x)$
else accept $W_i(x)$
$wts(x) \leftarrow ts(T_i)$
```

Conservative Timestamp Ordering

- Basic timestamp ordering tries to execute an operation as soon as it receives it
  - progressive
  - too many restarts since there is no delaying
- Conservative timestamping delays each operation until there is an assurance that it will not be restarted
- Assurance?
  - No other operation with a smaller timestamp can arrive at the scheduler
  - Note that the delay may result in the formation of deadlocks

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

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

Optimistic Concurrency Control Algorithms

Pessimistic execution

Validate Read Compute Write

Optimistic execution

Read Compute Validate Write

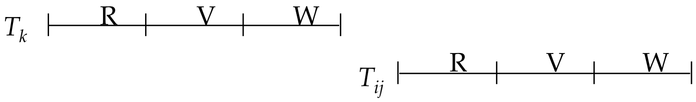
Optimistic Concurrency Control Algorithms

- Transaction execution model: divide into subtransactions each of which execute at a site
  - T_{ij}: transaction T_i that executes at site j
- Transactions run independently at each site until they reach the end of their read phases
- All subtransactions are assigned a timestamp at the end of their read phase
- Validation test performed during validation phase. If one fails, all rejected.

Optimistic CC Validation Test

① If all transactions T_k where $ts(T_k) < ts(T_{ij})$ have completed their write phase before T_{ij} has started its read phase, then validation succeeds

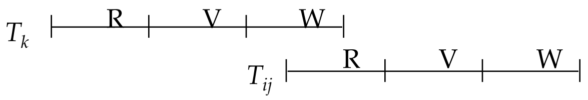
- Transaction executions in serial order



Optimistic CC Validation Test

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

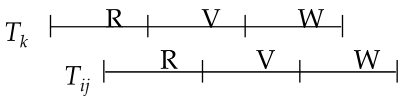
- Read and write phases overlap, but T_{ij} does not read data items written by T_k



Optimistic CC Validation Test

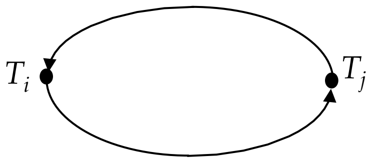
❸ If there is any transaction T_k such that $ts(T_k)< ts(T_{ij})$ and which completes its read phase before T_{ij} completes its read phase, then validation succeeds if $WS(T_k) \cap RS(T_{ij}) = \emptyset$ and $WS(T_k) \cap WS(T_{ij}) = \emptyset$

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



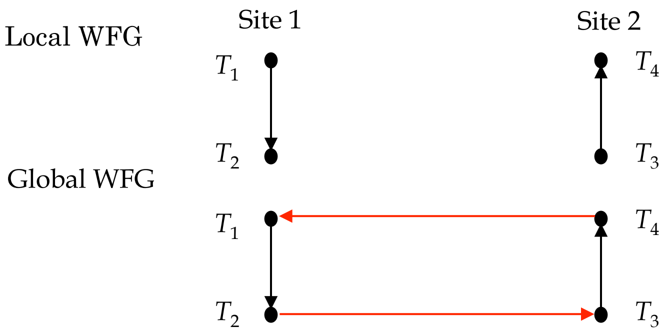
Deadlock

- A transaction is deadlocked if it is blocked and will remain blocked until there is intervention.
- Locking-based CC algorithms may cause deadlocks.
- TO-based algorithms that involve waiting 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.



Local versus Global WFG

Assume T_1 and T_2 run at site 1, T_3 and T_4 run at site 2. Also assume T_3 waits for a lock held by T_4 which waits for a lock held by T_1 which waits for a lock held by T_2 which, in turn, waits for a lock held by T_3.



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 which 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
  - Unsuitability of the scheme in database environment
  - Suitable for systems that have no provisions for undoing processes.
- Evaluation:
  - – Reduced concurrency due to preallocation
  - – Evaluating whether an allocation is safe leads to added overhead.
  - – Difficult to determine (partial order)
  - \+ No transaction rollback or restart is involved.

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 either the data items or the sites and always request locks in that order.
- More attractive than prevention in a database environment.
- Wait-Die/Wound-Wait algorithms

Deadlock Detection

- Transactions are allowed to wait freely.
- Wait-for graphs and cycles.
- Topologies for deadlock detection algorithms
  - Centralized
  - Distributed
  - Hierarchical