Chapter 15 : Concurrency Control

Database System Concepts, 6th Ed.

Chapter 15: Concurrency Control

- Isolation
  - The fundamental properties of a transaction
- When several transactions execute concurrently in the database
  - The isolation property may no longer be preserved
    - So, the system must control the interaction among the concurrent transactions
  - The control is achieved through mechanism called *concurrency control* schemes

Concurrency Control vs. Serializability Tests

- Testing a schedule for serializability after it has executed is a little too late!
- *Goal – To develop concurrency control protocols that will* assure serializability
  - They will generally not examine the precedence graph as it is being created;
  - Instead a protocol will impose a discipline that avoids nonserializable schedules
- Require study of concurrency protocols in Chapter 15.
- *Tests for serializability help understand why a concurrency* control protocol is correct

Chapter 15: Concurrency Control

- Lock-Based Protocols
- Timestamp-Based Protocols
- Validation-Based Protocols
- Multiple Granularity
- Multiversion Schemes
- Insert and Delete Operations
- Concurrency in Index Structures

- Most frequently used schemes
  - Two-Phase Locking
  - Snapshot Isolation

Lock-Based Protocols

- A lock is a mechanism to control concurrent access to a data item
  - To allow MULTIPLE transactions to READ a data item
  - But, limits WRITE access to just ONE transaction at a time
- Every transaction require a lock on data item Q in an appropriate mode depending upon the type of operations it will perform on the data item Q
- Transaction makes Lock requests to concurrency-control manager
- Transaction can proceed only after request is granted

Lock-Based Protocols

- Data items can be locked by transaction in two modes

  1. *Exclusive (X) mode*

     Data item Q can be both <u>read</u> as well as <u>written</u>

     X-lock is requested using **lock-X(Q)** instruction

  2. *Shared (S) mode*

     Data item can only be <u>read</u>

     S-lock is requested using **lock-S(Q)** instruction

- To unlock a data item Q using Unlock**(Q)** instruction

Lock-Based Protocols (Cont.)

- **Lock-compatibility matrix**

	S	X
S	true	false
X	false	false

- A transaction may **be granted a lock on an item if the requested lock is COMPATIBLE with locks already held on the item by other transactions**

Lock-Based Protocols (Cont.)

- **Lock-compatibility matrix**
- **ANY NUMBER of transactions can hold SHARED locks on an item,**
- But if any **transaction HOLDS AD EXCLUSIVE on the item NO OTHER TRANSACTION may hold any lock on the item**
- If a lock cannot be granted,
  - The requesting transaction is made to wait till all incompatible locks held by other transactions have been released,
  - Then only the lock is granted

Lock-Based Protocols

- **Banking Example**
- T1 transfers $50 from Acct B to Acct A
- T2 displays the total money in Acct A and B
- A=$100
- B=$200
- If schedule,
  - T1□T2, then A+B=300
  - T2□T1, then A+B=300

- **Now, add lock information**

Transaction 1	**Transaction 2**
read (B)	read (A)
B=B-50	read (B)
write (B)	Display (A+B)
read (A)	
A=A+50	
write (A)	

Lock-Based Protocols

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- If schedule,
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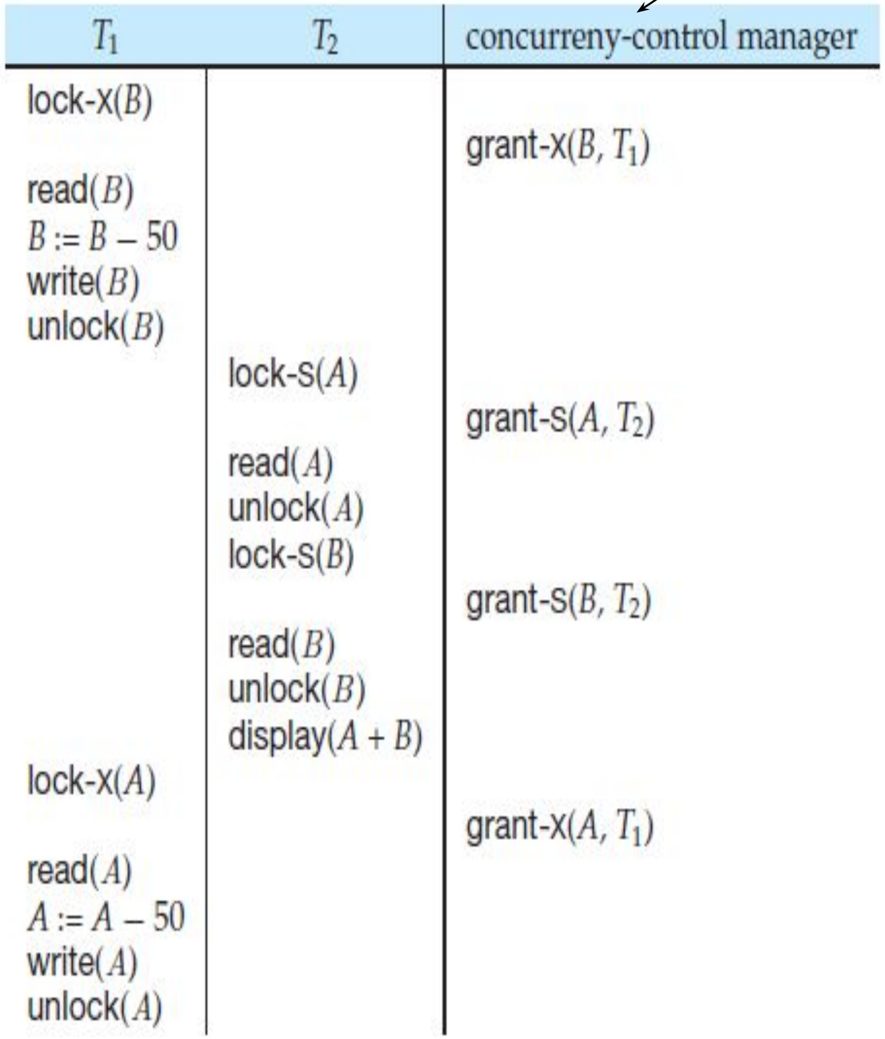
  - T2□T1, then A+B=300

Transaction 1	Transaction 2
lock-X(B)	**lock-S(A)**
read (B)	read (A)
B=B-50	**unlock (A)**
write (B)	**lock-S(B)**
unlock (B)	read (B)
lock-X(A)	**unlock (B)**
read (A)	Display (A+B)
A=A+50	
write (A)	
unlock (A)	

Lock-Based Protocols

- **The transaction making a lock request cannot execute its next action until the concurrency control manager grants the lock**
- Hence, the lock must be granted in the interval of time between the lock-request operation and the following action of the transaction

Shows points at which the concurrency-contro manager grants the locks

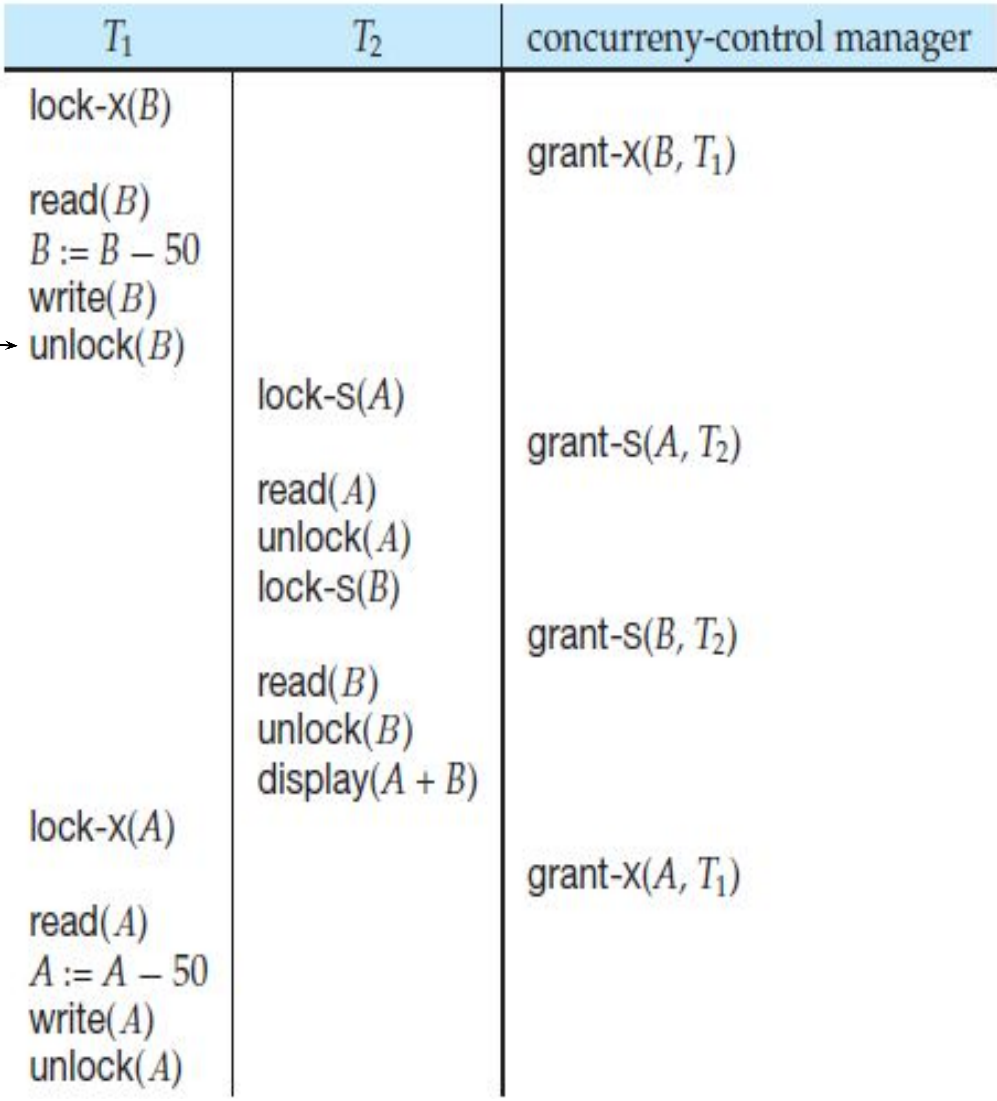


T_1	T_2	concurreny-control manager
lock-X(B)		
		grant-X(B, T_1)
read(B)		
$B := B - 50$		
write(B)		
unlock(B)		
	lock-S(A)	
		grant-S(A, T_2)
	read(A)	
	unlock(A)	
	lock-S(B)	
		grant-S(B, T_2)
	read(B)	
	unlock(B)	
	display($A + B$)	
lock-X(A)		
		grant-X(A, T_1)
read(A)		
$A := A - 50$		
write(A)		
unlock(A)		

Schedule 1

Lock-Based Protocols

- Transactions are executed concurrently
- T2 displays $250
  - As T1 unlocked data item B too early
  - Inconsistent state



T_1	T_2	concurreny-control manager
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		grant-X(B, T_1)
read(B)		
$B := B - 50$		
write(B)		
unlock(B)		
	lock-S(A)	
		grant-S(A, T_2)
	read(A)	
	unlock(A)	
	lock-S(B)	
		grant-S(B, T_2)
	read(B)	
	unlock(B)	
	display($A + B$)	
lock-X(A)		
		grant-X(A, T_1)
read(A)		
$A := A - 50$		
write(A)		
unlock(A)		

Schedule 1

Lock-Based Protocols

- **Banking Example (UNLOCKING DELAYED)**
- T3 transfers $50 from Acct B to Acct A
- T4 displays the total money in Acct A and B
- A=$100
- B=$200
- No possibility of incorrect display of total $250
- Consistent state

Transaction 3	**Transaction 4**
lock-X(B)	
read (B)	
B=B-50	
write (B)	
lock-X(A)	
read (A)	
A=A+50	
write (A)	
unlock (B)	
unlock (A)	
	lock-S(A)
	read (A)
	lock-S(B)
	read (B)
	Display (A+B)
	unlock (A)
	unlock (B)

Pitfalls of Lock-Based Protocols

1. Consider the partial schedule

T_3	T_4
lock-x (B)	
read (B)	
$B := B - 50$	
write (B)	
	lock-s (A)
	read (A)
	lock-s (B)
lock-x (A)	

- Neither T_3 nor T_4 can make progress — executing
  - **lock-S**(B) causes T_4 to wait for T_3 to release its lock on B, while
  - **lock-X**(A) causes T_3 to wait for T_4 to release its lock on A
- Such a situation is called a **deadlock**

Pitfalls of Lock-Based Protocols

- **Solution to deadlock**

T_3	T_4
lock-x (B)	
read (B)	
$B := B - 50$	
write (B)	
	lock-s (A)
	read (A)
	lock-s (B)
lock-x (A)	

  - To handle a deadlock one of the two transactions (T_3 or T_4) must ROLL BACK and release locks of that transaction
- The potential for deadlock exists in most locking protocols

Pitfalls of Lock-Based Protocols (Cont.)

2. **Starvation** is also possible, if concurrency control manager is badly designed
   - For example:
     - A sequence of transactions that each requests a S-lock on the data item and each transactions releases the lock a short while after it is granted, but T_x never gets the X-lock on the data item
       - The Transaction T_x may never make progress, and said to be starved
     - **A transaction may be waiting** for an X-lock on an item, while a **sequence of other transactions request and are granted** an S-lock on the same item
     - The same transaction T_x is repeatedly rolled back due to deadlocks
   - Concurrency control manager can be designed to prevent starvation

Prevent Starvation

- Avoid starvation of transactions by granting locks as shown
  - When a transaction *Ti requests a lock on a data item Q in a particular* mode *M, the concurrency-control manager grants the lock provided that:*

    1. There is no other transaction holding a lock on *Q in a mode that conflicts* with M

    2. There is no other transaction that is waiting for a lock on *Q and that made its lock request before Ti*
  - Thus, a lock request will never get blocked by a lock request that is made later

Lock-Based Protocols (Cont.)

- Example of a transaction performing locking:

```
$T_2$: lock-S(A);
    read (A);
    unlock(A);
    lock-S(B);
    read (B);
    unlock(B);
    display(A+B)
```

- Locking is not sufficient to guarantee serializability
  - if *A* and *B* get updated in-between the read of *A* and *B*, the displayed sum would be wrong
- A **locking protocol** is a set of rules followed by all transactions while requesting and releasing locks

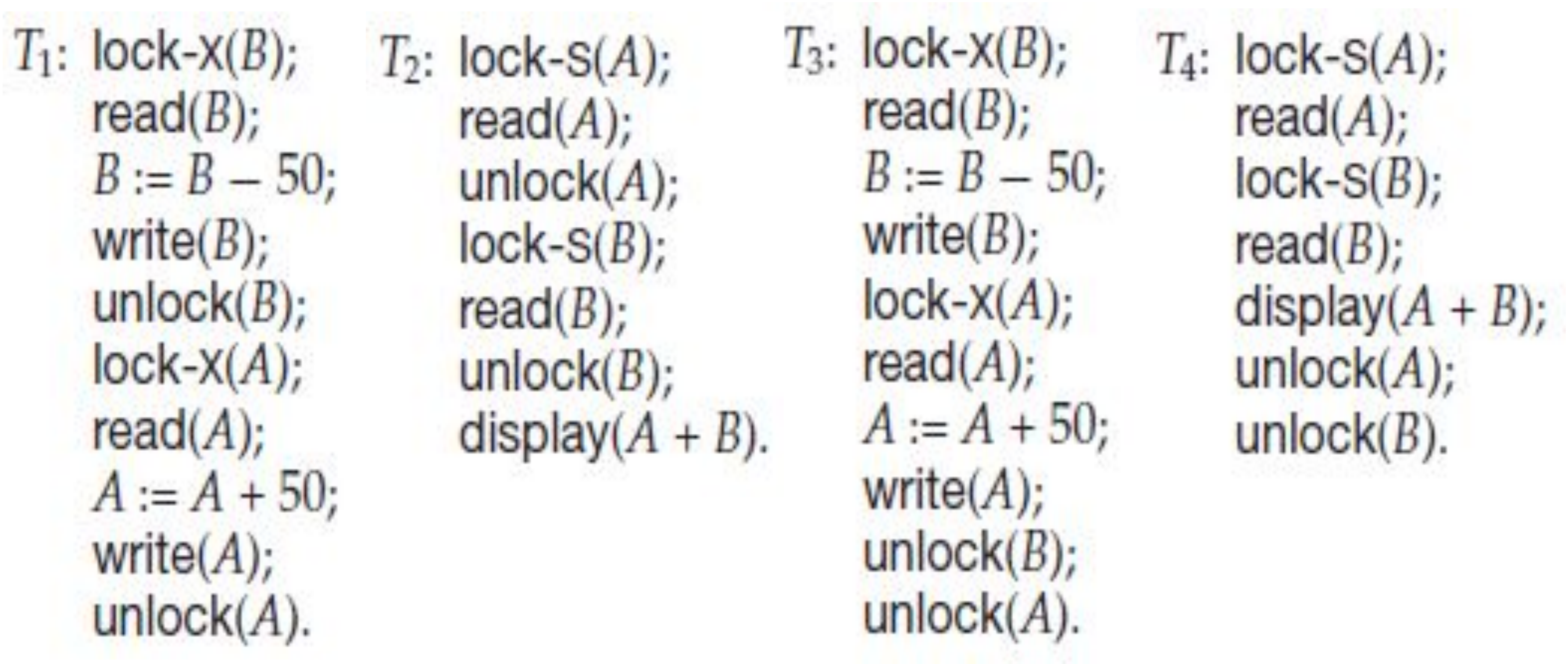
Lock-Based Protocols (Cont.)

- Locking protocols
  - Restrict the set of possible schedules
  - The set of all such schedules is a proper subset of all possible serializable schedules
  - Allow only conflict serializable schedule

Two-Phase Locking Protocol

- A protocol which ensures conflict-serializable schedules
- Requires two phases
  - Phase 1: Growing Phase
    - Transaction may **obtain locks**
    - Transaction may not release locks
  - Phase 2: Shrinking Phase
    - Transaction may **release locks**
    - Transaction may not obtain locks

Check Transaction for Two-Phase Locking Property



```
T1: lock-X(B);
    read(B);
    B := B – 50;
    write(B);
    unlock(B);
    lock-X(A);
    read(A);
    A := A + 50;
    write(A);
    unlock(A).
```

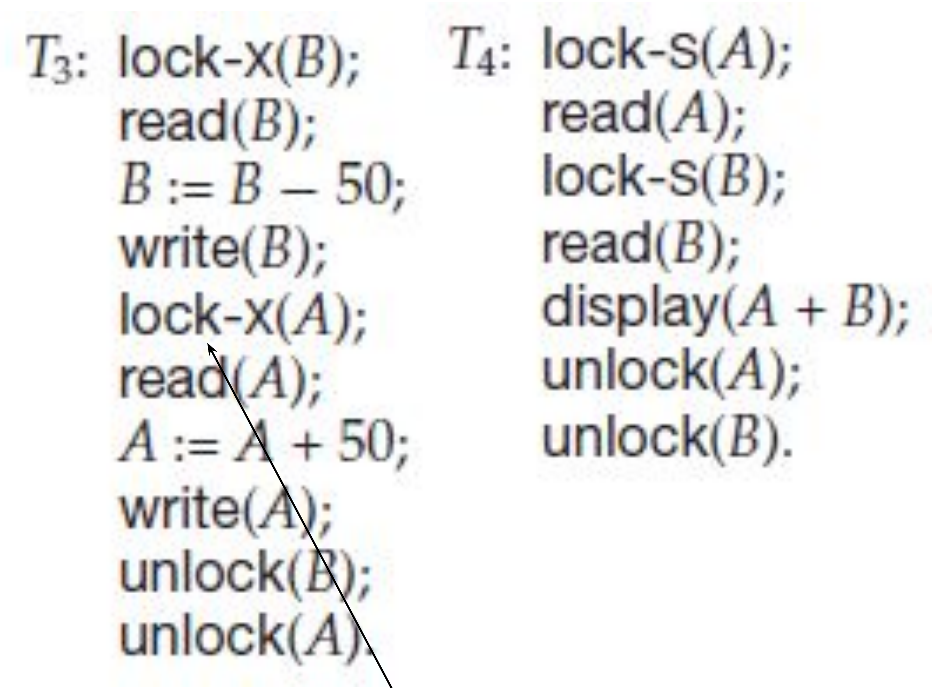
```
T2: lock-S(A);
    read(A);
    unlock(A);
    lock-S(B);
    read(B);
    unlock(B);
    display(A + B).
```

```
T3: lock-X(B);
    read(B);
    B := B – 50;
    write(B);
    lock-X(A);
    read(A);
    A := A + 50;
    write(A);
    unlock(B);
    unlock(A).
```

```
T4: lock-S(A);
    read(A);
    lock-S(B);
    read(B);
    display(A + B);
    unlock(A);
    unlock(B).
```

- *Transactions T1 and T2 are not two phase, here mix of lock and unlock*
- *While,* Transactions ***T3 and T4 are two phase****, as all locks first and then all unlock*
    - *Clear boundary where the transaction has obtained its final lock (the end of its growing phase) is known as* ***lock point (a point of final lock)***

Check Transaction for Two-Phase Locking Property



```
T3: lock-X(B);             T4: lock-S(A);
    read(B);                   read(A);
    B := B – 50;               lock-S(B);
    write(B);                  read(B);
    lock-X(A);                 display(A + B);
    read(A);                   unlock(A);
    A := A + 50;               unlock(B).
    write(A);
    unlock(B);
    unlock(A).
```

- *The unlock instructions do not need* to appear at the end of the transaction
- For example, in the case of transaction *T3,* we could **move the unlock(*B*)** *instruction to **just after the lock-X(A) instruction***, and still retain the two-phase locking property

Two-Phase Locking Protocol

- The protocol assures serializability
  - Can be proved that the transactions can be serialized in the order of their **lock points** (i.e. the point where a transaction acquired its final lock □ the end of its growing phase)
    - 4 Now, transactions can be ordered according to their lock points—this ordering is, in fact, a serializability ordering for the transactions

Two-Phase Locking Protocol

T_3	T_4
lock-x (B)	
read (B)	
$B := B - 50$	
write (B)	
	lock-s (A)
	read (A)
	lock-s (B)
lock-x (A)	

- The protocol assures serializability, BUT NOT ENSURE FREEDOM FROM DEADLOCK

Two-Phase Locking Protocol

- To being serializable schedule, schedules should be cascadeless
- But, cascading rollback may occur

T_5	T_6	T_7
lock-x (A)		
read (A)		
lock-s (B)		
read (B)		
write (A)		
unlock (A)		
	lock-x (A)	
	read (A)	
	write (A)	
	unlock (A)	
		lock-s (A)
		read (A)

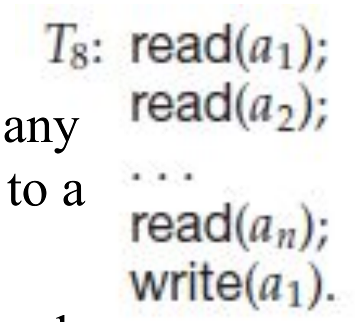
- Here in this schedule, the failure of T_5 after the read(A) step of T_7 leads to cascading rollback of T_6 and T_7

The Two-Phase Locking Protocol (Cont.)

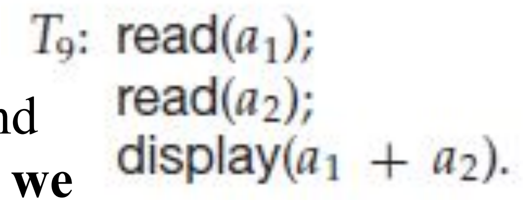
- Pitfalls
  - D*oes not* ensure freedom from deadlocks
  - Cascading roll-back is possible
- Solution to Two-Phase Locking Protocol (Used commercially)
  1. **Strict two-phase locking** is a modified protocol
     - Transaction must hold all its **Exclusive locks** till it commits/aborts
     - Preventing any other transaction from reading the data
  2. **Rigorous two-phase locking** is even stricter
     - Here ***all*** **locks** are held till commit/abort
     - In this protocol transactions can be serialized in the order in which they commit

Lock Conversions

- If, Two-phase locking
  - Then T_8 *must lock* a_1 *in exclusive* mode, therefore, any concurrent execution of both transactions amounts to a serial execution
- However, T_8 *needs an exclusive lock on* a_1 *only at* the end of its execution, when it writes a_1
  - *Thus, if* T_8 *could initially lock* a_1 *in* shared mode, and then could later change the lock to exclusive mode, **we could get more concurrency**, since T_8 *and* T_9 ***could access*** a_1 ***and*** a_2 ***simultaneously***
- Solution
  - A refinement of the basic two-phase locking protocol
    - 4 **Lock conversions**



```
T8: read(a1);
    read(a2);
    . . .
    read(an);
    write(a1).
```



```
T9: read(a1);
    read(a2);
    display(a1 + a2).
```

Lock Conversions

- **A mechanism** for upgrading a shared lock to an exclusive lock, and downgrading an exclusive lock to a shared lock
- Conversion
  - From shared to exclusive modes by **upgrade**, and
  - From exclusive to shared by **downgrade**
- **Lock conversion cannot be** allowed arbitrarily, Rather
  - Upgrading can take place in only the growing phase
  - Downgrading can take place in only the shrinking phase

Lock Conversions

- Two-phase locking with lock conversions:
  - **First Phase:**
    - Can acquire a lock-S on item
    - Can acquire a lock-X on item
    - Can convert a lock-S to a lock-X (upgrade)
  - **Second Phase:**
    - Can release a lock-S
    - Can release a lock-X
    - Can convert a lock-X to a lock-S (downgrade)
- This protocol assures serializability
- But still relies on the programmer to insert the various locking instructions

Lock Conversions

```
T8: read(a1);
    read(a2);
    . . .
    read(an);
    write(a1).

T9: read(a1);
    read(a2);
    display(a1 + a2).
```

T_8	T_9
lock-S(a_1)	
	lock-S(a_1)
lock-S(a_2)	
	lock-S(a_2)
lock-S(a_3)	
lock-S(a_4)	
	unlock(a_1)
	unlock(a_2)
lock-S(a_n)	
upgrade(a_1)	

Incomplete Schedule with lock conversion

- *TransactionsT_8 and T_9 can run concurrently under* the refined two-phase locking protocol (here shown only some of the locking instructions)
  - A transaction attempting to upgrade a lock on an item *Q may* be forced to wait
    - 4 **Enforced wait** occurs if *Q is currently locked by another* transaction in shared mode (T_8 last line in schedule)

Lock Conversions

- Like the two-phase locking protocol, two-phase locking with lock conversion generates
  - Only conflict-serializable schedules
    - Transactions can be serialized by their lock points
- If exclusive locks are held until the end of the transaction
  - Then, the schedules are cascadeless

Automatic Acquisition of Locks

- A transaction T_i issues the standard read/write instruction, without explicit locking calls
- The operation **read**(D) is processed as:

```
if $T_i$ has a lock on $D$
  then
      read($D$)
  else begin
        if necessary wait until no other transaction has a lock-X on $D$
            grant $T_i$ a lock-S on $D$;
        read($D$)
      end
```

Automatic Acquisition of Locks (Cont.)

- The operation **write**(D) is processed as:

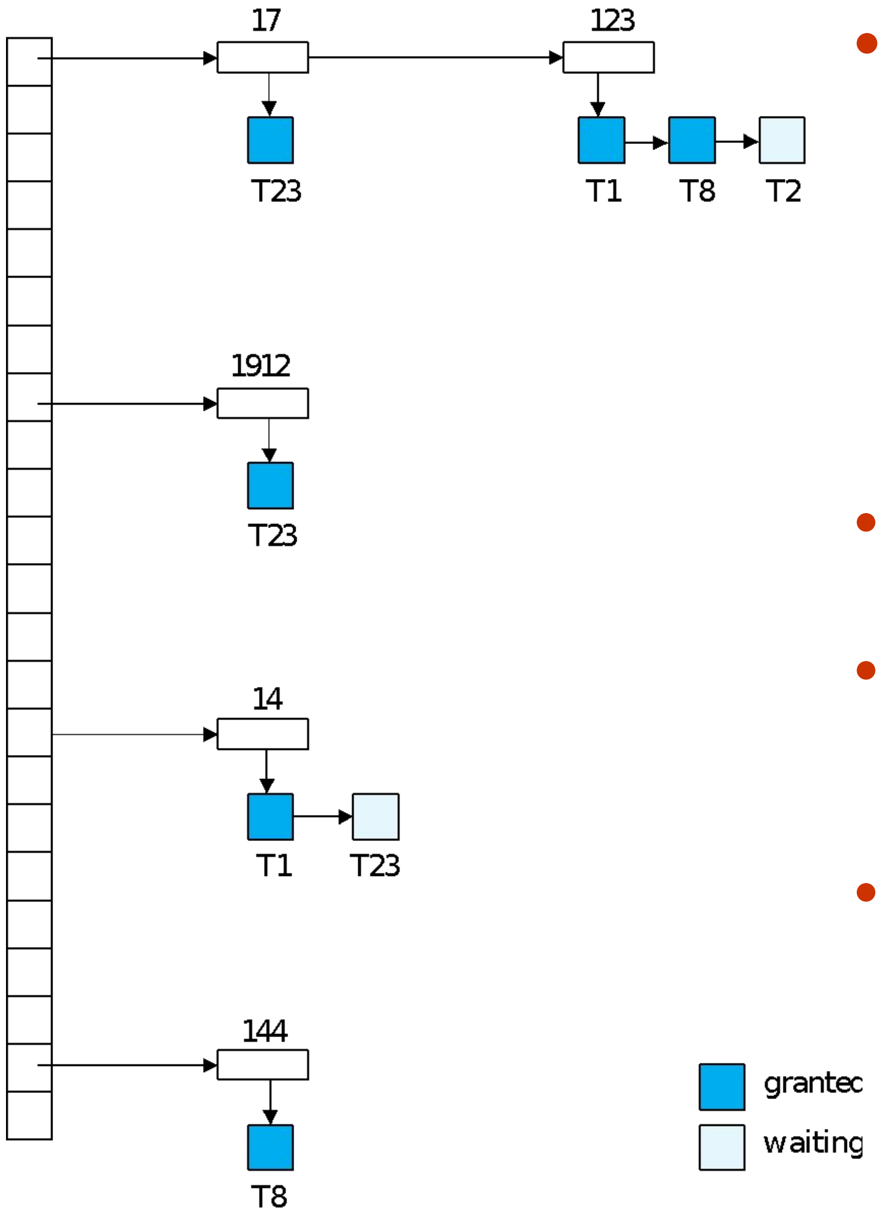
```
if $T_i$ has a  lock-X on $D$
   then
     write($D$)
  else begin
      if necessary wait until no other trans. has any lock on $D$,
      if $T_i$ has a lock-S on $D$
           then
              upgrade lock on $D$  to lock-X
          else
              grant $T_i$ a lock-X on $D$
    write($D$)
    end;
```

- **All locks are released after commit or abort**

Implementation of Locking

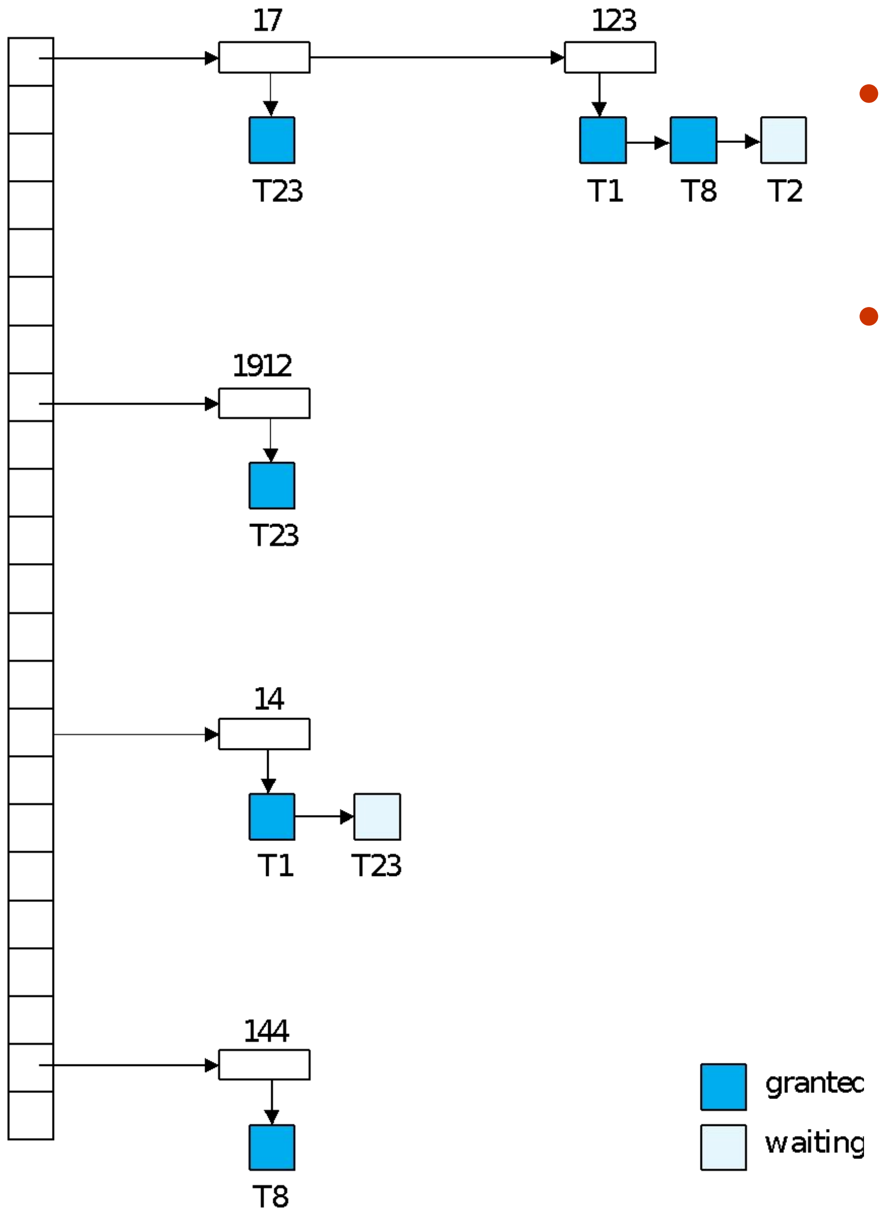
- **Lock manager** can be implemented as a separate process to which transactions send lock and unlock requests
  - It replies, to a lock request by sending
    - A lock grant messages
    - A message asking the transaction to roll back (in case of a deadlock)
  - The requesting transaction waits until its request is answered
  - It maintains a data-structure called a **lock table** to record granted locks and pending requests

Lock Table



- Implemented as an **in-memory hash table indexed on the name of the data item being locked**
  - Data item maintains **link list of transaction record**, one for each request, **in the order in which the requests arrived**
- Data Items
  - 17, 1912, 14, 144 and 123
- Colored rectangles
  - Dark indicate granted locks
  - Light indicate waiting requests
- It also **records the type of lock** granted or requested (here not shown)

Lock Table



- Example: **Transaction T23** has been
  - Granted locks on items 1912 and 17
  - Waiting for a lock on item 14
- When **lock request arrives**

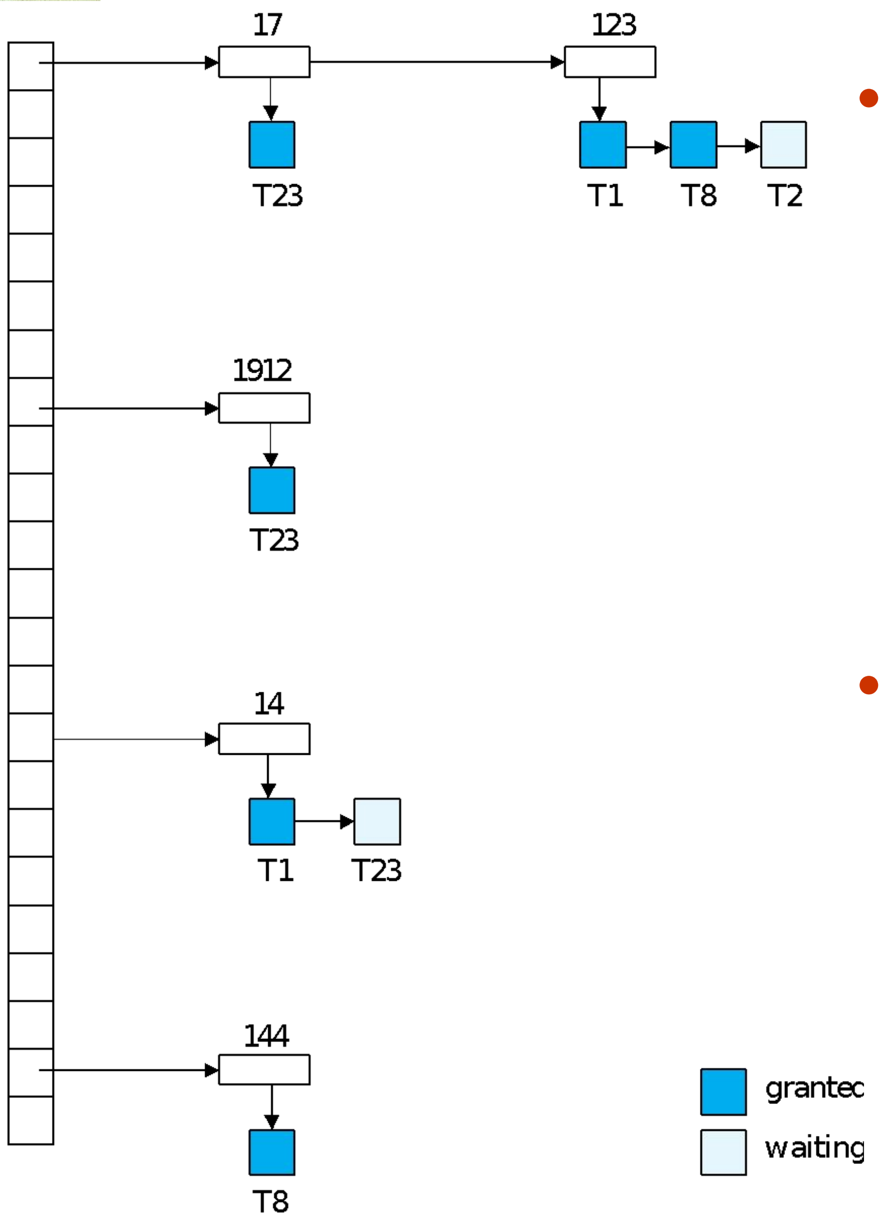
  Step 1. if link list is present

  - Adds a record to the end of the link list queue of requests for the data item,
  - **OR** creates a new link list

  Step 2. Either Grants,

  - If not currently locked, or If it is compatible with all earlier locks and ALL EARLIER REQUESTS HAVE BEEN GRANTED
  - **OR** Waits

Lock Table



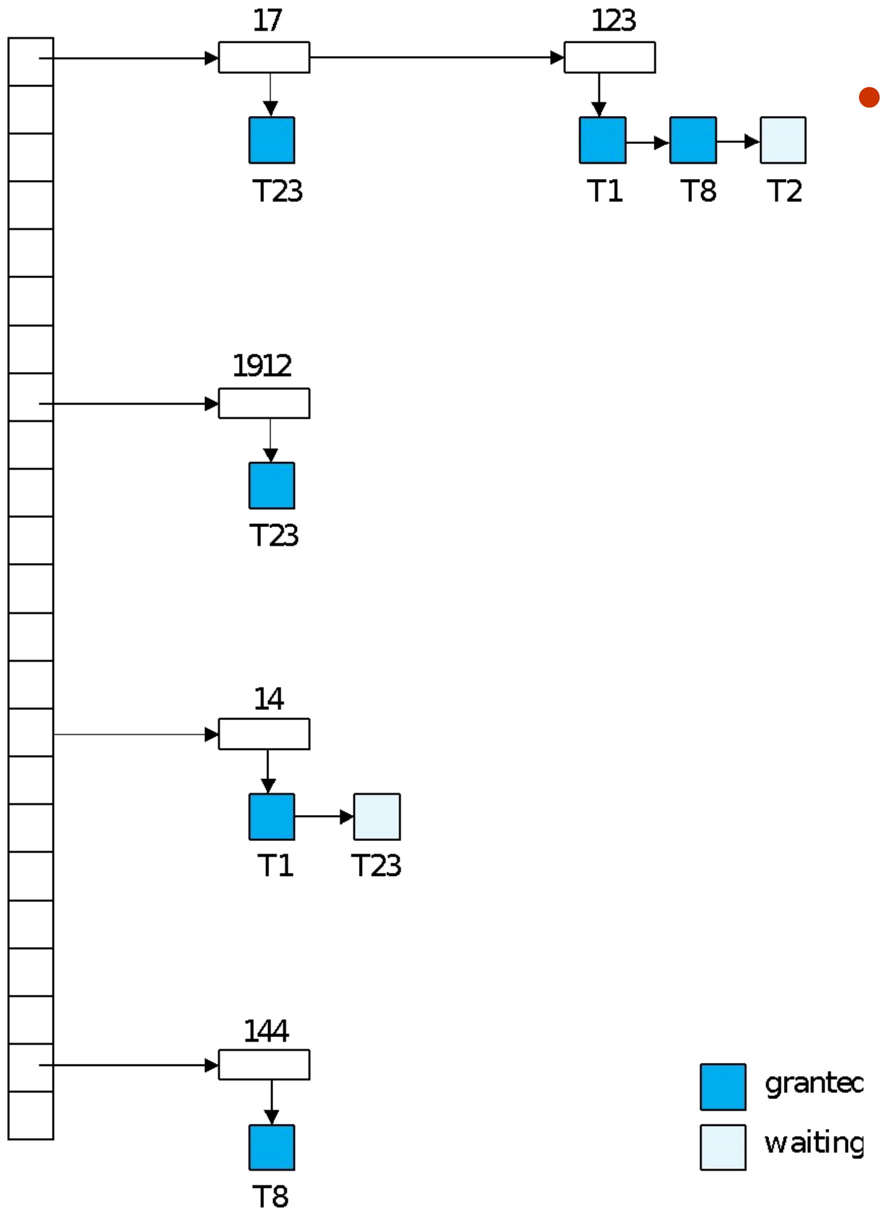
- When **unlock request arrives**

  Step 1. Deletes the record for that data item in the linked list corresponding to that transaction

  Step 2. Also it checks, following requests are checked to see if they can now be granted. If it can, grants the request and process the record following it and so on

- If transaction **aborts**
  - Deletes all waiting or granted requests of the transaction
  - Lock manager may keep a list of locks held by each transaction, to implement this efficiently (that helps in Recovery Ch. 16))

Lock Table

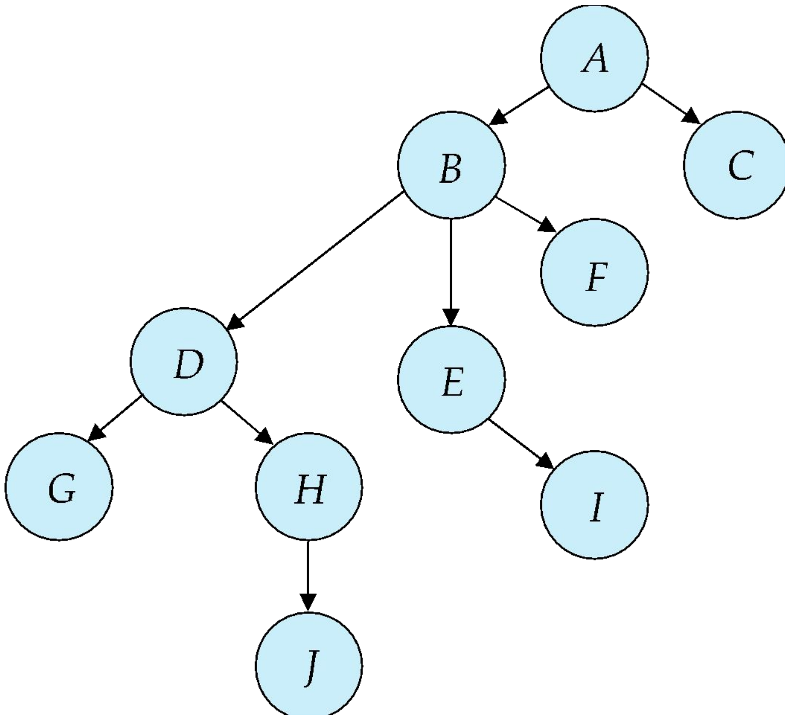


- Advantages
  - Freedom from starvation for lock requests
    - As request can never be granted while a request received earlier is waiting to be granted
  - Deadlock can occur
    - But, Deadlock can be resolved (later section)

Graph-Based Protocols

- An alternative to two-phase locking
- Based on PRIOR KNOWLEDGE
  - About the order in which the database items will be accessed
- Impose a partial ordering $\rightarrow$ on the set **D** = $\{d_1, d_2, \ldots, d_h\}$ of all data items
  - If $d_i \rightarrow d_j$ then any transaction accessing both d_i and d_j must access d_i before accessing d_j
  - Implies that the set **D** may now be viewed as a directed acyclic graph, called a ***database graph***
    - 4 **Considering Graphs as Rooted Trees**
- A simple kind of graph protocol
  - The ***tree-protocol***
    - 4 Considering *o*nly **exclusive locks (lock-x)**

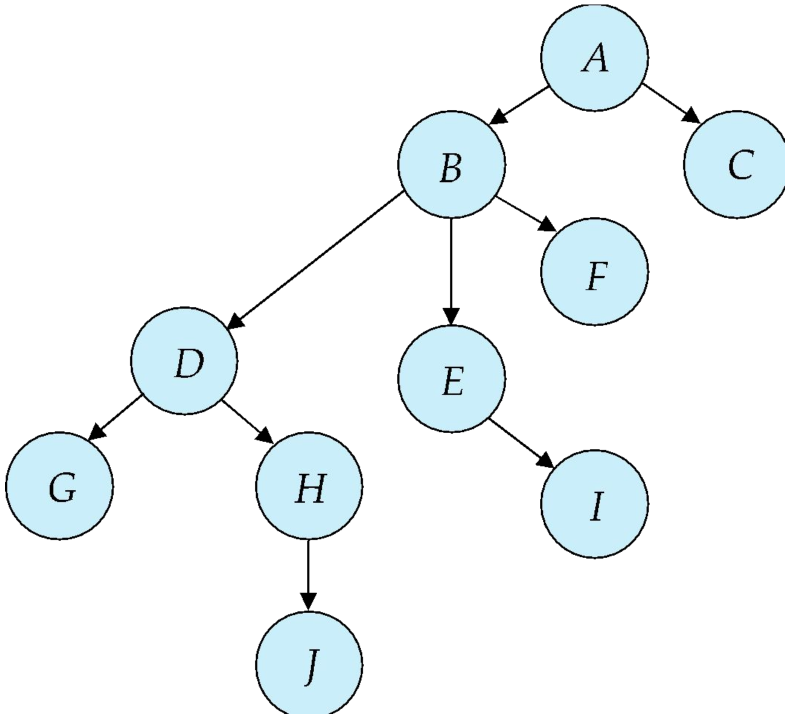
Tree Protocol



- Transaction T_i can lock a data item by following rules:

1. The FIRST **lock** by T_i may be on ANY data item
2. Subsequently, a data item Q can be locked by T_i only **if the parent of *Q* is currently locked by *T*$_i$**
3. Data items may be **unlocked at any time**
4. A data item that has been locked and unlocked by T_i **cannot subsequently be relocked** by T_i

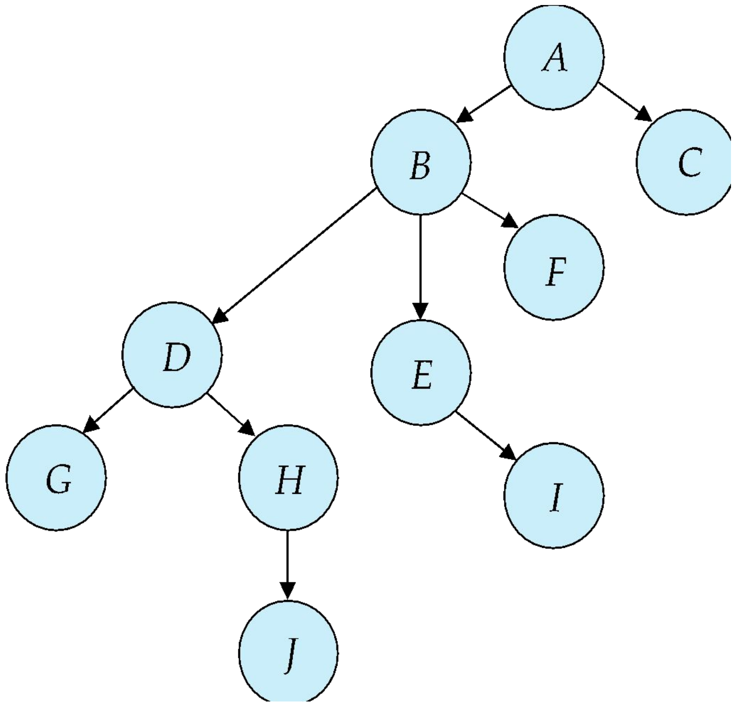
Tree Protocol



- Four Transactions
  - T_{10} : lock-x(B), lock-x(E), lock-x(D), unlock(B), unlock(E), lock-x(G), unlock(D), unlock (G)
  - T_{11} : lock-x(D), lock-x(H), unlock(D), unlock (H)
  - T_{12} : lock-x(B), lock-x(E), unlock(E), unlock(B)
  - T_{13} : lock-x(D), lock-x(H), unlock(D), unlock (H)

Tree Protocol

Serialized Schedule



T_{10}	T_{11}	T_{12}	T_{13}
lock-x (*B*)			
	lock-x (*D*)		
	lock-x (*H*)		
	unlock (*D*)		
lock-x (*E*)			
lock-x (*D*)			
unlock (*B*)			
unlock (*E*)			
		lock-x (*B*)	
		lock-x (*E*)	
	unlock (*H*)		
lock-x (*G*)			
unlock (*D*)			
			lock-x (*D*)
			lock-x (*H*)
			unlock (*D*)
			unlock (*H*)
		unlock (*E*)	
		unlock (*B*)	
unlock (*G*)			

- Transaction T_{10} holds locks on two disjoint subtrees

Graph-Based Protocols (Cont.)

- Tree Protocol
  - Ensures conflict serializability
  - Advantages over two-phase locking
    - Free from deadlock, so no rollbacks are required
    - Unlocking may occur earlier
      - Leads to shorter waiting times
      - Increases concurrency

Graph-Based Protocols (Cont.)

- Tree Protocol Drawbacks
  - Transactions may have to lock data items that they do not access
    - **Increased locking overhead**, and **additional waiting time**
    - **Potential decrease in concurrency**
  - Protocol does not guarantee recoverable or cascadelessness schedules
    - To achieve this, protocol can be modified by not permitting x-lock until the end of transaction
      - But, that reduces concurrency
    - To achieve recoverability, need to introduce **commit dependencies**

Graph-Based Protocols (Cont.)

- **Commit dependencies**
  - For each data item with an uncommitted write, record which transaction performed the last write to the data item
  - When transaction T_i reads uncommitted data, record the commit dependency of T_i transaction that performed the last write to the data item
  - Transaction T_i is not permitted to commit until the commit of all transactions on which it has a commit dependency
  - If any of these transactions aborts, T_i must also be aborted

Deadlock Handling

- Consider the following two transactions:

  T_1: write (X) write(Y) T_2: write(Y) write(X)

- Schedule with deadlock

T_1	T_2
lock-X on A	
write (A)	
	lock-X on B
	write (B)
	wait for **lock-X** on A
wait for **lock-X** on B	

- System is deadlocked if there is a set of transactions such that every transaction in the set is **waiting for another transaction in the set**

Deadlock Handling Methods

1. Deadlock Prevention

- Ensures that the system will *never* enter into a deadlock state

2. Deadlock Detection and Recovery

- Allow the system to enter a deadlock state and then try to recover

- Utilize, If the probability that the system would enter a deadlock state,
  - Relatively high
    - Deadlock Prevention
  - Low
    - Deadlock Detection and Recovery

Deadlock Prevention

1. ***Deadlock Prevention Schemes based on***
   - A. The **ordering of lock** requests or all locks to be acquired together
   - B. Using transaction **rollback** instead of waiting for a lock

Deadlock Prevention

A. Deadlock Prevention Schemes based on ordering and all locks together

- Impose partial ordering of all data items and require that a transaction can **lock data items only in the order** specified by the partial order (graph-based protocol)
  - 4 Disadvantages
    - Transactions may have to lock data items that they do not access and thus **increased locking overhead**, additional waiting time and decrease in concurrency
    - Protocol does not guarantee recoverable or cascadelessness schedules

Deadlock Prevention

A. ***Deadlock Prevention Schemes based on ordering and all locks together***

- Require that each transaction locks all its data items before it begins execution (**predeclaration**)
  - Disadvantages
    - Before the transaction begins, it is **hard to predict, what data items need to be locked**
    - Data item utilization may be very low, as many of data items may be locked but **unused for a long time**

Deadlock Prevention

B. Deadlock Prevention Schemes using Rollbacks

- Uses the concept of **Preemption**
  - When a transaction Tx requests a lock that transaction Ti holds, the lock granted to Ti may be preempted by rolling back of Ti and granting of the lock to Tx
  - To decide whether to roll back or wait, assigns transaction timestamp based on a
    1. Counter

       Time stamp is the value of the counter when the transaction enters the system

       Incremented after a new timestamp has been assigned
    2. System clock

       Value of the clock when the transaction enters the system

Deadlock Prevention

B. Deadlock Prevention Schemes using Rollbacks

- If the transaction is rollback, it retains the old timestamp when restarted
- Schemes
  - **wait-die and wound-wait**

More Deadlock Prevention Strategies

- Transaction timestamp based schemes for the deadlock prevention
  - **wait-die** scheme — non-preemptive
    - Allows the **older transaction to wait but kills the younger one**
    - If $TS(T_i) < TS(T_j)$: T_i is older than T_j − then, T_i is allowed to **wait**
      - Older transaction may wait for younger one to release data item
    - If $TS(T_i) > TS(t_j)$: T_i is younger than T_j − then T_i **die**s and T_i is restarted later with a random delay but with the same timestamp
      - Younger transactions never wait for older ones; they are rolled back instead
    - Transaction may die several times before acquiring needed data item

More Deadlock Prevention Strategies

- Transaction timestamp based schemes for the deadlock prevention
  - **wait-die** scheme — non-preemptive
    - 4 Example
    - 4 Transaction T_{22}, T_{23}, T_{24} have time-stamps 5, 10 and 15 respectively
      - (5 is older timestamp, 15 younger timestamp)
      - If T_{22} requests a data item held by T_{23} then T_{22} will wait
      - If T_{24} requests a data item held by T_{23}, then T_{24} will be rolled back

More Deadlock Prevention Strategies

- Transaction timestamp based schemes for the deadlock prevention
  - **wound-wait** scheme — preemptive
    - Older transaction *wounds* (forces to abort or release the item by rollback) of younger transaction instead of waiting for it
    - If $TS(T_i) < TS(T_j)$, then
      - T_i forces T_j to be rolled back − that is T_i **wound**s T_j
      - T_j is restarted later with a random delay but with the same timestamp
    - Younger transactions may wait for older ones
    - If $TS(T_i) > TS(T_j)$, then T_i is forced to **wait** until the data item is available

More Deadlock Prevention Strategies

- Transaction timestamp based schemes for the deadlock prevention
  - **wound-wait** scheme — preemptive
    - 4 Example
    - 4 Transactions T_{22}, T_{23}, T_{24} have time-stamps 5, 10 and 15 respectively
      - If T_{22} requests a data item held by T_{23}, then data item will be preempted from T_{23} and T_{23} will be rolled back
      - If T_{24} requests a data item held by T_{23}, then T_{24} will wait

Deadlock prevention (Cont.)

- **Time-stamp based Schemes**
  - Wait-Die „
    - Wait: If Ti is older than Tj, then Ti waits
    - Die: If Ti is younger than Tj, then abort Ti
  - Wound-Wait „
    - Wound: If Ti is older than Tj, then abort Tj
    - Wait: If Ti is younger than Tj, then Ti waits
  - Rolled back transactions are restarted with its original timestamp
  - Older transactions thus have precedence over newer ones, and starvation is hence avoided

Deadlock prevention (Cont.)

- Timeout-Based Schemes
  - A transaction waits for a lock only for a specified amount of time After that, the wait times out and the transaction is rolled back
    - Thus deadlocks are not possible
  - Simple to implement; but starvation is possible
  - Also difficult to determine good value of the timeout interval

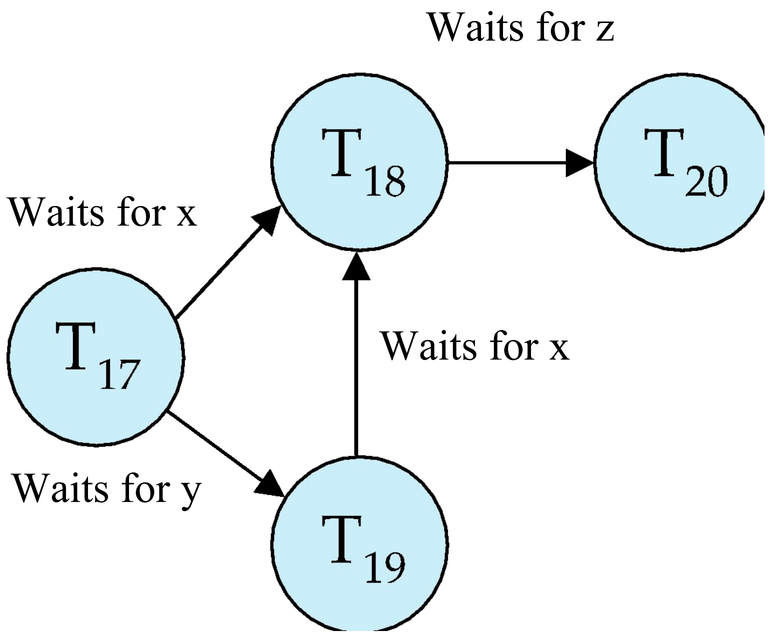
Deadlock Detection & Recovery

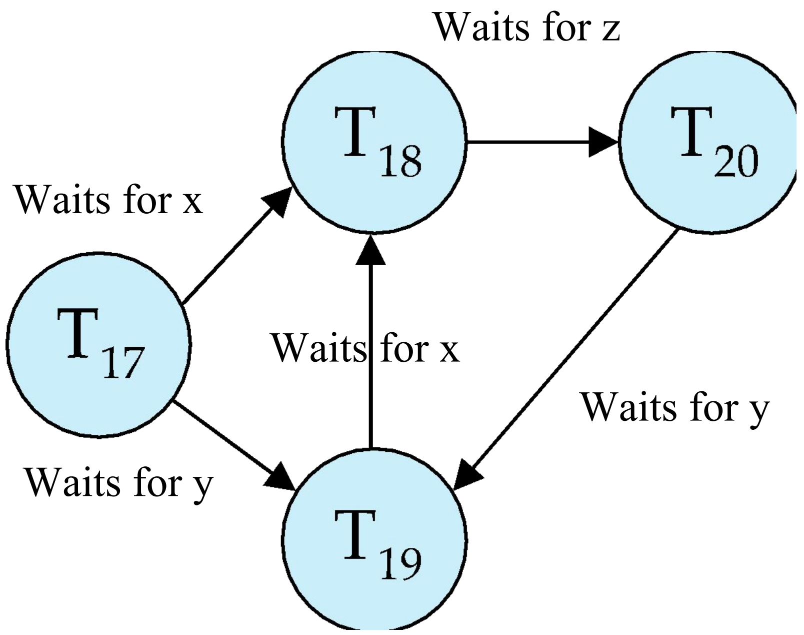
- Aborting a transaction is not always a practical approach
- Instead, deadlock avoidance mechanisms can be used to detect any deadlock situation in advance
  - Method "wait-for graph“
    - Suitable for only those systems where transactions are lightweight having fewer instances of resource
    - In a bulky system, deadlock prevention techniques may work well

Deadlock Detection

- ***wait-for* graph**
  - Consists of a pair $G = (V,E)$,
    - V is a set of vertices (all the transactions in the system)
    - E is a set of edges; each element is an ordered pair $T_i \rightarrow T_j$
  - If $T_i \rightarrow T_j$ is in E, Directed edge from T_i to T_j,
    - Implying that T_i is waiting for T_j to release a data item
  - When T_i requests a data item currently being held by T_j, then the edge T_i T_j is inserted in the wait-for graph
    - This edge is removed only when T_j is no longer holding a data item needed by T_i
  - The system is in a deadlock state if and only if the wait-for graph has a cycle
    - Must invoke a deadlock-detection algorithm periodically to look for cycles

Deadlock Detection (Cont.)





Wait-for graph without a cycle

Wait-for graph with a cycle

T_{17} waiting for T_{18} and T_{19}
T_{19} waiting for T_{18}
T_{18} waiting for T_{20}

One more, T_{20} waiting for T_{19}
T_{18}, T_{19} and T_{20} are **deadlocked**

Deadlock Recovery

- When deadlock is detected, actions : For the rollback
    1. Selection of a victim -- determine which transaction (made a victim) to rollback to break deadlock with minimum cost factors
        a. How long the transaction has computed, and how much longer the transaction will compute before it completes
        b. How many data items used by the transaction
        c. How many more data items needs for the completion
        d. How many transactions will be involved in rollback

Deadlock Recovery

- When deadlock is detected, actions : For the rollback
  1. Selection of a victim
  2. Rollback -- determine how far to roll back transaction
     - Total rollback: Abort the transaction and then restart it
     - Partial rollback: More effective to roll back transaction only as far as necessary to break deadlock requires to manage extra information
  3. Starvation -- if same transaction is always chosen as victim, not allowing it to complete
     - Pick victim only for finite number of times and use number of rollbacks as cost factor

Multiple Granularity

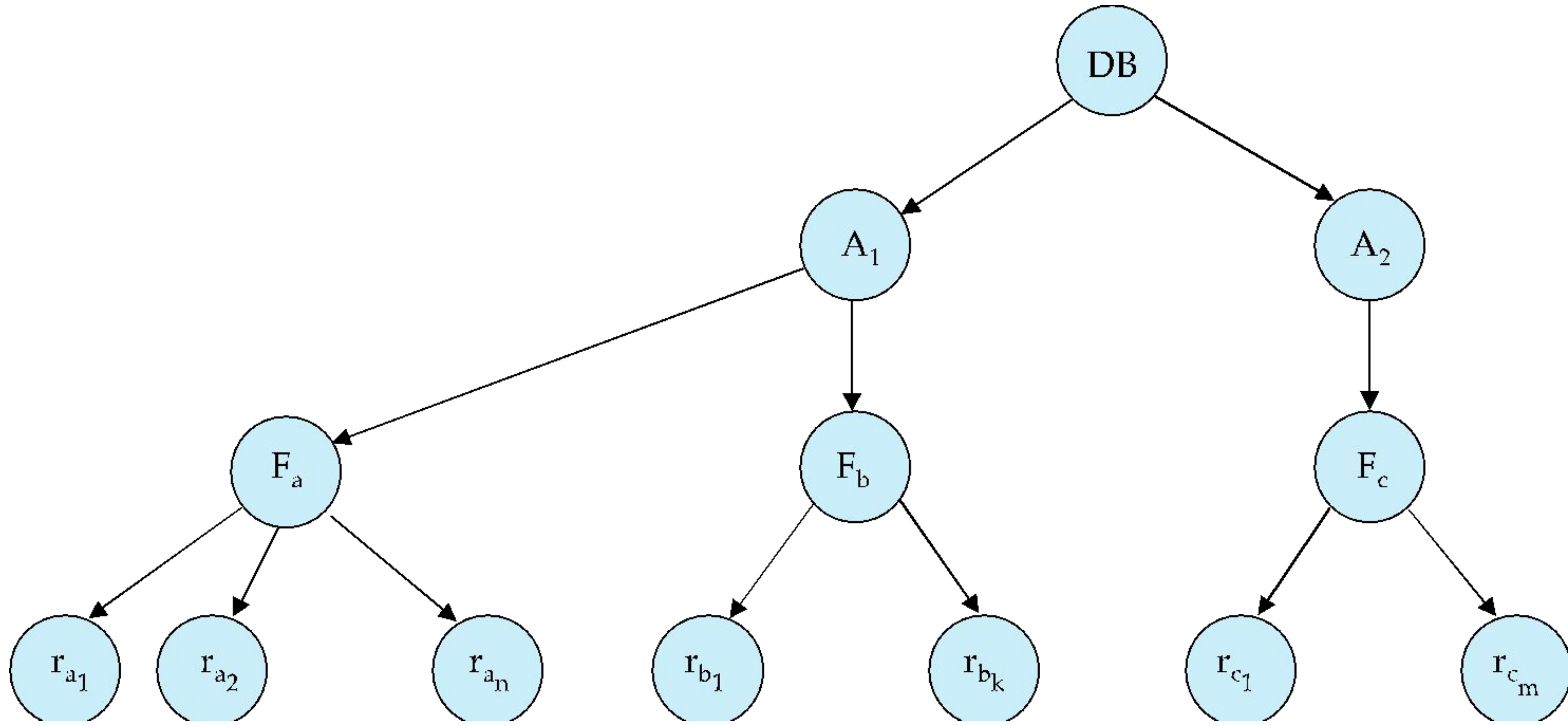
- Till this, used individual data items as the synchronization unit
- Advantageous, if consider groups of several data items and treat them as one individual synchronization unit
  - If locks of all items of database is needed
    - Time consuming, if locking each item individually in the database
    - Better, if using a single lock for the entire database
  - If locks of only few data item is needed
    - Not to lock entire database, otherwise concurrency will lost

Multiple Granularity

- Allow data items to be of various sizes and define a hierarchy of data granularities, where the small granularities are nested within larger ones
- Can be represented graphically as a tree (but don't confuse with tree-locking protocol)
- **When a transaction locks a node in the tree *explicitly*, it *implicitly* locks all the node's descendents in the same mode**

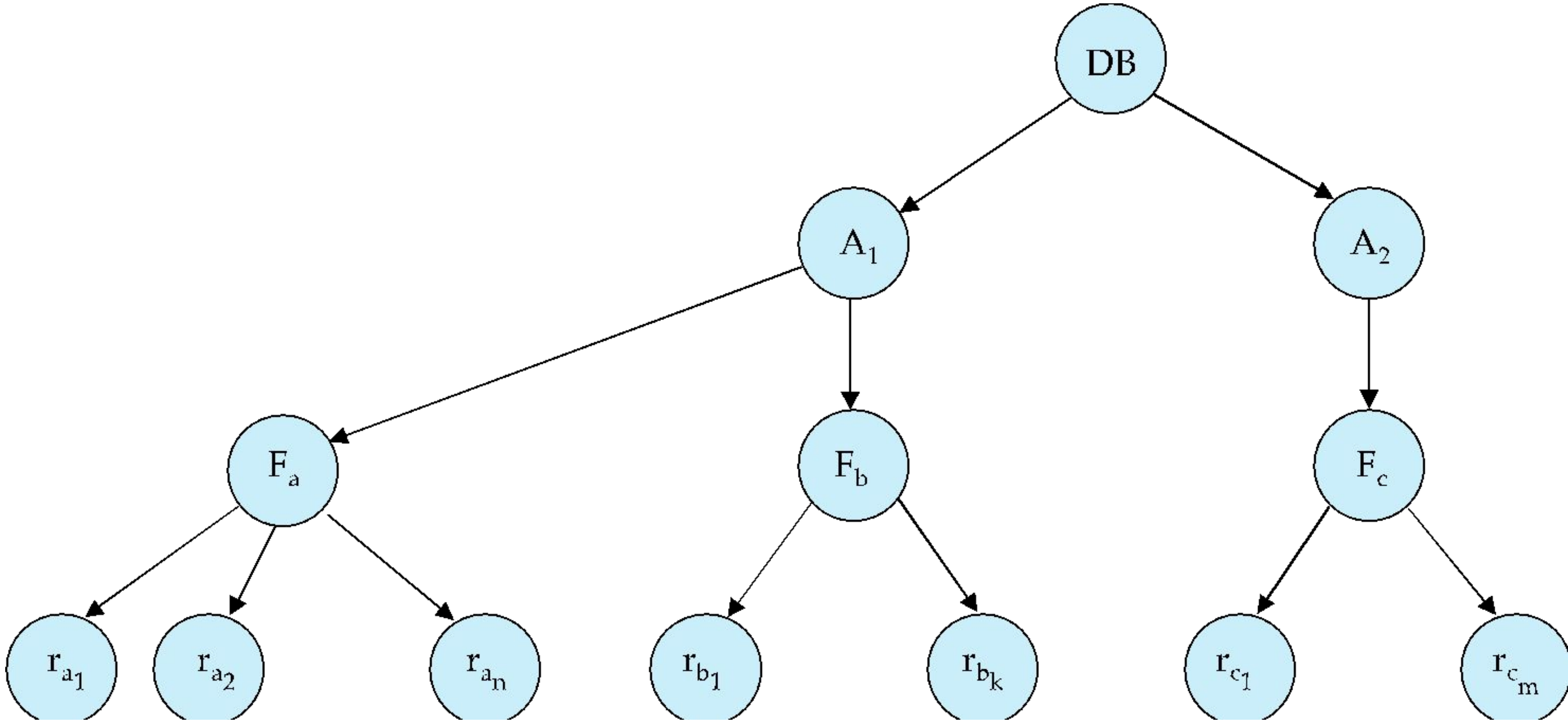
Multiple Granularity

- If transaction Ti gets an explicit lock on file Fc in X-mode
  - Then, it has an implicit lock in X-mode on all the records belonging to that file
  - Does not require to lock the individual records of Fc explicitly



Multiple Granularity

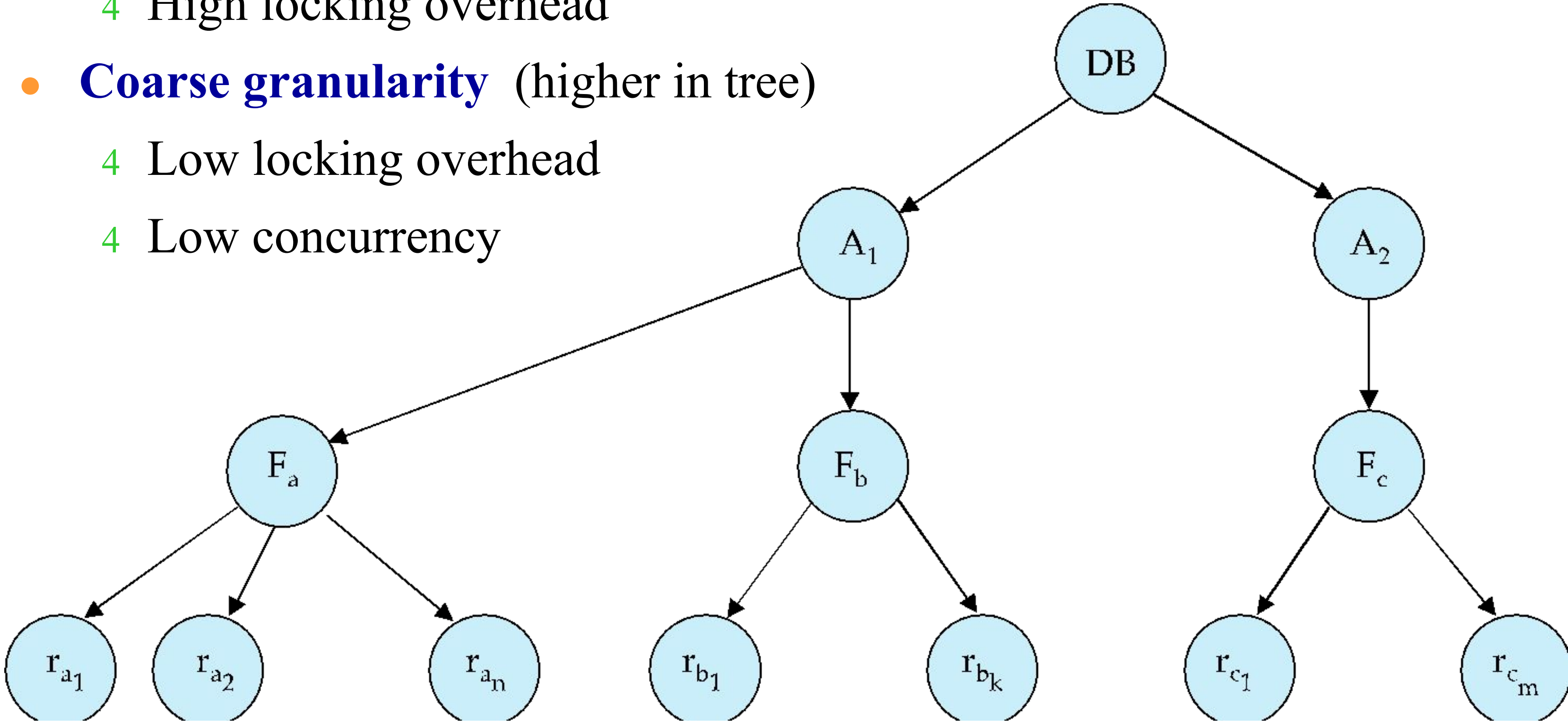
- If Transaction Tj wishes to lock record rb6 of file Fb, since Ti has locked Fb explicitly, it follows that rb6 is also locked (implicitly)
  - Whether to lock or not, Tj must traverse the tree from the root to record rb6. if any node in that path is locked in an incompatible mode, then Tj must be delayed



Multiple Granularity

- Granularity of locking (level in tree where locking is done)
  - **Fine granularity** (lower in tree)
    - High concurrency
    - High locking overhead
  - **Coarse granularity** (higher in tree)
    - Low locking overhead
    - Low concurrency

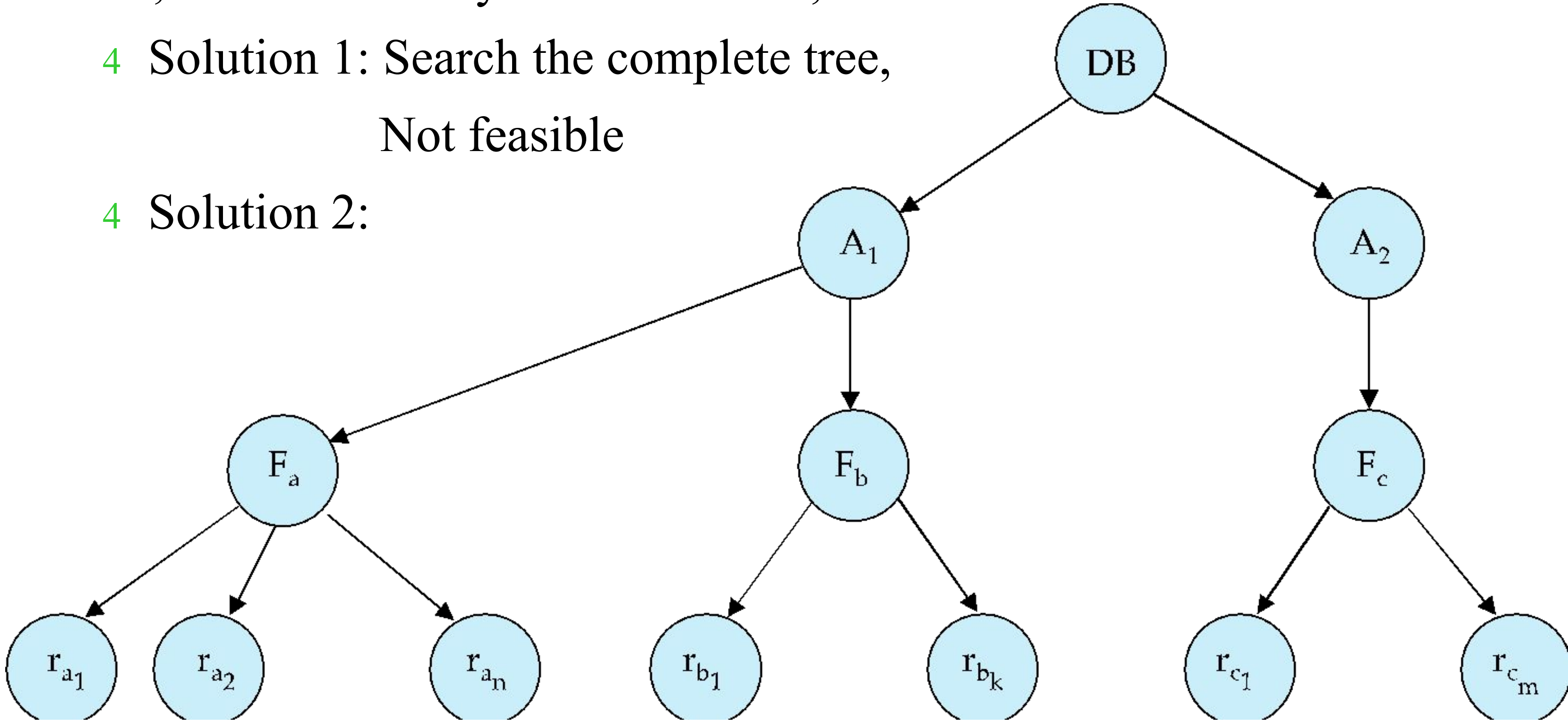
The levels, starting from the coarsest (top) level are
Database, Area , File, Record



Multiple Granularity

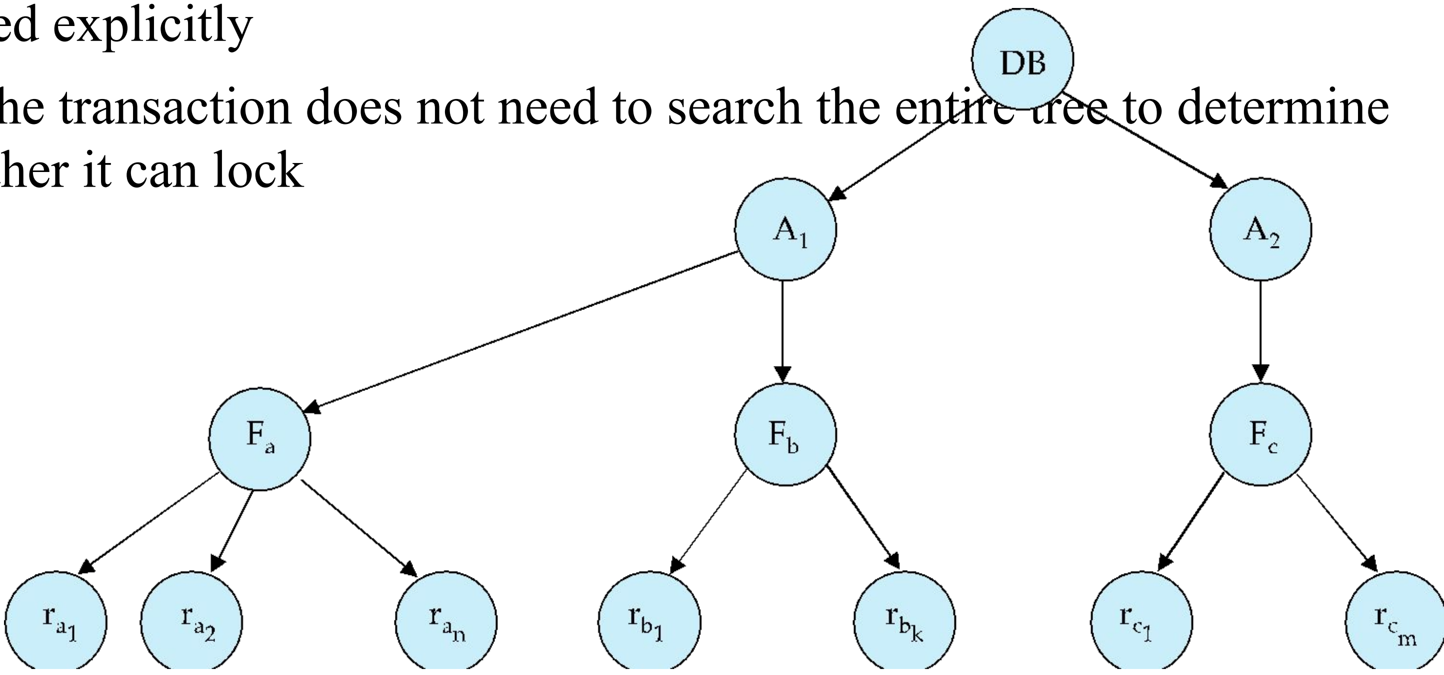
- If Transaction Tk wishes to lock the entire database, it is simply must lock the root of the hierarchy
  - But, Tk should not succeed in locking the root node, since Ti is currently holding a lock on part of the tree (e.g. if, Fb)
  - But, how does the system determine, if the root node can be locked?
    - Solution 1: Search the complete tree,

      Not feasible
    - Solution 2:



Multiple Granularity

- But, how does the system determine, if the root node can be locked?
  - Solution 1: Search the complete tree, Not feasible
  - Solution 2: Introduced New class of lock – INTENSION lock modes
    - If a node is locked in an intention mode, explicit locking is done at a lower level of the tree
    - Intention locks are put on all the ancestors of a node before that node is locked explicitly
    - So, the transaction does not need to search the entire tree to determine whether it can lock



Intention Lock Modes

- In addition to S and X lock modes, there are three additional lock modes with multiple granularity:
  - ***intention-shared*** (IS): Indicates explicit locking at a lower level of the tree but only with shared locks
  - ***intention-exclusive*** (IX): Indicates explicit locking at a lower level with exclusive or shared locks
  - ***shared and intention-exclusive*** (SIX): The subtree rooted by that node is locked explicitly in shared mode and explicit locking is being done at a lower level with exclusive-mode locks
- intention locks allow a higher level node to be locked in S or X mode without having to check all descendent nodes

Compatibility Matrix with Intention Lock Modes

- The compatibility matrix for all lock modes is:

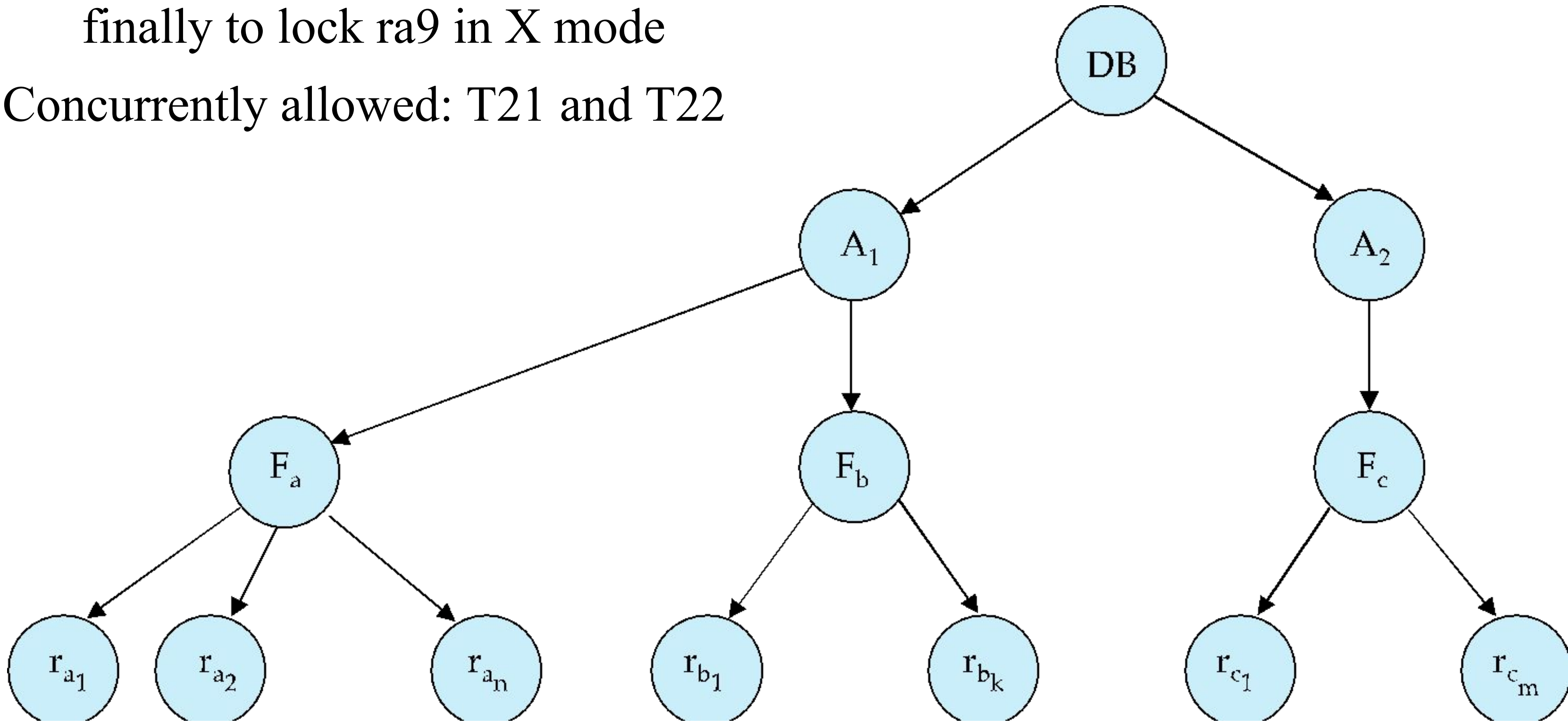
	IS	IX	S	SIX	X
IS	true	true	true	true	false
IX	true	true	false	false	false
S	true	false	true	false	false
SIX	true	false	false	false	false
X	false	false	false	false	false

Multiple Granularity Locking Scheme

- Transaction T_i can lock a node Q, using the following rules:
  1. The lock compatibility matrix must be observed.
  2. The root of the tree must be locked first, and may be locked in any mode.
  3. A node Q can be locked by T_i in S or IS mode only if the parent of Q is currently locked by T_i in either IX or IS mode.
  4. A node Q can be locked by T_i in X, SIX, or IX mode only if the parent of Q is currently locked by T_i in either IX or SIX mode.
  5. T_i can lock a node only if it has not previously unlocked any node (that is, T_i is two-phase).
  6. T_i can unlock a node Q only if none of the children of Q are currently locked by T_i.
- Observe that locks are acquired in root-to-leaf order, whereas they are released in leaf-to-root order.
- **Lock granularity escalation**: in case there are too many locks at a particular level, switch to higher granularity S or X lock

Intention Lock Modes

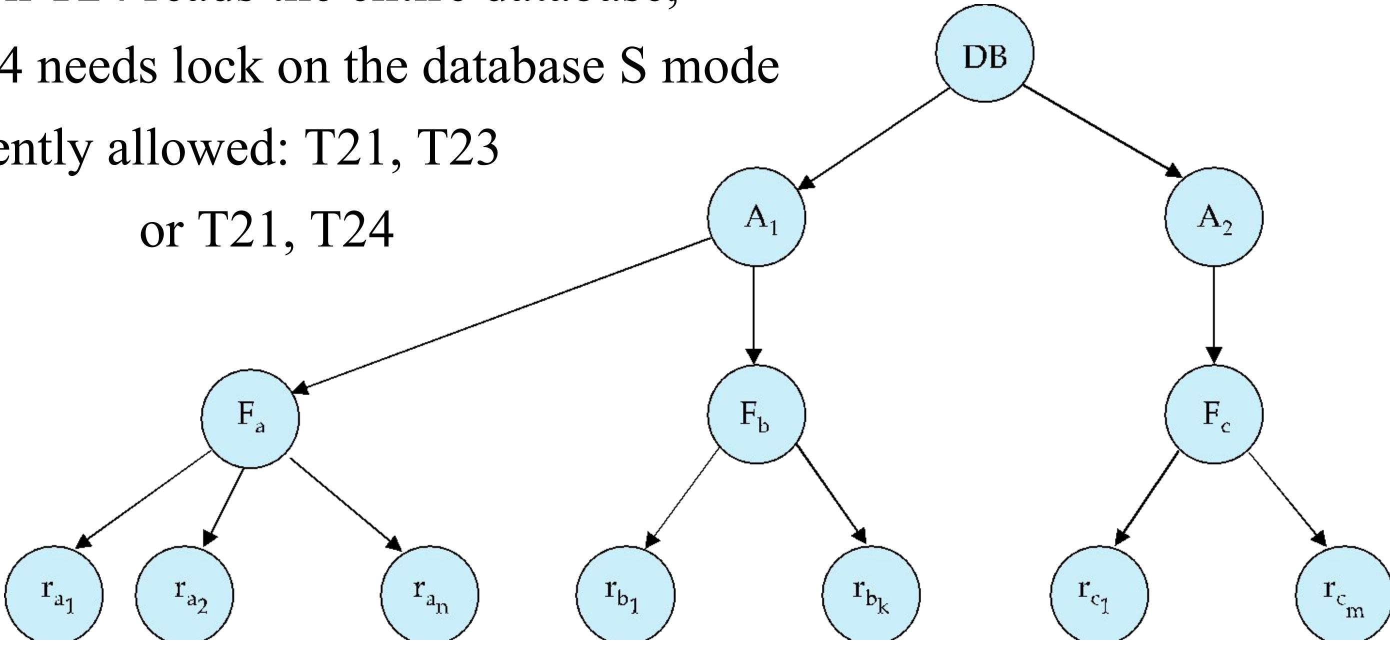
- If Transaction T21 reads a record ra2 in file Fa,
  - Then T21 needs to lock the database area A1 and Fa in IS mode and finally to lock ra2 in S mode
- If Transaction T22 modifies a record ra9 in file Fa,
  - Then T22 needs to lock the database area A1 and Fa in IX mode and finally to lock ra9 in X mode
- Concurrently allowed: T21 and T22



Intention Lock Modes

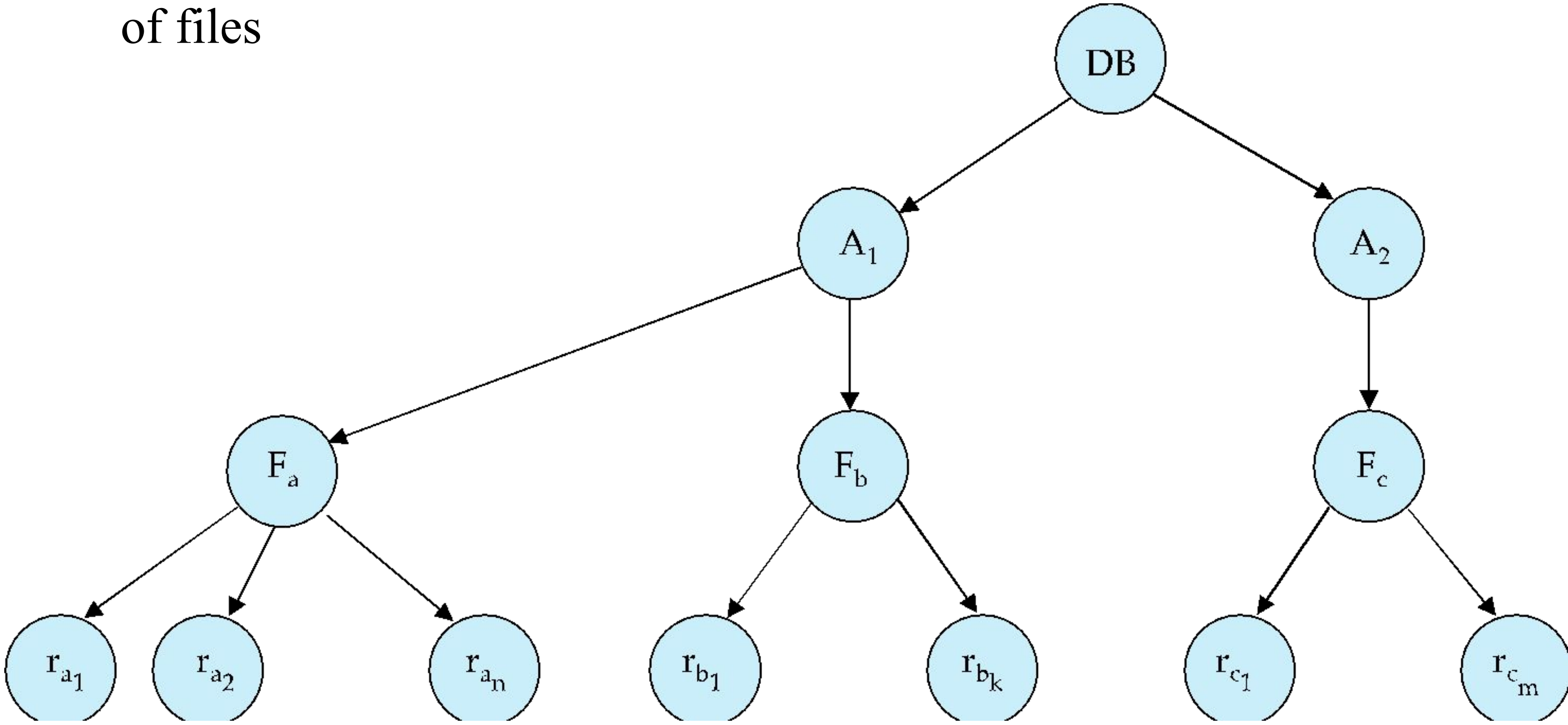
- If Transaction T21 reads a record ra2 in file Fa,
  - Then T21 needs to lock the database area A1 and Fa in IS mode and finally to lock ra2 in S mode
- If Transaction T23 reads all the records in file Fa,
  - Then T23 needs to lock the database area A1 in IS mode and and finally to lock Fa in S mode
- If Transaction T24 reads the entire database,
  - Then T24 needs lock on the database S mode
- Not concurrently allowed: T21, T23

  or T21, T24



Intention Lock Modes

- Enhances concurrency and reduces lock overhead
- Useful in applications, that include a mix of
  - Short transactions that access only a few data items
  - Long transactions that produce reports from an entire file or set of files



View Serializability

Check for Conflict Serializability

T1	T2
R(A)	
W(A)	
	R(A)
R(B)	
	W(A)
W(B)	
	R(B)
	W(B)

YES, Conflict Serializable
Serial Schedule: <T1, T2>

View Serializability

- Let *S1* and *S2* be two schedules with the same set of transactions. *S1* and *S2* are **view equivalent** if the following three conditions are met, for each data item *A,*
  1. Schedules S1 and S2 are view equivalent, If Ti reads initial value of A in S1, then Ti also reads initial value of A in S2
  2. If Ti reads value of A written by Tj in S1, then Ti also reads value of A written by Tj in S2
  3. If Ti writes final value of A in S1, then Ti also writes final value of A in S2

View Serializability (Cont.)

- **Example: Check View Serializabiltiy:** W3(Z), R2(X), W2(Y), R1(Z), W3(Y), W1(Y)
  - To check for view serializability of a schedule, you must create all possible combinations of the Transactions
  - Here three transactions, then you need to check for these combinations:
    < T1, T2, T3 >
    < T1, T3, T2 >
    < T2, T1, T3 >
    < T2, T3, T1 >
    < T3, T1, T2 >
    < T3, T2, T1 >
- Now the schedule is view serializable if:
  1. *A Tx reads an initial data in a Schedule, the same Tx also should read the initial data in one of the transaction combination.*
     - Here, at least T2 must occur first, though it actually doesn't matter also because no one else writes X, so we still keep all our Tx combinations

View Serializability (Cont.)

- **Example:** W3(Z), R2(X), W2(Y), R1(Z), W3(Y), W1(Y)
   2. *A Tx reads a data after another Tx has written in a Schedule, the same Tx also should read the data after another Tx has written it in one of the transaction combination.*
      4 Now, this means that **T1 must occur after T3 because T1 reads Z after T3 writes it.** So we **remove all where T1 is before T3**

< T1, T2, T3 >
< T1, T3, T2 >
< T2, T1, T3 >
< T2, T3, T1 >
< T3, T1, T2 >
< T3, T2, T1 >

$\Rightarrow$

– < T1, T2, T3 >
– < T1, T3, T2 >
– < T2, T1, T3 >

$\Rightarrow$

< T2, T3, T1 >
< T3, T1, T2 >
< T3, T2, T1 >

View Serializability (Cont.)

- **Example:** W3(Z), R2(X), W2(Y), R1(Z), W3(Y), W1(Y)

  3. *A Tx writes the final value for a data in a Schedule, the same Tx should also write the final data in one of the transaction combination.*

     4 Here, **T1 must occur last after T3 or T2** because if not T3 or T2 will overwrites Y that T1 writes in our schedule. So we **remove** < T3, T1, T2 >

< T2, T3, T1 >
< T3, T1, T2 >
< T3, T2, T1 >

$\Rightarrow$ $\Rightarrow$

< T2, T3, T1 >
< T3, T2, T1 >

- So two combinations left satisfy the view serializability, they are:

< T2, T3, T1 >

< T3, T2, T1 >

View Serializability (Cont.)

- **Example:** R1(X),R2(Y),R2(Y),W2(X),W3(Y),R1(X)
  1. *A Tx reads an initial data in a Schedule, the same Tx also should read the initial data in one of the transaction combination.*

< T1, T2, T3 >
< T1, T3, T2 >
< T2, T1, T3 >
< T2, T3, T1 >
< T3, T1, T2 >
< T3, T2, T1 >

- Here, at least **T1 must occur first, before T2**, so we remove
- $\Rightarrow$ <T2, T1, T3>
- <T2, T3, T1>
- <T3, T2, T1>

$\Rightarrow$

< T1, T2, T3 >
< T1, T3, T2 >
< T3, T1, T2 >

View Serializability (Cont.)

- **Example:** R1(X),R2(Y),R2(Y),W2(X),W3(Y),R1(X)

  2. *A Tx reads a data after another Tx has written in a Schedule, the same Tx also should read the data after another Tx has written it in one of the transaction combination*

     4 **T1 reads X after T2 writes,** means that **T2 should occur before T1**

     » But wait a minute, we've just said that **T1 should occur before T2** on the previous condition

     » Because a cycle in the graph also caused

     » Need T1 before T2 and at the same time, need T2 before T1

     » Because of this, **none of the combinations can satisfy these two conditions**, so it is **not view serializable**.

View Serializability (Cont.)

- **Example:**
-

T_1:			$r_1(A)$		$w_1(B)$		
T_2:	$r_2(B)$	$w_2(A)$				$w_2(B)$	
T_3:				$r_3(A)$			$w_3(B)$

- **Conflict Serializable?**

$$\begin{tikzcd}
T_1 \arrow[r, bend right, "B"'] & T_2 \arrow[l, "A"'] \arrow[r, "A{,}B"] & T_3
\end{tikzcd}$$

- **Conflict is NOT resolved, so it is NOT Conflict Serializable**
- **View Serializable?**
  - **<T2, T1,T3>**
- **YES, view serializable schedule and schedule T2,T1,T3 is view equivalent schedule for the given schedule**