Transactions and Concurrency Control

- Transaction: a unit of program execution that accesses and possibly updates some data items.
- A transaction is a collection of operations that logically form a single unit.
- Executing a transaction: either all operations are executed, or none are.
- Each transactions may consist of several steps, some involving I/O activity, and some CPU activity.
- Moreover, typically several transactions are running on a system; some are long, some are short.
- This creates an opportunity for concurrent execution. Problem: how to ensure consistency?

Transaction model

- Operation $\mathbf{read}$(X) – transfers the data item X from the database to a local buffer belonging to the transaction
- Operation $\mathbf{write}$(X) — transfers the data item X from the local buffer back to the database
- Example: transfer $100 from account A to account B

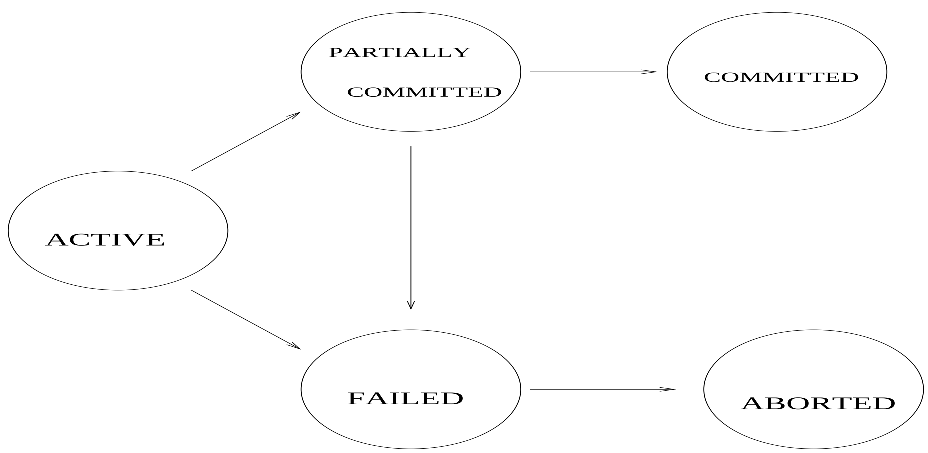
  $\mathbf{read}$(A);
  A := A - 100;
  $\mathbf{write}$(A);
  $\mathbf{read}$(B);
  B := B + 100;
  $\mathbf{write}$(B)
- It executes as a single unit: at no point between $\mathbf{read}$(A) and $\mathbf{write}$(B) can a user query the database, as it might be in an inconsistent state.

ACID properties

- **Atomicity**: either all operations of a transaction are reflected properly in the database, or none are.
- **Consistency**: execution of a transaction in isolation preserves the consistency of the database.
- **Isolation**: even though many transactions may run concurrently, the DBMS ensures that for any two transactions T, T', it appears to T that either T' finished before T started, or T' started execution after T finished.
- **Durability**: after a transaction completes successfully, the changes it has made persist.

States of a transaction

- *Active*: it stays in this state while it is executing
- *Partially committed*: after the final statement has been executed.
- *Failed*: after the discovery that normal execution cannot proceed.
- *Aborted*: after it has been rolled back, and the database state restored to the one prior to the start of the execution.
- *Committed*: after successful completion.



Two transactions

- T takes \$100 from account A to account B.
- T' takes 10% of account A to account B.
- Property of T and T': they don't change A+B.
  Money isn't created, and doesn't disappear.

T: **read**(A);
A := A - 100;
write(A);
read(B);
B = B+100;
write(B)

T': **read**(A);
tmp := A*0.1;
A := A - tmp;
write(A);
read(B);
B = B+tmp;
write(B)

Two serial executions: $T; T'$ and $T'; T$

T	T'
read(A);	
A := A - 100;	
write(A);	
read(B);	
B = B+100;	
write(B);	
	read(A);
	tmp := A*0.1;
	A := A - tmp;
	write(A);
	read(B);
	B = B+tmp;
	write(B);

T'	T
read(A);	
tmp := A*0.1;	
A := A - tmp;	
write(A);	
read(B);	
B = B+tmp;	
write(B);	
	read(A);
	A := A - 100;
	write(A);
	read(B);
	B = B+100;
	write(B);

Transaction invariant

- A+B doesn't change after T and T' execute.
- Assume that both A and B have $1,000.
- Evaluating $T;T'$:

  after T: A=900, B=1100.

  after T': A=810, B=1190.

  A+B=2000.
- Evaluating $T';T$:

  after T': A=900, B=1100

  after T: A=800, B=1200.

  A+B=2000.

Concurrent execution I

T	T'
read(A);	
A := A - 100;	
write(A);	
	read(A);
	tmp := A*0.1;
	A := A - tmp;
	write(A);
read(B);	
B = B+100;	
write(B);	
	read(B);
	B = B+tmp;
	write(B);

Result:
A=810
B=1190
A+B=2000

Concurrent execution II

T	T'
read(A);	
A := A - 100;	
	read(A);
	tmp := A*0.1;
	A := A - tmp;
	write(A);
write(A);	
read(B);	
B = B+100;	
write(B);	
	read(B);
	B = B+tmp;
	write(B);

Result:
A=900
B=1200
A+B=2100
We created $100!

Serializability

- Why is schedule I good and schedule II bad?
- Because schedule I is equivalent to a serial execution of T and T', and schedule II is not.
- We formalize this via *conflict serializability*.
- Transaction scheduling in DBMSs always ensures serializability.

Simplified representation of transactions

- For scheduling, the only important operations are **read** and **write**. What operations are performed on each data item does not affect the schedule.
- We thus represent transactions by a sequence of **read**-**write** operations, assuming that between each **read**(A) and **write**(A) some computation is done on A.

Simplified representation of transactions cont'd

- Examples of two concurrent executions in the new model:

Schedule I

T	T'
read(A);	
write(A);	
	read(A);
	write(A);
read(B);	
write(B);	
	read(B);
	write(B);

Schedule II

T	T'
read(A);	
	read(A);
	write(A);
write(A);	
read(B);	
write(B);	
	read(B);
	write(B);

Analyzing conflicts

- Let Op_1 and Op_2 be two consecutive operations in a schedule.
- Conflict – the order matters:

$$\mathsf{Op}_1; \mathsf{Op}_2 \qquad \text{and} \qquad \mathsf{Op}_2; \mathsf{Op}_1$$

  may give us different results.
- If there is no conflict, Op_1 and Op_2 can be swapped.
- If Op_1 and Op_2 refer to different data items, they do not cause a conflict, and can be swapped.
- If they are both operations on the same data item X, then:

  if both are $\mathbf{read}$(X), the order does not matter;

  if $\mathsf{Op}_1 = \mathbf{read}$(X), $\mathsf{Op}_2 = \mathbf{write}$(X), the order matters.

  if $\mathsf{Op}_1 = \mathbf{write}$(X), $\mathsf{Op}_2 = \mathbf{read}$(X), the order matters.

  if $\mathsf{Op}_1 = \mathbf{write}$(X), $\mathsf{Op}_2 = \mathbf{write}$(X), the order matters.

Conflict serializability

- Swapping a pair of operations in a schedule is allowed when:

  they refer to different data items, or,

  they refer to the same data item and are both **read** operations.

- A schedule is called **conflict serializable** if it can be transformed into a serial schedule by a sequence of such swap operations.

Schedule I is conflict serializable

T	T'
read(A);	
write(A);	
	read(A);
	write(A);
read(B);	
write(B);	
	read(B);
	write(B);

→

T	T'
read(A);	
write(A);	
	read(A);
read(B);	
	write(A);
write(B);	
	read(B);
	write(B);

→

T	T'
read(A);	
write(A);	
read(B);	
	read(A);
	write(A);
write(B);	
	read(B);
	write(B);

→

T	T'
read(A);	
write(A);	
read(B);	
	read(A);
write(B);	
	write(A);
	read(B);
	write(B);

→

T	T'
read(A);	
write(A);	
read(B);	
write(B);	
	read(A);
	write(A);
	read(B);
	write(B);

Schedule II is not conflict serializable

T	T'
$\mathbf{read}$(A);	
	$\mathbf{read}$(A);
	$\mathbf{write}$(A);
$\mathbf{write}$(A);	
$\mathbf{read}$(B);	
$\mathbf{write}$(B);	
	$\mathbf{read}$(B);
	$\mathbf{write}$(B);

- In a serial schedule, either:
  $\mathbf{write}$(A) by T precedes $\mathbf{read}$(A) by T', or
  $\mathbf{write}$(A) by T' precedes $\mathbf{read}$(A) by T
- But:
  $\mathbf{write}$(A) by T cannot be swapped with $\mathbf{write}$(A) by T', and
  $\mathbf{write}$(A) by T' cannot be swapped with $\mathbf{read}$(A) by T
- Hence the schedule is not serializable.

Testing conflict serializability

- Construct the **precedence graph** of a schedule S
- Nodes: transactions in the system
- Edges: there is an edge

$$T \longrightarrow T'$$

if T executes an operation Op_1 before T' executes an operation Op_2 such that Op_1 and Op_2 cannot be swapped.

- That is, one of these conditions holds:

  T executes **write**(X) before T' executes **read**(X)

  T executes **read**(X) before T' executes **write**(X)

  T executes **write**(X) before T' executes **write**(X)

Testing conflict serializability

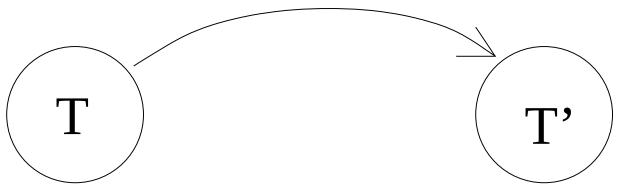
- Given a schedule S, construct its precedence graph
- If there is an edge $T \rightarrow T'$, then in any serial schedule S' equivalent to S, the transaction T must appear before T'.
- A schedule S is conflict serializable if and only if its precedence graph contains no cycles.
- Testing serializability:

  Construct the conflict graph

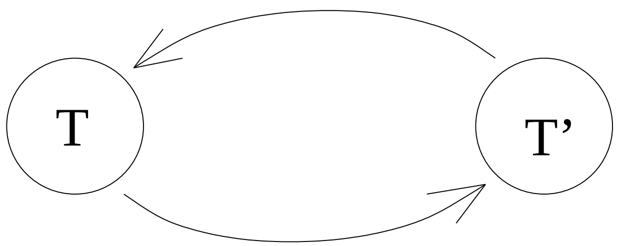
  Check if it has cycles

  If it doesn't have cycles, do topological sort
- The result of the topological sort gives an equivalent serial schedule.
- Reminder: a topological sort of an acyclic graph G produces an order $\prec$ on its nodes consistent with G – if there is an edge from x to y, then $x \prec y$.

Testing conflict serializability: examples



PRECEDENCE GRAPH FOR SCHEDULE I



PRECEDENCE GRAPH FOR SCHEDULE 2

- Thus, schedule I is conflict serializable, and schedule II is not.

Concurrency control: lock-based protocols

- Main goal of concurrency control: to ensure the isolation property for concurrently running transactions
- Typically achieved via **locks**
- Each data item is locked by at most one transaction; while it is locked, no other transaction has access to it.
- Two new primitives: **lock**(A) and **unlock**(A)
- A typical transaction:

```
...
lock(A);
read(A);
...
write(A);
unlock(A);
...
```

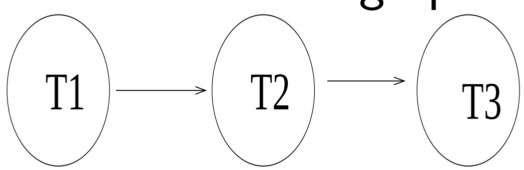
Locking and serializability

- A new abstract view of transaction: only the order of **lock** and **unlock** operations matters
- If data item A is locked by transaction T, and transaction T' issues a **lock**(A) command, it must wait until T executes **unlock**(A).
- New representation of schedules:

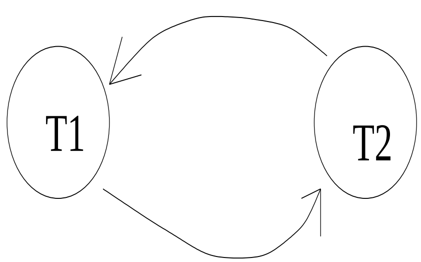
Schedule S_1	Schedule S_2
T_2: **lock**(A)	T_1: **lock**(A)
T_2: **unlock**(A)	T_2: **lock**(B)
T_3: **lock**(A)	T_2: **unlock**(B)
T_3: **unlock**(A)	T_1: **lock**(B)
T_1: **lock**(B)	T_1: **unlock**(A)
T_1: **unlock**(B)	T_2: **lock**(A)
T_2: **lock**(B)	T_2: **unlock**(A)
T_2: **unlock**(B)	T_1: **unlock**(B)

Locking and serializability

- Precedence graph: for each operation T_i: $\mathbf{unlock}$(A), locate the following T_j: $\mathbf{lock}$(A) statement, and put an edge from T_i to T_j
- Conflict-serializability with locking: a schedule is conflict-serializable if the precedence graph does not have cycles.
- Precedence graphs:



FOR S1



FOR S2

- Hence S_1 is conflict-serializable, S_2 is not.

Locking and serializability cont'd

- A conflict-serializable schedule of **lock-unlock** operations ensures a conflict-serializable schedule of **read-write** operations:

T_2	**lock**(A)
T_2	**unlock**(A)
T_1	**lock**(B)
T_1	**unlock**(B)
T_2	**lock**(B)
T_2	**unlock**(B)

$\longrightarrow$

T_1	T_2
	read(A)
	write(A)
read(B)	
write(B)	
	read(B)
	write(B)

$\longrightarrow$

T_1	T_2
read(B)	
write(B)	
	read(A)
	write(A)
	read(B)
	write(B)

Two-phase locking

- A protocol which guarantees conflict-serializable schedule
- Used in most commercial DBMSs
- Each transaction has two phases:
- *Growing phase*: a transaction may request new locks, but may not release any locks
- *Shrinking phase*: a transaction may release locks, but may not request any locks
- That is, after transaction released a lock, it may not request any new locks
- Main property of two-phase locking:

  A schedule S in which every transaction satisfies the two-phase locking protocol is conflict-serializable

Two-phase locking and serializability: proof

Assume that every transaction conforms to the two-phase locking protocol (or: is a 2PL transaction)

Assume S is not serializable, and the precedence graph contains a cycle:

$$T_1 \rightarrow T_2 \rightarrow T_3 \rightarrow \ldots \rightarrow T_k \rightarrow T_1$$

Trace the cycle:

- T_1 locks and unlocks something
- T_2 locks and unlocks something
- ...
- T_k locks and unlocks something
- T_1 locks and unlocks something

Then T_1 locks some data item after it released a lock, and hence it is not 2PL.

Two-phase locking and serializability cont'd

- The result is best possible
- For any non-2PL transaction T, there is a 2PL transaction T' and a schedule S for T, T' that is not serializable.
- Idea:

T	T'
lock(A)	**lock**(A)
unlock(A)	**lock**(B)
lock(B)	**unlock**(A)
unlock(B)	**unlock**(B)

Schedule:

T	**lock**(A), **unlock**(A)
T'	all operations
T	**lock**(B), **unlock**(B)

- This schedule is not serializable.

2PL in practice

- Majority of commercial DBMSs implement some form of 2PL
- Rigorous 2PL: all locks must be held until the transaction commits
- Two types of locks:

  Exclusive: the transaction can both read and write the data item

  Shared: the transaction can only read the data item
- At most one transaction can possess an exclusive lock for a data item at any given time, but several transactions can possess a shared lock
- Strict 2PL: all exclusive locks taken by the transaction must be held until it commits
- Strict and rigorous 2PL are the most common concurrency control mechanisms

Deadlocks

time	T_1	T_2	
1	**lock**(A)		
2		**lock**(B)	
3	**lock**(B)		now T_1 waits for T_2 to unlock B
4		**lock**(A)	now T_2 waits for T_1 to unlock A
5	...	...	

- Deadlock: T_1 waits for T_2, T_2 waits for T_1
- In general, there is a set of transactions $T_1, \ldots, T_k$ such that:
  - T_1 waits for T_2
  - T_2 waits for T_3
  - ...
  - T_k waits for T_1

Dealing with deadlocks

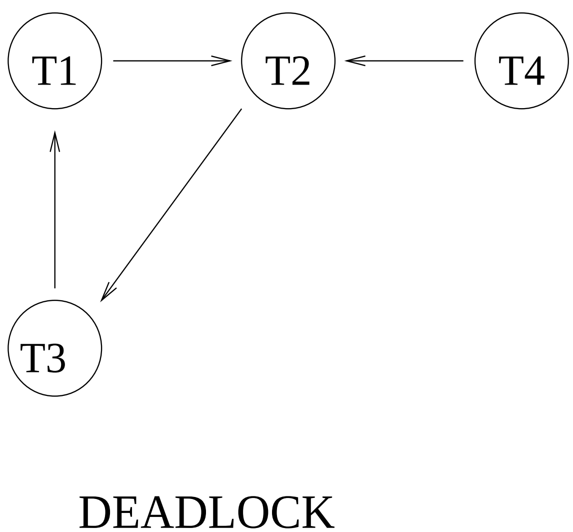
- Two main mechanisms: prevention and detection
- Prevention: find a concurrency control mechanism which ensures that there is no "waits-for" cycle
- Simple deadlock prevention: each transaction locks all data items before it starts execution. Such a locking constitutes $one\ step$.
- Disadvantage: data utilization is very low
- Another approach: use preemption. If T_1 has a lock on A, and T_2 requests it, then the system has three choices:
  - let T_2 wait, or
  - roll back T_1 and grant the lock to T_2, or
  - roll back T_2

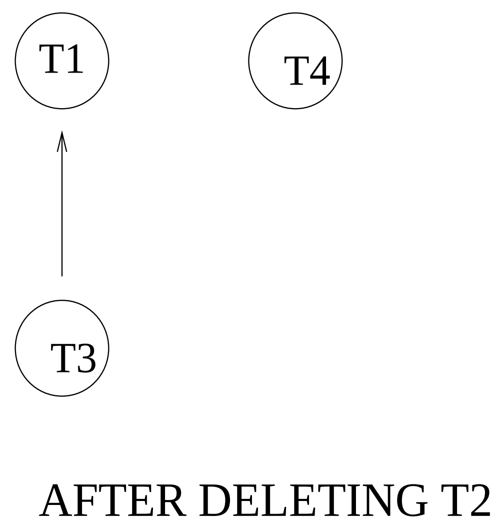
Deadlock prevention cont'd

- The decision is based on *timestamps*, that say how old transactions are.
- Timestamp: the time when transaction started its execution. The larger the timestamp, the younger the transaction.
- Example: the *wound-wait* scheme. If T_1 requests a lock held by T_2, then T_1 waits if T_1 is younger than T_2. Otherwise T_2 is rolled back.
- The *wait-die* scheme. If T_1 requests a lock held by T_2, then T_1 waits if T_1 is older than T_2. Otherwise T_1 is rolled back.
- Issue: starvation may occur. Some transactions may never commit, as they keep being rolled back.

Deadlock detection and recovery

- The $wait\text{-}for$ graph. Nodes are transactions. There is an edge from T to T' if T' waits for T to release a lock.
- There is a deadlock if there is a cycle in the wait-for graph.
- Deadlock recovery: identify a minimal set of transactions such that rolling them back will make the wait-for graph cycle-free.





Query Processing and Optimization

- *Query optimization*: finding a good way to evaluate a query
- Queries are declarative, and can be translated into procedural languages in more than one way
- Hence one has to choose the best (or at least good) procedural query
- This happens in the context of *query processing*
- A query processor turns queries and updates into sequences of of operations on the database

Query processing and optimization stages

- Which relational algebra expression, equivalent to a given declarative query, will lead to the most efficient algorithm?
- For each algebraic operator, what algorithm do we use to compute that operator?
- How do operations pass data (main memory buffer, disk buffer?)

- We first concentrate the first step: finding efficient relational algebra expressions
- For the second step, we need to know how data is stored, and how it is accessed

Overview of query processing

- Start with a declarative query:

```
SELECT R.A, S.B, T.E
FROM R,S,T
WHERE R.C=S.C AND S.D=T.D AND R.A>5 AND S.B<3 AND T.D=T.E
```

- Translate into an algebra expression:

$$\pi_{R.A,S.B,T.E}(\sigma_{R.A>5 \wedge S.B<3 \wedge T.D=T.E}(R \bowtie S \bowtie T))$$

- Optimization step: rewrite to an equivalent but more efficient expression:

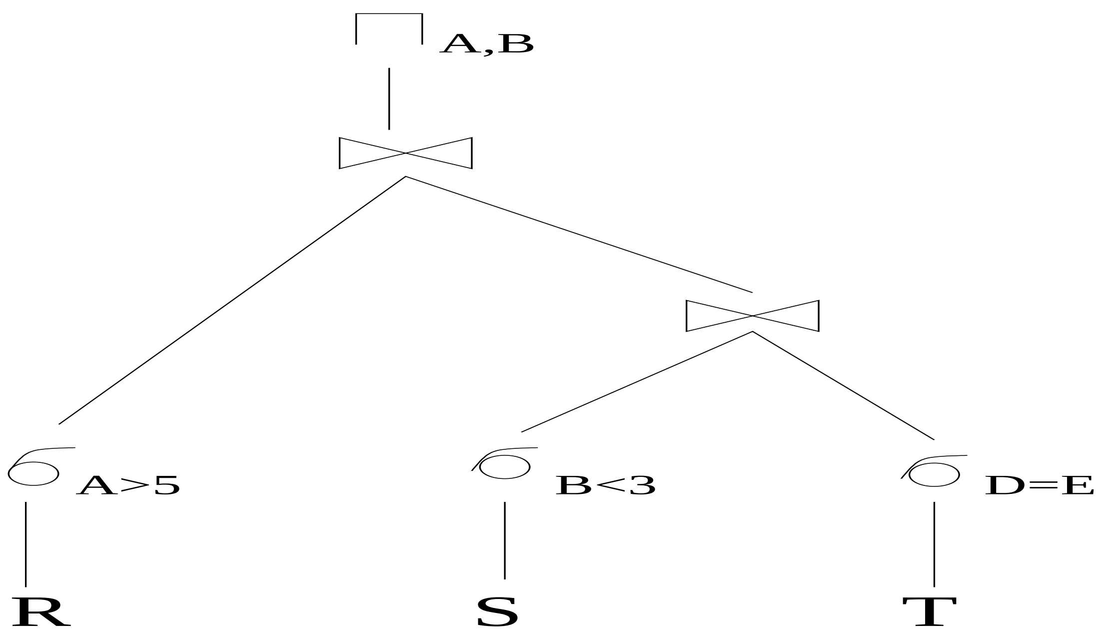
$$\pi_{R.A,S.B,T.E}(\sigma_{A>5}(R) \bowtie \sigma_{B<3}(S) \bowtie \sigma_{D=E}(T)))$$

- Why is it more efficient?

  Because selections are evaluated early, and joined relations are not as large as R, S, T.

Overview of query processing cont'd

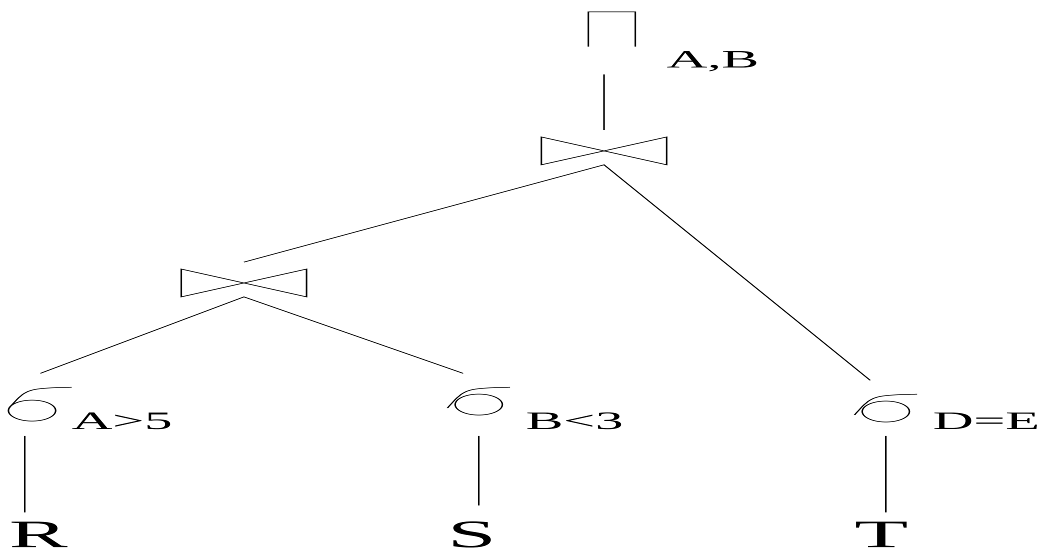
- Evaluating the optimized expression. Choices to make: order of joins.
- Two possible *query plans*:



first joins S, T, and then joins the result with R.

Overview of query processing cont'd

- Another query plan:



It first joins S, T, and then joins the result with R.

- Both query plans produce the same result.
- How to choose one?

Optimization by algebraic manipulations

- Given a relational algebra expression e, find another expression e' equivalent to e that is easier (faster) to evaluate.
- Basic question: Given two relational algebra expressions e_1, e_2, are they equivalent?
- This is the same as asking if an expression e always produces the empty answer:

$$e_1 = e_2 \quad \Leftrightarrow \quad e_1 - e_2 = \emptyset \text{ and } e_2 - e_1 = \emptyset$$

- Problem: testing $e = \emptyset$ is undecidable for relational algebra expressions.
- Good news:

  We can still list some useful equalities, and

  It is decidable for very important classes of queries (SPJ queries)

Optimization by algebraic manipulations

- Join and Cartesian product are commutative and associative, hence they can be applied in any order:

$$\begin{aligned} R \times S &= S \times R \\ R \times (S \times T) &= (R \times S) \times T \\ R \bowtie S &= S \bowtie R \\ R \bowtie (S \bowtie T) &= (R \bowtie S) \bowtie T \end{aligned}$$

- Cascade of projections. Assume that attributes $A_1, \ldots, A_n$ are among $B_1, \ldots, B_m$. Then

$$\pi_{A_1,\ldots,A_n}(\pi_{B_1,\ldots,B_m}(E)) = \pi_{A_1,\ldots,A_n}(E)$$

- Cascade of selections:

$$\sigma_{c_1}(\sigma_{c_2}(E)) = \sigma_{c_1 \wedge c_2}(E)$$

Optimization by algebraic manipulations

- Commuting selections and projections. Assume that condition c involves attributes $A_1, \ldots, A_n,\ B_1, \ldots, B_m$. Then

$$\pi_{A_1,\ldots,A_n}(\sigma_c(E)) \quad = \quad \pi_{A_1,\ldots,A_n}(\sigma_c(\pi_{A_1,\ldots,A_n,\ B_1,\ldots,B_m}(E)))$$

- A useful special case: if c only involves attributes $A_1, \ldots, A_n$, then

$$\pi_{A_1,\ldots,A_n}(\sigma_c(E)) \quad = \quad \sigma_c(\pi_{A_1,\ldots,A_n}(E))$$

- Commuting selection with join. If c only involves attributes from E_1, then

$$\sigma_c(E_1 \bowtie E_2) \quad = \quad \sigma_c(E_1) \bowtie E_2$$

Optimization by algebraic manipulations cont'd

- Let c_1 only mention attributes of E_1 and c_2 only mention attributes of E_2. Then

$$\sigma_{c_1 \wedge c_2}(E_1 \bowtie E_2) = \sigma_{c_1}(E_1) \bowtie \sigma_{c_2}(E_2)$$

- Because:

$$\begin{array}{rl} & \sigma_{c_1 \wedge c_2}(E_1 \bowtie E_2) \\ = & \sigma_{c_1}(\sigma_{c_2}(E_1 \bowtie E_2)) \\ = & \sigma_{c_1}(E_1 \bowtie \sigma_{c_2}(E_2)) \\ = & \sigma_{c_1}(E_1) \bowtie \sigma_{c_2}(E_2) \end{array}$$

- Another useful rule: If c only mentions attributes present in both E_1 and E_2, then

$$\sigma_c(E_1 \bowtie E_2) \quad = \quad \sigma_c(E_1) \bowtie \sigma_c(E_2)$$

Optimization by algebraic manipulations cont'd

- Rules combining σ, π with $\cup$ and $-$
- Commuting selection and union:

$$\sigma_c(E_1 \cup E_2) \quad = \quad \sigma_c(E_1) \cup \sigma_c(E_2)$$

- Commuting selection and difference:

$$\sigma_c(E_1 - E_2) \quad = \quad \sigma_c(E_1) - \sigma_c(E_2)$$

- Commuting projection and union:

$$\pi_{A_1,\ldots,A_n}(E_1 \cup E_2) \quad = \quad \pi_{A_1,\ldots,A_n}(E_1) \cup \pi_{A_1,\ldots,A_n}(E_2)$$

- Question: what about projection and difference?
  Is $\pi_A(E_1 - E_2)$ equal to $\pi_A(E_1) - \pi_A(E_2)$?

Optimization by algebraic manipulations: example

- Recall

$$\pi_{R.A,S.B,T.E}(\sigma_{R.A>5 \wedge S.B<3 \wedge T.D=T.E}(R \bowtie S \bowtie T))$$

- Optimization: pushing selections

$$\pi_{R.A,S.B,T.E}(\sigma_{R.A>5 \wedge S.B<3 \wedge T.D=T.E}(R \bowtie S \bowtie T))$$

$$= \pi_{R.A,S.B,T.E}(\sigma_{R.A>5}(\sigma_{S.B<3}(\sigma_{T.D=T.E}(R \bowtie S \bowtie T))))$$

$$= \pi_{R.A,S.B,T.E}(\sigma_{R.A>5}(\sigma_{S.B<3}(R \bowtie S \bowtie (\sigma_{T.D=T.E}(T)))))$$

$$= \pi_{R.A,S.B,T.E}(\sigma_{R.A>5}(R \bowtie \sigma_{S.B<3}(S) \bowtie (\sigma_{T.D=T.E}(T))))$$

$$= \pi_{R.A,S.B,T.E}(\sigma_{A>5}(R) \bowtie \sigma_{B<3}(S) \bowtie \sigma_{D=E}(T)))$$

Implementation of individual operations

- Depends on access method and file organization
- Suppose EmplId is a key; how long does it take to answer:

$$\sigma_{\text{EmplId}=1234567}(\text{Employee})?$$

- Time is linear in the worst case
- But one can perform the selection much faster if there is an *index* on attribute EmplId
- **Index**: auxiliary structure that provides fast access to tuples in a table based on a given key value
- Most common example: B-trees
- With B-trees, the above selection takes $O(\log n)$

Note on indices and SQL

- SQL allows one to create an index on a given attribute or a sequence of attributes
- Once an index is created, the table can be accessed fast if the values of index attributes are known
- SQL always creates an index for attributes declared as a primary key of a table
- Syntax:

```
CREATE INDEX <Index_Name> ON
          <Table_Name>(<attr1>,...,<attrN>)
```

- Example:

```
CREATE INDEX EmplIndex ON Employee(EmplId)
```

Processing individual operators: join

- Join is the costliest operator of relational algebra
- Query: $R \bowtie S = \sigma_{R.A=S.A}(R \times S)$
- ```
  SELECT R.A, R.B, S.C
  FROM R, S
  WHERE R.A=S.A
  ```
- Naive implementation:

  ```
  for every tuple t1 in R do
      for every tuple t2 in S do
          if t1.A=t2.A then output (t1.A,t1.B,t2.C)
      end
  end
  ```

- Time complexity: $O(n^2)$
  ```

Join processing

- Assumption: $R.A$ is the primary key of R.
- New $O(n \log n)$ algorithm:

```
Sort R and S on attribute A;
scanS := first tuple in S;
for each tuple t1 in R do
      scan S starting from scanS until a tuple
      t2 with t2.A ≥ t1.A is found;
      if t2.A=t1.A then
          while t2.A=t1.A do
                if t1.A=t2.A then output (t1.A,t1.B,t2.C);
                move to the next tuple t2 of S
          end
      set scanS := current tuple t2
end
```

Join processing cont'd

- Previous algorithm can be extended to the case when the common attributes of R and S do not form a key in either relation
- One uses two pointers then to scan the relations
- Name: Sort-Merge join
- Both algorithms would be implemented differently in practice
- No need to do a new disk read to get each tuple; instead, read one block at a time
- Complexity of sort-merge join: If the relations are sorted, it requires $B_R + B_S$ disk reads, where B_R, B_S are the numbers of disk blocks in R, S.

Join processing: hash join

- Reminder: hashing.
- Bucket – a unit of storage that can store one or more tuples. Typically several disk blocks
- K – a set of search-key values; B – a set of buckets
- Hash function $h : K \to B$
- Good properties: uniform, random distribution
- Example of hashing: first two digits of the student $\#$ (assumes 100 buckets)
- Example of bad hashing: (account balance mod 100 000) div 10 000
- Overflows. Reason: bad distribution, insufficient buckets.
- Handling of overflows: a linked list of overflow buckets

Join processing: hash join of R and S

- X - the set of common attributes
- Step 1: Select M, the number of buckets
- Step 2: Select a hash function h on attributes from X:
  h : {tuples over X} $\rightarrow \{1, \ldots, M\}$
- Step 3: Partition R and S:

```
for each t in R do                for each t in S do
    i := h(t.X)                        i := h(t.X)
    H_i^R := H_i^R ∪ {t}               H_i^S := H_i^S ∪ {t}
end                               end
```

- If there are no overflows, this requires $O(B_R + B_S)$ I/O operations (read the relations, and write them back)
- With overflows, one uses recursive partitioning, and then complexity becomes $O(n \log n)$, where $n = B_R + B_S$.

Join processing: hash join of R and S

- Assume that the relations are partitioned
- Algorithm:

  for $i = 1$ to M do
  read H_i^R
  read H_i^S
  add $H_i^R \bowtie H_i^S$ to the output
  end

- Why does it work? If two tuples $t_1 \in R$, $t_2 \in S$ match, $t_1.X = t_2.X$ and $h(t_1) = h(t_2)$; hence they are in the same partition class
- Improvements: how does one compute $H_i^R \bowtie H_i^S$? One possibility: use another hash function. If it doesn't create overflows, the time for the algorithm is $O(B_R + B_S)$

Using hash functions for Boolean operations

- Observe:

$$R \cap S \quad = \quad (H_1^R \cap H_1^S) \cup \ldots \cup (H_M^R \cap H_M^S)$$

- Because: if $t \in R \cap S$ and $t \in H_i^R$, then $t \in H_i^S$
- Advantage: each tuple $t \in R$ must only be compared with $H_{h(t)}^S$, and not with the whole relation S
- Using hash functions for difference:

for each t in R do
    $i := h(t)$
    if $t \notin H_i^S$, include t in the output
end

Other operations

- Set union $R \cup S$: if no index is needed on the result, just append S to R
- If index is needed, then do as above, and then build a new index
- Duplicate elimination: On a sorted relation, it takes linear time. Thus, sort relation R first, based on any attribute(s), and then do one pass and eliminate duplicate
- Complexity: $O(n \log n)$.
- Aggregation with GROUP BY: similarly, sort on the group by attributes, before computing aggregate functions.

Query processing cont'd

- Find names of theaters that play movies featuring Nicholson

```
SELECT S.theater
FROM Movies M, Schedule S
WHERE M.title=S.title AND M.actor='Nicholson'
```

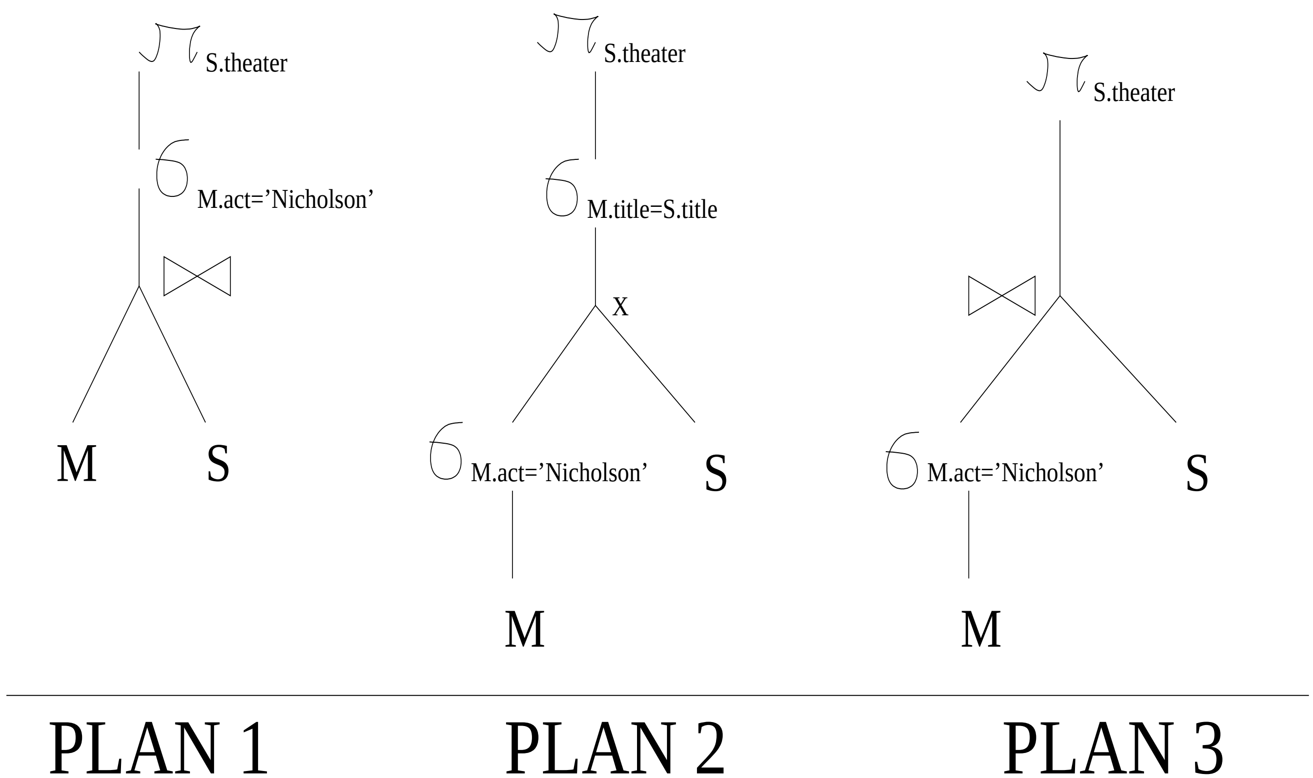
- Translate into algebra:

$$\pi_{\text{theater}}(\sigma_{\text{actor='Nicholson'}}(M \bowtie S))$$

- Next step: choose a query plan
- To do so, use algebraic rewritings to create several equivalent expressions, and then choose algorithms for performing individual operators.

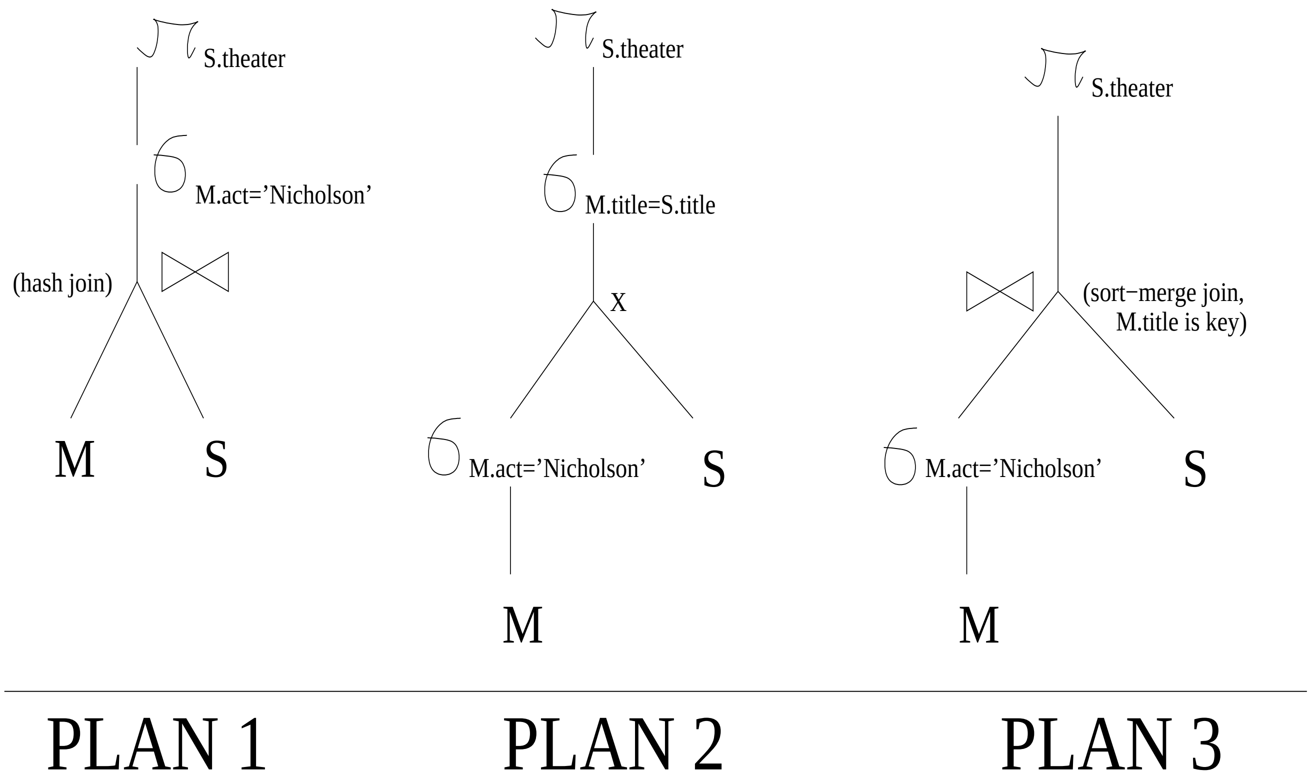
Query processing cont'd

Step 1



Query processing cont'd

Step 2



Query processing cont'd

- Choosing the best plan: cost-based optimization
- Query optimizer estimates the cost of evaluating each plan
- Particularly important: selectivity estimation (how many tuples in $\sigma_c(E)$?) and join size estimation
- Techniques used: statistics. Sometimes a sampling is done before a query is processed.
- Problem with cost-based optimization: the set of all query plans is extremely large; the optimizer cannot try them all
- Another problem: how long can the optimizer run? Hopefully not as long as the savings it provides.

Join order

- We know that join is commutative and associative.
- How does one evaluate

$$R_1 \bowtie R_2 \bowtie R_3 \bowtie R_4 \bowtie R_5?$$

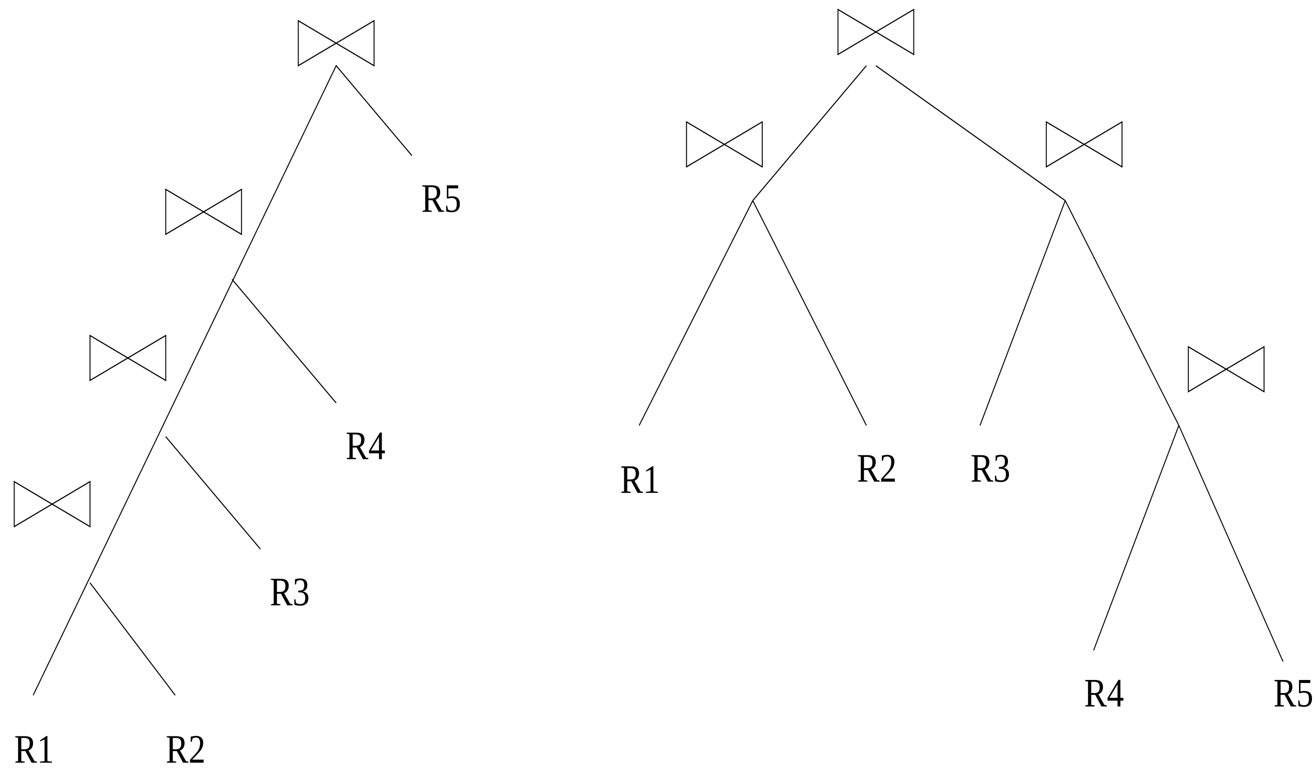
- Possibilities:

$$(\ (\ (R_1 \bowtie R_2) \bowtie R_3\ ) \bowtie R_4\ ) \bowtie R_5$$

$$(R_1 \bowtie R_2) \bowtie (R_3 \bowtie (R_4 \bowtie R_5))$$

$$(R_1 \bowtie (R_3 \bowtie R_5)) \bowtie (R_4 \bowtie R_2)$$

Join order



- DB2 optimizer only considers deep join orders like the one on the left.
- In general, choosing an optimal join order is computationally hard (usually NP-complete for reasonable cost measures)

SQL and query optimization

- Query optimizer helps turn your query into a more efficient one, but you can help the query optimizer do its job better.
- The search space of all possible query plans is extremely large, and optimizers only run for a short time, and thus may fail to find a good plan.
- There are several rules that usually ensure a better query plan; however, a lot depends on a particular system, version, and its optimizers, and these rules may not be universally applicable. Still, if your query isn't running fast enough, it's worth giving them a try.

Order does matter!

```
SELECT *
FROM Students
WHERE grade='A'
   AND sex='female'
```

is better than

```
SELECT *
FROM Students
WHERE sex='female'
   AND grade='A'
```

- Because usually there are fewer A students than female students.
- Using orders instead of <>

```
SELECT *
FROM Movies
WHERE Length > 120
   OR Length < 120
```

is better than

```
SELECT *
FROM Movies
WHERE Length <> 120
```

- Because the ordered version forces SQL to use an index on Length, if there is one
- Without such an index, the version with `OR` runs longer

Provide more JOIN information

- ```
  SELECT *
  FROM T1, T2, T3
  WHERE T1.common = T3.common AND T1.common=T2.common
  ```
- ```
  SELECT *
  FROM T1, T2, T3
  WHERE T1.common = T3.common AND T3.common=T2.common
  ```
- These may not be as good as

  ```
  SELECT *
  FROM T1, T2, T3
  WHERE T1.common = T2.common
    AND T2.common = T3.common
    AND T3.common = T1.common
  ```

Avoid unions if OR is sufficient

```
  SELECT *
  FROM Personnel
  WHERE location=‘Edinburgh’
UNION
  SELECT *
  FROM Personnel
  WHERE location=’Glasgow’
```

is not as good as

```
  SELECT DISTINCT*
  FROM Personnel
  WHERE location=’Edinburgh’
    OR  location=’Glasgow’
```

The optimizer normally works within a single SELECT-FROM-WHERE.

Joins are better than nested queries

```
SELECT S.Theater
FROM Schedule S
WHERE S.Title IN (SELECT M.Title
                  FROM Movies M
                  WHERE M.director='Spielberg')
```

is likely to run slower than

```
SELECT S.Theater
FROM Schedule S, Movies M
WHERE S.Title = M.Title
  AND M.director='Spielberg'
```