Database Management Systems

Module 36: Recovery/1

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Database System Concepts, 6th Ed.

Week 07 Recap

- **Module 31: Transactions/1**
  - Transaction Concept
  - Transaction State
  - Concurrent Executions
- **Module 32: Transactions/2: Serializabilty**
  - Serializability
  - Conflict Serializability
- **Module 33: Transactions/3: Recoverability**
  - Recoverability and Isolation
  - Transaction Definition in SQL
  - View Serializability
  - Complex Notions of Serializability
- **Module 34: Concurrency Control/1**
  - Lock-Based Protocols
  - Implementing Locking
- **Module 35: Concurrency Control/2**
  - Deadlock Handling
  - Timestamp-Based Protocols

Module Objectives

- We need to understand what are the possible sources for failure for transactions in a database
- Various types of storages are used for recovery from failures to ensure Atomicity, Consistency and Durability – these models need to be explored
- To understand recovery scheme based on logging
- To focus on single transactions only

Module Outline

- Failure Classification
- Storage Structure
- Recovery and Atomicity
- Log-Based Recovery

- **Failure Classification**
- Storage Structure
- Recovery and Atomicity
- Log-Based Recovery

FAILURE CLASSIFICATION

Database System Recovery

- All database reads/writes are within a transaction
- Transactions have the “ACID” properties
  - Atomicity - all or nothing
  - Consistency - preserves database integrity
  - Isolation - execute as if they were run alone
  - Durability - results are not lost by a failure
- Concurrency control guarantees I, contributes to C
- Application program guarantees C
- Recovery subsystem guarantees A & D, contributes to C

Failure Classification

- **Transaction failure**:
  - **Logical errors**: transaction cannot complete due to some internal error condition
  - **System errors**: the database system must terminate an active transaction due to an error condition (for example, deadlock)
- **System crash**: a power failure or other hardware or software failure causes the system to crash
  - **Fail-stop assumption**: non-volatile storage contents are assumed to not be corrupted as result of a system crash
    - Database systems have numerous integrity checks to prevent corruption of disk data
- **Disk failure**: a head crash or similar disk failure destroys all or part of disk storage
  - Destruction is assumed to be detectable
    - Disk drives use checksums to detect failures

Recovery Algorithms

- Consider transaction T_i that transfers \$50 from account *A* to account *B*
  - Two updates: subtract 50 from A and add 50 to B
- Transaction T_i requires updates to A and B to be output to the database
  - A failure may occur after one of these modifications have been made but before both of them are made
  - Modifying the database without ensuring that the transaction will commit may leave the database in an inconsistent state
  - Not modifying the database may result in lost updates if failure occurs just after transaction commits
- Recovery algorithms have two parts
  1. Actions taken during normal transaction processing to ensure enough information exists to recover from failures
  2. Actions taken after a failure to recover the database contents to a state that ensures atomicity, consistency and durability

- Failure Classification
- **Storage Structure**
- Recovery and Atomicity
- Log-Based Recovery

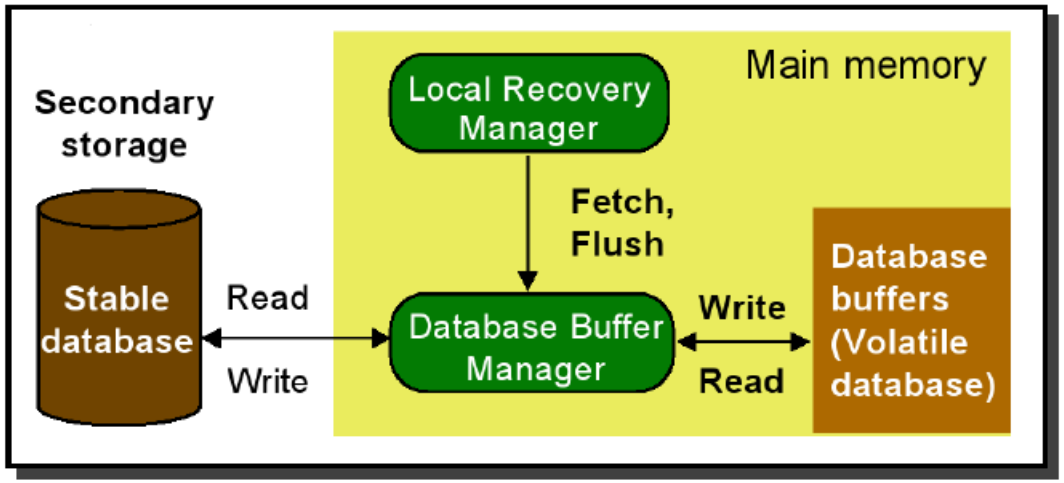
STORAGE STRUCTURE

Storage Structure

- **Volatile storage**:
  - does not survive system crashes
  - examples: main memory, cache memory
- **Nonvolatile storage**:
  - survives system crashes
  - examples: disk, tape, flash memory, non-volatile (battery backed up) RAM
  - but may still fail, losing data
- **Stable storage**:
  - a mythical form of storage that survives all failures
  - approximated by maintaining multiple copies on distinct nonvolatile media

Stable-Storage Implementation

- Maintain multiple copies of each block on separate disks
  - copies can be at remote sites to protect against disasters such as fire or flooding
- Failure during data transfer can still result in inconsistent copies. Block transfer can result in
  - Successful completion
  - Partial failure: destination block has incorrect information
  - Total failure: destination block was never updated
- Protecting storage media from failure during data transfer (one solution):
  - Execute output operation as follows (assuming two copies of each block):
    1. Write the information onto the first physical block
    2. When the first write successfully completes, write the same information onto the second physical block
    3. The output is completed only after the second write successfully completes



Stable-Storage Implementation (Cont.)

Protecting storage media from failure during data transfer (cont.):

- Copies of a block may differ due to failure during output operation. To recover from failure:
  1. First find inconsistent blocks:
     1. *Expensive solution*: Compare the two copies of every disk block
     2. *Better solution*:
        - Record in-progress disk writes on non-volatile storage (Non-volatile RAM or special area of disk)
        - Use this information during recovery to find blocks that may be inconsistent, and only compare copies of these
        - Used in hardware RAID systems
  2. If either copy of an inconsistent block is detected to have an error (bad checksum), overwrite it by the other copy
  3. If both have no error, but are different, overwrite the second block by the first block

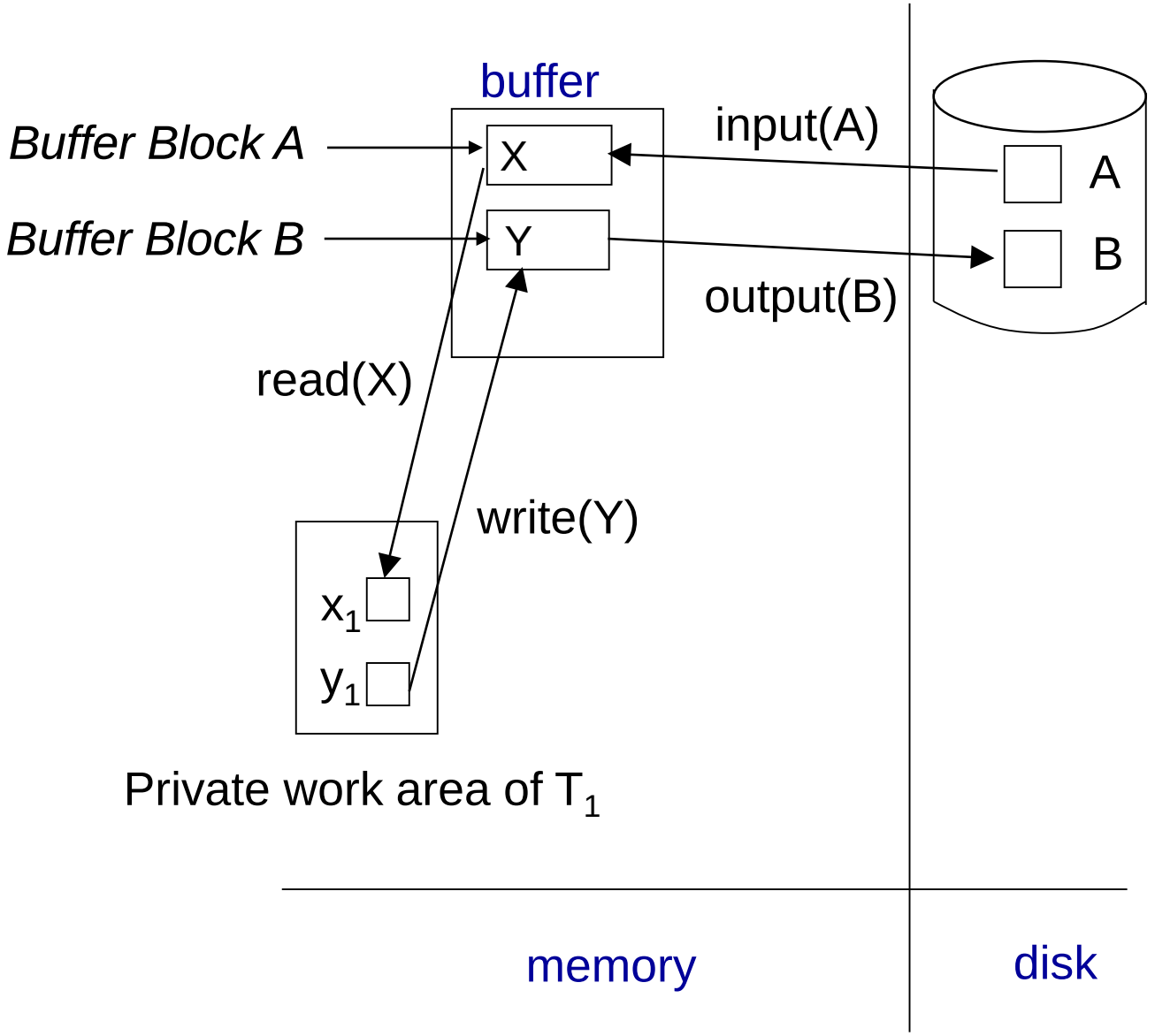
Data Access

- **Physical blocks** are those blocks residing on the disk
- **System buffer blocks** are the blocks residing temporarily in main memory
- Block movements between disk and main memory are initiated through the following two operations:
  - **input**(*B*) transfers the physical block *B* to main memory
  - **output**(*B*) transfers the buffer block *B* to the disk, and replaces the appropriate physical block there
- We assume, for simplicity, that each data item fits in, and is stored inside, a single block

Data Access (Cont.)

- Each transaction T_i has its private work-area in which local copies of all data items accessed and updated by it are kept
  - T_i's local copy of a data item X is denoted by x_i
  - B_X denotes block containing X
- Transferring data items between system buffer blocks and its private work-area done by:
  - **read**(X) assigns the value of data item X to the local variable x_i
  - **write**(X) assigns the value of local variable x_i to data item {X} in the buffer block
- Transactions
  - Must perform **read**(X) before accessing X for the first time (subsequent reads can be from local copy)
  - The **write**(X) can be executed at any time before the transaction commits
- Note that **output**(B_X) need not immediately follow **write**(X). System can perform the **output** operation when it deems fit

Example of Data Access



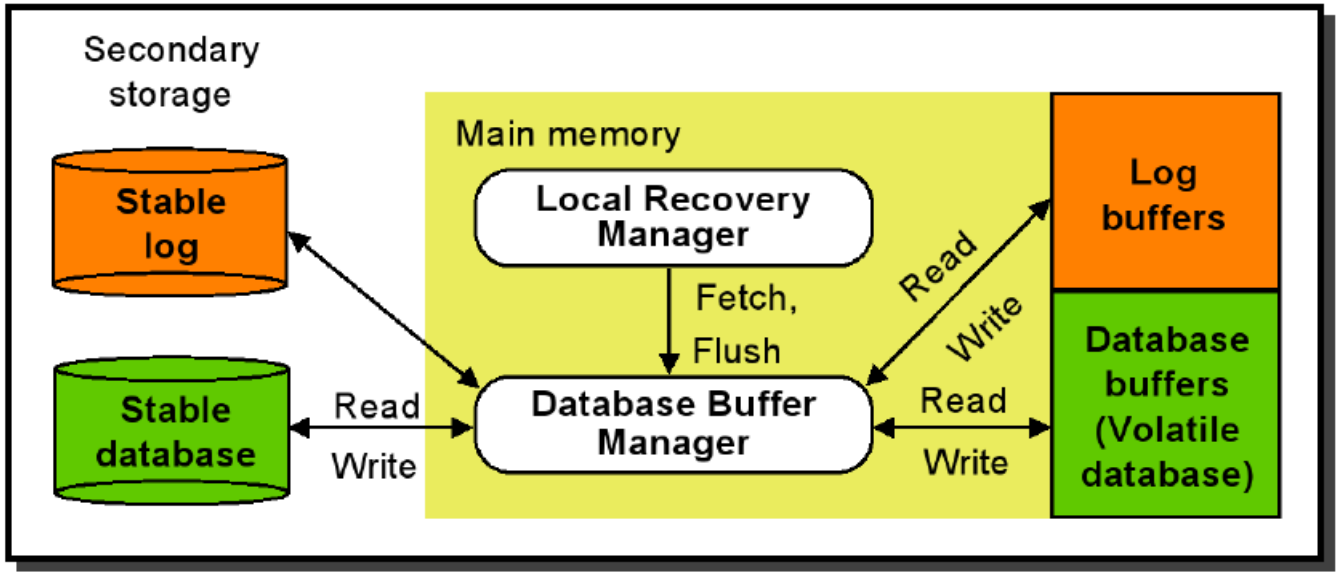
- Failure Classification
- Storage Structure
- **Recovery and Atomicity**
- Log-Based Recovery

RECOVERY AND ATOMICITY

Recovery and Atomicity

- To ensure atomicity despite failures, we first output information describing the modifications to stable storage without modifying the database itself
- We study **log-based recovery mechanisms** in detail
  - We first present key concepts
  - And then present the actual recovery algorithm
- Less used alternative: **shadow-paging**
- In this Module we assume serial execution of transactions
- In the next Module, we consider the case of concurrent transaction execution

- Failure Classification
- Storage Structure
- Recovery and Atomicity
- **Log-Based Recovery**



LOG-BASED RECOVERY

Log-Based Recovery

- A **log** is kept on stable storage
  - The log is a sequence of **log records**, which maintains information about update activities on the database
- When transaction T_i starts, it registers itself by writing a record
  $<T_i$ **start**$>$
  to the log
- *Before* T_i executes **write**(X), a log record
  $<T_i, X, V_1, V_2>$
  is written, where V_1 is the value of X before the write (the **old value**), and V_2 is the value to be written to X (the **new value**)
- When T_i finishes it last statement, the log record $<T_i$ **commi**t$>$ is written
- Two approaches using logs
  - Immediate database modification
  - Deferred database modification

Database Modification

- The **immediate-modification** scheme allows updates of an uncommitted transaction to be made to the buffer, or the disk itself, before the transaction commits
- Update log record must be written ***before*** a database item is written
  - We assume that the log record is output directly to stable storage
- Output of updated blocks to disk storage can take place at any time before or after transaction commit
- Order in which blocks are output can be different from the order in which they are written
- The **deferred-modification** scheme performs updates to buffer/disk only at the time of transaction commit
  - Simplifies some aspects of recovery
  - But has overhead of storing local copy
- We cover here only the immediate-modification scheme

Transaction Commit

- A transaction is said to have committed when its commit log record is output to stable storage
  - All previous log records of the transaction must have been output already
- Writes performed by a transaction may still be in the buffer when the transaction commits, and may be output later

Immediate Database Modification Example

Log	Write	Output
<T_0 **start**>		
<T_0, A, 1000, 950>		
<T_0, B, 2000, 2050>		
	A = 950 B = 2050	
<T_0 **commit**>		
<T_1 **start**>		
<T_1, C, 700, 600>		
	C = 600	
<T_1 **commit**>		

- Note: B_X denotes block containing X

B_B , B_C — B_C output before T_1 commits

B_A — B_A output after T_0 commits

Undo and Redo Operations

- **Undo** of a log record <T_i, X, V_1, V_2> writes the **old** value V_1 to X
- **Redo** of a log record <T_i, X, V_1, V_2> writes the **new** value V_2 to X
- **Undo and Redo of Transactions**
  - **undo**(T_i) restores the value of all data items updated by T_i to their old values, going backwards from the last log record for T_i
    - Each time a data item X is restored to its old value V a special log record (called r**edo-only**) <T_i , X, V> is written out
    - When undo of a transaction is complete, a log record <T_i **abort**> is written out (to indicate that the undo was completed)
  - **redo**(T_i) sets the value of all data items updated by T_i to the new values, going forward from the first log record for T_i
    - No logging is done in this case

Undo and Redo Operations (Cont.)

- The **undo** and **redo** operations are used in several different circumstances:
  - The **undo is** used for transaction rollback during normal operation
    - in case a transaction cannot complete its execution due to some logical error
  - The **undo** and **redo** operations are used during recovery from failure
- We need to deal with the case where during recovery from failure another failure occurs prior to the system having fully recovered

Transaction rollback (during normal operation)

- Let T_i be the transaction to be rolled back
- Scan log backwards from the end, and for each log record of T_i of the form $<T_i, X_j, V_1, V_2>$
  - Perform the undo by writing V_1 to X_j,
  - Write a log record $<T_i, X_j, V_1>$
    - such log records are called **compensation log records**
- Once the record $<T_i$ **start**> is found stop the scan and write the log record $<T_i$ **abort**>

Undo and Redo on Recovering from Failure

- When recovering after failure:
  - Transaction T_i needs to be undone if the log
    - contains the record <T_i **start**>,
    - but does not contain either the record <T_i **commit**> *or* <T_i **abort**>
  - Transaction T_i needs to be redone if the log
    - contains the records <T_i **start**>
    - and contains the record <T_i **commit**> *or* <T_i **abort**>
  - It may seem strange to redo transaction T_i if the record <T_i **abort**> record is in the log
    - To see why this works, note that if <T_i **abort**> is in the log, so are the redo-only records written by the undo operation. Thus, the end result will be to undo T_i 's modifications in this case. This slight redundancy simplifies the recovery algorithm and enables faster overall recovery time
    - such a redo redoes all the original actions including the steps that restored old value – Known as **repeating history**

Immediate Modification Recovery Example

Below we show the log as it appears at three instances of time.

(a)	(b)	(c)
<T_0 start>	<T_0 start>	<T_0 start>
<T_0, A, 1000, 950>	<T_0, A, 1000, 950>	<T_0, A, 1000, 950>
<T_0, B, 2000, 2050>	<T_0, B, 2000, 2050>	<T_0, B, 2000, 2050>
	<T_0 commit>	<T_0 commit>
	<T_1 start>	<T_1 start>
	<T_1, C, 700, 600>	<T_1, C, 700, 600>
		<T_1 commit>

Recovery actions in each case above are:

(a) undo (T_0): B is restored to 2000 and A to 1000, and log records <T_0, B, 2000>, <T_0, A, 1000>, <T_0, **abort**> are written out

(b) redo (T_0) and undo (T_1): *A* and *B* are set to 950 and 2050 and C is restored to 700. Log records <T_1, C, 700>, <T_1, **abort**> are written out

(c) redo (T_0) and redo (T_1): A and B are set to 950 and 2050 respectively. Then *C* is set to 600

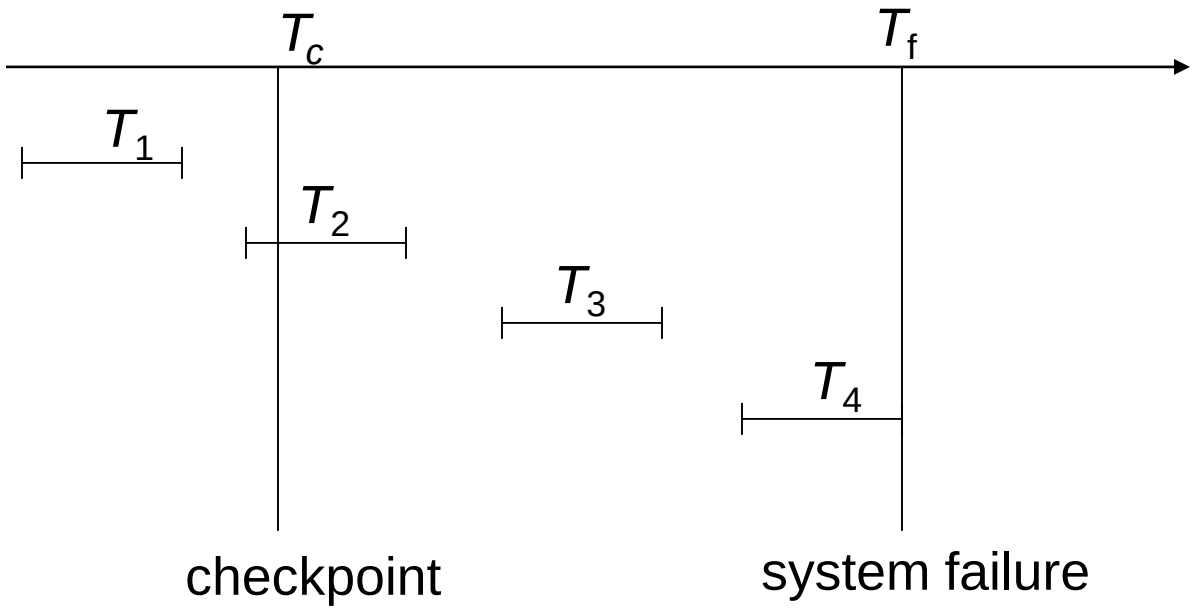
Checkpoints

- Redoing/undoing all transactions recorded in the log can be very slow
  - Processing the entire log is time-consuming if the system has run for a long time
  - We might unnecessarily redo transactions which have already output their updates to the database
- Streamline recovery procedure by periodically performing **checkpointing**
- All updates are stopped while doing checkpointing
  1. Output all log records currently residing in main memory onto stable storage
  2. Output all modified buffer blocks to the disk
  3. Write a log record < **checkpoint** *L*> onto stable storage where *L* is a list of all transactions active at the time of checkpoint

Checkpoints (Cont.)

- During recovery we need to consider only the most recent transaction T_i that started before the checkpoint, and transactions that started after T_i
  - Scan backwards from end of log to find the most recent <**checkpoint** *L*> record
  - Only transactions that are in *L* or started after the checkpoint need to be redone or undone
  - Transactions that committed or aborted before the checkpoint already have all their updates output to stable storage
- Some earlier part of the log may be needed for undo operations
  - Continue scanning backwards till a record <T_i **start**> is found for every transaction T_i in *L*
  - Parts of log prior to earliest <T_i **start**> record above are not needed for recovery, and can be erased whenever desired

Example of Checkpoints



- Any transactions that committed before the last checkpoint should be ignored
  - T_1 can be ignored (updates already output to disk due to checkpoint)
- Any transactions that committed since the last checkpoint need to be redone
  - T_2 and T_3 redone
- Any transaction that was running at the time of failure needs to be undone and restarted
  - T_4 undone

Module Summary

- Failures may be due to variety of sources – each needs a strategy for handling
- A proper mix and management of volatile, non-volatile and stable storage can guarantee recovery from failures and ensure Atomicity, Consistency and Durability
- Log-based recovery is efficient and effective

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Database Management Systems

Module 37: Recovery/2

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Module Recap

- Failure Classification
- Storage Structure
- Recovery and Atomicity
- Log-Based Recovery

Module Objectives

- To focus on concurrent transactions and understand the recovery algorithms
- To understand operation logging for recovery with early lock release

Module Outline

- Recovery Algorithm
- Recovery with Early Lock Release

- **Recovery Algorithm**
- Recovery with Early Lock Release

RECOVERY ALGORITHM

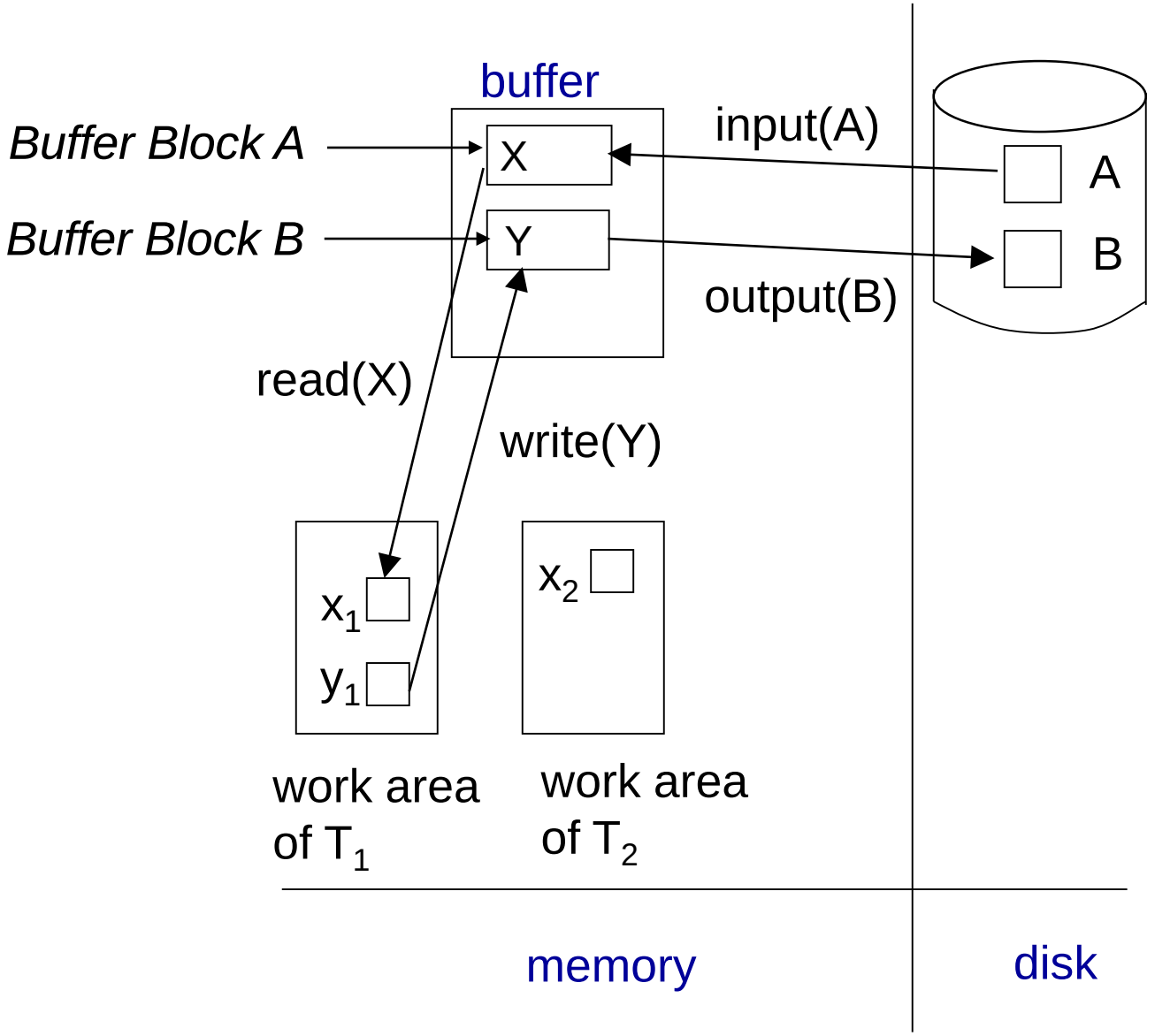
Recovery Schemes

- **So far:**
  - We covered key concepts
  - We assumed serial execution of transactions
- **Now**:
  - We discuss concurrency control issues
  - We present the components of the basic recovery algorithm

Concurrency Control and Recovery

- With concurrent transactions, all transactions share a single disk buffer and a single log
  - A buffer block can have data items updated by one or more transactions
- We assume that *if a transaction T_i has modified an item, no other transaction can modify the same item until T_i has committed or aborted*
  - That is, the updates of uncommitted transactions should not be visible to other transactions
    - Otherwise how do we perform undo if T_1 updates A, then T_2 updates A and commits, and finally T_1 has to abort?
  - Can be ensured by obtaining exclusive locks on updated items and holding the locks till end of transaction (strict two-phase locking)
- Log records of different transactions may be interspersed in the log

Example of Data Access with Concurrent transactions



Recovery Algorithm

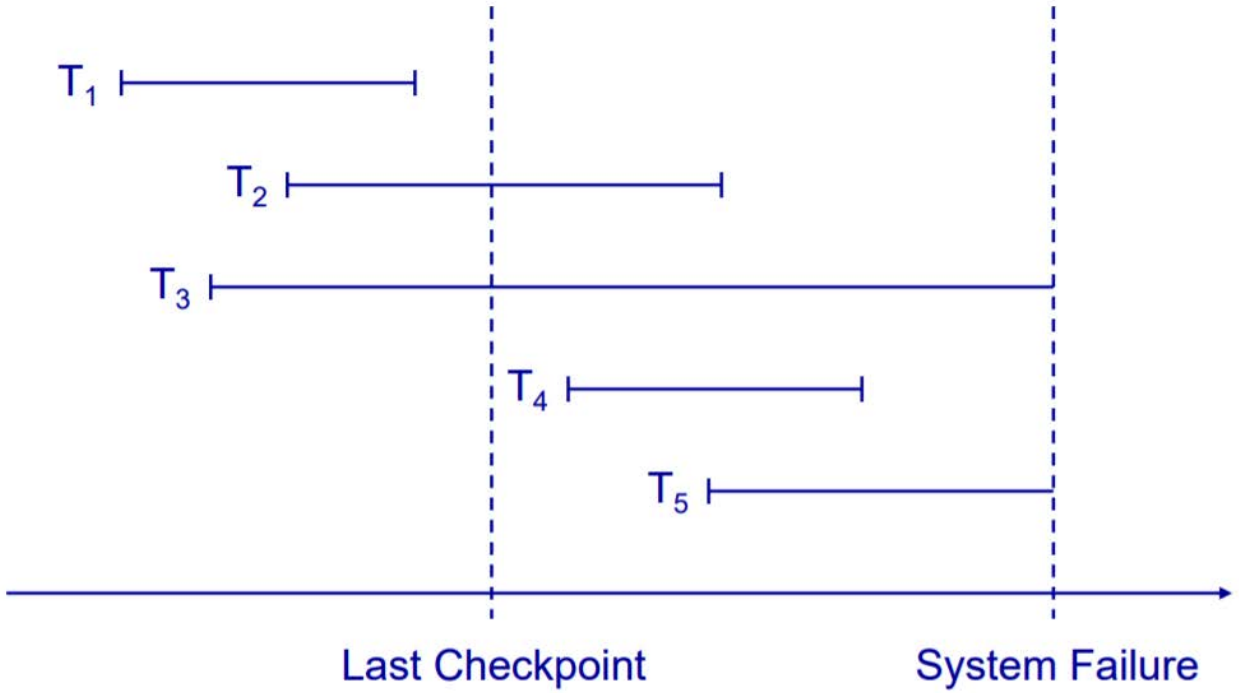
- **Logging** (during normal operation):
  - <T_i **start**> at transaction start
  - <T_i, X_j, V_1, V_2> for each update, and
  - <T_i **commit**> at transaction end

Recovery Algorithm (Contd.)

- **Transaction rollback (during normal operation)**
  - Let T_i be the transaction to be rolled back
  - Scan log backwards from the end, and for each log record of T_i of the form $\langle T_i, X_j, V_1, V_2 \rangle$
    - perform the undo by writing V_1 to X_j,
    - write a log record $\langle T_i, X_j, V_1 \rangle$
      - such log records are called **compensation log records**
  - Once the record $\langle T_i$ **start**$\rangle$ is found stop the scan and write the log record $\langle T_i$ **abort**$\rangle$

Recovery Algorithm (Cont.)

- **Recovery from failure**: Two phases
  - **Redo phase**: replay updates of **all** transactions, whether they committed, aborted, or are incomplete
  - **Undo phase**: undo all incomplete transactions



Requirement:
- Transactions of type T1 need no recovery
- Transactions of type T2 or T4 need to be redone
- Transactions of type T3 or T5 need to be undone and restarted

Strategy:
- Ignore T1
- Redo T2, T3, T4 and T5
- Undo T3 and T5

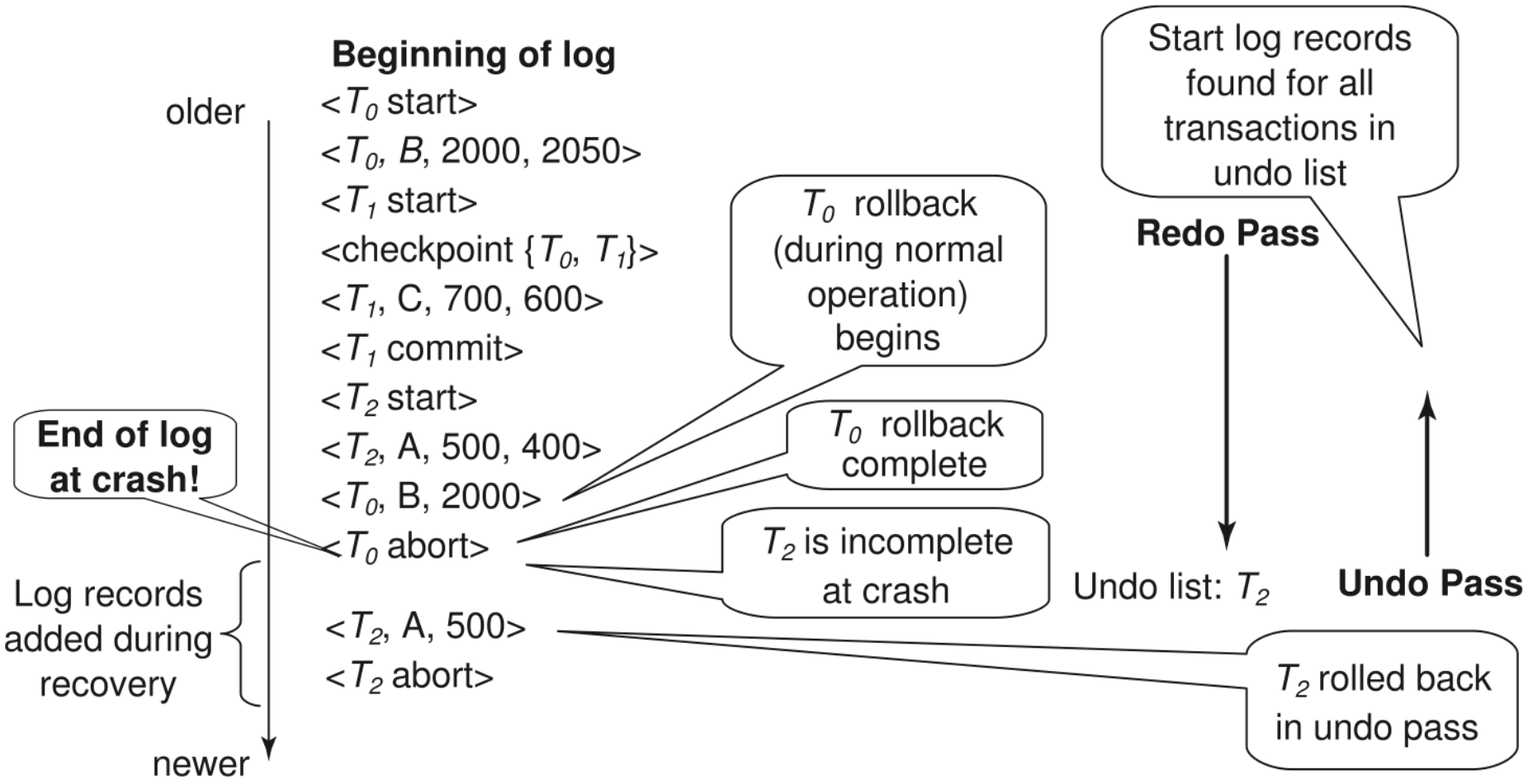
Recovery Algorithm (Cont.)

- **Redo phase**:
  1. Find last <**checkpoint** *L*> record, and set undo-list to *L*
  2. Scan forward from above <**checkpoint** *L*> record
     1. Whenever a record <T_i, X_j, V_1, V_2> is found, redo it by writing V_2 to X_j
     2. Whenever a log record <T_i **start**> is found, add T_i to undo-list
     3. Whenever a log record <T_i **commit**> *or* <T_i **abort**> is found, remove T_i from undo-list

Recovery Algorithm (Cont.)

- **Undo phase:**
  1. Scan log backwards from end
     1. Whenever a log record <T_i, X_j, V_1, V_2> is found where T_i is in undo-list perform same actions as for transaction rollback:
        1. Perform undo by writing V_1 to X_j
        2. Write a log record <T_i , X_j, V_1>
     2. Whenever a log record <T_i **start**> is found where T_i is in undo-list,
        1. Write a log record <T_i **abort**>
        2. Remove T_i from undo-list
     3. Stop when undo-list is empty
        - That is,<T_i **start**> has been found for every transaction in undo-list
- After undo phase completes, normal transaction processing can commence

Example of Recovery



- **Recovery Algorithm**
- Recovery with Early Lock Release

RECOVERY WITH EARLY LOCK RELEASE

Recovery with Early Lock Release

- Support for high-concurrency locking techniques, such as those used for B^+-tree concurrency control, which release locks early
  - Supports “logical undo”
- Recovery based on “repeating history”, whereby recovery executes exactly the same actions as normal processing

Logical Undo Logging

- Operations like B$^+$-tree insertions and deletions release locks early
  - They cannot be undone by restoring old values (**physical undo**), since once a lock is released, other transactions may have updated the B$^+$-tree
  - Instead, insertions (resp. deletions) are undone by executing a deletion (resp. insertion) operation (known as **logical undo**)
- For such operations, undo log records should contain the undo operation to be executed
  - Such logging is called **logical undo logging**, in contrast to **physical undo logging**
    - Operations are called **logical operations**
  - Other examples:
    - delete of tuple, to undo insert of tuple
      - allows early lock release on space allocation information
    - subtract amount deposited, to undo deposit
      - allows early lock release on bank balance

Physical Redo

- Redo information is logged **physically** (that is, new value for each write) even for operations with logical undo
  - Logical redo is very complicated since database state on disk may not be “operation consistent” when recovery starts
  - Physical redo logging does not conflict with early lock release

Operation Logging

- Operation logging is done as follows:
  1. When operation starts, log <T_i, O_j, **operation-begin**>. Here O_j is a unique identifier of the operation instance
  2. While operation is executing, normal log records with physical redo and physical undo information are logged
  3. When operation completes, <T_i, O_j, **operation-end**, U> is logged, where U contains information needed to perform a logical undo information

Example: insert of (key, record-id) pair (K5, RID7) into index I9

<T1, O1, operation-begin>

….

<T1, X, 10, K5>

<T1, Y, 45, RID7>

} Physical redo of steps in insert

<T1, O1, operation-end, (delete I9, K5, RID7)>

Operation Logging (Cont.)

- If crash/rollback occurs before operation completes:
  - the **operation-end** log record is not found, and
  - the physical undo information is used to undo operation
- If crash/rollback occurs after the operation completes:
  - the **operation-end** log record is found, and in this case
  - logical undo is performed using *U*; the physical undo information for the operation is ignored
- Redo of operation (after crash) still uses physical redo information

Transaction Rollback with Logical Undo

Rollback of transaction T_i, scan the log backwards

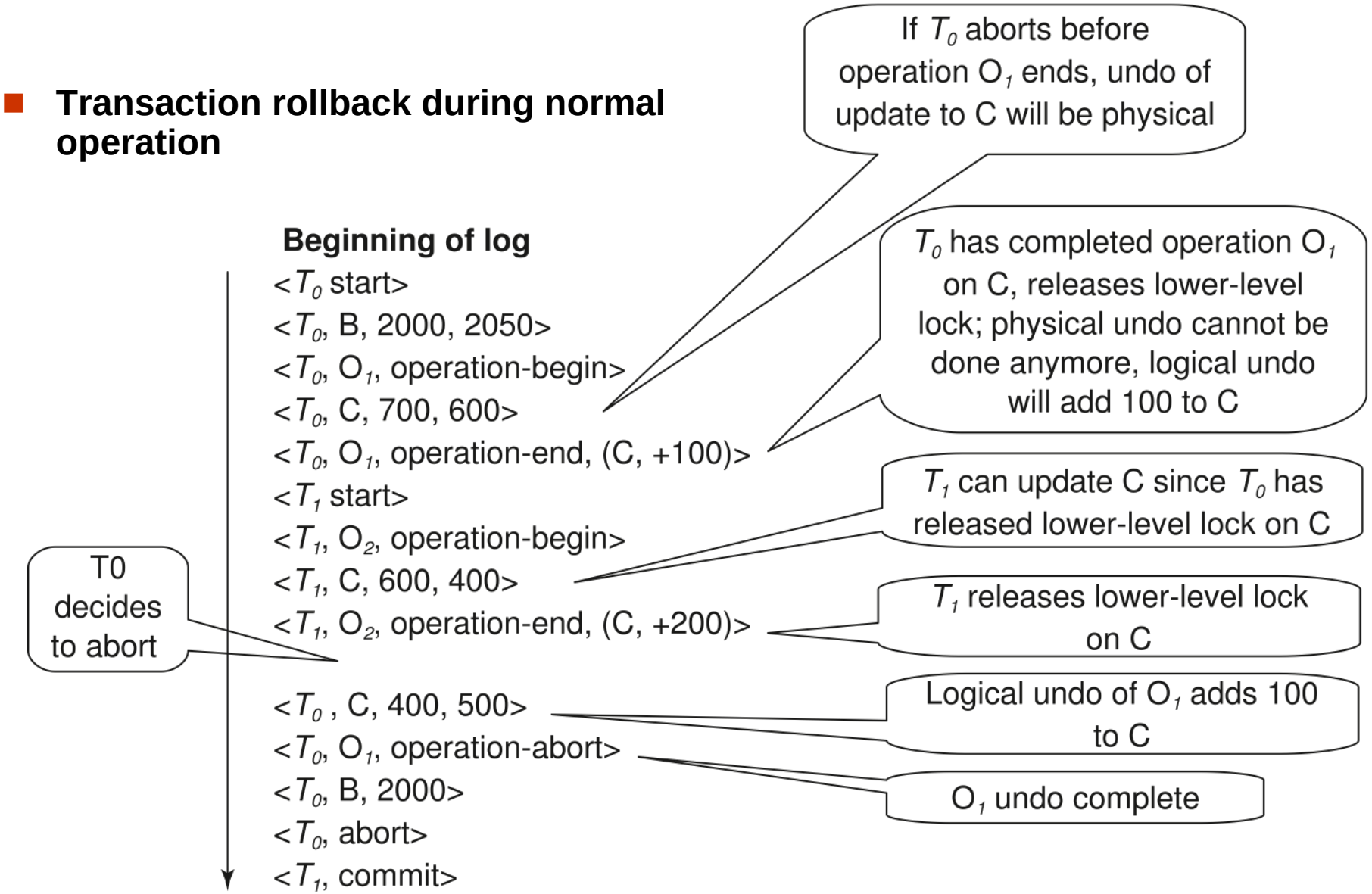
1. If a log record $<T_i, X, V_1, V_2>$ is found, perform the undo and log $<T_i, X, V_1>$
2. If a $<T_i, O_j,$ **operation-end**, $U>$ record is found
   - Rollback the operation logically using the undo information U
     - Updates performed during roll back are logged just like during normal operation execution
     - At the end of the operation rollback, instead of logging an **operation-end** record, generate a record $<T_i, O_j,$ **operation-abort**$>$
   - Skip all preceding log records for T_i until the record $<T_i, O_j$ **operation-begin**$>$ is found
3. If a redo-only record is found ignore it
4. If a $<T_i, O_j,$ **operation-abort**$>$ record is found:
   - skip all preceding log records for T_i until the record $<T_i, O_j,$ **operation-begin**$>$ is found
5. Stop the scan when the record $<T_i,$ **start**$>$ is found
6. Add a $<T_i,$ **abort**$>$ record to the log

Note:

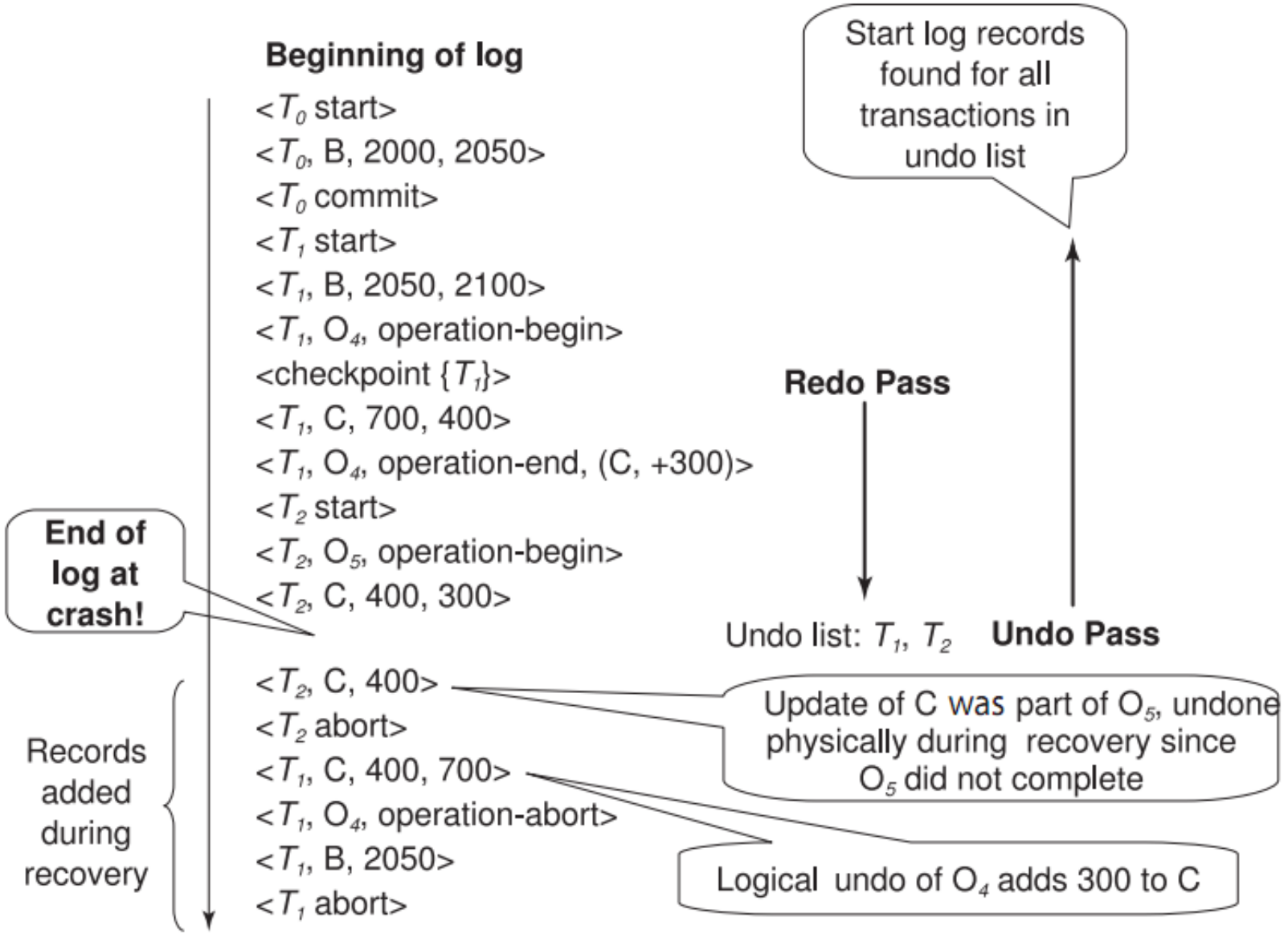
- Cases 3 and 4 above can occur only if the database crashes while a transaction is being rolled back
- Skipping of log records as in case 4 is important to prevent multiple rollback of the same operation

Transaction Rollback with Logical Undo

- **Transaction rollback during normal operation**



Failure Recovery with Logical Undo



Transaction Rollback: Another Example

- Example with a complete and an incomplete operation

<T1, start>

<T1, O1, operation-begin>

….

<T1, X, 10, K5>

<T1, Y, 45, RID7>

<T1, O1, operation-end, (delete I9, K5, RID7)>

<T1, O2, operation-begin>

<T1, Z, 45, 70>

← T1 Rollback begins here

<T1, Z, 45> ← redo-only log record during physical undo (of incomplete O2)

<T1, Y, .., ..> ← Normal redo records for logical undo of O1

…

<T1, O1, operation-abort> ← What if crash occurred immediately after this?

<T1, abort>

Recovery Algorithm with Logical Undo

Basically same as earlier algorithm, except for changes described earlier for transaction rollback

1. (**Redo phase**): Scan log forward from last < **checkpoint** *L*> record till end of log
   1. **Repeat history** by physically redoing all updates of all transactions,
   2. Create an undo-list during the scan as follows
      - *undo-list* is set to *L* initially
      - Whenever <T_i **start**> is found T_i is added to *undo-list*
      - Whenever <T_i **commit**> or <T_i **abort**> is found, T_i is deleted from *undo-list*

   This brings database to state as of crash, with committed as well as uncommitted transactions having been redone

   Now *undo-list* contains transactions that are **incomplete**, that is, have neither committed nor been fully rolled back

Recovery with Logical Undo (Cont.)

Recovery from system crash (cont.)

2. (**Undo phase**): Scan log backwards, performing undo on log records of transactions found in *undo-list*
   - Log records of transactions being rolled back are processed as described earlier, as they are found
     - Single shared scan for all transactions being undone
   - When <T_i **start**> is found for a transaction T_i in *undo-list*, write a <T_i **abort**> log record.
   - Stop scan when <T_i **start**> records have been found for all T_i in *undo-list*
- This undoes the effects of incomplete transactions (those with neither **commit** nor **abort** log records). Recovery is now complete

Module Summary

- Studies the recovery algorithms for concurrent transactions
- Recovery based on operation logging supplements log-based recovery

PPD

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Database Management Systems

Module 38: Query Processing and Optimization/1: Processing

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Module Recap

- Failure Classification
- Storage Structure
- Recovery and Atomicity
- Log-Based Recovery

Module Objectives

- To understand the overall flow for Query Processing
- To define the Measures of Query Cost
- To understand the algorithms for processing Selection Operations, Sorting, Join Operations, and a few Other Operations

PPD

Module Outline

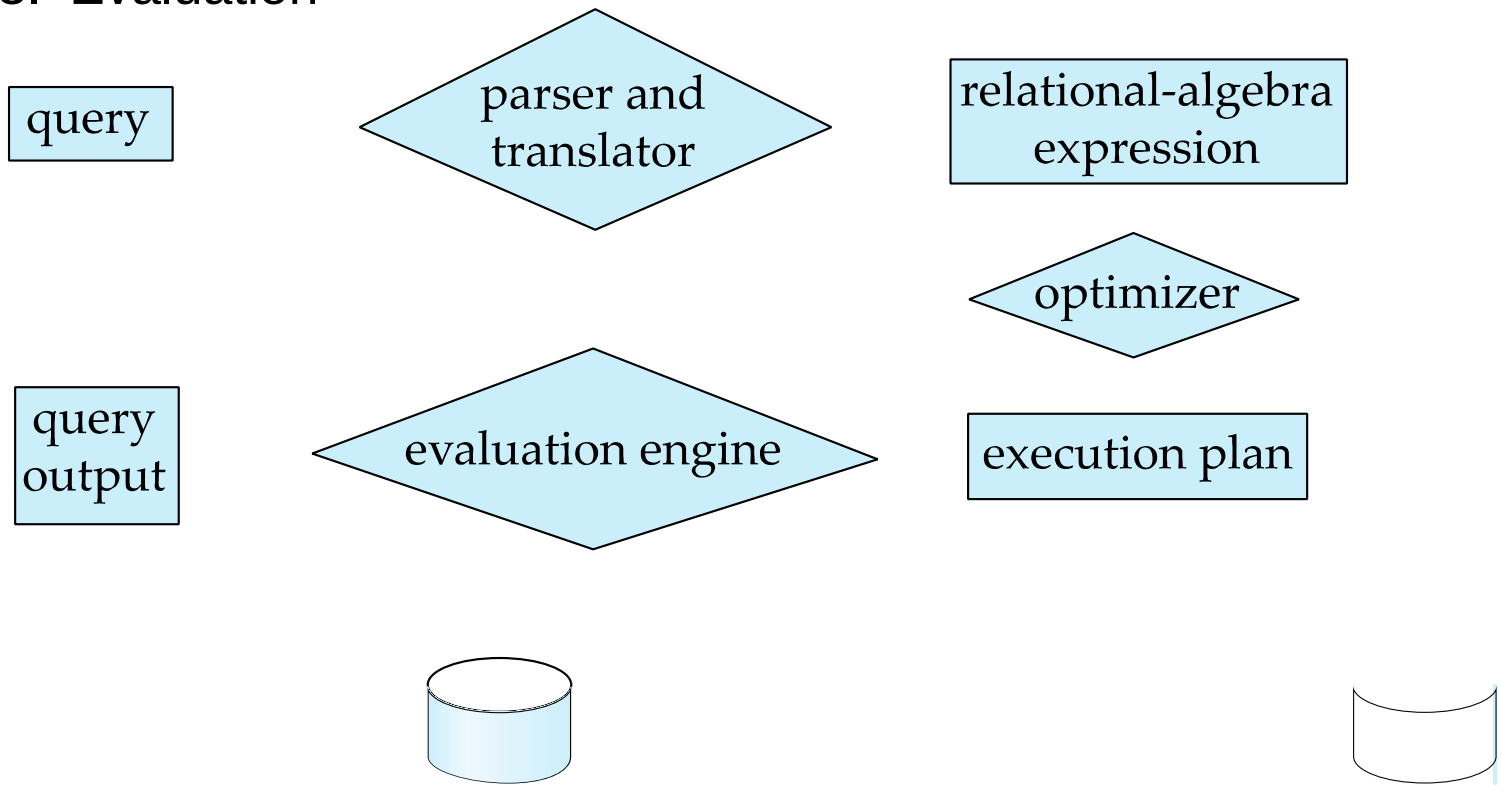
- Overview of Query Processing
- Measures of Query Cost
- Selection Operation
- Sorting
- Join Operation
- Other Operations

- **Overview of Query Processing**
- Measures of Query Cost
- Selection Operation
- Sorting
- Join Operation
- Other Operations

OVERVIEW OF QUERY PROCESSING

Basic Steps in Query Processing

1. Parsing and translation
2. Optimization
3. Evaluation



Basic Steps in Query Processing (Cont.)

- Parsing and translation
  - translate the query into its internal form
    - This is then translated into relational algebra
  - Parser checks syntax, verifies relations
- Evaluation
  - The query-execution engine takes a query-evaluation plan, executes that plan, and returns the answers to the query

Basic Steps in Query Processing : Optimization

- A relational algebra expression may have many equivalent expressions
  - E.g., $\sigma_{salary<75000}(\Pi_{salary}(instructor))$ is equivalent to $\Pi_{salary}(\sigma_{salary<75000}(instructor))$
- Each relational algebra operation can be evaluated using one of several different algorithms
  - Correspondingly, a relational-algebra expression can be evaluated in many ways
- Annotated expression specifying detailed evaluation strategy is called an **evaluation-plan**.
  - E.g., can use an index on *salary* to find instructors with salary < 75000,
  - or can perform complete relation scan and discard instructors with salary ≥ 75000

Basic Steps: Optimization (Cont.)

- **Query Optimization**: Amongst all equivalent evaluation plans choose the one with lowest cost
  - Cost is estimated using statistical information from the database catalog
    - e.g. number of tuples in each relation, size of tuples, etc.
- In this module we study
  - How to measure query costs
  - Algorithms for evaluating relational algebra operations
  - How to combine algorithms for individual operations in order to evaluate a complete expression
- In the next module
  - We study how to optimize queries, that is, how to find an evaluation plan with lowest estimated cost

- Overview of Query Processing
- **Measures of Query Cost**
- Selection Operation
- Sorting
- Join Operation
- Other Operations

MEASURES OF QUERY COST

Measures of Query Cost

- Cost is generally measured as total elapsed time for answering query
  - Many factors contribute to time cost
    - *disk accesses, CPU*, or even network *communication*
- Typically disk access is the predominant cost, and is also relatively easy to estimate
- Measured by taking into account
  - Number of seeks * average-seek-cost
  - Number of blocks read * average-block-read-cost
  - Number of blocks written * average-block-write-cost
    - Cost to write a block is greater than cost to read a block
      - data is read back after being written to ensure that the write was successful

Measures of Query Cost (Cont.)

- For simplicity we just use the **number of block transfers** *from disk and the* **number of seeks** as the cost measures
  - t_T – time to transfer one block
  - t_S – time for one seek
  - Cost for b block transfers plus S seeks
    $$b * t_T + S * t_S$$
- We ignore CPU costs for simplicity
  - Real systems do take CPU cost into account
- We do not include cost to writing output to disk in our cost formulae

Measures of Query Cost (Cont.)

- Several algorithms can reduce disk IO by using extra buffer space
  - Amount of real memory available to buffer depends on other concurrent queries and OS processes, known only during execution
    - We often use worst case estimates, assuming only the minimum amount of memory needed for the operation is available
- Required data may be buffer resident already, avoiding disk I/O
  - But hard to take into account for cost estimation

- Overview of Query Processing
- Measures of Query Cost
- **Selection Operation**
- Sorting
- Join Operation
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SELECTION OPERATION

Selection Operation

- **File scan**
- Algorithm **A1** (**linear search**). Scan each file block and test all records to see whether they satisfy the selection condition
  - Cost estimate = b_r block transfers + 1 seek
    - b_r denotes number of blocks containing records from relation r
  - If selection is on a key attribute, can stop on finding record
    - cost = (b_r /2) block transfers + 1 seek
  - Linear search can be applied regardless of
    - selection condition or
    - ordering of records in the file, or
    - availability of indices
- Note: binary search generally does not make sense since data is not stored consecutively
  - except when there is an index available,
  - and binary search requires more seeks than index search

Selections Using Indices

- **Index scan** – search algorithms that use an index
  - selection condition must be on search-key of index
  - h_i = height of B+ Tree
- **A2** (**primary index, equality on key**). Retrieve a single record that satisfies the corresponding equality condition
  - *Cost* = $(h_i + 1) * (t_T + t_S)$
- **A3** (**primary index, equality on nonkey**) Retrieve multiple records
  - Records will be on consecutive blocks
    - Let b = number of blocks containing matching records
  - *Cost* = $h_i * (t_T + t_S) + t_S + t_T * b$

Selections Using Indices

- **A4** (**secondary index, equality on nonkey**).
  - Retrieve a single record if the search-key is a candidate key
    - *Cost* = $(h_i + 1) * (t_T + t_S)$
  - Retrieve multiple records if search-key is not a candidate key
    - each of *n* matching records may be on a different block
    - Cost = $(h_i + n) * (t_T + t_S)$
      - Can be very expensive!

Selections Involving Comparisons

- Can implement selections of the form $\sigma_{A \le V}(r)$ or $\sigma_{A \ge V}(r)$ by using
  - a linear file scan,
  - or by using indices in the following ways:
- **A5** (**primary index, comparison**). (Relation is sorted on A)
  - For $\sigma_{A \ge V}(r)$ use index to find first tuple $\ge v$ and scan relation sequentially from there
    - Cost $= h_i * (t_T + t_S) + b * t_T$
  - For $\sigma_{A \le V}(r)$ just scan relation sequentially till first tuple $> v$; do not use index
    - Cost $= t_S + b * t_T$

Selections Involving Comparisons

- Can implement selections of the form $\sigma_{A \le V}(r)$ or $\sigma_{A \ge V}(r)$ by using
  - a linear file scan,
  - or by using indices in the following ways:
- **A6** (**secondary index, comparison**).
  - For $\sigma_{A \ge V}(r)$ use index to find first index entry $\ge v$ and scan index sequentially from there, to find pointers to records
    - Cost = $(h_i + n) * (t_T + t_S)$
  - For $\sigma_{A \le V}(r)$ just scan leaf pages of index finding pointers to records, till first entry $> v$
  - In either case, retrieve records that are pointed to
    - requires an I/O for each record
    - Linear file scan may be cheaper

Implementation of Complex Selections

- **Conjunction:** $\sigma_{\theta 1 \wedge \theta 2 \wedge \ldots \theta n}(r)$
- **A7** (**conjunctive selection using one index**)
  - Select a combination of θ_i and algorithms A1 through A6 that results in the least cost for $\sigma_{\theta i}(r)$
  - Test other conditions on tuple after fetching it into memory buffer
- **A8** (**conjunctive selection using composite index**)
  - Use appropriate composite (multiple-key) index if available
- **A9** (**conjunctive selection by intersection of identifiers**)
  - Requires indices with record pointers
  - Use corresponding index for each condition, and take intersection of all the obtained sets of record pointers
  - Then fetch records from file
  - If some conditions do not have appropriate indices, apply test in memory

Algorithms for Complex Selections

- **Disjunction:** $\sigma_{\theta 1 \vee \theta 2 \vee \ldots \theta n}(r)$.
- **A10** (**disjunctive selection by union of identifiers**)
  - Applicable if *all* conditions have available indices
    - Otherwise use linear scan
  - Use corresponding index for each condition, and take union of all the obtained sets of record pointers
  - Then fetch records from file
- **Negation:** $\sigma_{\neg\theta}(r)$
  - Use linear scan on file
  - If very few records satisfy $\neg\theta$, and an index is applicable to θ
    - Find satisfying records using index and fetch from file

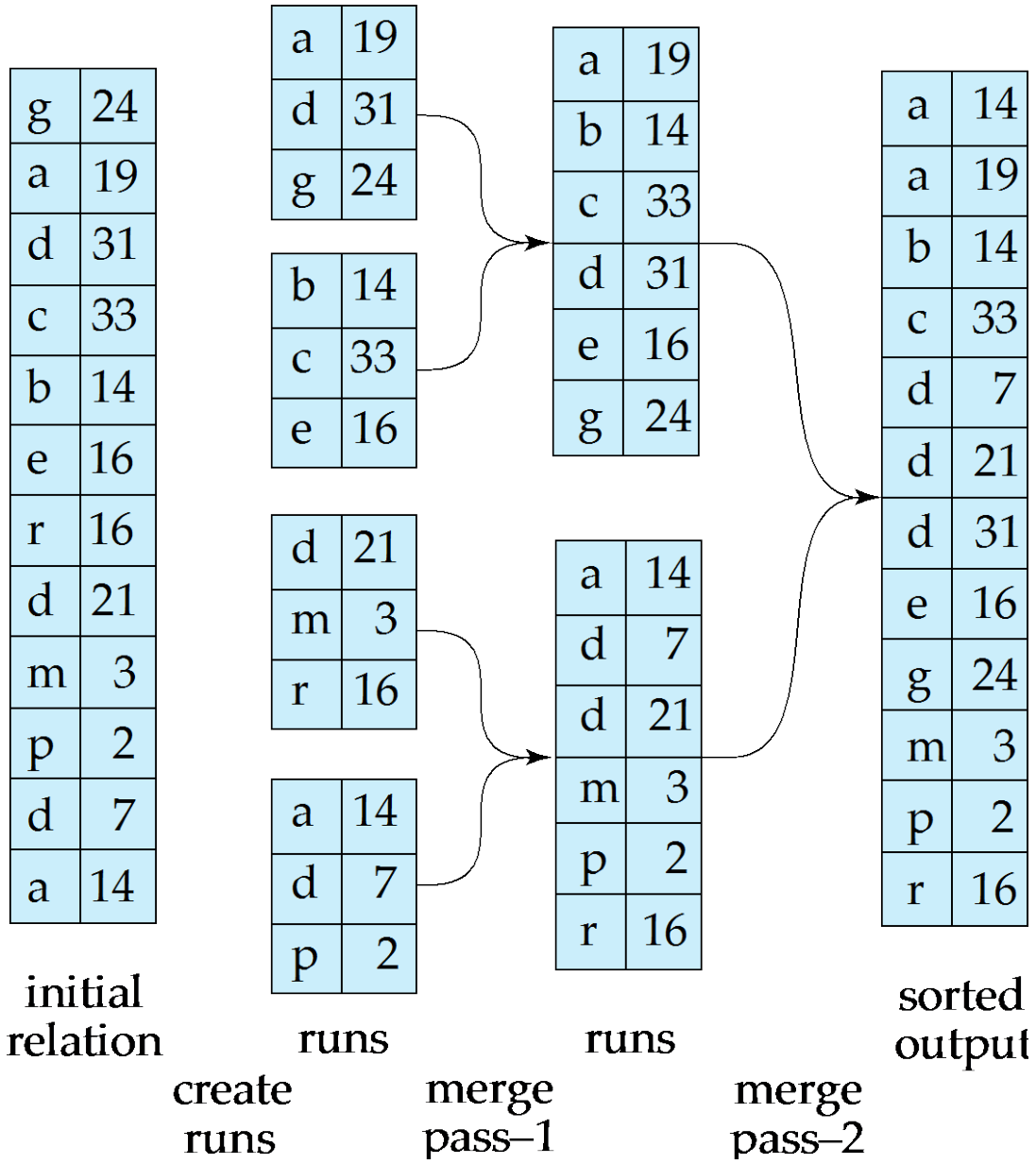
- Overview of Query Processing
- Measures of Query Cost
- Selection Operation
- **Sorting**
- Join Operation
- Other Operations

SORTING

Sorting

- We may build an index on the relation, and then use the index to read the relation in sorted order
  - May lead to one disk block access for each tuple
- For relations that fit in memory, techniques like quicksort can be used
- For relations that do not fit in memory, **external sort-merge** is a good choice

Example: External Sorting Using Sort-Merge



External Sort-Merge

Let *M* denote memory size (in pages)

1. **Create sorted runs**. Let *i* be 0 initially

   Repeatedly do the following till the end of the relation:

   (a) Read *M* blocks of relation into memory

   (b) Sort the in-memory blocks

   (c) Write sorted data to run R_i; increment *i.*

   Let the final value of *i* be *N*

2. *Merge the runs (next slide)…..*

External Sort-Merge (Cont.)

2. **Merge the runs (N-way merge)**. We assume (for now) that $N < M$
   1. Use N blocks of memory to buffer input runs, and 1 block to buffer output. Read the first block of each run into its buffer page
   2. **repeat**
      1. Select the first record (in sort order) among all buffer pages
      2. Write the record to the output buffer. If the output buffer is full write it to disk.
      3. Delete the record from its input buffer page
         If the buffer page becomes empty **then**
         read the next block (if any) of the run into the buffer
   3. **until** all input buffer pages are empty:

External Sort-Merge (Cont.)

- If $N \geq M$, several merge *passes* are required
  - In each pass, contiguous groups of M - 1 runs are merged.
  - A pass reduces the number of runs by a factor of M -1, and creates runs longer by the same factor
    - E.g. If M=11, and there are 90 runs, one pass reduces the number of runs to 9, each 10 times the size of the initial runs
  - Repeated passes are performed till all runs have been merged into one

- Overview of Query Processing
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JOIN OPERATION

Join Operation

- Several different algorithms to implement joins
  - **Nested-loop join**
  - **Block nested-loop join**
  - **Indexed nested-loop join**
  - Merge-join
  - Hash-join
- Choice based on cost estimate
- Examples use the following information
  - Number of records of *student*: 5,000 *takes*: 10,000
  - Number of blocks of *student*: 100 *takes*: 400

Nested-Loop Join

- To compute the theta join $r \bowtie_\theta s$

  for each tuple t_r **in** r **do begin**

  for each tuple t_s **in** s **do begin**

  test pair (t_r, t_s) to see if they satisfy the join condition θ

  if they do, add $t_r \bullet t_s$ to the result.

  end

  end

- r is called the **outer relation** and s the **inner relation** of the join
- Requires no indices and can be used with any kind of join condition
- Expensive since it examines every pair of tuples in the two relations

Nested-Loop Join (Cont.)

- In the worst case, if there is enough memory only to hold one block of each relation, the estimated cost is
  $n_r * b_s + b_r$ block transfers, plus
  $n_r + b_r$ seeks
- If the smaller relation fits entirely in memory, use that as the inner relation.
  - Reduces cost to $b_r + b_s$ block transfers and 2 seeks
- Example of join of *students* and *takes*:
  - Number of records of *student*: 5,000 *takes*: 10,000
  - Number of blocks of *student*: 100 *takes*: 400
- Assuming worst case memory availability cost estimate is
  - with *student* as outer relation:
    - 5000 * 400 + 100 = 2,000,100 block transfers,
    - 5000 + 100 = 5100 seeks
  - with *takes* as the outer relation
    - 10000 * 100 + 400 = 1,000,400 block transfers and 10,400 seeks
- If smaller relation (*student*) fits entirely in memory, the cost estimate will be 500 block transfers
- Block nested-loops algorithm (next slide) is preferable

Block Nested-Loop Join

- Variant of nested-loop join in which every block of inner relation is paired with every block of outer relation

```
for each block B_r of r do begin
    for each block B_s of s do begin
        for each tuple t_r in B_r do begin
            for each tuple t_s in B_s do begin
                Check if (t_r,t_s) satisfy the join condition
                if they do, add t_r • t_s to the result.
            end
        end
    end
end
```

Block Nested-Loop Join (Cont.)

- Worst case estimate: $b_r * b_s + b_r$ block transfers + 2 * b_r seeks
  - Each block in the inner relation *s* is read once for each *block* in the outer relation
- Best case: $b_r + b_s$ block transfers + 2 seeks.
- Improvements to nested loop and block nested loop algorithms:
  - In block nested-loop, use *M* — 2 disk blocks as blocking unit for outer relations, where *M* = memory size in blocks; use remaining two blocks to buffer inner relation and output
    - Cost = $\lceil b_r / (M-2) \rceil * b_s + b_r$ block transfers + $2 \lceil b_r / (M-2) \rceil$ seeks
  - If equi-join attribute forms a key or inner relation, stop inner loop on first match
  - Scan inner loop forward and backward alternately, to make use of the blocks remaining in buffer (with LRU replacement)
  - Use index on inner relation if available (next slide)

Indexed Nested-Loop Join

- Index lookups can replace file scans if
  - join is an equi-join or natural join and
  - an index is available on the inner relation's join attribute
    - Can construct an index just to compute a join.
- For each tuple t_r in the outer relation *r,* use the index to look up tuples in *s* that satisfy the join condition with tuple t_r.
- Worst case: buffer has space for only one page of *r*, and, for each tuple in *r*, we perform an index lookup on *s.*
- Cost of the join: $b_r\,(t_T + t_S) + n_r * c$
  - Where *c* is the cost of traversing index and fetching all matching *s* tuples for one tuple or *r*
  - *c* can be estimated as cost of a single selection on *s* using the join condition.
- If indices are available on join attributes of both *r* and *s,* use the relation with fewer tuples as the outer relation.

Example of Nested-Loop Join Costs

- Compute *student* ⋈ *takes,* with *student* as the outer relation.
- Let *takes* have a primary B^+-tree index on the attribute *ID,* which contains 20 entries in each index node.
- Since *takes* has 10,000 tuples, the height of the tree is 4, and one more access is needed to find the actual data
- *student* has 5000 tuples
- Cost of block nested loops join
  - 400*100 + 100 = 40,100 block transfers + 2 * 100 = 200 seeks
    - assuming worst case memory
    - may be significantly less with more memory
- Cost of indexed nested loops join
  - 100 + 5000 * 5 = 25,100 block transfers and seeks.
  - CPU cost likely to be less than that for block nested loops join

- Overview of Query Processing
- Measures of Query Cost
- Selection Operation
- Sorting
- Join Operation
- **Other Operations**

OTHER OPERATIONS

Other Operations

- **Duplicate elimination**
- **Projection**
- **Aggregation**
- Set Operations
- Outer Join

Other Operations

- **Duplicate elimination** can be implemented via hashing or sorting
  - On sorting duplicates will come adjacent to each other, and all but one set of duplicates can be deleted
  - *Optimization:* duplicates can be deleted during run generation as well as at intermediate merge steps in external sort-merge
  - Hashing is similar – duplicates will come into the same bucket
- **Projection**:
  - perform projection on each tuple
  - followed by duplicate elimination

Other Operations : Aggregation

- **Aggregation** can be implemented in a manner similar to duplicate elimination
  - Sorting or hashing can be used to bring tuples in the same group together, and then the aggregate functions can be applied on each group
  - *Optimization:* combine tuples in the same group during run generation and intermediate merges, by computing partial aggregate values
    - For count, min, max, sum: keep aggregate values on tuples found so far in the group
      - When combining partial aggregate for count, add up the aggregates
    - For avg, keep sum and count, and divide sum by count at the end

Module Summary

- Understood the overall flow for Query Processing and defined the Measures of Query Cost
- Studied the algorithms for processing Selection Operations, Sorting, Join Operations and a few Other Operations

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Database Management Systems

Module 39: Query Processing and Optimization/2: Optimization

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Module Recap

- Overview of Query Processing
- Measures of Query Cost
- Selection Operation
- Sorting
- Join Operation
- Other Operations

Module Objectives

- To understand the basic issues for optimizing queries
- To understand how transformation of Relational Expressions can create alternates for optimization

Module Outline

- Introduction to Query Optimization
- Transformation of Relational Expressions

- **Introduction to Query Optimization**
- Transformation of Relational Expressions

INTRODUCTION TO QUERY OPTIMIZATION

Introduction

- Alternative ways of evaluating a given query
  - Equivalent expressions
  - Different algorithms for each operation

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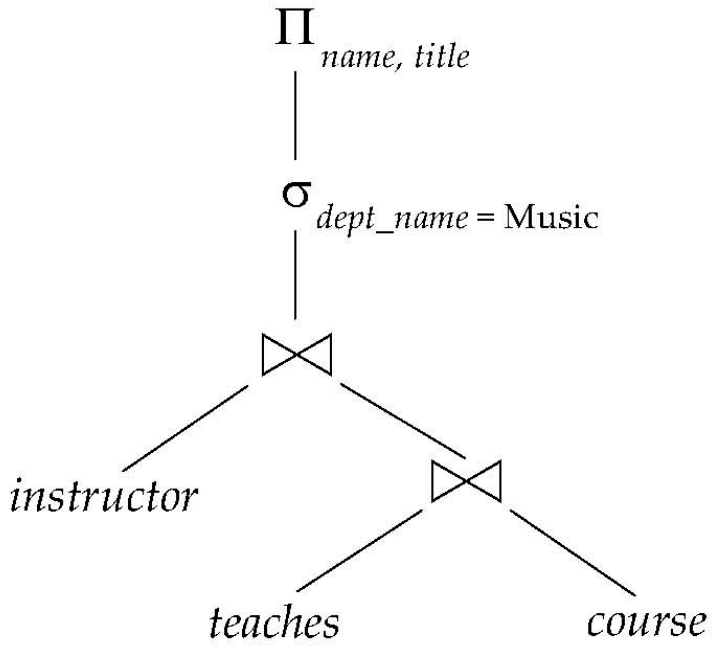
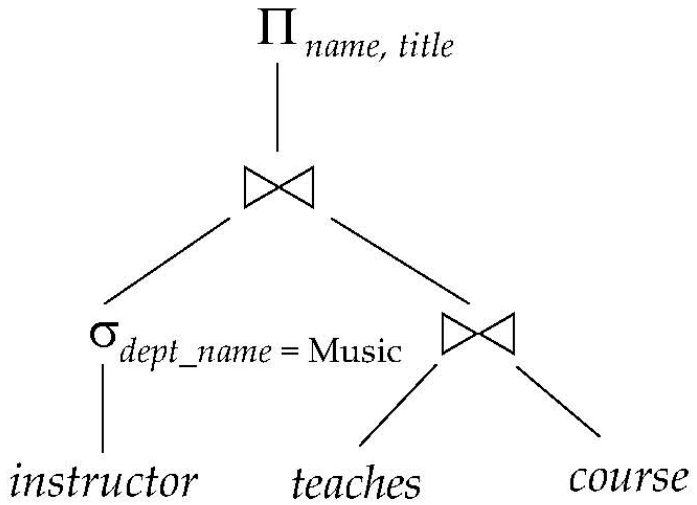
instructor(*ID*, *name*, *dept name*, *salary*)
teaches(*ID*, *course id*, *sec id*, *semester*, *year*)

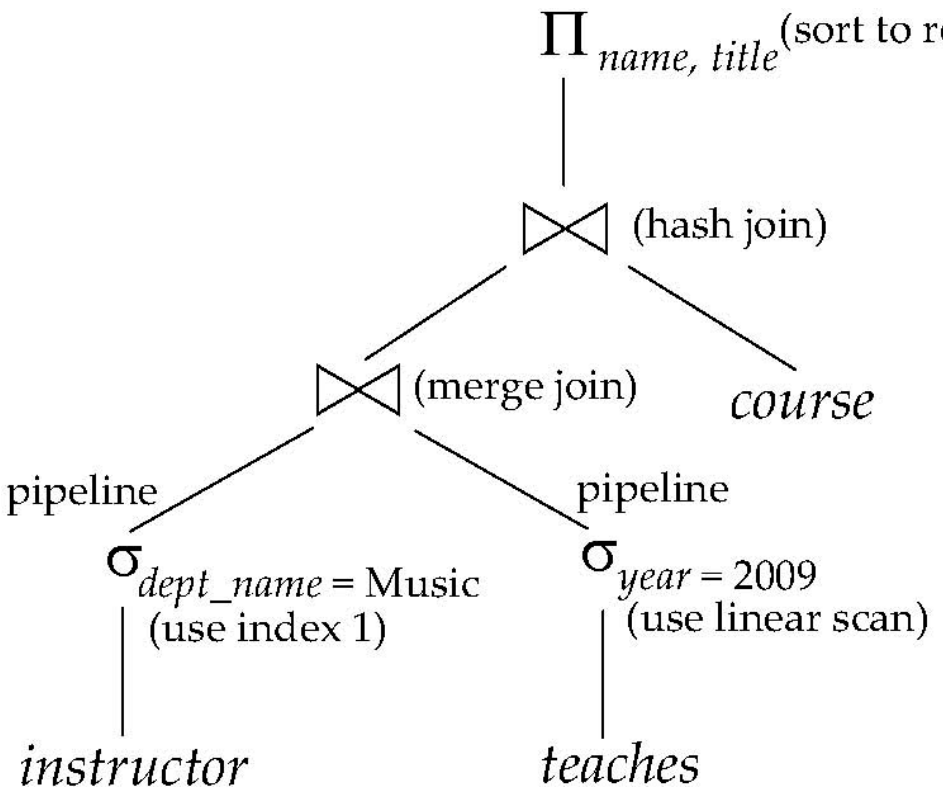




Introduction (Cont.)

- An **evaluation plan** defines exactly what algorithm is used for each operation, and how the execution of the operations is coordinated

$$\Pi_{name,\ title}(\sigma_{dept\_name=\text{“Music”} \wedge year = 2009}(instructor \bowtie teaches \bowtie course))$$



course(*course id*, *title*, *dept name*, *credits*)
instructor(*ID*, *name*, *dept name*, *salary*)
teaches(*ID*, *course id*, *sec id*, *semester*, *year*)

- Find out how to view query execution plans on your favorite database

Introduction (Cont.)

- Cost difference between evaluation plans for a query can be enormous
  - E.g. seconds vs. days in some cases
- Steps in **cost-based query optimization**
  1. Generate logically equivalent expressions using **equivalence rules**
  2. Annotate resultant expressions to get alternative query plans
  3. Choose the cheapest plan based on **estimated cost**
- Estimation of plan cost based on:
  - Statistical information about relations.
    - Examples: number of tuples, number of distinct values for an attribute
  - Statistics estimation for intermediate results
    - to compute cost of complex expressions
  - Cost formulae for algorithms, computed using statistics

- Introduction to Query Optimization
- **Transformation of Relational Expressions**

TRANSFORMATION OF RELATIONAL EXPRESSIONS

Transformation of Relational Expressions

- Two relational algebra expressions are said to be **equivalent** if the two expressions generate the same set of tuples on every *legal* database instance
  - Note: order of tuples is irrelevant
  - We do not care if they generate different results on databases that violate integrity constraints
- In SQL, inputs and outputs are multisets of tuples
  - Two expressions in the multiset version of the relational algebra are said to be equivalent if the two expressions generate the same multiset of tuples on every legal database instance.
- An **equivalence rule** says that expressions of two forms are equivalent
  - Can replace expression of first form by second, or vice versa

Equivalence Rules

1. Conjunctive selection operations can be deconstructed into a sequence of individual selections

$$\sigma_{\theta_1 \wedge \theta_2}(E) = \sigma_{\theta_1}(\sigma_{\theta_2}(E))$$

2. Selection operations are commutative

$$\sigma_{\theta_1}(\sigma_{\theta_2}(E)) = \sigma_{\theta_2}(\sigma_{\theta_1}(E))$$

3. Only the last in a sequence of projection operations is needed, the others can be omitted

$$\Pi_{L_1}(\Pi_{L_2}(\ldots(\Pi_{Ln}(E))\ldots)) = \Pi_{L_1}(E)$$

4. Selections can be combined with Cartesian products and theta joins
   a. $\sigma_{\theta}(E_1 \text{ X } E_2) = E_1 \bowtie_{\theta} E_2$
   b. $\sigma_{\theta 1}(E_1 \bowtie_{\theta 2} E_2) = E_1 \bowtie_{\theta 1 \wedge \theta 2} E_2$

Equivalence Rules (Cont.)

5. Theta-join operations (and natural joins) are commutative

$$E_1 \bowtie_\theta E_2 = E_2 \bowtie_\theta E_1$$

6. (a) Natural join operations are associative:

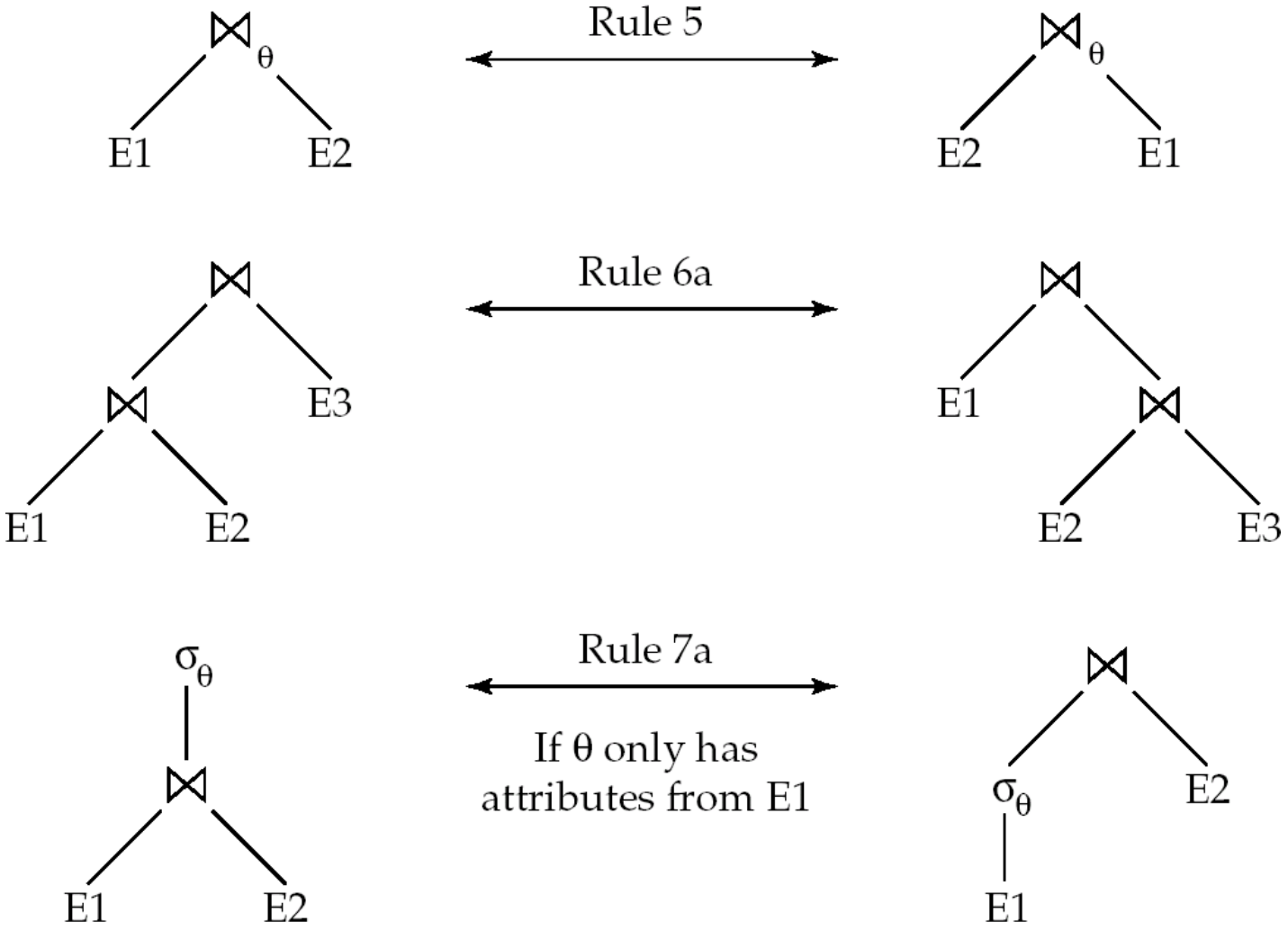
$$(E_1 \bowtie E_2) \bowtie E_3 = E_1 \bowtie (E_2 \bowtie E_3)$$

(b) Theta joins are associative in the following manner:

$$(E_1 \bowtie_{\theta 1} E_2) \bowtie_{\theta 2 \wedge \theta 3} E_3 = E_1 \bowtie_{\theta 1 \wedge \theta 3} (E_2 \bowtie_{\theta 2} E_3)$$

where θ_2 involves attributes from only E_2 and E_3.

Pictorial Depiction of Equivalence Rules



Equivalence Rules (Cont.)

7. The selection operation distributes over the theta join operation under the following two conditions:
   (a) When all the attributes in θ_0 involve only the attributes of one of the expressions (E_1) being joined

$$\sigma_{\theta 0}(E_1 \bowtie_{\theta} E_2) = (\sigma_{\theta 0}(E_1)) \bowtie_{\theta} E_2$$

   (b) When θ_1 involves only the attributes of E_1 and θ_2 involves only the attributes of E_2.

$$\sigma_{\theta 1 \wedge \theta 2}(E_1 \bowtie_{\theta} E_2) = (\sigma_{\theta 1}(E_1)) \bowtie_{\theta} (\sigma_{\theta 2}(E_2))$$

Equivalence Rules (Cont.)

8. The projection operation distributes over the theta join operation as follows:

   (a) if θ involves only attributes from $L_1 \cup L_2$:

$$\Pi_{L_1 \cup L_2}(E_1 \bowtie_\theta E_2) = (\Pi_{L_1}(E_1)) \bowtie_\theta (\Pi_{L_2}(E_2))$$

   (b) Consider a join $E_1 \bowtie_\theta E_2$.

   - Let L_1 and L_2 be sets of attributes from E_1 and E_2, respectively
   - Let L_3 be attributes of E_1 that are involved in join condition θ, but are not in $L_1 \cup L_2$, and
   - Let L_4 be attributes of E_2 that are involved in join condition θ, but are not in $L_1 \cup L_2$.

$$\Pi_{L_1 \cup L_2}(E_1 \bowtie_\theta E_2) = \Pi_{L_1 \cup L_2}((\Pi_{L_1 \cup L_3}(E_1)) \bowtie_\theta (\Pi_{L_2 \cup L_4}(E_2)))$$

Equivalence Rules (Cont.)

9. The set operations union and intersection are commutative

$$E_1 \cup E_2 = E_2 \cup E_1$$
$$E_1 \cap E_2 = E_2 \cap E_1$$

   - (set difference is not commutative).

10. Set union and intersection are associative.

$$(E_1 \cup E_2) \cup E_3 = E_1 \cup (E_2 \cup E_3)$$
$$(E_1 \cap E_2) \cap E_3 = E_1 \cap (E_2 \cap E_3)$$

11. The selection operation distributes over $\cup$, $\cap$ and –.

$$\sigma_\theta (E_1 - E_2) = \sigma_\theta (E_1) - \sigma_\theta(E_2)$$

and similarly for $\cup$ and $\cap$ in place of –

Also: $$\sigma_\theta (E_1 - E_2) = \sigma_\theta(E_1) - E_2$$

and similarly for $\cap$ in place of –, but not for $\cup$

12. The projection operation distributes over union

$$\Pi_L(E_1 \cup E_2) = (\Pi_L(E_1)) \cup (\Pi_L(E_2))$$

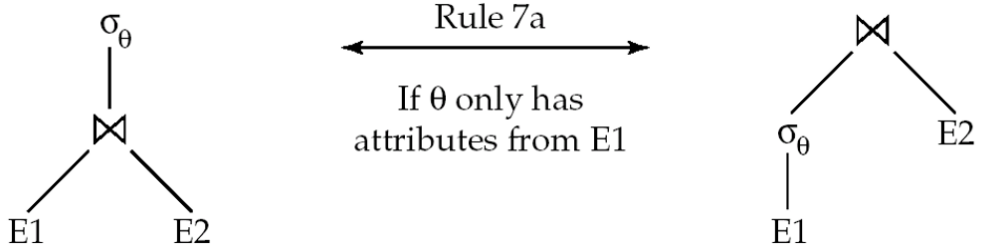
Exercise

- Create equivalence rules involving
  - The group by/aggregation operation
  - Left outer join operation

Transformation Example: Pushing Selections

- Query: Find the names of all instructors in the Music department, along with the titles of the courses that they teach
  - $\Pi_{name,\ title}(\sigma_{dept\_name=\ \text{“Music”}}\ (instructor \bowtie (teaches \bowtie \Pi_{course\_id,\ title}\ (course))))$
- Transformation using rule 7a
  - $\Pi_{name,\ title}((\sigma_{dept\_name=\ \text{“Music”}}(instructor)) \bowtie (teaches \bowtie \Pi_{course\_id,\ title}\ (course)))$
- Performing the selection as early as possible reduces the size of the relation to be joined

course(*course id*, *title*, *dept name*, *credits*)
instructor(*ID*, *name*, *dept name*, *salary*)
teaches(*ID*, *course id*, *sec id*, *semester*, *year*)

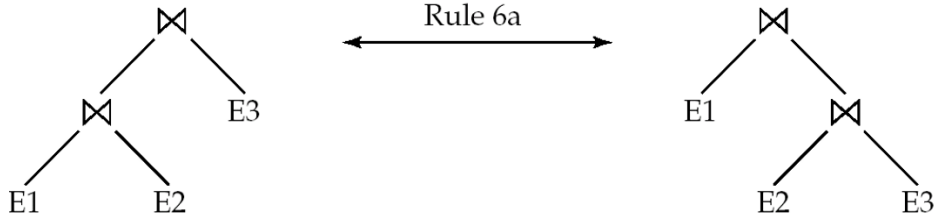


Example with Multiple Transformations

- Query: Find the names of all instructors in the Music department who have taught a course in 2009, along with the titles of the courses that they taught
  - $\Pi_{name,\ title}(\sigma_{dept\_name = \text{“Music”} \wedge year = 2009}(instructor \bowtie (teaches \bowtie \Pi_{course\_id,\ title}(course))))$
- Transformation using join associatively (Rule 6a):
  - $\Pi_{name,\ title}(\sigma_{dept\_name = \text{“Music”} \wedge year = 2009}((instructor \bowtie teaches) \bowtie \Pi_{course\_id,\ title}(course)))$
- Second form provides an opportunity to apply the “perform selections early” rule, resulting in the subexpression

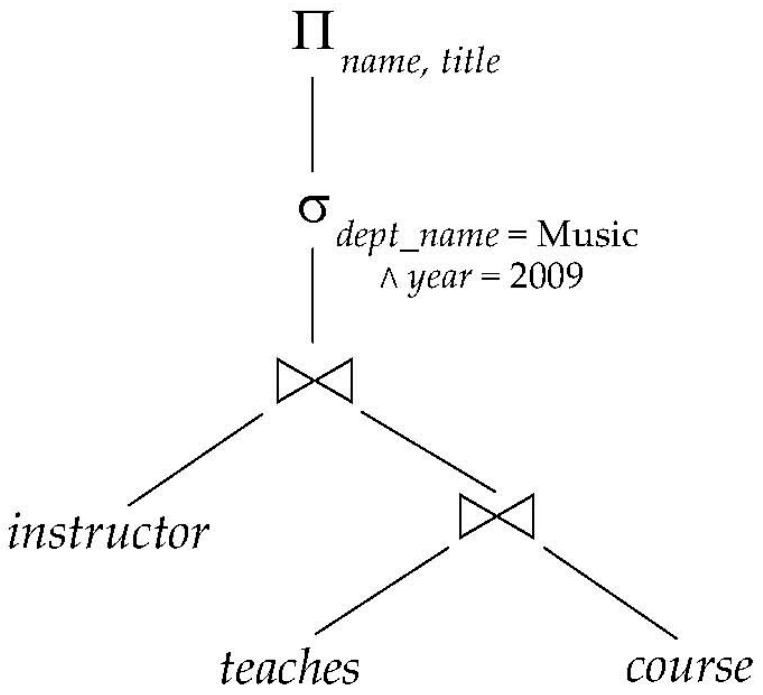
$$\sigma_{dept\_name = \text{“Music”}}(instructor) \bowtie \sigma_{year = 2009}(teaches)$$

course(*course id*, *title*, *dept name*, *credits*)
instructor(*ID*, *name*, *dept name*, *salary*)
teaches(*ID*, *course id*, *sec id*, *semester*, *year*)

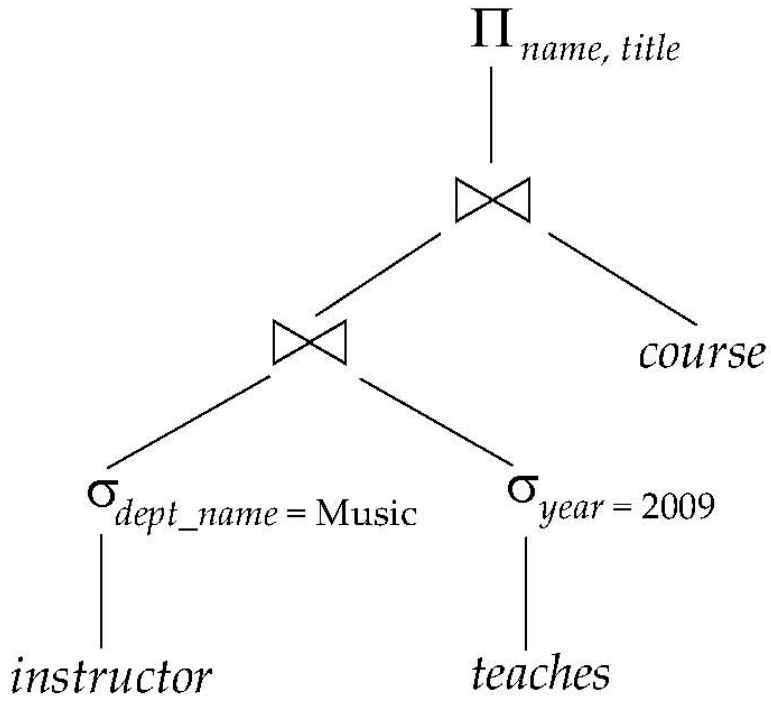


Multiple Transformations (Cont.)

course(*course id*, *title*, *dept name*, *credits*)
instructor(*ID*, *name*, *dept name*, *salary*)
teaches(*ID*, *course id*, *sec id*, *semester*, *year*)



(a) Initial expression tree



(b) Tree after multiple transformations

Transformation Example: Pushing Projections

- Consider: $\Pi_{name,\ title}(\sigma_{dept\_name=\ \text{“Music”}}(instructor) \bowtie teaches) \bowtie \Pi_{course\_id,\ title}(course)$
- When we compute

  $(\sigma_{dept\_name\ =\ \text{“Music”}}(instructor \bowtie teaches)$

  we obtain a relation whose schema is:
  (*ID, name, dept_name, salary, course_id, sec_id, semester, year)*
- Push projections using equivalence rules 8a and 8b; eliminate unneeded attributes from intermediate results to get:

  $\Pi_{name,\ title}(\Pi_{name,\ course\_id}(\sigma_{dept\_name=\ \text{“Music”}}(instructor) \bowtie teaches)) \bowtie \Pi_{course\_id,\ title}(course)$
- Performing the projection as early as possible reduces the size of the relation to be joined

course(<u>*course id*</u>, *title*, *dept name*, *credits*)
instructor(<u>*ID*</u>, *name*, *dept name*, *salary*)
teaches(<u>*ID*</u>, <u>*course id*</u>, <u>*sec id*</u>, <u>*semester*</u>, *year*)

$$\Pi_{L_1 \cup L_2}(E_1 \bowtie_\theta E_2) = (\Pi_{L_1}(E_1)) \bowtie_\theta (\Pi_{L_2}(E_2))$$

$$\Pi_{L_1 \cup L_2}(E_1 \bowtie_\theta E_2) = \Pi_{L_1 \cup L_2}((\Pi_{L_1 \cup L_3}(E_1)) \bowtie_\theta (\Pi_{L_2 \cup L_4}(E_2)))$$

Join Ordering Example

- For all relations r_1, r_2, and r_3,

$$(r_1 \bowtie r_2) \bowtie r_3 = r_1 \bowtie (r_2 \bowtie r_3)$$

(Join Associativity)

- If $r_2 \bowtie r_3$ is quite large and $r_1 \bowtie r_2$ is small, we choose

$$(r_1 \bowtie r_2) \bowtie r_3$$

so that we compute and store a smaller temporary relation

Join Ordering Example (Cont.)

- Consider the expression

$$\Pi_{name,\ title}(\sigma_{dept\_name=\ \text{“Music”}}(instructor) \bowtie teaches) \bowtie \Pi_{course\_id,\ title}(course))))$$

- Could compute $teaches \bowtie \Pi_{course\_id,\ title}(course)$ first, and join result with

$$\sigma_{dept\_name=\ \text{“Music”}}(instructor)$$

but the result of the first join is likely to be a large relation

- Only a small fraction of the university's instructors are likely to be from the Music department
  - it is better to compute

$$\sigma_{dept\_name=\ \text{“Music”}}(instructor) \bowtie teaches$$

first

course(*course id*, *title*, *dept name*, *credits*)
instructor(*ID*, *name*, *dept name*, *salary*)
teaches(*ID*, *course id*, *sec id*, *semester*, *year*)

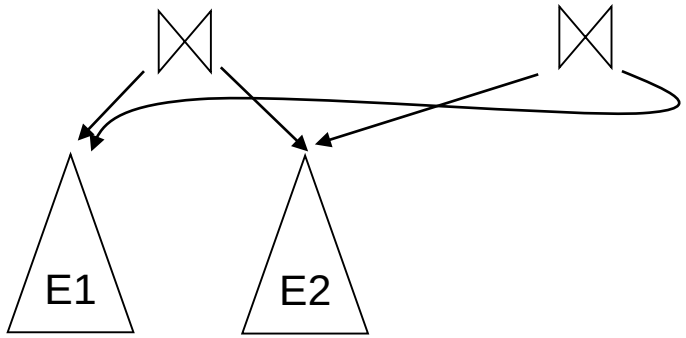
Enumeration of Equivalent Expressions

- Query optimizers use equivalence rules to **systematically** generate expressions equivalent to the given expression
- Can generate all equivalent expressions as follows:
  - Repeat
    - apply all applicable equivalence rules on every subexpression of every equivalent expression found so far
    - add newly generated expressions to the set of equivalent expressions

    Until no new equivalent expressions are generated above
- The above approach is very expensive in space and time
  - Two approaches
    - Optimized plan generation based on transformation rules
    - Special case approach for queries with only selections, projections and joins

Implementing Transformation Based Optimization

- Space requirements reduced by sharing common sub-expressions:
  - when E1 is generated from E2 by an equivalence rule, usually only the top level of the two are different, subtrees below are the same and can be shared using pointers
    - E.g. when applying join commutativity



  - Same sub-expression may get generated multiple times
    - Detect duplicate sub-expressions and share one copy
- Time requirements are reduced by not generating all expressions
  - Dynamic programming

Module Summary

- Understood the basic issues for optimizing queries
- For every relational expression, usually there are a number of equivalent expressions that can be created by simple transformations
- Final execution plan can be created by choose the estimated least cost expression from the alternates

PPD

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Database Management Systems

Module 40: Course Summarization

Material presented in this module is for overall understanding.

These are not included in the assignments or examination.

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www.db-book.com

Course Recap

- What did we do?

PPD

Week 01: Introduction to DBMS & Relational Model

- **Module 01: Course Overview**
  - Why Databases?
  - KYC: Know Your Course
- **Module 02: Introduction to DBMS/1**
  - Levels of Abstraction
  - Schema & Instance
  - Data Models
  - DDL & DML
  - SQL
  - Database Design
- **Module 03: Introduction to DBMS/2**
  - Database Design
  - Database Engine, Users, Architecture
  - History of DBMS
- **Module 04: Introduction to Relational Model/1**
  - Attribute Types
  - Relation Schema and Instance
  - Keys
  - Relational Query Languages
- **Module 05: Introduction to Relational Model/2**
  - Relational Operations
  - Aggregate Operations

Week 02: SQL – Introductory & Intermediate

- **Module 06: Introduction to SQL/1**
  - History of SQL
  - Data Definition Language (DDL)
  - Basic Query Structure (DML)
- **Module 07: Introduction to SQL/2**
  - Additional Basic Operations
  - Set Operations
  - Null Values
  - Aggregate Functions
- **Module 08: Introduction to SQL/3**
  - Nested Subqueries
  - Modification of the Database
- **Module 09: Intermediate SQL/1**
  - Join Expressions
  - Views
  - Transactions
- **Module 10: Intermediate SQL/2**
  - Integrity Constraints
  - SQL Data Types and Schemas
  - Authorization

Week 03: Advanced SQL and ER Modeling

- **Module 11: Advanced SQL**
  - Accessing SQL From a Programming Language
  - Functions and Procedural Constructs
  - Triggers
- **Module 12: Formal Relational Query Languages**
  - Relational Algebra
  - Tuple Relational Calculus (Overview only)
  - Domain Relational Calculus (Overview only)
  - Equivalence of Algebra and Calculus
- **Module 13: Entity-Relationship Model/1**
  - Design Process
  - E-R Model
- **Module 14: Entity-Relationship Model/2**
  - E-R Diagram
  - E-R Model to Relational Schema
- **Module 15: Entity-Relationship Model/3**
  - Extended E-R Features
  - Design Issues

PPD

Week 04: RDBMS Design – Dependency & Normal Form

- **Module 16: Relational Database Design/1**
  - Features of Good Relational Design
  - Atomic Domains and First Normal Form
  - Functional Dependencies
- **Module 17: Relational Database Design/2**
  - Decomposition Using Functional Dependencies
  - Functional Dependency Theory
- **Module 18: Relational Database Design/3**
  - Algorithms for Functional Dependencies
  - Lossless Join Decomposition
  - Dependency Preservation
- **Module 19: Relational Database Design/4**
  - Normal Forms
  - Decomposition to 3NF
  - Decomposition to BCNF
- **Module 20: Relational Database Design/5**
  - Multivalued Dependencies
  - Decomposition to 4NF
  - Database-Design Process
  - Modeling Temporal Data

Week 05: Application Design and Storage

- **Module 21: Application Design and Development/1**
  - Application Programs and User Interfaces
  - Web Fundamentals
  - Servlets and JSP
- **Module 22: Application Design and Development/2**
  - Application Architectures
  - Rapid Application Development
  - Application Performance
  - Application Security
  - Mobile Apps
- **Module 23: Application Design and Development/3**
  - Case Studies of Database Applications
- **Module 24: Storage and File Structure/1 (Storage)**
  - Overview of Physical Storage Media
  - Magnetic Disks
  - RAID
  - Tertiary Storage
- **Module 25: Storage and File Structure/2 (File Structure)**
  - File Organization
  - Organization of Records in Files
  - Data-Dictionary Storage
  - Storage Access

Week 06: Indexing and Hashing

- **Module 26: Indexing and Hashing/1 (Indexing/1)**
  - Basic Concepts of Indexing
  - Ordered Indices
- **Module 27: Indexing and Hashing/2 (Indexing/2)**
  - Balanced Binary Search Trees
  - 2-3-4 Tree
- **Module 28: Indexing and Hashing/3 (Indexing/3)**
  - B+-Tree Index Files
  - B-Tree Index Files
- **Module 29: Indexing and Hashing/4 (Hashing)**
  - Static Hashing
  - Dynamic Hashing
  - Comparison of Ordered Indexing and Hashing
  - Bitmap Indices
- **Module 30: Indexing and Hashing/5 (Index Design)**
  - Index Definition in SQL
  - Guidelines for Indexing

Week 07: Transaction and Concurrency Control

- **Module 31: Transactions/1**
  - Transaction Concept
  - Transaction State
  - Concurrent Executions
- **Module 32: Transactions/2: Serializabilty**
  - Serializability
  - Conflict Serializability
- **Module 33: Transactions/3: Recoverability**
  - Recoverability and Isolation
  - Transaction Definition in SQL
  - View Serializability
  - Complex Notions of Serializability
- **Module 34: Concurrency Control/1**
  - Lock-Based Protocols
  - Implementing Locking
- **Module 35: Concurrency Control/2**
  - Deadlock Handling
  - Timestamp-Based Protocols

Week 08: Recovery and Query Processing & Optimization

- **Module 36: Recovery/1**
  - Failure Classification
  - Storage Structure
  - Recovery and Atomicity
  - Log-Based Recovery
- **Module 37: Recovery/2**
  - Recovery Algorithm
  - Recovery with Early Lock Release
- **Module 38: Query Processing and Optimization/1: Processing**
  - Overview of Query Processing
  - Measures of Query Cost
  - Selection Operation
  - Sorting
  - Join Operation
  - Other Operations
- **Module 39: Query Processing and Optimization/2: Optimization**
  - Introduction to Query Optimization
  - Transformation of Relational Expressions
- **Module 40: Course Summarization**

Module Objectives

- The space of RDBMSs is crowded. We take a look into common RDBMS systems
- Non-Relational database systems are starting to dominate emerging applications. We present a brief overview
- What is the road forward? We outline likely job profiles in terms of a skills-profiles matrix and the companies to work for

Module Outline

- Common RDBMSs
- Non-relational DBMSs
- Skill – Job Profile Matrix

- **Common RDBMSs**
- Non-relational DBMSs
- Skill – Job Profile Matrix

COMMON RDBMS

Ref: https://en.wikipedia.org/wiki/Comparison_of_relational_database_management_systems

Ref: http://infocenter.sybase.com/help/index.jsp?topic=/com.sybase.infocenter.dc38151.1540/doc/html/san1278453579697.html

Ref: https://www.ibm.com/support/knowledgecenter/en/SSEPGG_11.1.0/com.ibm.db2.luw.welcome.doc/doc/welcome.html

Ref: https://docs.microsoft.com/en-us/azure/sql-database/sql-database-develop-cplusplus-simple

Relational Databases

- Based on the relational model of data
- This model organizes data into one or more tables (or “relations”) of rows and columns, with a unique key for each row
- Since each row in a table has its own unique key, rows in a table can be linked to rows in other tables by storing the unique key of the row to which it should be linked (where such unique key is known as a “foreign key”)
- Mostly the relational database systems use SQL (Structured Query Language) as the language for querying and maintaining the database
- The reasons for the dominance of relational databases are: simplicity, robustness, flexibility, performance, scalability and compatibility in managing generic data
- The most popular of these are Microsoft SQL Server, Oracle Database, MySQL, and IBM DB2.
- These RDBMS’s are mostly used in large enterprise scenarios

Common RDBMS

- Commercial Software
  - Oracle (Oracle)
  - Sybase (Sybase Corporation / SAP AG**)**
  - DB2 (IBM)
  - SQL Server (Microsoft)
  - Teradata (Caltech and Citibank)
- Free / GPL / Open Source:
  - PostgreSQL (PostgreSQL Global Development Group)
  - MySQL (MySQL AB / Oracle Corporation)
- Object Oriented DBMSs

Oracle

- Multi-model commercial database management system produced and marketed by **Oracle Corporation**.
- Larry Ellison, Bob Miner and Ed Oates started a consultancy called Software Development Laboratories (SDL) in 1977, and developed the original version of Oracle.
- Latest Version: **Oracle Database 12*c* Release 2: 12.2.0.1 (patchset as of March 2017)**
- Used for running online transaction processing (OLTP), data warehousing (DW) and mixed (OLTP & DW) database workloads
- Languages: Structured Query language (SQL), Procedural SQL (PL- SQL)
- Tools/ Editions: Oracle SQL Developer, Oracle Forms, Oracle Jdeveloper, Oracle Reports for development of applications, Oracle Live SQL for test environment
- Oracle can be accessed from Java through JDBC, Microsoft.NET through ODP.NET, C, C++ through OCI, ODBC, ODPI-C, Python through cx_Oracle

Sybase

- Relational model database server product for businesses developed by **Sybase Corporation which became part of SAP AG**.
- Originally for unix platforms in 1987, Sybase Corporation's primary DBMS product was initially marketed under the name Sybase SQL Server.
- Latest Version: **Sybase 16, released on 2014**
- Languages: Sybase IQ, Transact-SQL
- Tools/ Editions: Sybase SQL server for development of applications. Has a developer and express edition.
- Sybase can be accessed from C, C++ through SQLAPI++, Java through JDBC

DB2

- Db2 contains database-server products developed by **IBM**. Mostly relational models, but now includes object relational models
- In 1970, Edgar F.Codd, researcher in IBM published the model for data manipulation.
- Latest Version: **DB2 LUW 11.1 released on 2016**
- Used for running online transaction processing (OLTP), data warehousing (DW) and mixed (OLTP & DW) database workloads
- Languages: Structured Query language (SQL), XML Query
- Tools/ Editions: Advanced Enterprise Server Edition, Enterprise Server Edition, Advanced Workgroup Server Edition, Workgroup Server Edition, Direct and Developer Editions and Express-C.
- Db2 can be accessed from C, C++, Java, Ruby, Perl through a package of DB2 API's

SQL Server

- Relational database management system developed by **Microsoft**.
- SQL Server 1.0, a 16-bit server for the OS/2 operating system in 1989
- Latest Version: **SQL Server 2017**
- Used for running online transaction processing (OLTP) and online analytical processing (OLAP)
- Languages: Transact SQL
- Tools/ Editions: Enterprise, Standard, Web, Business Intelligence, WorkGroup, Express
- SQL server can be accessed from Java through JDBC, C, C++ through ODBC

Teradata

- Relational database management system developed by **Caltech and Citibank's advanced technology group**
- In 1984, the first version of Teradata was released
- Latest Version: **Teradata 15**
- Used for running online transaction processing (OLTP), data warehousing (DW) and mixed (OLTP & DW) database workloads
- Languages: BTEQ(Basic Teradata query)
- Tools/ Editions: Developer Edition, Express Edition
- SQL server can be accessed from Java through JDBC, C, C++ through ODBC

PostgreSQL

- Open source relational database management system produced by **PostgreSQL Global Development Group**, a diverse group of many companies and individual contributors.
- First version in 1988 by researchers of POSTGRES project
- Latest Version: **PostgreSQL 10.3 released on 2018**
- Used for running online transaction processing (OLTP), data warehousing (DW) and mixed (OLTP & DW) database workloads, Supports big data analytics
- Languages: Structured Query language (SQL), Procedural SQL (PL- SQL)
- Oracle can be accessed from Java through JDBC, Microsoft.NET through npgsql, C, C++ through libpq,

MYSQL

- Open source relational database management system produced by **Swedish company MySQL AB, now owned by Oracle Corporation**
- First internal release on 23 May 1995
- Latest Version: **MySQL 8.0.4 released on 2018**
- Used for running online transaction processing (OLTP), data warehousing (DW) and mixed (OLTP & DW) database workloads
- Languages: Structured Query language (SQL), Procedural SQL (PL- SQL)
- Oracle can be accessed from Java through JDBC, Microsoft.NET through ADO.NET, C, C++ through ODBC

Object-oriented DBMS (OODBMSs)

- Combines database capabilities with object oriented programming language capabilities
- OODBMSs allow object-oriented programmers to develop the product, store them as objects, and replicate or modify existing objects to make new objects within the OODBMS
- Objects have a many to many relationship and are accessed by the use of pointers.
- Access to data can be faster because an object can be retrieved directly without a search, by following pointers.
- Most object databases also offer some kind of query language, allowing objects to be found using a declarative programming approach.
- Examples:
  - Objectivity/DB,
  - O2,
  - Object Store

Ref: https://en.wikipedia.org/wiki/Object_database

Parameters

- We compare the RDMBSs based on the following parameters:
  - OS support
  - Fundamental features
  - Limits
  - Tables and views
  - Indexes
  - Database capabilities
  - Data types
  - Other objects
  - Partitioning
  - Access control
  - Programming Language Support

Comparative Study

OS support

Oracle	Sybase	SQL Server	DB2	Teradata	PostgreSQL	My SQL
Linux, Window, Mac, Unix, Haiku, z/OS, OpenVMS	Linux, Window, Mac, Unix, BareMetal, Android	Linux, Window	Linux, Window, Mac (Express-C image), OS/2, Unix, z/OS, iOS	Linux, Window, Mac, Unix,	Linux, Window, Mac, Unix, BSD, AmigaOS, z/OS, Android	Linux, Window, Mac, Unix, BSD, AmigaOS, z/OS, Android

Comparative Study

Basic Features

Oracle	Sybase	SQL Server	DB2	Teradata	PostgreSQL	My SQL
Supports ACID properties for transactions, implicit commit for DDL, referential integrity, row level locking for fine grained locking, Concurrency control	Supports ACID properties for transactions, referential integrity, Concurrency control	Supports ACID properties for transactions, referential integrity, row level locking for fine grained locking, Concurrency control	Supports ACID properties for transactions, referential integrity, row level locking for fine grained locking, Concurrency control	Supports ACID properties for transactions, referential integrity, hash and partition for fine grained locking, Concurrency control	Supports ACID properties for transactions, referential integrity, row level locking for fine grained locking, Concurrency control	Supports ACID properties for transactions, referential integrity, row level locking for fine grained locking, Concurrency control

Comparative Study

Limits

Oracle	Sybase	SQL Server	DB2	Teradata	PostgreSQL	My SQL
Max DB Size: 2PB Max Table Size: 4GB * block size Max Row Size: 8KB Max Column per Row: 1,000 Max CHAR size: 32,767 B Max Number size: 126 bits Max Column Name size: 128	Max DB Size: 104TB Max Table Size: File size Max Row Size: File size Max Column per Row: 45,000 Max CHAR size: 2GB Max Number size: 64 bits	Max DB Size: 524,272 TB Max Table Size: 524,272 TB Max Row Size: 2TB Max Column per Row: 1,024 Max CHAR size: 2GB Max Number size: 126 bits Max Column Name size: 128	Max DB Size: Unlimited Max Table Size: 2 ZB Max Row Size: 32,677 B Max Column per Row: 1,012 Max CHAR size: 32 KB Max Number size: 64 bits Max Column Name size: 128	Max DB Size: Unlimited Max Table Size: Unlimited Max Row Size: 64 GB Max Column per Row: 2048 Max CHAR size: 64,000 bits Max Number size: 38 bits Max Column Name size: 128	Max DB Size: Unlimited Max Table Size: 32 TB Max Row Size: 1.6TB Max Column per Row: 1600 Max CHAR size: 1GB Max Number size: Unlimited Max Column Name size: 63	Max DB Size: Unlimited Max Table Size: 256 TB Max Row Size: 64KB Max Column per Row: 4096 Max CHAR size: 64 KB Max Number size: 64 bits Max Column Name size: 64

Comparative Study

Tables and Views

Oracle	Sybase	SQL Server	DB2	Teradata	PostgreSQL	My SQL
Supports Temporary tables and Materialised views (apart from basic)	Supports Temporary tables and Materialised views (apart from basic)	Supports Temporary tables and Materialised views (apart from basic)	Supports Temporary tables and Materialised views (apart from basic)	Supports Temporary tables and Materialised views (apart from basic)	Supports Temporary tables and Materialised views (apart from basic)	Supports Temporary tables (apart from basic)

Type System

Oracle	Sybase	SQL Server	DB2	Teradata	PostgreSQL	My SQL
Static+Dynamic	Static	Static	Static+Dynamic	Static	Static	Static

Comparative Study

Data Types

Oracle	Sybase	SQL Server	DB2	Teradata	PostgreSQL	My SQL
Supports various variants of Integer; Floating Point; Decimal; String; Binary; Date/Time; And other miscellaneous types like Spacial, Image, Audio, Dicom, Video	Supports various variants of Integer; Floating Point; Decimal; String; Binary; Date/Time; Bit And other miscellaneous types like Money	Supports various variants of Integer; Floating Point; Decimal; String; Binary; Date/Time; Bit And other miscellaneous types like Timestamp, Rowversion, UniqueIdentifier identity	Supports various variants of Integer; Floating Point; Decimal; String; Binary; Date/Time; And other miscellaneous types like Graphic, Vargraphic, xml, DbClob	Supports various variants of Integer; Floating Point; Decimal; String; Binary; Date/Time; And other miscellaneous types like Period, Interval, Geometry, xml, json	Supports various variants of Integer; Floating Point; Decimal; String; Binary; Date/Time; Boolean And other miscellaneous types like Enum, xml Circle, Path, UUID	Supports various variants of Integer; Floating Point; Decimal; String; Binary; Date/Time; Bit And other miscellaneous types like Enum, Set, MultiCurve, Geometry, LineString, Surface, Polygon

Comparative Study

Indexes

Oracle	Sybase	SQL Server	DB2	Teradata	PostgreSQL	My SQL
Supports R/R++, Hash, Partial, Bitmap, Reverse Apart from Basic B/B++ indexes	Supports only Basic B/B++ indexes	Supports R/R++, Hash, Partial, Bitmap, Reverse Apart from Basic B/B++ indexes	Supports R/R++, Hash, Partial, Bitmap, Reverse Apart from Basic B/B++ indexes	Supports Hash, Partial, Bitmap, Apart from Basic B/B++ indexes	Supports R/R++, Hash, Partial, Bitmap, Reverse Apart from Basic B/B++ indexes	Supports R/R++, Hash, Apart from Basic B/B++ indexes

Comparative Study

Database Capabilities

Oracle	Sybase	SQL Server	DB2	Teradata	PostgreSQL	My SQL
Supports Union, Intersect, Inner Joins, Outer Joins, Except, Inner Selects, Merger Joins, Blobs and Clobs, Common Table Expressions, Windowing Functions, Parallel Query	Supports Union, Intersect, Inner Joins, Outer Joins, Except, Inner Selects, Merger Joins, Blobs and Clobs, Common Table Expressions, Windowing Functions, Parallel Query	Supports Union, Intersect, Inner Joins, Outer Joins, Except, Inner Selects, Merger Joins, Blobs and Clobs, Common Table Expressions, Windowing Functions, Parallel Query	Supports Union, Intersect, Inner Joins, Outer Joins, Except, Inner Selects, Merger Joins, Blobs and Clobs, Common Table Expressions, Windowing Functions, Parallel Query	Supports Union, Intersect, Inner Joins, Outer Joins, Except, Inner Selects, Merger Joins, Blobs and Clobs, Common Table Expressions, Windowing Functions, Parallel Query	Supports Union, Intersect, Inner Joins, Outer Joins, Except, Blobs and Clobs	Supports Union, Outer Joins, Except, Inner Selects, Blobs and Clobs, Common Table Expressions

Comparative Study

Other Objects

Oracle	Sybase	SQL Server	DB2	Teradata	PostgreSQL	My SQL
Supports Data Domain, Cursor, Trigger, Function, Procedure, External Routine	Supports Data Domain, Cursor, Trigger, Function, Procedure, External Routine	Supports Data Domain, Cursor, Trigger, Function, Procedure, External Routine	Supports Data Domain, Cursor, Trigger, Function, Procedure, External Routine	Supports Cursor, Trigger, Function, Procedure, External Routine	Supports Data Domain, Cursor, Trigger, Function, Procedure, External Routine	Supports Cursor, Trigger, Function, Procedure, External Routine

Comparative Study

Partitioning

Oracle	Sybase	SQL Server	DB2	Teradata	PostgreSQL	My SQL
Supports Range, Hash, Composite, List	Supports none	Supports Range, Hash, Composite, List	Supports Range, Hash, Composite, List	Supports Range, Hash, Composite, List	Supports Range, Hash, Composite, List	Supports Range, Hash, Composite, List

Comparative Study

Access Control

Oracle	Sybase	SQL Server	DB2	Teradata	PostgreSQL	My SQL
Supports Native network encryption, Separation of Duties, Password Complexity Rules, Enterprise Directory compatibility, Audit, Resource Limit,	Supports Native network encryption, Separation of Duties, Password Complexity Rules, Enterprise Directory compatibility, Audit, Resource Limit,	Supports Native network encryption, Separation of Duties, Password Complexity Rules, Enterprise Directory compatibility, Audit, Resource Limit, Patch Access	Supports Native network encryption, Separation of Duties, Password Complexity Rules, Enterprise Directory compatibility, Audit, Resource Limit,	Supports Native network encryption, Separation of Duties, Password Complexity Rules, Enterprise Directory compatibility, Audit, Resource Limit, Patch Access	Supports Native network encryption, Separation of Duties, Password Complexity Rules, Enterprise Directory compatibility, Audit, Resource Limit, Patch Access	Supports Native network encryption, Enterprise Directory compatibility, Patch Access

- Common RDBMSs
- **Non-relational DBMSs**
- Skill – Job Profile Matrix

Basis for these DBMSs have not been covered in the course

NON-RELATIONAL DATABASES

Ref: https://www.digitalocean.com/community/tutorials/a-comparison-of-nosql-database-management-systems-and-models

Ref: https://www.thoughtworks.com/insights/blog/nosql-databases-overview

Ref: https://www.mongodb.com/scale/what-is-a-non-relational-database

Ref: http://www.jamesserra.com/archive/2015/08/relational-databases-vs-non-relational-databases/

Ref: https://www.mongodb.com/scale/relational-vs-non-relational-database

Ref: https://dzone.com/articles/eclipse-jnosql-a-quick-overview-with-redis-cassand

Ref: http://coreviewsystems.com/nosql-databases-key-value-store/

What is Big Data?

- Big data is data sets that are so voluminous and complex that traditional data-processing application software are inadequate to deal with them
- Big data challenges include capturing data, data storage, data analysis, search, sharing, transfer, visualization, querying, updating, information privacy and data source
- **5V's (characteristics) of big data**:
  - **Volume**: The quantity of generated and stored data. The size of the data determines the value and potential insight, and whether it can be considered big data or not.
  - **Variety**: The type and nature of the data. This helps people who analyze it to effectively use the resulting insight. Big data draws from text, images, audio, video; plus it completes missing pieces through data fusion.
  - **Velocity**: In this context, the speed at which the data is generated and processed to meet the demands and challenges that lie in the path of growth and development. Big data is often available in real-time.
  - **Variability**: Inconsistency of the data set can hamper processes to handle and manage it.
  - **Veracity**: The data quality of captured data can vary greatly, affecting the accurate analysis

Why do we need non-relational databases?

- To effectively support Big Data

Non-Relational Databases

- **Does not follow the relational model**
- Offer flexible schema design
- **Handle unstructured data that does not fit neatly into rows and columns**
- Typically Open Source
- Scalable using cheap commodity servers
- The popular ones are:
  - MongoDB, DocumentDB, Cassandra, Coachbase, HBase, Redis, and Neo4j
- These databases are usually grouped into four categories:
  - Key-value stores
  - Graph stores
  - Column stores, and
  - Document stores

Non-Relational Databases are also known as NoSQL Databases

Relational vs. Non-Relational

	Relational	Non-Relational
Flexible Data Model	Works on only structured data (relational tables)	Can handle unstructured and semi structured data (xml, json), along with dynamic modification of schema. Suited for BigData
Cost, Complexity, Speed	Faster but less capable operations, Cheaper and less complex	Much more database operations supported, Highly complex internally and costlier
Performance and Scalability	Incurs issues, as data integrity needs to be maintained at all levels, in case of distributed architecture	Better Scalability and performance by exploring distributed systems using sharding and partitioning
Consistency	Enforces strong consistent systems. Less overhead for developers	Enforces eventual consistent systems. More overhead for developers
Enterprise Management and Integrations	Fits into the Enterprise IT stack, much more secure and robust	Designed to cope with agility of modern cloud based applications

Types of NoSQL Databases

1. **Key-value stores**:
   - These type of databases work by matching keys with values, similar to a dictionary. There is no structure nor relation. **Example: Redis, MemcacheDB**
2. **Graph stores**:
   - These use tree-like structures (i.e. graphs) with nodes and edges connecting each other through relations. **Example: OrientDB, Neo4J**
3. **Column stores**:
   - Column-based NoSQL databases are two dimensional arrays whereby each key (i.e. row / record) has one or more key / value pairs attached to it and these management systems allow very large and un-structured data to be kept and used (e.g. a record with tons of information). **Example: Cassandra, Hbase**
4. **Document stores**:
   - These DBMS work in a similar fashion to column-based ones; however, they allow much deeper nesting and complex structures to be achieved (e.g. a document, within a document, within a document).

     Documents overcome the constraints of one or two level of key / value nesting of columnar databases. **Example: MongoDB, Couchbase**

Comparative Study

When to Use

Redis	MemcacheDB	OrientDB	Neo4J	Cassandra	Hbase	MongoDB	Couchbase
Caching, Queuing frequent information, Keeping Live information, Supports lists, sets, queues and more	Caching, Queuing frequent information, Keeping Live information,	Handling complex relational information, Modelling and handling classifications	Handling complex relational information, Modelling and handling classifications	Keeping unstructured non-volatile information, useful for content management	Keeping unstructured non-volatile information, useful for content management	Works with deeply nested and complex data structures, JavaScript friendly, useful for content management	Works with deeply nested and complex data structures, JavaScript friendly, useful for content management

Comparative Study

Handling Relational Data

Redis	Memcache DB	OrientDB	Neo4J	Cassandra	Hbase	MongoDB	Couchbase
Supports ACID, query only on key	Supports ACID, query only on key	Supports ACID and joins	Supports ACID and joins	Supports ACID, Multiple Queries	Supports ACID, Multiple Queries	Supports ACID, Multiple Queries, Nesting Data	Supports ACID, Multiple Queries, Nesting Data

Comparative Study

Performance

Redis	Memcache DB	OrientDB	Neo4J	Cassandra	Hbase	MongoDB	Couchbase
Highly Scalable, Highly Flexible, not complex in terms of representation and use	Highly Scalable, Highly Flexible, not complex in terms of representation and use	Variable Scalability, Highly Flexible, Highly complex in terms of representation and use	Variable Scalability, Highly Flexible, Highly complex in terms of representation and use	Highly Scalable, Moderately Flexible, Moderately complex in terms of representation and use	Highly Scalable, Moderately Flexible, Moderately complex in terms of representation and use	Highly Scalable, Highly Flexible, Moderately complex in terms of representation and use	Highly Scalable, Highly Flexible, Moderately complex in terms of representation and use

- Common RDBMSs
- Non-relational DBMSs
- **Skill – Job Profile Matrix**

SKILL – JOB PROFILE MATRIX

Skill – Profile Mapping

Job Profiles	Years of Experience	Understanding Specs and Schema	Coding Query in SQL (DML)	Analyzing Specification, Schema Design and Normalization (DDL)	Application / Database Architecture, Indexing, Performance Optimization	Database Administration	Databases, Algorithms, Architecture, Compilers, …	Data Mining, Machine Learning, Big Data, Programming
Application Programmer	0-4	X	X					
Senior Application Programmer	2-6	X	X	X	X			
Database Analyst / Architect	4-8	X	X	X	X			
Database Administrator	8-10	X	X	X	X	X		
Database Engineer (multiple grades)	2-10	X	X	X	X	X	X	
Big Data Programmer, Analyst	0-6	X	X	X	X			X

Companies in RDBMS & Big Data Space

All consultancies and product development companies use database management systems as backend:

1. TCS
2. Cognizant Ltd
3. IBM
4. Lexmark
5. Accenture
6. Intel
7. Amazon
8. NetApp
9. Ericsson
10. PWC
11. Deloitte
12. Tech mahindra
13. Wipro
14. HCL
15. Mindtree
16. Mphasis
17. Capegemini
18. Microsoft
19. Abobe
20. and so on.

DB Application Development

Companies working to develop new DBMS products and provide services:

1. Oracle - Oracle
2. Teradata - Teradata
3. IBM - DB2, Informix
4. Microsoft - SQL Server, My SQL
5. SAP - Sybase
6. Amazon - SimpleDB

DB System Development

Companies working to develop new DBMS products in NoSQL area and providing services:

1. KPMG, Google, SAP, Nokia, Adobe, Facebook - MangoDB (Document)
2. Microsoft, Ebay, Walmart, Nvidia, Sony - Cassandra (Column)
3. Uber, Twitter, Instagram, Airbnb - Redis (key value)
4. Blockchain, IBM, Walmart, ebay, Cisco, Microsoft - Neo4j (graph stores)

Big Data Application or System Development

Final Words

- Read the DBMS Text book thoroughly and solve exercises
- Practice query coding
- Practice database design from specs
- Besides DBMS, develop good knowledge in programming, data structure, algorithms and discrete structures
- Seek help, if you need to – mail us

PPD

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