Problems Caused by Failures

- Update all account balances at a bank branch.

  `Accounts(Anum, CId, BranchId, Balance)`

```
Update Accounts
Set Balance = Balance * 1.05
Where BranchId = 12345
```

Partial Updates - Lack of Atomicity

If the system crashes while processing this update, some, but not all, tuples with `BranchId = 12345` may have been updated.

Another Failure-Related Problem

- transfer money between accounts:

```
Update Accounts
Set Balance = Balance - 100
Where Anum = 8888

Update Accounts
Set Balance = Balance + 100
Where Anum = 9999
```

Partial Updates - Lack of Atomicity

If the system fails between these updates, money may be withdrawn but not redeposited

Problems Caused by Concurrency

- Application 1:

```
Update Accounts
Set Balance = Balance - 100
Where Anum = 8888

Update Accounts
Set Balance = Balance + 100
Where Anum = 9999
```

- Application 2:

```
Select Sum(Balance)
From Accounts
```

Lack of Isolation

If the applications run concurrently, the total balance returned to application 2 may be inaccurate.

Another Concurrency Problem

- Application 1:

```
Select balance into :balance
From Accounts
Where Anum = 8888

compute :newbalance using :balance

Update Accounts
Set Balance = :newbalance
Where Anum = 8888
```

- Application 2: same as Application 1

Lost Updates

If the applications run concurrently, one of the updates may be “lost”.

Transaction Properties

- Transactions are *durable*, *atomic* application-specified units of work.

  Atomic: indivisible, all-or-nothing.

  Durable: effects survive failures.

The "ACID" Properties

A tomic: a transaction occurs entirely, or not at all

C onsistent

I solated: a transaction's unfinished changes are not visible to others

D urable: once it is complete, a transaction's changes are permanent

Abort and Commit

Commit:

- When a transaction *commits*, any updates it made become durable, and they become visible to other transactions.
- A commit is the "all" in "all-or-nothing" execution.
- SQL: **commit work**

Abort:

- When a transaction *aborts* any updates it may have made are undone (erased), as if the transaction never ran at all.
- An abort is the "nothing" in "all-or-nothing" execution.
- SQL: **rollback work**
- the DBMS may unilaterally abort a running transaction

Serializability (informal)

- Concurrent transactions must appear to have been executed sequentially, i.e., one at a time, in some order.
- If T_i and T_j are concurrent transactions, then either:
  - T_i will appear to precede T_j , meaning that T_j will "see" any updates made by T_i , and T_i will not see any updates made by T_j , or
  - T_i will appear to follow T_j , meaning that T_i will see T_j's updates and T_j will not see T_i's.

Concurrency Control

- Serializability can be guaranteed by executing transactions serially, but this may result in poor performance
- Alternative: allow transactions to execute concurrently, but use a concurrency control protocol is used to ensure that their execution is serializable
- Some tools used by concurrency control protocols:
  - block, or delay, operations
  - abort transactions
  - multi-versioning
- Many concurrency control protocols have been proposed, based on:
  - locking, or
  - timestamps, or
  - conflict analysis

Two-Phase Locking

- The rules
  1. Before a transaction may read or write an object, it must have a lock on that object.
     - a *shared lock* is required to read an object
     - an *exclusive lock* is required to write an object
  2. Two or more transactions may not hold conflicting locks on the same object at the same time
     - exclusive locks conflict with exclusive and shared locks
     - shared locks do not conflict with other shared locks
  3. Once a transaction has released (unlocked) any object, it may not obtain any new locks.
     - Phase 1: acquiring locks, Phase 2: releasing locks
     - In strict 2PL, all locks are held until commit or abort.

If all transactions use two-phase locking, the execution history is guaranteed to be serializable.

Transaction Blocking

- Consider the following sequence of events:
  - T_1 acquires a shared lock on x and reads x
  - T_2 attempts to acquire an exclusive lock on x (so that it can write x)
- The two-phase locking rules prevent T_2 from acquiring its exlusive lock - this is called a *lock conflict*.
- Lock conflicts can be resolved in one of two ways:
  1. T_2 can be *blocked* - forced to wait until T_1 releases its lock
  2. T_1 can be *pre-empted* - forced to abort and give up its locks

Deadlocks

- transaction blocking can result in *deadlocks*
- for example:
  - T_1 reads object x
  - T_2 reads object y
  - T_2 attempts to write object x (it is blocked)
  - T_1 attempts to write object y (it is blocked)

A deadlock can be resolved only by forcing one of the transactions involved in the deadlock to abort.

Serializability Theory: A Brief Detour

- A transaction is a sequence of read and write operations.
- An *execution history* over a set of transactions $T_1 \ldots T_n$ is an interleaving of the the operations of $T_1 \ldots T_n$ in which the operation ordering imposed by each transaction is preserved.
- Two operations conflict if:
  - they belong to different transactions
  - they operate on the same object
  - at least one of the operations is a write

Serial and Serializable Histories

- $T_1 = w_1[x]\ w_1[y]$, $T_2 = r_2[x]\ r_2[y]$
- An interleaved execution of T_1 and T_2:

$$H_a = w_1[x]\ r_2[x]\ w_1[y]\ r_2[y]$$

- An equivalent serial execution of T_1 and T_2:

$$H_b = w_1[x]\ w_1[y]\ r_2[x]\ r_2[y]$$

- An interleaved execution of T_1 and T_2 with no equivalent serial execution:

$$H_c = w_1[x]\ r_2[x]\ r_2[y]\ w_1[y]$$

H_a is serializable because it is equivalent to H_b , a serial schedule. H_c is not serializable.

Testing for Serializability

$r_1[x]\ r_3[x]\ w_4[y]\ r_2[u]\ w_4[z]\ r_1[y]\ r_3[u]\ r_2[z]\ w_2[z]\ r_3[z]\ r_1[z]\ w_3[y]$

Is this history serializable?

Serialization Graph

A history is serializable iff its serialization graph is acyclic.

Serialization Graphs

$$r_1[x]\ r_3[x]\ w_4[y]\ r_2[u]\ w_4[z]\ r_1[y]\ r_3[u]\ r_2[z]\ w_2[z]\ r_3[z]\ r_1[z]\ w_3[y]$$

The history above is equivalent to

$$w_4[y]\ w_4[z]\ r_2[u]\ r_2[z]\ w_2[z]\ r_1[x]\ r_1[y]\ r_1[z] r_3[x]\ r_3[u]\ r_3[z]\ w_3[y]$$

That is, it is equivalent to executing T_4 followed by T_2 followed by T_1 followed by T_3.

Two-Phase Locking Revisited

- How does 2PL ensure serializability?
- Consider again non-serializable H_c:

$$H_c = \; w_1[x] \; r_2[x] \; r_2[y] \; w_1[y]$$

- 2PL prevents non-serializable histories by blocking (and hence reordering) operations that might lead to non-serializability
- 2PL can be too conservative - it may also prevent some serializable histories from occurring

$$H_a = w_1[x] \; r_2[x] \; w_1[y] \; r_2[y]$$

Phantoms

Transaction 1:

```
Insert Into Employee
Values ('123','Shel',
'Jetstream','D11',52000)
```

Transaction 2:

```
Select *
From Employee
Where WorkDept = 'D11'

Select *
From Employee
Where Salary > 50000
```

- Transaction 2 may observe a phantom tuple, not possible in a serial execution.
- 2PL of database records (or pages) may not be enough to ensure serializability in the presence of insertions or delations.

Insertions, Deletions and Serializability

- Queries must conflict with (and hence "lock") all tuples that satisfy the query predicates, including previously-deleted or to-be-inserted tuples that are not currently in the database.
- One solution: relation-level locks
- Another solution: index key-range locking
  - consider query with predicate `WorkDept = 'D11'`
  - suppose there is an index on `WorkDept`
  - query locks index key range covering 'D11', preventing insertions in that range

Multi-Granularity Locking

- allow transactions to lock entire relation, or individual records in the relation, as appropriate
- before locking smaller granules (e.g., records), set intention-mode locks on the containing larger granule (e.g., relation)
- lock conflict table, including intention-mode locks

	X	S	IX	IS
X	no	no	no	no
S	no	yes	no	yes
IX	no	no	yes	yes
IS	no	yes	yes	yes

- IX = intention exclusive, IS = intention shared

Snapshot Isolation (SI)

- every transaction *T* "sees" a snapshot of the database
  - *T*'s snapshot includes updates made by all transactions that committed before *T* starts
  - *T*'s snapshot does not included any updates made by concurrent transactions
- each transaction sees its own updates
- concurrent transactions may not perform conflicting updates

SI vs. serializability

Pro: read-only transactions never block

Con: potential anomalies from non-serializable behavior

Implementing Snapshot Isolation

- multi-versioning
  - if transaction T updates object (e.g, page) p, concurrent transactions must continue to see pre-update version of p
- detecting write-write conflicts
  - can be done using write locks (no need for read locks)
  - can be done using commit-time validation
    - each transaction T maintains a list of updated objects (e.g. pages)
    - when T trys to commit, ensure no already-committed concurrent transactions updated any of the same objects. If no conflicts, commit T else abort T.
    - implements a first committer wins rule for concurrent conflicting upates

Recovery Management

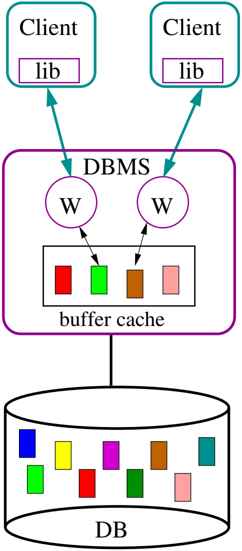
Recovery management means:

- implementing voluntary or involuntary rollback of individual transactions
- implementing recovery from system failures so that transaction ACID properties are guaranteed
- *system failure* means:
  - the database server is halted
  - processing of in-progress SQL command(s) is halted
  - connections to application programs (clients) are broken.
  - contents of memory buffers are lost

Failures and Transactions

- To ensure that transactions are atomic, every transaction that is active when a system failure occurs must either be
  - restarted after the failure from the point it which it left off, or
  - rolled back after the failure
- It is difficult to restart applications after a system failure, so the recovery manager does the following:
  - abort transactions that were active at the time of the failure
  - ensure that changes made by transactions that committed before the failure are not lost

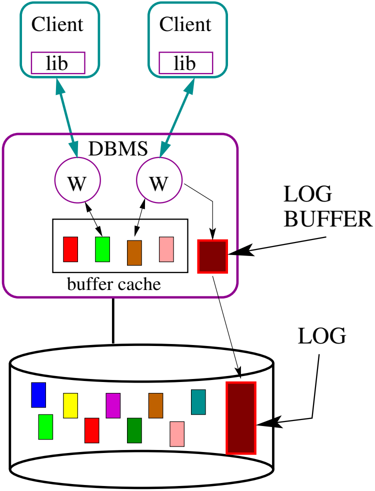
Buffers and Persistent Storage



Committing a Transaction

- Suppose that a running transaction results in the following sequence of events:
  - update page P_a
  - update page P_b
  - update page P_c
  - update page P_d
  - **commit**
- How should this transaction be committed?

Logging



- log is an append-only list of log records
- log tail (most recent entries) is in memory
- log entries are flushed from log buffer to disk in order
- log entries are flushed in batches when possible

Committing a Transaction Using Logging

Events for transaction T:

- update page P_a
- update page P_b
- update page P_c
- update page P_d
- **commit**

Logging for T:

- log updated state of P_a
- log updated state of P_b
- log updated state of P_c
- log updated state of P_d
- log **commit** record for T

- ensure the **commit** record is on disk before acknowledging **commit** to application
- buffer manager need not flush updated pages to disk
- use log records to restore effects of T after a failure

UNDO Logging and WAL

- the previous example illustrated REDO logging
  - each log entry describes how to re-apply an update that has been lost
  - REDO logging is used to ensure durability of committed updates
- UNDO logging is also useful
  - an UNDO log entry describes how to erase or undo an update that has already been applied
  - UNDO logging is used to ensure that the effects of aborted transactions are erased.

Write-Ahead Logging (WAL) Protocol

The WAL protocol requires that the log record describing an update be on persistent storage before the update itself is on persistent storage.

Log Example

log head	$\rightarrow$	T_0,begin
(oldest part of the log)		T_0, P_a, a_0, a_1
		T_1,begin
		T_1, P_b, b_0, b_1
		T_2,begin
		T_2, P_c, c_0, c_1
		T_1, P_a, a_0, a_1
		T_1,commit
		T_3,begin
on disk		T_2,abort
in memory		T_3, P_b, b_1, b_2
		T_4,begin
(newest part of the log)		T_4, P_a, a_1, a_2
log tail	$\rightarrow$	T_3,commit

Log-Based Recovery

- on recovery from a failure, use the log to ensure that the database
  - contains the effects of all committed transactions
  - does not contain any effects of aborted transactions

  before allowing new transactions to begin executing
- simple two-pass log-based recovery

  Pass 1 (tail to head): identify losers and winners and rollback the losers

  Pass 2 (head to tail): redo the winners
- this simple log and recovery algorithm assumes
  - page-level locking (why??)
  - idempotent log records

Transaction Commit

A transaction is atomically and durably committed when its **commit** log record is flushed to the log disk.

Checkpoints

- As the log grows, the time required to recover from a system failure also grows.
- checkpoints are used to reduce the amount of log data that must be scanned after a system failure.
- simple checkpointing algorithm
    1. prevent new transactions from starting, and wait for active transactions to finish
    2. flush all modified pages from the buffer pool to the disk
    3. truncate the log
- simple algorithm is effective but expensive
- other checkpointing algorithms try to achieve a similar effect with less impact on performance

Buffer Management and Transactions

- Force vs. No Force Buffer Management
  - Force: All of a transaction's changes are present on the disk by the time the transaction commits.
  - No Force: Some of a transaction's changes may not be on disk by the time the transaction commits.
- Steal vs. No Steal Buffer Management
  - Steal: Uncommitted changes may be present on the disk.
  - No Steal: Uncommitted changes are never present on the disk.

Buffer Management and Transactions (cont'd)

Force,No Steal: no logging required, but impractical (why?)

Force,Steal: UNDO logging required, transaction commits are expensive

No Force, No Steal: REDO logging required, No Steal constrains buffer manager

No Force, Steal: REDO and UNDO logging required, only constraint on buffer management is WAL

Enforcing WAL

- each log entry is assigned a log sequence number (LSN)
- log manager tracks $\mathbf{safeLSN}$, the largest LSN among log entries that have been flushed to disk
- for each page p, buffer manager tracks $\mathbf{pageLSN}(p)$, the LSN of the most recent update applied to p
- buffer manager may not flush a dirty page p to disk unless $\mathbf{pageLSN}(p) \leq \mathbf{safeLSN}$

Introduction to ARIES

- ARIES has the same goal (durable, failure-atomic transactions) as the simple logging technique already described, but tries to achieve it with less impact on transaction performance during normal (non-failure) operation
- some differences between ARIES and simple technique
  - ARIES allows fine-grained (i.e., record-level) locking
  - ARIES allows operational logging
  - ARIES supports non-idempotent log operations
  - ARIES supports fuzzy checkpointing
  - ARIES recovery uses three log passes, not two

Physical State Logging

$$s_0 \xrightarrow{Op_1} s_1$$

- REDO log info for Op_1 consists s_1, the after-image of the affected object (e.g., page)
- UNDO log info for Op_1 consists of s_0, the before-image of the affected object
- the object (page) must remain locked until Op_1's transaction commits, to avoid lost updates
- log entries are idempotent: REDOing Op_1 multiple times has the same effect as REDOing it one time. Same for UNDO.

(Page-level) Operational Logging

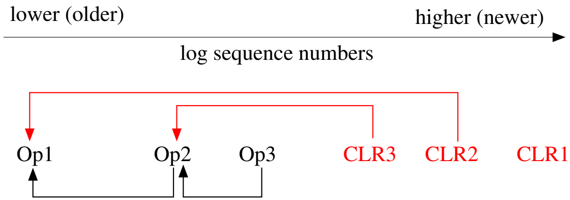
$$s_0 \xrightarrow{Op_1} s_1$$

- REDO log info for Op_1 consists of a description of Op_1
- UNDO log info for Op_1 consists of a description of a compensating operation for Op_1.
- the affected object (page) need not remain locked until Op_1's transaction commits
- log entries may not be idempotent

Eventually Exactly Once Execution

- recall that ARIES tracks $\mathbf{pageLSN}(p)$ for each page p
- suppose the ARIES is REDOing a logged operation, with $\mathbf{LSN} = n$, on page p
- ARIES will only REDO the operation if $n > \mathbf{pageLSN}(p)$, otherwise the page already reflects the effects of the operation.

Rolling Back Transactions in ARIES



- each compensation is logged and gets a LSN
- CLR = compensation log record
- compensations are never undone

Checkpointing in ARIES

- ARIES checkpoints periodically during normal operation
- checkpointing involves logging checkpoint information including:
  - list of active transactions
  - LSN of most recent log record for each active transaction
  - list of dirty buffered pages, including their recLSNs.
- $\mathrm{recLSN}(p)$ is the LSN of the update that made p dirty,
- there is no need to quiesce transactions
- there is no need to flush any pages to the disk - the buffer manager can do this any time (as long as WAL is observed), asynchronously
- called fuzzy checkpointing: no sharp log boundary

Recovery in ARIES

Analysis Pass:

- start at most recent complete checkpoint
- $\mathbf{redoLSN}$ is minimum $\mathbf{recLSN}(p)$ of pages in the checkpointed dirty page list
- scan forward to identify losers and the most recent LSN for each

REDO Pass:

- start at $\mathbf{redoLSN}$
- scan forwards, redoing all updates, including compensations and loser updates

UNDO Pass:

- scan backwards, perform compensations for uncompensated updates of losers

ARIES Log Example

log head $\rightarrow$ 1, T_0,P_d,update,prev=NULL
2, T_1,P_b,update,prev=NULL
3, T_2,P_c,update,prev=NULL
checkpoint: active=T_0(1),T_1(2),T_2(3),
dirty=P_c(3),P_d(1)
4, T_1,P_a,update,prev=2
5, T_1,commit
6, T_2,P_a,update,prev=3
7, T_2,CLR for LSN=6,prev=3
8, T_3,P_b,update,prev=NULL
9, T_3,P_c,update,prev=8
10, T_2,CLR for LSN=3,prev=NULL
11, T_2,abort
12, T_4,P_a,update,prev=NULL
log tail $\rightarrow$ 13, T_3,commit