ECE 650
Systems Programming & Engineering

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Database Transaction Processing

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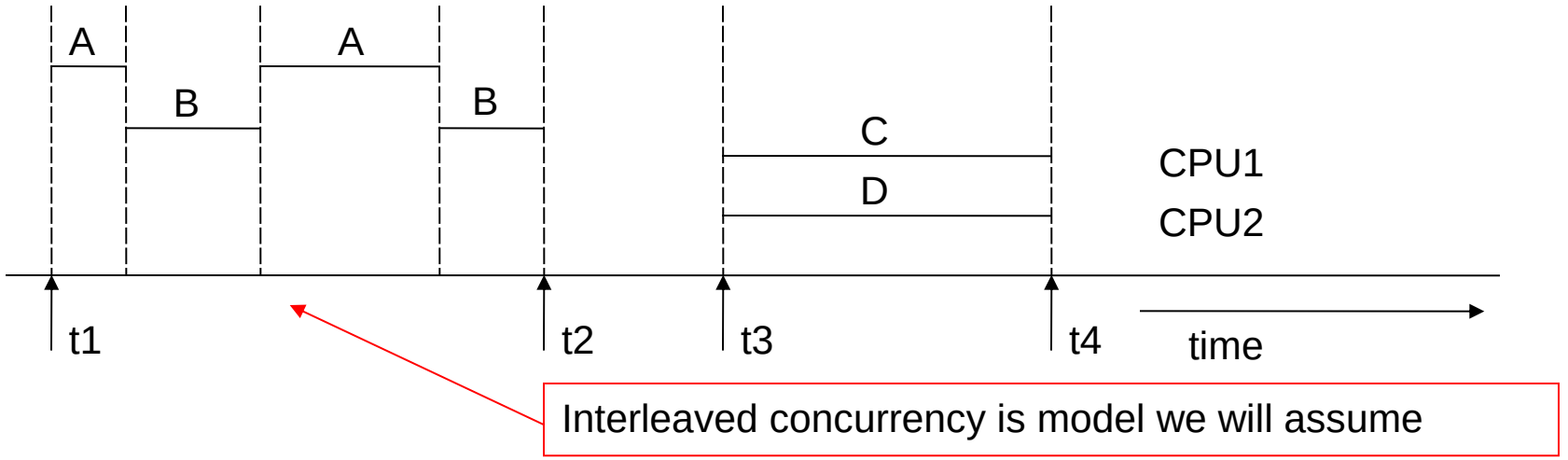
Slides are adapted from Brian Rogers (Duke)

Transaction Processing Systems

- Systems with large DB's; many concurrent users
  - As a result, many concurrent database transactions
  - E.g. Reservation systems, banking, credit card processing, stock markets, supermarket checkout
- Need high availability and fast response time
- Concepts
  - Concurrency control and recovery
  - Transactions and transaction processing
  - ACID properties (desirable for transactions)
  - Schedules of transactions and recoverability
  - Serializability
  - Transactions in SQL

Single-User vs. Multi-User

- DBMS can be single-user or multi-user
  - How many users can use the system concurrently?
  - Most DBMSs are multi-user (e.g. airline reservation system)
- Recall our concurrency lectures (similar issues here)
  - Multiprogramming
  - Interleaved execution of multiple processes
  - Parallel processing (if multiple processor cores or HW threads)



Transactions

- Transaction is logical unit of database processing
  - Contains ≥ 1 access operation
  - Operations: insertion, deletion, modification, retrieval
    - E.g. things that happen as part of the queries we've learned
- Specifying database operations of a transaction:
  - Can be embedded in an application program
  - Can be specified interactively via a query language like SQL
  - May mark transaction boundaries by enclosing operations with:
    - "**begin transaction**" and "**end transaction**"
- Read-only transaction:
  - No database update operations; only retrieval operations

Database Model for Transactions

- Database represented as collection of named data items
  - Size of data item is its “granularity”
  - E.g. May be **field** of a record (row) in a database
  - E.g. May be a **whole record (row)** or **table** in a database
- Database access operations can include:
  - read_item(X): read database item named X into a program variable (assume program variable also named X)
  - write_item(X): write value of program variable X into database item named X

Read & Write Commands

- read_item(X)
  1. Find address of disk block containing item X
  2. Copy disk block into a buffer in memory (if not already there)
  3. Copy item X from memory buffer to program variable named X
- write_item(x)
  1. Find address of disk block containing item X
  2. Copy disk block into a buffer in memory (if not already there)
  3. Copy item X from the program variable named X into memory
  4. Store updated block from memory buffer back to disk
     - At some point; does not need to be immediately
     - This is where database is actually updated

Example

T1

```
----------------------
read_item(X);
X=X-N;
write_item(X);
read_item(Y);
Y=Y+N;
write_item(Y);
```

T2

```
----------------------
read_item(X);
X=X+M;
write_item(X);
```

- Two example transactions: T1, T2
- Read-set: T1={X,Y}, T2={X}
- Write-set: T1={X,Y}, T2={X}

Concurrency Control Motivation

- **Three problems** can occur with concurrent transactions if executed in an uncontrolled manner:
  1. **Lost Update Problem**
  2. **Temporary Update (Dirty Read) Problem**
  3. **Incorrect Summary Problem**

- We'll use example of an airline reservation database
  - Record (row) is stored for each airline flight
  - One record field is the number of reserved seats
    - A named data item

Lost Update Problem

T1	T2
read_item(X);	
X=X-N;	
	read_item(X);
	X=X+M;
write_item(X);	
read_item(Y);	
	write_item(X);
Y=Y+N;	
write_item(Y);	

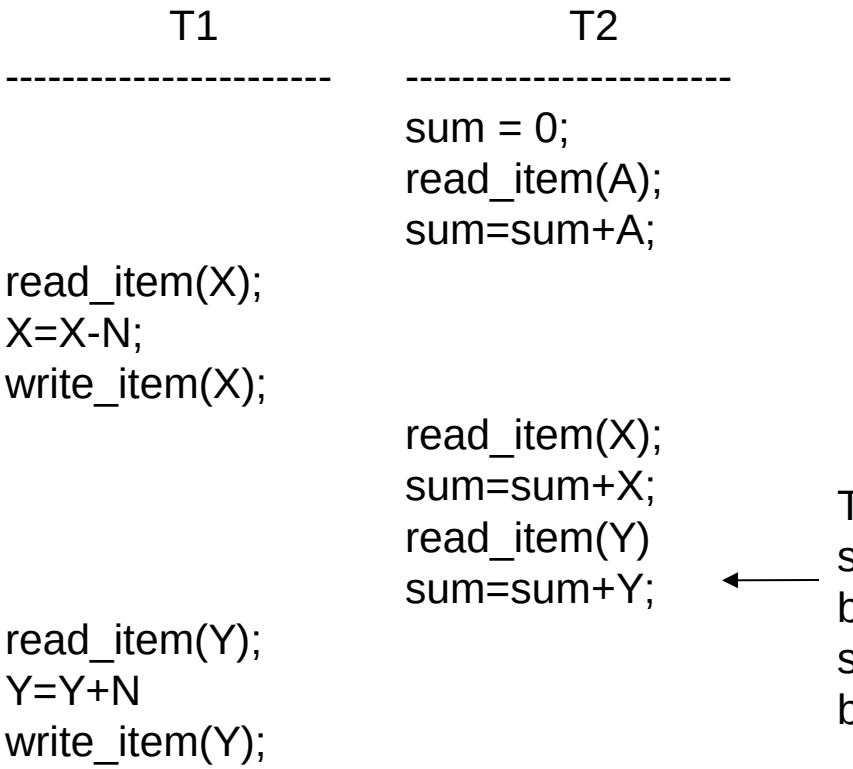
- T1 transfers N reservations from flight X to flight Y
- T2 reserves M new seats on flight X
- Update to flight X from T1 is lost!
  - Similar to our concurrency examples

Temporary Update Problem

T1	T2
read_item(X);	
X=X-N;	
write_item(X);	
	read_item(X);
	X=X+M;
	write_item(X);
read_item(Y);	
…	

- Transaction T1 fails for some reason
- DBMS must *undo* T1; change X back to its original value
- But T2 has already read the temporarily updated value of X
- Value T2 read is **dirty data**
  - Created by transaction not yet completed and committed

Incorrect Summary Problem



- One transaction is calculating an aggregate summary function
- Other transactions are updating records
- E.g. calculate total number of reservations on all flights

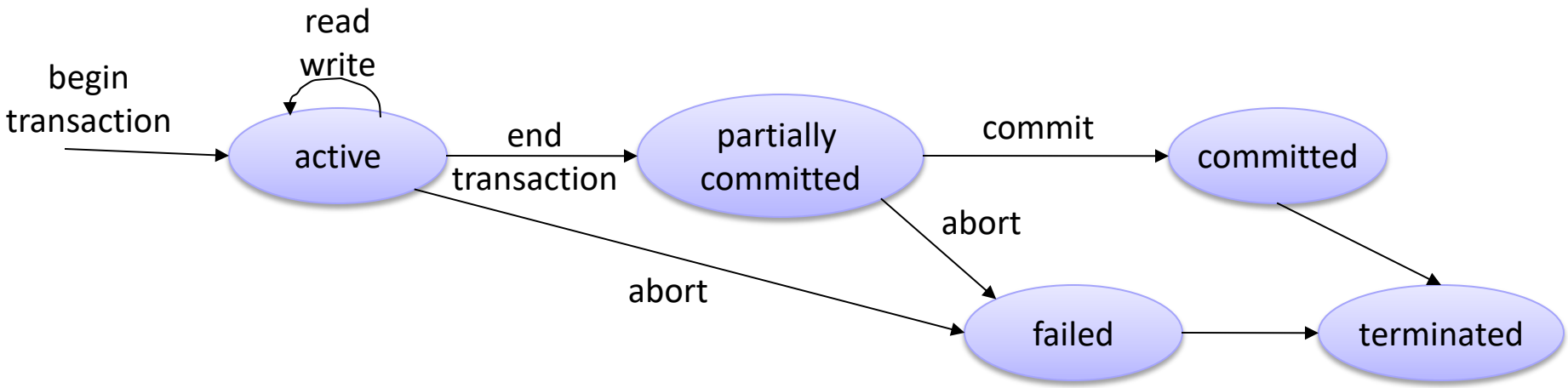
Recovery

- For each transaction, DBMS is responsible for either:
  - All ops in transaction complete; their effect is recorded in database
    OR
  - Transaction has no effect on database or any other transaction
- DBMS can't allow some operations to apply and not others
  - This can happen if a transaction fails part of the way through its ops
- How can a failure happen?
  - Logical abort (we tried to reserve enough seats but there weren't enough)
    ^ This one is common and mundane! Must support!
  - System crash (HW, SW, or network error during transaction exe)
  - Transaction or system error (e.g. integer overflow or divide by 0)
  - Local errors (e.g. data for the transaction is not found)
  - Concurrency control (discussed in a bit may abort transaction)
  - Disk failure (read or write malfunction due to disk crash)
  - Physical problems (power failure, natural disaster, …)

Transaction Concepts

- Transaction is an atomic unit of work
  - All operations completed in entirety or none of them are done
- DBMS tracks when transaction starts, terminate, commit or abort
  - BEGIN_TRANSACTION: beginning of transaction execution
  - READ or WRITE: read or write ops on database items
  - END_TRANSACTION: specifies that READ and WRITE operations have completed in the transaction
    - DBMS may need to check whether the changes can be *committed*
      - i.e. permanently applied to the database
    - Or whether transaction must be aborted
  - COMMIT_TRANSACTION: successful end of transaction
    - Changes (updates) can be safely committed to database
  - ABORT: unsuccessful end of transaction
    - Changes that may have been applied to database must be undone

State Transition Diagram



- Transaction moves to active state right when it begins
- Transaction can issue read & write operations until it ends
- Transaction moves to partial committed state
  - Recovery protocols need to ensure absence of a failure
- Transaction has reached commit point; changes can be recorded in DB
- Transaction can be aborted & go to failed state
- Terminated state corresponds to transaction leaving system
- Transaction info maintained in DBMS tables; failed trans may be restarted

System Log

- Used to recover from failures that affect transactions
  - Track transaction operations that affect DB values
  - Keep log on disk so it is not affected except by catastrophic fails
- Log records (T is a unique transaction ID)
  - [start_transaction,T]
    - transaction T has started
  - [write_item,T,X,old_val,new_val]
    - transaction T has changed database item X from old_val to new_val
  - [read_item,T,X] (not strictly needed)
    - transaction T has read the value of item X
  - [commit,T]
    - transaction T has completed successfully, effects can be
  - [abort,T]
    - transaction T has been aborted

Transaction Commit Point

- **“Commit point”**
  - A point in time in which all operations that access the DB have executed successfully
  - Effect of all operations on the DB have been recorded in the log
  - Sometimes also called a “consistency point” or “checkpoint”
- Transaction said to be “committed”
  - Its effect assumed to be permanently recorded in the DB
  - Transaction writes a commit record [commit,T] to the log
- On a failure:
  - Search log for started but not committed transactions
    - Roll back their effects to undo their effects of updating the DB
  - Search for transactions that have written their commit record
    - Apply their write operations from the log to the DB

ACID Properties

- Transactions should possess ACID properties
  - These should be enforced by concurrency control & recovery methods of the DBMS
    - **A**tomicity
    - **C**onsistent
    - **I**solation
    - **D**urability

Atomicity

- **"Atomicity"**:
  - Transaction is atomic unit of processing
  - It is performed entirely or not at all
- Managed by the DBMS
  - As part of the transaction recovery subsystem
  - Requires executing every transaction (eventually) to completion
  - Partial effects of an aborted transaction must be undone

Consistency

- **“Consistency”**:
  - Complete execution of a transaction takes the database from one consistent state to another
- Responsibility:
  - Programmers of database programs
  - And/Or DBMS module that enforces integrity constraints
- Database State
  - Collection of all stored data items in the DB at a given point in time
  - Consistent state satisfies all constraints of the schemas
  - DB program should be written to guarantee this

Isolation

- **“Isolation”**:
  - Transaction appears as if executed in isolation from other transactions (no interference)
- Enforced by the “concurrency control” subsystem of DBMS
  - E.g. a transaction only makes its updates visible to other transactions after it commits
  - There are many options for these types of protocols

Durability

- **“Durability”**:
  - Changes applied to database by a committed transaction must be persistent (e.g. not lost due to any failure)
- Responsibility of recover subsystem of DBMS
  - Also many options for recovery protocols

Schedule of Transactions

- Schedule of n transactions: T1, T2, …, Tn
  - Ordering of operations of the transactions
  - Each operation is in-order within a given transaction, Ti
  - But operations may be interleaved between Ti and Tj
- Notation
  - read_item, write_item, commit, abort abbreviated as r, w, c, a
  - Transaction ID is subscript following the operation
  - E.g. S_a: $r_1(X)$; $r_2(X)$; $w_1(X)$; $r_1(Y)$; $w_2(X)$; $w_1(Y)$

Complete Schedule

- Conflicting operations:
  1. Belong to different transactions
  2. Access the same named item X
  3. At least one of the operations is a write_item(X)

For a more formal introduction to this, see Wikipedia: Schedule (computer science)

- Schedule **S** of n transactions is complete schedule if:
  1. Operations in S are exactly the operations in T_1, T_2, …, T_n, with a commit or abort operation as the last op for each transaction
  2. Any pair of ops from same transaction T_i appear in order
  3. For any 2 conflicting ops, one must occur before the other (i.e., order is explicit)

- Trivially correct schedule: **serial schedule**
  - When all transactions are done strictly in order with no interleaving
  - Definitely correct, but this kills performance
  - We want this property but also to allow some interleaving...

Schedule Recoverability

- One strategy: **Recovery**.
  - For schedules where transactions commit only after all transactions whose changes they read have committed.
  - If first transaction aborts, then we can abort second transaction.
  - Ability to do this depends on the schedule, some are not recoverable
    - We can characterize schedules for which recovery is possible
  - For recoverable schedules there may be a variety of algorithms
- Recoverable schedules:
  - Once a trans T is committed, should never be necessary to undo it
  - If no trans T in S commits until all transactions T' that have written an item that T reads have committed
  - If this is not true, then the schedule is nonrecoverable
- Example of recoverable schedule
  - S_a: $r_1(X)$; $w_1(X)$; $r_2(X)$; $r_1(Y)$; $w_1(Y)$; c_1; $w_2(X)$; c_2;

Non-Recoverable Schedule

- Example:
  - S_c: $r_1(X)$; $w_1(X)$; $r_2(X)$; $r_1(Y)$; $w_2(X)$; $w_1(Y)$; c_2; a_1
  - Non-recoverable because T2 reads X from T1; T2 commits before T1 commits; what if T1 aborts?
    - Value T2 read for X is no longer valid; it needs to abort as well
- Examples of making previous schedule recoverable:
  - S_c: $r_1(X)$; $w_1(X)$; $r_2(X)$; $r_1(Y)$; $w_2(X)$; $w_1(Y)$; c_1; c_2
  - S_c: $r_1(X)$; $w_1(X)$; $r_2(X)$; $r_1(Y)$; $w_2(X)$; $w_1(Y)$; a_1; a_2
- Summary of above:
  - $r_1(X)$; $w_1(X)$; $r_2(X)$; $r_1(Y)$; $w_1(Y)$; c_1; $w_2(X)$; c_2; — Recoverable (from last slide)
  - $r_1(X)$; $w_1(X)$; $r_2(X)$; $r_1(Y)$; $w_2(X)$; $w_1(Y)$; c_2; a_1 — Unrecoverable (top of slide)
  - $r_1(X)$; $w_1(X)$; $r_2(X)$; $r_1(Y)$; $w_2(X)$; $w_1(Y)$; c_1; c_2 — Fix #1
  - $r_1(X)$; $w_1(X)$; $r_2(X)$; $r_1(Y)$; $w_2(X)$; $w_1(Y)$; a_1; a_2 — Fix #2

Cascading Rollback

- **"Cascading Rollback"**:
  - When an *uncommitted* transaction needs to rollback because it read an item from a transaction that failed
  - E.g. S_e from previous slide
- This can be costly; thus important to characterize schedules where this is guaranteed not to occur
  - Called a **cascadeless schedule**
  - If every transaction only reads items that were written by already committed transactions
  - E.g., $r_1(A)$; $w_1(A)$; $r_2(A)$; $w_2(A)$; c_1; c_2 becomes $r_2(A)$; $r_1(A)$; $w_1(A)$; $w_2(A)$; a_1; c_2
- Final type of schedule: **strict schedule**
  - Transactions cannot read or write X until last transaction that write X has committed (or aborted)
  - Even more restrictive than cascadeless (eases recovery)
  - E.g., $r_1(A)$; $w_1(A)$; $r_2(A)$; $w_2(A)$; c_1; c_2 becomes $r_1(A)$; $w_1(A)$; c_1; $r_2(A)$; $w_2(A)$; c_2

Serializability of Schedules

- Another strategy: **serializability**
- Characterize types of schedules considered correct…
  - Even when concurrent transactions are executing!
- Consider two transactions T1 and T2
  - E.g. the airline reservation transactions we looked at earlier
  - If no operation interleaving is possible then two outcomes:
    - Execute all of T1 then all of T2
    - Or execute all of T2 then all of T1
  - If operation interleaving is possible then many possible orderings
- **Serializability of schedules**:
  - Used to identify which schedules are correct when transaction executions have interleaving operations

Serial Schedule

"Serial Schedule":

- All operation of each transaction executed consecutively
- No interleaving
- Formally:
  - If for every transaction T in the schedule, all operations of T are executed consecutively in the schedule
  - Commit or abort of a transaction signals start of next transaction
  - Otherwise the schedule is **nonserial**
- Easy to reason about correctness, but…
  - Problem with serial schedules is performance
  - Limited concurrency
    - What if one operation requires a slow I/O operation?

Serializable Schedule

- A schedule S of n transactions is **serializable** if:
  - Results are equivalent to *some* serial schedule of the same n transactions
- Saying that a nonserial schedule S is serializable is equivalent to saying that it is correct

Example: NOT a serializable schedule

T1	T2
read_item(X);	
X=X-N;	
	read_item(X);
	X=X+M;
write_item(X);	
read_item(Y);	
	write_item(X);
Y=Y+N;	
write_item(Y);	

- Recall our Lost Update problem
  - Assume X=90 and Y=90 at start; N=3 and M=2
  - We'd expect X=89 and Y=93 in database at end
  - In this interleaving we end up with X=92 and Y=93

    BROKEN!

Example: Serializable schedule

T1	T2
read_item(X);	
X=X-N;	
write_item(X);	
read_item(Y);	
	read_item(X);
	X=X+M;
Y=Y+N;	
write_item(Y);	
	write_item(X);

- This is a serializable schedule
- Would be allowed by the DBMS
- Non-serializable schedules can be aborted before commit

Conclusion

- We want parallelism in our database ***and*** we want ACID properties
  - But we're accessing shared data, so conflicts arise
- Simple mutex too expensive
- Unlike simple RAM (like the malloc assignment), our data is *structured*, so we can reason about *how* we interleave operations
- Database schedules operations to ensure correctness
- Tradeoffs exist between performance and cost/correctness of recovery in exceptional circumstances