Models of Transactions

Chapter 19

Structuring Applications

- Many applications involve long transactions that make many database accesses
- To deal with such complex applications many transaction processing systems provide mechanisms for imposing some structure on transactions

Flat Transaction

- Consists of:
  - Computation on local variables
    - not seen by DBMS; hence will be ignored in most future discussion
  - Access to DBMS using call or statement level interface
    - This is **transaction schedule**; commit applies to these operations
- No internal structure
- Accesses a single DBMS
- Adequate for simple applications

```
begin transaction
    ⋮
  EXEC SQL …..
    ⋮
  EXEC SQL …..
    ⋮
commit
```


Flat Transaction

- Abort causes the execution of a program that restores the variables updated by the transaction to the state they had when the transaction first accessed them.

```
begin transaction
    ⋮
  EXEC SQL …..
    ⋮
  EXEC SQL …..
    ⋮
  if condition then abort
    ⋮
commit
```


Some Limitations of Flat Transactions

- Only total rollback (abort) is possible
  - Partial rollback not possible
- All work lost in case of crash
- Limited to accessing a single DBMS
- Entire transaction takes place at a single point in time

Providing Structure Within a Single Transaction

Savepoints

- **Problem**: Transaction detects condition that requires rollback of *recent* database changes that it has made
- **Solution 1**: Transaction reverses changes itself
- **Solution 2**: Transaction uses the rollback facility within DBMS to undo the changes

Savepoints

```
begin transaction
   S1;
   sp1 := create_savepoint();     <-- Call to DBMS
   S2;
   sp2 := create_savepoint();
   S3;
   if (condition) {rollback (sp1); S5};
   S4;
commit
```

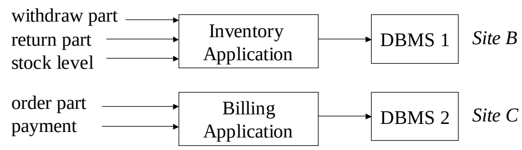
- Rollback to sp_i causes *database updates* subsequent to creation of sp_i to be undone
  - S2 and S3 updated the database (else there is no point rolling back over them)
- Program counter and local variables are *not* rolled back
- Savepoint creation does not make prior database changes durable (abort rolls *all* changes back)

Example of Savepoints

- Suppose we are making airplane reservations for a long trip
  - London-NY   NY-Chicago   Chicago-Des Moines
- We might put savepoints after the code that made the London-NY and NY-Chicago reservations
- If we cannot get a reservation from Chicago to Des Moines, we would rollback to the savepoint after the London-NY reservation and then perhaps try to get a reservation through St Louis

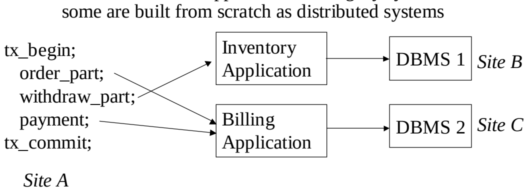
Distributed Systems: Integration of Legacy Applications

- **Problem**: Many enterprises support multiple **legacy systems** doing separate tasks
  - Increasing automation requires that these systems be integrated



Distributed Transactions

- Incorporate transactions at multiple servers into a single (distributed) transaction
  - Not all distributed applications are legacy systems; some are built from scratch as distributed systems



Distributed Transactions

- **Goal**: distributed transaction should be ACID
  - Each subtransaction is *locally* ACID (*e.g., local* constraints maintained, *locally* serializable)
  - In addition the transaction should be *globally* ACID
    - **A**: Either *all* subtransactions commit or all abort
    - **C**: *Global* integrity constraints are maintained
    - **I**: Concurrently executing distributed transactions are *globally* serializable
    - **D**: Each subtransaction is durable

Banking Example

- **Global atomicity** - funds transfer
  - Either both subtransactions commit or neither does

```
tx_begin;
  withdraw(acct1);
  deposit(acct2);
tx_commit;
```

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Banking Example (con’t)

- **Global consistency -**
  - Sum of all account balances at bank branches = total assets recorded at main office

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Banking Example (con’t)

- **Global isolation** - local serializability at each site does not guarantee global serializability
  - *post_interest* subtransaction is serialized after *audit* subtransaction in DBMS at branch 1 and before *audit* in DBMS at branch 2 (local isolation), *but*
  - there is no global order

time ↓	*post_interest*	*audit*
		sum balances at branch 1;
	post interest at branch 1;	
	post interest at branch 2;	
		sum balances at branch 2;

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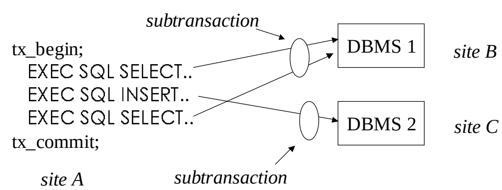
Exported Interfaces

Local system might export an interface for executing individual SQL statements.



Alternatively, the local system might export an interface for executing subtransactions.

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Multidatabase

- Set of databases accessed by a distributed transaction is referred to as a **multidatabase** (or federated database)
  - Each database retains its autonomy and might support local (non-distributed) transactions
- Multidatabase might have global integrity constraints
  - *e.g.,* Sum of balances of individual bank accounts at all branch offices = total assets stored at main office

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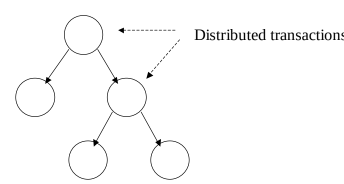
Transaction Hierarchy

- A distributed transaction invokes subtransactions.
- General model: one distributed transaction might invoke another as a subtransaction, yielding a hierarchical structure



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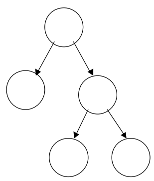
Models of Distributed Transactions



- Can siblings execute concurrently?
- Can parent execute concurrently with children?
- Who initiates commit?

Hierarchical Model: No concurrency among subtransactions, root initiates commit

Peer Model: Concurrency among siblings and between parent and children, any subtransaction can initiate commit

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Distributed Transactions

- Transaction designer has little control over the structure. Decomposition fixed by distribution of data and/or exported interfaces (legacy environment)
- Essentially a *bottom-up* design

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Nested Transactions

- **Problem**: Lack of mechanisms that allow:
  - a *top-down*, functional decomposition of a transaction into subtransactions
  - individual subtransactions to abort without aborting the entire transaction
- Although a nested transaction looks similar to a distributed transaction, it is *not* conceived of as a tool for accessing a multidatabase

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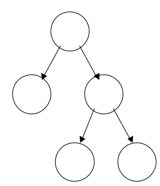
Characteristics of Nested Transactions



- (1) Parent can create children to perform subtasks; children might execute sequentially or concurrently; parent waits until all children complete (no communication between parent and children).
- (2) Each subtransaction (together with its descendants) is isolated with respect to each sibling (and its descendants). Hence, siblings are serializable, but order is not determined and nested transaction is *non-deterministic*.
- (3) Concurrent nested transactions are serializable.

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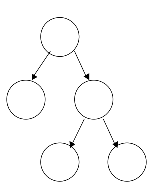
Characteristics of Nested Transactions



- (4) A subtransaction is atomic. It can abort or commit independently of other subtransactions. Commit is *conditional* on commit of parent (since child task is a subtask of parent task). Abort causes abort of all subtransaction's children.
- (5) Nested transaction commits when root commits. At that point updates of committed subtransactions are made durable.

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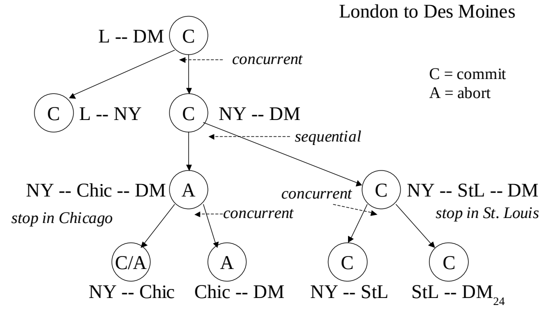
Nested Transaction - Example

Booking a flight from London to Des Moines



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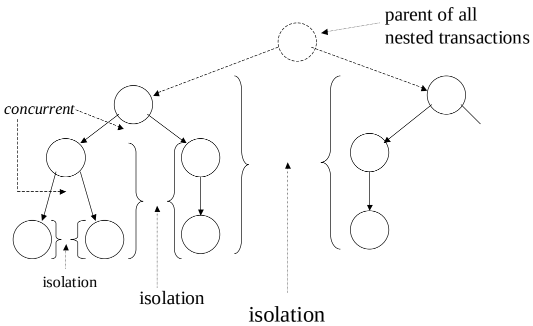
Nested Transactions



Characteristics of Nested Transactions

- (6) Individual subtransactions are not necessarily consistent, but nested transaction as a whole is consistent

Structuring to Increase Transaction Performance

- **Problem**: In the models previously discussed, a transaction generally locks items it accesses and holds locks until commit time to guarantee serializabiltiy

acquire lock on x ↓   *release lock on x* ↓

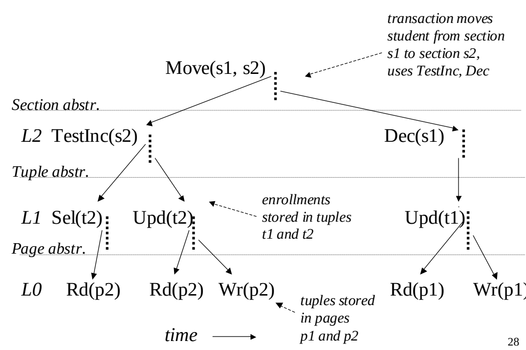
T1: r(x:12) .. *compute* .. w(x:13) commit

T2: *request read(x)* r(x:13) ..*compute*.. w(x:14) ..

↑ *(wait)*   ↑ *acquire lock on x*

  – This eliminates bad interleavings, but limits concurrency and hence performance

Example - Switch Sections



Structuring into Multiple Transactions

Chained Transactions

- **Problem 1** (trivial): Invoking begin_transaction at the start of each transaction involves communication overhead
- With chaining, a new transaction is started automatically for an application program when the program commits or aborts the previous one
  – This is the approach taken in SQL

Chained Transactions

begin transaction S1 commit S2 begin transaction S3 commit	begin transaction S1 commit begin transaction S2 S3 commit	S1 commit S2 S3 commit
S2 not included in a transaction since it has no db operations	Equivalent since S2 does not access the database	Chaining equivalent

transaction starts implicitly

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Chained Transactions

- **Problem 2**: If the system crashes during the execution of a long-running transaction, considerable work can be lost
- Chaining allows a transaction to be decomposed into sub-transactions with intermediate commit points
- Database updates are made durable at intermediate points => less work is lost in a crash

S1 S2 S3 commit	=>	S1; commit; S2; commit; S3; commit;

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Example

S1; -- *update recs 1 - 1000*
commit;
S2; -- *update recs 1001 - 2000*
commit;
S3; -- *update recs 2001 - 3000*
commit;

- Chaining compared with savepoints:
  - Savepoint: explicit rollback to arbitrary savepoint; all updates lost in a crash
  - Chaining: abort rolls back to last commit; only the updates of the most recent transaction lost in a crash

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Chaining Considerations - Atomicity

- Transaction as a whole is not atomic. If crash occurs
  - *DBMS* cannot roll the entire transaction back
    - Initial subtransactions have committed,
      - Their updates are durable
      - The updates might have been accessed by other transactions (locks have been released)
  - Hence, the *application* must roll itself forward

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Chaining Considerations - Atomicity

- Roll forward requires that on recovery the application can determine how much work has been committed
  - Each subtransaction must tell successor where it left off
- Communication between successive subtransactions cannot use local variables (they are lost in a crash)
  - Use the database to communicate between subtransactions

```
r(rec_index:0);
S1;                  -- update records 1 - 1000
w(rec_index:1000);   -- save index of last record updated
commit;
r(rec_index:1000);   -- get index of last record updated
S2;                  -- update records 1001 – 2000
w(rec_index:2000);
commit;
```

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Chaining Considerations

- Transaction as a whole is not isolated.
  - Database state between successive subtransactions might change since locks are released (but performance improves)

	subtransaction 1		*subtransaction 2*
T1:	r(x:15)…w(x:24)… commit		r(x:30)…
T2:		…w(x:30)…commit	

- Subtransactions might not be consistent
  - Inconsistent intermediate states visible to concurrent transactions during execution or after a crash

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Alternative Semantics for Chaining

S1;
chain;
S2;
chain;
S3;
commit;

- Chain commits the transaction (makes it durable) and starts a new transaction, but does not release locks
  - Individual transactions do not have to be consistent
  - Recovery is complicated (as before); rollforward required
  - No performance gain

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A Problem With Obtaining Atomicity With Chaining

- Suppose we use the first semantics for chaining
  - Subtransactions give up locks when they commit
- Suppose that after a subtransaction of a transaction *T* makes its changes to some item and commits
  - Another transaction changes the same item and commits
  - *T* would then like to abort
  - Based on our usual definition of chained transactions, atomicity cannot be achieved because of the committed subtransactions

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Partial Atomicity

- Suppose we want to achieve some measure of atomicity by undoing the effects of all the committed subtransactions when the overall transaction wants to abort
- We might think we can undo the updates made by *T* by just restoring the values each item had when T started (physical logging)
  - This will not work

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An Example

T_1: *Update(x)*$_{1,1}$ *commit*$_{1,1}$ … *abort*$_1$
T_2: *Update(x) commit*

If, when T_1 aborts, we just restore the value of *x* to the value it had before T_1 updated it, T_2's update would be lost

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Compensation

- One approach to this problem is **compensation**
- Instead of restoring a value physically, we restore it logically by executing a compensating transaction
  - In the student registration system, a *Deregistration* subtransaction compensates for a successful *Registration* subtransaction
  - Thus *Registration* increments the *Enrollment* attribute and *Deregistration* decrements that same attribute
    - Compensation works even if some other concurrent *Registration* subtransaction has also incremented *Enrollment*

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Sagas: An Extension To Chained Transactions That Achieves Partial Atomicity

- For each subtransaction, $ST_{i,j}$ in a chained transaction, T_i a compensating transaction, CT_i is designed
- Thus if a transaction T_1 consisting of 5 chained subtransactions aborts after the first 3 subtransactions have committed, then

  $ST_{1,1}ST_{1,2}ST_{1,3}CT_{1,3}CT_{1,2}CT_{1,1}$

  will perform the desired compensation

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Sagas and Atomicity

- With this type of compensation, when a transaction aborts, the value of every item it changed is eventually restored to the value it had before that transaction started
- However, complete atomicity is not guaranteed
  - Some other concurrent transaction might have read the changed value before it was restored to its original value

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Declarative Transaction Demarcation

- We have already talked about two ways in which procedures can execute within a transaction
  - As a part of the transaction
    - Stored procedure
  - As a child in a nested transaction

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Declarative Transaction Demarcation (con't)

- Two other possible ways
  - The calling transaction is suspended, and a new transaction is started. When it completes the first transaction continues
    - Example: The called procedure is at a site that charges for its services and wants to be paid even if the calling transaction aborts
  - The calling transaction is suspended, and the called procedure executes outside of any transaction. When it completes the first transaction continues
    - Example: The called procedure accesses a non-transactional file system

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Declarative Transaction Demarcation (con't)

- One way to implement such alternatives is through **declarative transaction demarcation**
  - Declare in some data structure, outside of any transaction, the desired transactional behavior
  - When the procedure is called, the system intercepts the call and provides the desired behavior

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Implementation of Declarative Transaction Demarcation

- Declarative transaction demarcation is implemented within J2EE and .NET
  - We discuss J2EE (.NET is similar)
- The desired transactional behavior of each procedure is declared as an attributed in a separate file called the **deployment descriptor**

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Transaction Attributes

- Possible attributes (in J2EE) are
  - *Required*
  - *RequiresNew*
  - *Mandatory*
  - *NotSupported*
  - *Supports*
  - *Never*
- The behavior for each attribute depends on whether or not the procedure is called from within a procedure
  - All possibilities are on the next slide

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	Status of Calling Method	
Attribute of Called Method	**Not in a Transaction**	**In a Transaction**
Required	Starts a New Transaction	Executes Within the Transaction
RequiresNew	Starts a New Transaction	Starts a New Transaction
Mandatory	Exception Thrown	Executes Within the Transaction
NotSupported	Transaction Not Started	Transaction Suspended
Supports	Transaction Not Started	Executes Within the Transaction
Never	Transaction Not Started	Exception Thrown

All Possibilities

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Description of Each Attribute

- *Required:*
  - The procedure must execute within a transaction
    - If called from outside a transaction, a new transaction is started
    - If called from within a transaction, it executes within that transaction

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Description (con't)

- *RequiresNew:*
  - Must execute within a new transaction
    - If called from outside a transaction, a new transaction is started
    - If called from within a transaction, that transaction is suspended and a new transaction is started. When that transaction completes, the first transaction resumes
      - Note that this semantics is different from nested transactions. In this case the commit of the new transaction is not conditional.

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Description (con't)

- *Mandatory:*
  - Must execute within an existing transaction
    - If called from outside a transaction, an exception is thrown
    - If called from within a transaction, it executes within that transaction

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Description (con't)

- *NotSupported:*
  - Does not support transaction
    - If called from outside a transaction, a transaction is not started
    - If called from inside a transaction, that transaction is suspended until the procedure completes after which the transaction resumes

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Description (con't)

- *Supports:*
  - Can execute within or not within a transaction, but cannot start a new transaction
    - If called from outside a transaction, a transaction is not started
    - If called from inside a transaction, it executes within that transaction

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Description (con't)

- *Never:*
  - Can never execute within a transaction
    - If called from outside a transaction, a new transaction is not started
    - If called from within a transaction, an exception is thrown

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Example

- The **Deposit** and **Withdraw** transactions in a banking application would have attribute *Required.*
  - If called to perform a deposit, a new transaction would be started
  - If called from within a **Transfer** transaction to transfer money between accounts, they would execute within that transaction

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Advantages

- Designer of individual procedures does not have to know the transactional context in which the procedure will be used
- The same procedure can be used in different transaction contexts
  - Different attributes are specified for each different context
- We discuss J2EE in more detail and how declarative transaction demarcation is implemented in J2EE in the Architecture chapter.

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Multilevel Transactions

- A multilevel transaction is a nested set of subtransactions.
  - The commitment of a subtransaction is **unconditional**, causing it to release its locks, *but*
  - Multilevel transactions are atomic and their concurrent execution is serializable

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Multilevel Transactions

- Data is viewed as a sequence of increasing, application oriented, levels of abstraction
- Each level supports a set of abstract objects and abstract operations (methods) for accessing those objects
- Each abstract operation is implemented as a transaction using the abstractions at the next lower level

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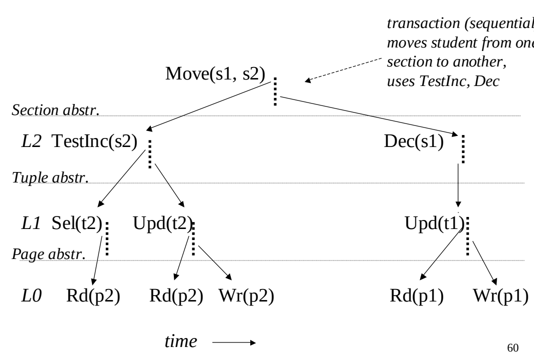
Example - Switch Sections



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Multilevel Transactions

- Parent initiates a single subtransaction at a time and waits for its completion. Hence a multilevel transaction is sequential.
- All leaf subtransactions in the tree are at the same level
- Only leaf transactions access the database.
- *Compare with distributed and nested models*

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Multilevel Transactions

- When a subtransaction (at any level) completes, it commits unconditionally and releases locks that it has acquired on items at the next lower level.
  - *TestInc(s2)* locks t2; unlocks t2 when it commits
- The change it has made to the locked item becomes visible to subtransactions of other transactions
  - The incremented value of t2 is visible to a subsequent execution of *TestInc* or *Dec* by concurrent transactions
- This creates problems maintaining isolation and atomicity.

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Maintaining Isolation

p2 is unlocked
when Sel commits
↓
TestInc1: *Sel(t2)* *Upd(t2)*
TestInc2: *Sel(t2)* *Upd(t2)*
↑
Sel2 can lock p2

- **Problem**: Interleaved execution of two *TestInc*'s results in error (we will return to this later)

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Maintaining Atomicity

Move1: *TestInc(s2) Dec(s1)* *abort*
Move2: *TestInc(s3) Dec(s1) commit*

- When T1 aborts, the value of *s1* that existed prior to its access cannot simply be restored (physical restoration)
- Logical restoration must be done using **compensating transactions**
  - *Inc* compensates for *Dec*; *Dec* compensates for a successful *TestInc*; no compensation needed for unsuccessful *TestInc*

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Compensating Transactions

- Multilevel model uses compensating transaction

logical restoration
(using compensation)
caused by abort

T1: *TestInc(s2) Dec(s1)* *Inc(s1) Dec(s2)*
T2: *TestInc(s3) Dec(s1) commit*

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Correctness of Multilevel Transactions

- As we shall see later,
  - Multilevel transactions are atomic
    - In contrast with Sagas, which also use compensation, but do not guarantee atomicity
  - Concurrent execution of multilevel transactions is serializable

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Recoverable Queues

- **Problem**: Distributed model assumes that the subtransactions of a transaction follow one another immediately (or are concurrent).
- In some applications the requirement is that a subtransaction be *eventually* executed, but not necessarily immediately.
- A recoverable queue is a transactional data structure in which information about transactions to be executed later can be durably stored.

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Transactional Features

T1: begin transaction;
compute;
item := *service description*
enqueue(item);
commit;

→ recoverable queue →

T2: begin transaction;
dequeue(item);
perform requested service;
commit;

- Item is enqueued if T1 commits (deleted if it aborts); item is deleted if T2 commits (restored if it aborts)
- An item enqueued by T1 cannot be dequeued by T2 until T1 commits
- Queue is durable

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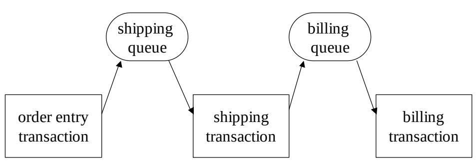
Pipeline Queue for Billing Application



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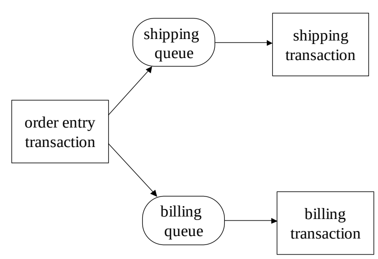
Concurrent Implemention of the Same Application



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Recoverable Queue

- Queue could be implemented within database, but performance suffers
  - A transaction should not hold long duration locks on a heavily used data structure

acquire lock on queue in db ↓ … *release lock on queue* ↓

T1: enq(I_1) …………..compute………………commit
T2: *request enq(I_2) (wait)* … enq(I_2)
T3: *request enq(I_3) (wait)*
T4: *request enq(I_4) (wait)*

↑ *acquire lock on queue*

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Recoverable Queue

- Separate implementation takes advantage of semantics to improve performance
  - *enqueue* and *dequeue* are atomic and isolated, but some queue locks are released immediately

acquire lock on queue and entry I_1
release lock on queue … *release lock on I_1*

T1: enq(I_1) …………..compute………………commit
T2: enq(I_2) …………….compute…………..
T3: enq(I_3) ………………..compute …………
T4: enq(I_4)……………compute …..

↑ *acquire lock on queue and I_2*

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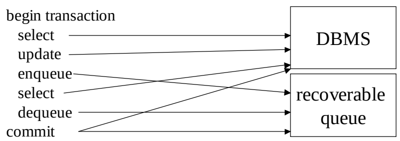
Recoverable Queue



- Queue and DBMS are two separate systems
  - Transaction must be committed at both but
    - isolation is implemented at the DBMS and applies to the schedule of requests made to the DBMS only

Scheduling

- As a result, any scheduling policy for accessing the queue might be enforced
  - but a FIFO queue might not behave in a FIFO manner

T1: enq(I_1) …commit *restore I_1*
T2: enq(I_2) …commit
T3: deq(I_1) … abort
T4: deq(I_2) …commit

Performing Real-World Actions

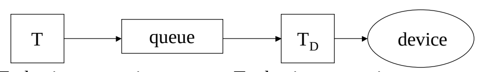
- **Problem**: A real-world action performed from within a transaction, T, cannot be rolled back if crash occurs before commit.

T: begin_transaction;
compute;
update database; *crash*
activate device;
commit;

- On recovery after a crash, how can we tell if the action has occurred?
  - ATM example: We do not want to dispense cash twice.

Performing Real-World Actions

- **Solution**: (part 1) T enqueues entry. If T aborts, item is dequeued; if T commits action executed later

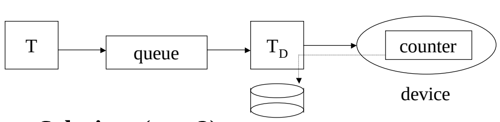


T: begin_transaction;
compute;
update database;
enqueue entry;
commit;

T_D: begin_transaction;
dequeue entry;
activate device;
commit;

- Server executes T_D in a loop
  - *but* problem still exists within T_D

Performing Real-World Actions



- **Solution**: (part 2)
  - Device maintains read-only counter (hardware) that is automatically incremented with each action
    - Action and increment are assumed to occur atomically
  - Server performs:

T_D: begin_transaction;
dequeue;
activate device;
record counter in db;
commit;

Performing Real-World Actions

- On recovery:

Restore queue and database (value read from counter) to last commit;
if (*device value* > *recorded value*)
then *discard head entry;*
Restart server;

Example of Real World Action

- Suppose the hardware counter and the database counter were both at 100 before the transaction started
  - When the hardware performs its action, it increments its counter to 101
  - T_D would then increment the database counter to 101
- If the system crashed after the hardware performed its action the database increment (if it had occurred) would be rolled back to 100
- Thus when the system recovered
  - If the hardware counter was 101 and the database counter was 100, we would know that the action had been performed.
  - If both counters were the same (100), we would know that the action had not taken place.

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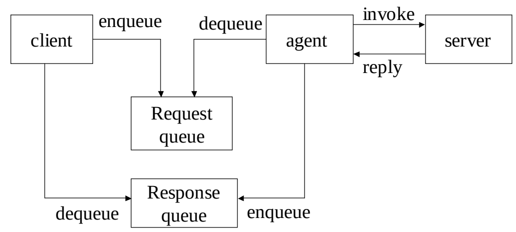
Forwarding Agent

- Implementing deferred service.



- In general there are multiple clients (producers) and multiple servers (consumers)

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Workflows

- **Problem**: None of the previous models are sufficiently flexible to describe complex, long-running enterprise processes involving computational and non-computational tasks in distributed, heterogeneous systems over extended periods of time

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Workflow Task

- Self-contained job performed by an **agent**
  - Inventory transaction (agent = database server)
  - Packing task (agent = human)
- Has an associated **role** that defines type of job
  - An agent can perform specified roles
- Accepts input from other tasks, produces output
- Has physical status: committed, aborted, ...
  - Committed task has logical status: success, failure

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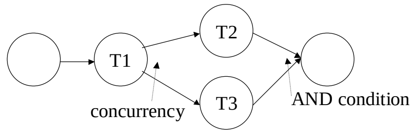
Workflow

- Task execution precedence specified separately from task itself
  - using control flow language:

    initiate T2, T3 *when* T1 *committed*
  - or using graphical tool:



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Workflow

- Conditional alternatives can be specified:

  if (condition) *execute* T1 *else execute* T2
- Conditions:
  - Logical/physical status of a task
  - Time of day
  - Value of a variable output by a task
- Alternative paths can be specified in case of task failure

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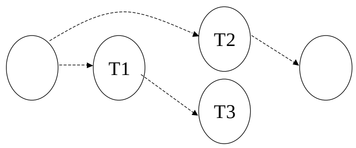
Workflow

- Specifies flow of data between tasks



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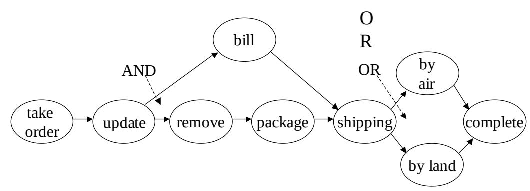
Execution Precedence in a Catalog Ordering System



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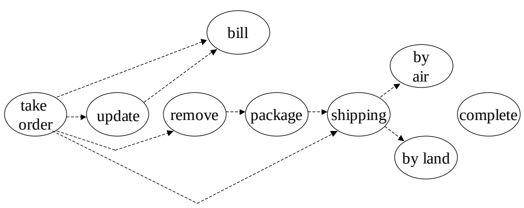
Flow of Data in a Catalog Ordering System



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Workflow Agent

- Capable of performing tasks
- Has a set of associated roles describing tasks it can do
- Has a worklist listing tasks that have been assigned to it
- Possible implementation:
  - Worklist stored in a recoverable queue
  - Agent is an infinitely looping process that processes one queue element on each iteration

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Workflow and ACID Properties

- Individual tasks might be ACID, but workflow as a whole is not
  - Some task might not be essential: its failure is ignored even though workflow completes
  - Concurrent workflows might see each other's intermediate state
  - Might not choose to compensate for a task even though workflow fails

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Workflow and ACID Properties

- Each task is either
  - **Retriable**: Can ultimately be made to commit if retried a sufficient number of times (*e.g.*, deposit)
  - **Compensatable**: Compensating task exists (*e.g.*, withdraw)
  - **Pivot**: Neither retriable nor compensatable (*e.g.*, buy a non-refundable ticket)

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Workflow and ACID Properties

- The atomicity of a workflow is guaranteed if each execution path is characterized by
  {compensatable}*, [pivot], {retriable}*
- This *does not* guarantee isolation since intermediate states are visible

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Workflow Management System

- Provides mechanism for specifying workflow (control flow language, GUI)
- Provides mechanism for controlling execution of concurrent workflows:
  - Roles and agents
  - Worklists and load balancing
  - Filters (data reformatting) and controls flow of data
  - Task activation
  - Maintain workflow state durably (data, task status)
  - Use of recoverable queues
  - Failure recovery of WFMS itself (resume workflows)

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Importance of Workflows

- Allows management of an enterprise to guarantee that certain activities are carried out in accordance with established business rules, even though those activities involve a collection of agents, perhaps in different locations and perhaps with minimal training

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