Database internals (transactions)

ISYS2120 Data and Information Management

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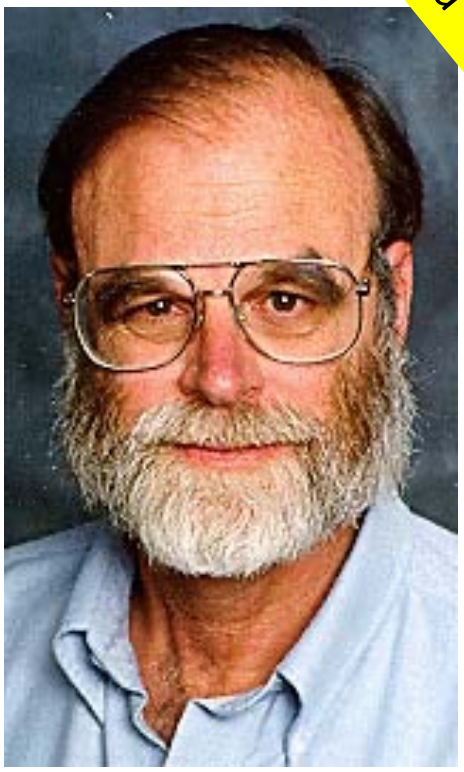
Acknowledge: slides from Uwe Roehm and Alan Fekete, and from the materials associated with reference books (c) McGraw-Hill, Pearson

Famous DB Researchers: Jim Gray

Not Examined

- One of the most influential database researchers and software designers
  - first Ph.D. from CS at UC Berkeley (1969)
  - worked for
    IBM (at System R)
    Tandem-Computers, DEC, …,
    Microsoft Research
- Turing Award (1998)
  - "for seminal contributions to database and ***transaction processing research*** and technical leadership in system implementation."



Jim Gray (1944-2007)

Overview

- Transactions and ACID properties
- Brief overview of Implementation Techniques [not examinable]
- Weak isolation issues

ACID

- Atomic
  - State shows either all the effects of txn, or none of them
- Consistent
  - Txn moves from a state where integrity holds, to another where integrity holds
- Isolated
  - Effect of txns is the same as txns running one after another (ie looks like batch mode)
- Durable
  - Once a txn has committed, its effects remain in the database

Definition

- A transaction is a collection of one or more operations on one or more databases, which reflects a single real-world transition
  - In the real world, this happened (completely) or it didn't happen at all (Atomicity)
  - Once it has happened, it isn't forgotten (Durability)
- Commerce examples
  - Transfer money between accounts
  - Purchase a group of products
- Student record system
  - Register for a class (either waitlist or allocated)

Coding a transaction

- Typically a computer-based system doing OLTP has a collection of *application programs*
- Each program is written in a high-level language, which calls DBMS to perform individual SQL statements
  - Either through embedded SQL converted by preprocessor
  - Or through Call Level Interface where application constructs appropriate string and passes it to DBMS

Why write programs?

- Why not just write a SQL statement to express "what you want"?
- An individual SQL statement can't do enough
  - It can't update multiple tables
  - It can't perform complicated logic (conditionals, looping, etc)

COMMIT

- As application program is executing, it is “in a transaction”
- Program can execute COMMIT
  - SQL command to finish the transaction successfully
  - The next SQL statement will automatically start a new transaction

Atomicity

- Two possible outcomes for a transaction
  - It *commits*: all the changes are made
  - It *aborts*: no changes are made
- That is, transaction's activities are all or nothing
  - Furthermore, once an outcome has been reached, it doesn't change

ROLLBACK

- If the application code gets to a place where it can't complete the transaction successfully, it can execute ROLLBACK
- This causes the system to "abort" the transaction
  - The database returns to the state without any of the previous changes made by activity of the transaction

API for Transactions

- A transaction ends by:
  - **COMMIT** *requests* to commit current transaction.
  - **ROLLBACK** causes current transaction to abort - always satisfied.
- The commit command is a request
  - The system might commit the transaction, or it might abort it for one of several reasons.

Reasons for Rollback

- User changes their mind (“ctl-C”/cancel)
- Explicit in program, when application code finds a problem
  - e.g. when qty on hand < qty being sold
- System-initiated abort
  - System crash
  - Housekeeping
    - e.g. due to timeouts

Autocommit

- Application programmer can set the connection to autocommit
  - every single SQL statement is a transaction in itself
  - no need for explicit commit/rollback code in application
  - but lose the capacity to group several table activities into a single real-world transition
- Be careful: some platforms make autocommit=true as the default!

Transactions in Python DB-API

- Python DB-APIs Connection Class:
  - Provides **`commit()`** and **`rollback()`** methods
  - allows to set SQL Isolation levels (see later)
  - allows to set **`autocommit`** mode on/off

Python DB-API

- By default, DB-API connections are in explicit mode
  - a new transaction starts implicitly with first SQL statement
  - must be explicitly ended by call to **`commit`**() or **`rollback`**() !
  - if no call to **`commit`**(), all changes get lost once connection closes !
  - no auto-commit, no beginTransaction statement
- Hence: need to call commit() after data manipulations

```
import pg8000

def bookFlight ( flight_num, flight_date, seat_no) :

    try: # connect to the database
            conn = pg8000.connect(database="postgres", user="X", password="secret")

            # execute the SQL statements within the transaction
            curs = conn.cursor()
            stmt = """SELECT occupied
                            FROM Flight
                           WHERE flightNum=%s AND flightDate=%s AND seat=%s"""
            curs.execute(stmt, (flight_num, flight_date, seat_no))
            result = curs.fetchone()

            if ( result is None ) or ( result[0] = False ) :
          update_stmt = """UPDATE Flight SET occupied=TRUE
                                        WHERE flightNum=%s AND flightDate=%s AND seat=%s"""
                curs.execute(update_stmt, (flight_num, flight_date, seat_no))

            # COMMIT the transaction
            conn.commit()

        except:
            # error handling
            ...
            conn.rollback()

        finally:
            curs.close()
            conn.close()
```

Integrity

- A real world state is reflected by collections of values in the tables of the DBMS
- But not every collection of values in a table makes sense in the real world
- The state of the tables is restricted by integrity constraints
- e.g. account number is unique
- e.g. stock amount can't be negative

Integrity (ctd)

- Many constraints are explicitly declared in the schema
  - So the DBMS will enforce them
  - Especially: primary key (some column's values are non null, and different in every row)
  - And referential integrity: value of foreign key column is actually found in another "referenced" table
- Some constraints are not declared
  - They are business rules that are supposed to hold

Dynamic Integrity Constraints

- Some constraints restrict allowable state transitions
  - A transaction might transform the database from one consistent state to another, but the transition might not be permissible
  - **Example:** Students can only progress from Junior via Intermediate to the Senior year, but can never be degraded.
- Dynamic constraints cannot be checked by examining the database state

Transaction Consistency

- A **transaction is consistent** if, assuming the database is in a consistent state initially, when the transaction completes:
  - All static integrity constraints are satisfied (but constraints might be violated in intermediate states)
    - Can be checked by examining snapshot of database
  - New state satisfies specifications of transaction
    - Cannot be checked from database snapshot
  - No dynamic constraints have been violated
    - Cannot be checked from database snapshot
- This is an obligation on the programmer
  - Usually the organization has a testing/checking and sign-off mechanism before an application program is allowed to get installed in the production system

Checking Integrity Constraints

- Automatic: Embed constraint in schema.
  - With CHECK, ASSERTION, TRIGGER
  - Increases confidence in correctness and decreases maintenance costs
  - Not always desirable since unnecessary checking (overhead) might result
    - Deposit transaction modifies *balance* but cannot violate constraint *balance* ≥ 0
- Manual: Perform check in application code.
  - Only necessary checks are performed
  - Scatters references to constraint throughout application
  - Difficult to maintain as transactions are modified/added

Integrity Constraints in Transactions

- When do we check integrity constraints?
- Integrity constraints may be declared:
  - **NOT DEFERRABLE**
    The default. It means that every time a database modification occurs, the constraint is checked immediately afterwards.
  - **DEFERRABLE**
    Gives the option to wait until a transaction is complete before checking the constraint.

```
CREATE TABLE UnitOfStudy (
   uos_code       VARCHAR(8),
   title          VARCHAR(220),
   lecturer       INTEGER,
   credit_points  INTEGER,
   CONSTRAINT UnitOfStudy_PK PRIMARY KEY (uos_code),
   CONSTRAINT UnitOfStudy_FK FOREIGN KEY (lecturer)
      REFERENCES Lecturer DEFERABBLE INITIALLY DEFERRED
);
BEGIN TRANSACTION;
   SET CONSTRAINTS UnitOfStudy_FK DEFERRED;
   INSERT INTO UnitOfStudy VALUES('info1000','Intro
   to…',42,6);
   INSERT INTO Lecturer VALUES(42,'Steve McQueen', …);
COMMIT;
```

System obligations

- Provided the application programs have been written properly,
- Then the DBMS is supposed to make sure that the state of the data in the DBMS reflects the real world accurately, as affected by all the committed transactions

Local to global reasoning

- Organization checks each application program as a separate task
  - Each application program running on its own moves from state where integrity constraints are valid to another state where they are valid
- System makes sure there are no nasty interactions
- So the final state of the data will satisfy all the integrity constraints

Example - Tables

- System for managing inventory
- InStore(prodID, storeID, qty)
- Product(prodID, desc, mnfr, …, warehouseQty)
- Order(orderNo, prodID, qty, rcvd, ….)
  - Rows never deleted!
  - Until goods received, rcvd is null
- Also Store, Staff, etc etc

Example - Constraints

- Primary keys
  - InStore: (prodID, storeID)
  - Product: prodID
  - Order: orderId
  - etc
- Foreign keys
  - Instore.prodID references Product.prodID
  - etc

Example - Constraints

- Data values
  - Instore.qty >= 0
  - Order.rcvd <= current_date or Order.rcvd is null
- Business rules
  - for each p, (Sum of qty for product p among all stores and warehouse) >= 50
  - for each p, (Sum of qty for product p among all stores and warehouse) >= 70 or there is an outstanding order of product p

Example - transactions

- MakeSale(store, product, qty)
- AcceptReturn(store, product, qty)
- RcvOrder(order)
- Restock(store, product, qty)
  - // move from warehouse to store
- ClearOut(store, product)
  - // move all held from store to warehouse
- Transfer(from, to, product, qty)
  - // move goods between stores

Example - ClearOut

- Validate Input (appropriate product, store)
- SELECT qty INTO :tmp
  FROM InStore
  WHERE storeID = :store AND prodID = :product
- UPDATE Product
  SET warehouseQty = warehouseQty + :tmp
  WHERE prodID = :product
- UPDATE InStore
  SET qty = 0
  WHERE storeID = :store AND prodID = :product
- COMMIT

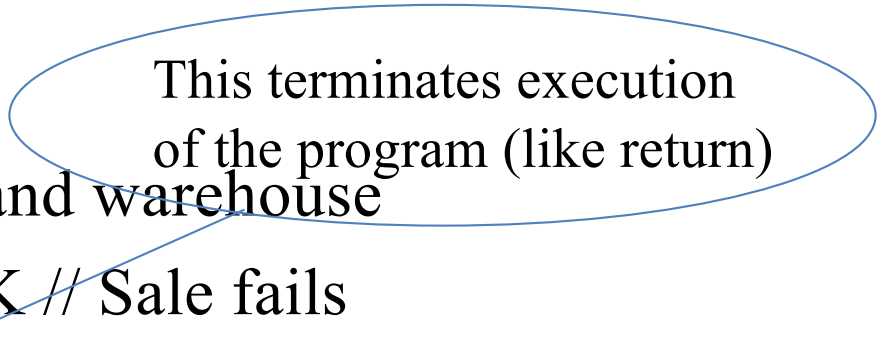
This is one way to write the application; other algorithms are also possible

Example - Restock

- Input validation
  - Valid product, store, qty
  - Amount of product in warehouse >= qty
- UPDATE Product
  SET warehouseQty = warehouseQty - :qty
  WHERE prodID = :product
- If no record yet for product in store
  INSERT INTO InStore (:product, :store, :qty)
- Else, UPDATE InStore
  SET qty = qty + :qty
  WHERE prodID = :product and storeID = :store
- COMMIT

Example - Consistency

- How to write the app to keep integrity holding?
- MakeSale logic:
  - Reduce Instore.qty
  - Calculate sum over all stores and warehouse
  - If sum < 50, then ROLLBACK // Sale fails
  - If sum < 70, check for order of this product where date is null
    - If none found, insert new order for say 25
  - COMMIT



Example - Consistency

- We don't need any fancy logic for checking the business rules in Restock, ClearOut, Transfer
  - Because sum of qty not changed; presence of order not changed
    - *provided integrity holds before txn, it will still hold afterwards*
- We don't need fancy logic to check business rules in AcceptReturn
  - *why?*
- Is checking logic needed for RcvOrder?

Threats to data integrity

- Need for application rollback
- System crash
- Concurrent activity

- The system has mechanisms to handle these

Application rollback

- A transaction may have made changes to the data before discovering that these aren't appropriate
  - the data is in state where integrity constraints are false
  - Application executes ROLLBACK
- System must somehow return to earlier state
  - Where integrity constraints hold
- So the aborted transaction *has no effect* at all

Example

- While running MakeSale, app changes InStore to reduce qty, then checks new sum
- If the new sum is below 50, txn aborts
- System must change InStore to restore previous value of qty
  - Somewhere, system must remember what the previous value was!

System crash

- At time of crash, an application program may be part-way through (and the data may not meet integrity constraints)
- Also, buffering can cause problems
  - Note that system crash loses all buffered data, restart has only disk state
  - Effects of a committed txn may be only in buffer, not yet recorded in disk state
  - Lack of coordination between flushes of different buffered pages, so even if current state satisfies constraints, the disk state may not

Example

- Suppose crash occurs after
  - MakeSale has reduced InStore.qty
  - found that new sum is 65
  - found there is no unfilled order
  - // but before it has inserted new order
- At time of crash, integrity constraint did not hold
- Restart process must clean this up (effectively aborting the txn that was in progress when the crash happened)

Restart and Durability

- After a crash, system must be restored to a state which includes all the effects of committed transactions
  - And none of the effects of aborted transactions, or those which were active at the time of the crash
- Each item should have the value placed there by the last committed transaction that modified the item

Concurrency

- When operations of concurrent threads are interleaved, the effect on shared state can be unexpected
- Well known issue in operating systems, thread programming
  - see OS textbooks on critical section
  - Java use of synchronized keyword

Famous anomalies

- Dirty data
  - One task T reads data written by T’ while T’ is running, then T’ aborts (so its data was not appropriate)
- Lost update
  - Two tasks T and T’ both modify the same data
  - T and T’ both commit
  - Final state shows effects of only T, but not of T’
- Inconsistent read
  - One task T sees some but not all changes made by T’
  - The values observed may not satisfy integrity constraints
  - This was not considered by the programmer, so code moves into absurd path

Example – Dirty data

(Thread 1) **(Thread 2)**

- AcceptReturn(p1,s1,50) MakeSale(p1,s2,65)
- Update row 1: 25 -> 75
- update row 2: 70->5
- find sum: 90
- // no need to insert
- // row in Order
- Abort
- // rollback row 1 to 25
- COMMIT

p1	s1	25
p1	s2	70
p2	s1	60
etc	etc	etc

p1	etc	10
p2	etc	44
etc	etc	etc

Initial state of InStore, Product

Integrity constraint is false:
Sum for p1 is only 40!

p1	s1	25
p1	s2	5
p2	s1	60
etc	etc	etc

p1	etc	10
p2	etc	44
etc	etc	etc

Final state of InStore, Product

Example – Lost update

- ClearOut(p1,s1) AcceptReturn(p1,s1,60)
- Query InStore; qty is 25
- Add 25 to warehouseQty: 40->65
- Update row 1: 25->85
- Update row 1, setting it to 0
- COMMIT
- COMMIT

60 returned p1's have vanished from system; total is still 115

p1	s1	25
p1	s2	50
p2	s1	45
etc	etc	etc

p1	etc	40
p2	etc	55
etc	etc	etc

Initial state of InStore, Product

p1	s1	0
p1	s2	50
p2	s1	45
etc	etc	etc

p1	etc	65
p2	etc	55
etc	etc	etc

Final state of InStore, Product

Example – Inconsistent read

- ClearOut(p1,s1) MakeSale(p1,s2,60)
- Query InStore: qty is 30
- Add 30 to warehouseQty: 10->40
- update row 2: 65->5
- find sum: 75
- // no need to insert
- // row in Order
- Update row 1, setting it to 0
- COMMIT
- COMMIT

Integrity constraint is false:
Sum for p1 is only 45!

p1	s1	30
p1	s2	65
p2	s1	60
etc	etc	etc

p1	etc	10
p2	etc	44
etc	etc	etc

Initial state of InStore, Product

p1	s1	0
p1	s2	5
p2	s1	60
etc	etc	etc

p1	etc	40
p2	etc	44
etc	etc	etc

Final state of InStore, Product

Serializability

- To make isolation precise, we say that an execution is serializable when
- There exists some serial (ie batch, no overlap at all) execution of the same transactions which has the same final state
  - Hopefully, the real execution runs faster than the serial one!
- NB: different serial txn orders may behave differently; we ask that *some* serial order produces the given state
  - Other serial orders may give different final states

Example – Serializable execution

- ClearOut(p1,s1) MakeSale(p1,s2,20)
- Query InStore: qty is 30
- update row 2: 45->25
- find sum: 65
- no order for p1 yet
- Add 30 to WarehouseQty: 10->40
- Update row 1, setting it to 0
- COMMIT
- Insert order for p1
- COMMIT

Execution is like serial MakeSale; ClearOut

p1	s1	30
p1	s2	45
p2	s1	60
etc	etc	etc

p1	etc	10
p2	etc	44
etc	etc	etc

Order: empty

Initial state of InStore, Product, Order

p1	s1	0
p1	s2	25
p2	s1	60
etc	etc	etc

p1	etc	40
p2	etc	44
etc	etc	etc

p1	25	Null	etc

Final state of InStore, Product, Order

Serializability Theory

Not Examined

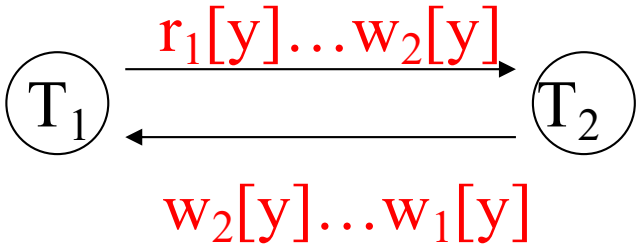
- There is a beautiful mathematical theory, based on formal languages
  - Model an execution as a sequence of operations on data items
    - eg $r_1[x]$ $w_1[x]$ $r_2[y]$ $r_2[x]$ c_1 c_2
  - Serializability of an execution can be defined by equivalence to a rearranged sequence ("view serializability")
- There is a nice sufficient condition (ie a conservative approximation) called conflict serializable, which can be efficiently tested
  - Draw a precedes graph whose nodes are the transactions
  - Edge from Ti to Tj when Ti accesses x, then later Tj accesses x, and the accesses conflict (not both reads)
  - The execution is conflict serializable iff the graph is acyclic

Example – Lost update

Not Examined

- ClearOut(p1,s1)
- AcceptReturn(p1,s1,60)
- Query InStore; qty is 25
- Add 25 to warehouseQty: 40->65
- Update row 1: 25->85
- Update row 1, setting it to 0
- COMMIT
- COMMIT

- Items: Product(p1) as x, Instore(p1,s1) as y
- Execution is
  - $r_1[y]\ r_1[x]\ w_1[x]\ r_2[y]\ w_2[y]\ w_1[y]\ c_1\ c_2$
- Precedes Graph



ACID

- Atomic
  - State shows either all the effects of txn, or none of them
- Consistent
  - Txn moves from a state where integrity holds, to another where integrity holds
- Isolated
  - Effect of txns is the same as txns running one after another (ie looks like batch mode)
- Durable
  - Once a txn has committed, its effects remain in the database

Big Picture

- If programmer writes applications so each txn is consistent
- And DBMS provides atomic, isolated, durable execution
  - i.e. actual execution has same effect as some serial execution of those txns that committed (but not those that aborted)
- Then the final state will satisfy all the integrity constraints

NB true even though system does not know all integrity constraints!

Vital skills

- In coding an application, recognize which SQL commands need to placed in the same transaction
  - Because problems would occur is some but not all are performed, or if other code intervenes between their execution
- Make sure there are appropriate settings (SERIALIZABLE, autocommit off)

Overview

- Transactions and ACID properties
- Brief overview of Implementation Techniques [not examinable]
- Weak isolation issues

Logging

Not Examined

- The log is an append-only collection of entries, showing all the changes to data that happened, in order as they happened
- e.g. when T1 changes qty in row 3 from 15 to 75, this fact is recorded as a log entry
- Log also shows when txns start/commit/abort
- Log must be frequently flushed to persistent store (eg disk) in particular, before commit

Using the log

Not Examined

- To abort/rollback txn T
  - Follow chain of T's log entries, *backwards*
  - For each entry, restore data to old value, and produce new log record showing the restoration
  - Produce log record for "abort T"
- After a crash, the goal is to get to a state of the database which has the effects of those transactions that committed before the crash
  - it does not show effects of transactions that aborted or were active at the time of the crash
  - To reach this state, follow the log *forward*, replaying the changes
    - i.e. re-install new value recorded in log
  - Then rollback all txns that were active at the end of the log
  - Now normal processing can resume

Locks

Not Examined

- DBMS remembers which txns have set locks on which data, in which modes
  - locks requested by system itself when needed
    - or requested explicitly by application code (SQL “LOCK TABLE” statement)
- Lock requests that conflict with already held locks are delayed until the lock is available
  - This blocks any progress by the transaction that needs the lock

Distributed commit

Not Examined

- For a transaction which involves activity at multiple databases
- When txn requests two commit, use two round-trips of messages
  - First check that all databases have log entries safe on disk ("prepare")
  - Second round to inform each database of outcome, and they do what is necessary (eg release locks; also rollback if txn aborts)

Implications

Not Examined

- Logging:
  - Extra storage needed
  - DBA must be very careful in configuring log
  - Possible delay in transaction commit
- Locks
  - blocking delays transactions
  - risk of deadlock
- Distributed commit
  - distributed transactions have very long delays
  - locks held during these delays may block other txns

Overview

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Problems with serializability

- The performance reduction from serializable isolation is high
  - Transactions are often blocked because they want to read data that another txn has changed
- For many applications, the accuracy of the data they read is not crucial
  - e.g. overbooking a plane is ok in practice
  - e.g. your banking decisions would not be very different if you saw yesterday's balance instead of the most up-to-date

A and D matter!

- Even when isolation isn't needed, no one is willing to give up atomicity and durability
  - These deal with modifications a txn makes
  - Writing is less frequent than reading, so log entries, and locks for writes (eg insert, update), are considered worth the effort

Explicit isolation levels

- A transaction can be declared to have isolation properties that are less stringent than serializability
  - However SQL standard says that default should be serializable
  - In practice, many systems have weaker default level, and most txns run at weaker levels!

Set Transaction for Browsing

- SET TRANSACTION ISOLATION LEVEL READ UNCOMMITTED
  - Many platforms force the txn to be read-only
  - Allows txn to read dirty data (from a txn that will later abort)

Read Committed

- SET TRANACTION ISOLATION LEVEL READ COMMMITTED
  - Data is never dirty (any value that gets read, was produced by a committed transaction)
  - but it can be inconsistent (between reads of different items, or even between one read and a later one of the same item)
    - Especially, weird things might happen between different rows returned by a cursor

Most common in practice!

Also, default level in PostgreSQL (and many other platforms)

So can lead to violation of undeclared data integrity properties

Repeatable read

- SET TRANACTION ISOLATION LEVEL REPEATABLE READ
  - Whenever txn T examines a record several times in a transaction, always see the same value (unless T itself modified the record in between)
- In some systems, including PostgreSQL, you get a stronger property (sometimes called “Snapshot” or “MVCC”): all data read by transaction T comes from a common state, reflecting the transactions that committed before T started (and no concurrent ones)
    - read-only transaction never blocks
    - a transaction may be aborted by the system if a concurrent one is modifying same data

Write Skew

- Snapshot breaks serializability when txns modify different items in each other's read sets
  - Neither txn sees the other, but in a serial execution one would come later and so see the other's impact
  - This is fairly rare in practice, but possible in some applications
    - if it occurs, it can lead to violation of undeclared integrity constraints

NB: sum uses old value of row1 and Product,
and self-changed value of row2

Example –Write Skew

- MakeSale(p1,s1,26) MakeSale(p1,s2,25)
- Update row 1: 30->4
- update row 2: 35->10
- find sum: 72
- // No need to Insert row in Order
- Find sum: 71
- // No need to insert row in Order
- COMMIT
- COMMIT

p1	s1	30
p1	s2	35
p2	s1	60
etc	etc	etc

p1	etc	32
p2	etc	44
etc	etc	etc

Order: empty

Initial state of InStore, Product, Order

p1	s1	4
p1	s2	10
p2	s1	60
etc	etc	etc

p1	etc	32
p2	etc	44
etc	etc	etc

Order: empty

Final state of InStore, Product, Order

Integrity constraint is false:
Sum is 46

Platform variations

- PostgreSQL
  - default isolation is “read committed”
  - can get true serializability (but performance may suffer) by “SET TRANSACTION ISOLATION LEVEL SERIALIZABLE”
- See https://www.postgresql.org/docs/9.1/static/transaction-iso.html

- Oracle
  - default isolation is “read committed”
  - Using “SET TRANSACTION ISOLATION LEVEL SERIALIZABLE” gives snapshot, not serializability
- See https://docs.oracle.com/cd/E25054_01/server.1111/e25789/consist.htm

PostgreSQL serializable mechanism based on design by Michael Cahill in his USyd PhD

Theory by Fekete et al: how to determine if this is a problem, how to set explicit locks if necessary to cope

Implications

- Know what isolation level your code is using
- Think carefully whether there are undeclared integrity constraints that matter to you
  - if so, you may need to run with serializable isolation
- Wise approach: start with serializable, then reduce isolation if necessary to meet user performance requirements

References

- Silberschatz/Korth/Sudarshan(7ed)
  - Chapter 17 (further reading in Ch 18-19)

Also

- Kifer/Bernstein/Lewis(complete version, 2ed)
  - Chapter 1.1, 18 (further reading in Chapters 19-22)
  - Does not cover much on weak isolation levels
- Ramakrishnam/Gehrke(3ed)
  - Chapter 16.1-16.3 (further reading in rest of Chapter 16, Ch 17-18)
- Garcia-Molina/Ullman/Widom(complete book, 2ed)
  - Chapter 2.4, 6.6 (further reading in Ch 17-19)
- *All these books have technical details on this topic, providing a lot of insight into how transactions are implemented. We only need an overview here; more technical details are covered in data3404.*

Summary

- Key concepts
  - Transaction properties
  - Transactions in application code
  - Weak isolation
- Key skills
  - Identify code that ought to be in a transaction
  - Recognize potential impact of weak isolation levels