CS5412: TRANSACTIONS (I)

Lecture XVII

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Transactions

- A widely used reliability technology, despite the BASE methodology we use in the first tier
- Goal for this week: in-depth examination of topic
  - How transactional systems really work
  - Implementation considerations
  - Limitations and performance challenges
  - Scalability of transactional systems
- Topic will span two lectures

Transactions

- There are several perspectives on how to achieve reliability
  - We've talked at some length about non-transactional replication via multicast
  - Another approach focuses on reliability of communication channels and leaves application-oriented issues to the client or server – "stateless"
  - But many systems focus on the data managed by a system. This yields transactional applications

Transactions on a single database:

- In a client/server architecture,
- A transaction is an execution of a single program of the application(client) at the server.
  - Seen at the server as a series of reads and writes.
- We want this setup to work when
  - There are multiple simultaneous client transactions running at the server.
  - Client/Server could fail at any time.

The ACID Properties

- Atomicity
  - All or nothing.
- Consistency:
  - Each transaction, if executed by itself, maintains the correctness of the database.
- Isolation (Serializability)
  - Transactions won't see partially completed results of other non-commited transactions
- Durability
  - Once a transaction commits, future transactions see its results

Transactions in the real world

- In cs5142 lectures, transactions are treated at the same level as other techniques
- But in the real world, transactions represent a huge chunk (in $ value) of the existing market for distributed systems!
  - The web is gradually starting to shift the balance (not by reducing the size of the transaction market but by growing so fast that it is catching up)
  - But even on the web, we use transactions when we buy products

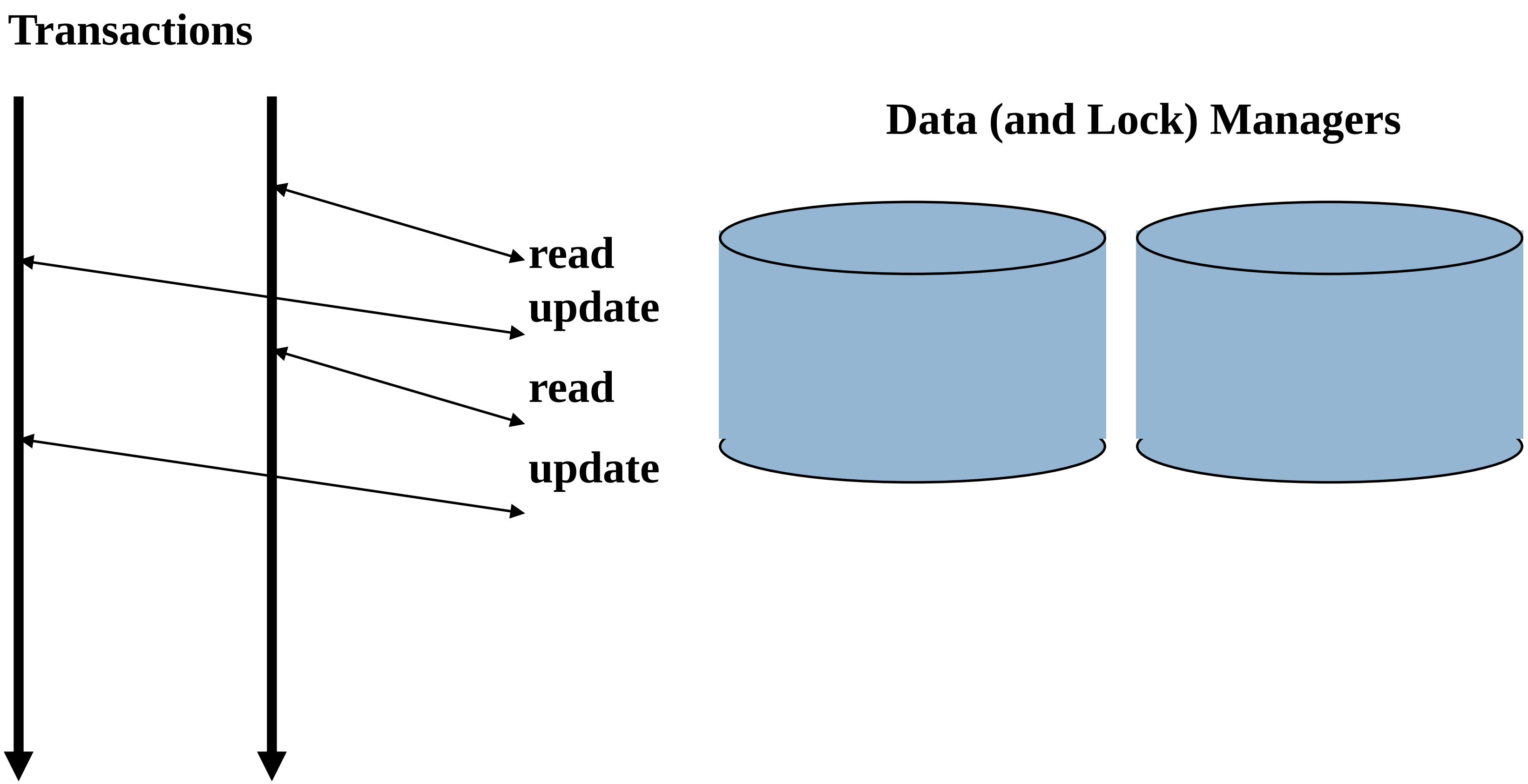
The transactional model

- Applications are coded in a stylized way:
  - begin transaction
  - Perform a series of read, update operations
  - Terminate by commit or abort.
- Terminology
  - The application is the transaction manager
  - The data manager is presented with operations from concurrently active transactions
  - It schedules them in an interleaved but serializable order

A side remark

- Each transaction is built up incrementally
  - Application runs
  - And as it runs, it issues operations
  - The data manager sees them one by one
- But often we talk as if we knew the whole thing at one time
  - We're careful to do this in ways that make sense
  - In any case, we usually don't need to say anything until a "commit" is issued

Transaction and Data Managers



transactions are stateful: transaction "knows" about database contents and updates

Typical transactional program


```
begin transaction;
    x = read("x-values", ....);
    y = read("y-values", ....);
    z = x+y;
    write("z-values", z, ....);
commit transaction;
```

What about locks?

- Unlike some other kinds of distributed systems, transactional systems typically lock the data they access
- They obtain these locks as they run:
  - Before accessing “x” get a lock on “x”
  - Usually we assume that the application knows enough to get the right kind of lock. It is not good to get a read lock if you’ll later need to update the object
- In clever applications, one lock will often cover many objects

Locking rule

- Suppose that transaction T will access object x.
  - We need to know that first, T gets a lock that "covers" x
- What does coverage entail?
  - We need to know that if any other transaction T' tries to access x it will attempt to get the same lock

Examples of lock coverage

- We could have one lock per object
- … or one lock for the whole database
- … or one lock for a category of objects
  - In a tree, we could have one lock for the whole tree associated with the root
  - In a table we could have one lock for row, or one for each column, or one for the whole table
- All transactions must use the same rules!
- And if you will update the object, the lock must be a "write" lock, not a "read" lock

Transactional Execution Log

- As the transaction runs, it creates a history of its actions. Suppose we were to write down the sequence of operations it performs.
- Data manager does this, one by one
- This yields a "schedule"
  - Operations and order they executed
  - Can infer order in which transactions ran
- Scheduling is called "concurrency control"

Observations

- Program runs “by itself”, doesn’t talk to others
- All the work is done in one program, in straight-line fashion. If an application requires running several programs, like a C compilation, it would run as several separate transactions!
- The persistent data is maintained in files or database relations external to the application

Serializability

- Means that effect of the interleaved execution is indistinguishable from some possible serial execution of the committed transactions
- For example: T1 and T2 are interleaved but it "looks like" T2 ran before T1
- Idea is that transactions can be coded to be correct if run in isolation, and yet will run correctly when executed concurrently (and hence gain a speedup)

Need for serializable execution

T_1: $R_1(X)$ $R_1(Y)$ $W_1(X)$ $commit_1$

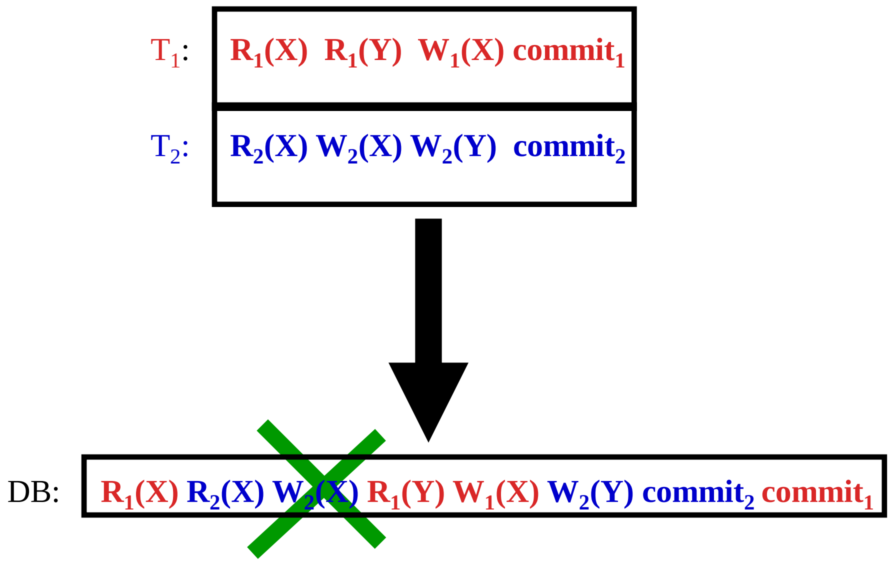
T_2: $R_2(X)$ $W_2(X)$ $W_2(Y)$ $commit_2$

↓

DB: $R_1(X)$ $R_2(X)$ $W_2(X)$ $R_1(Y)$ $W_1(X)$ $W_2(Y)$ $commit_1$ $commit_2$

Data manager interleaves operations to improve concurrency

Non serializable execution



Unsafe! Not serializable

Problem: transactions may "interfere". Here, T_2 changes x, hence T_1 should have either run first (read <u>and</u> write) or after (reading the changed value).

Serializable execution

T_1: $R_1(X)$ $R_1(Y)$ $W_1(X)$ $commit_1$

T_2: $R_2(X)$ $W_2(X)$ $W_2(Y)$ $commit_2$

DB: $R_2(X)$ $W_2(X)$ $R_1(X)$ $W_1(X)$ $W_2(Y)$ $R_1(Y)$ $commit_2$ $commit_1$

Data manager interleaves operations to improve concurrency but schedules them so that it looks as if one transaction ran at a time. This schedule "looks" like T_2 ran first.

Atomicity considerations

- If application ("transaction manager") crashes, treat as an abort
- If data manager crashes, abort any non-committed transactions, but committed state is persistent
  - Aborted transactions leave no effect, either in database itself or in terms of indirect side-effects
  - Only need to consider committed operations in determining serializability

Components of transactional system

- Runtime environment: responsible for assigning transaction id's and labeling each operation with the correct id.
- Concurrency control subsystem: responsible for scheduling operations so that outcome will be serializable
- Data manager: responsible for implementing the database storage and retrieval functions

Transactions at a “single” database

- Normally use 2-phase locking or timestamps for concurrency control
- Intentions list tracks “intended updates” for each active transaction
- Write-ahead log used to ensure all-or-nothing aspect of commit operations
- Can achieve thousands of transactions per second

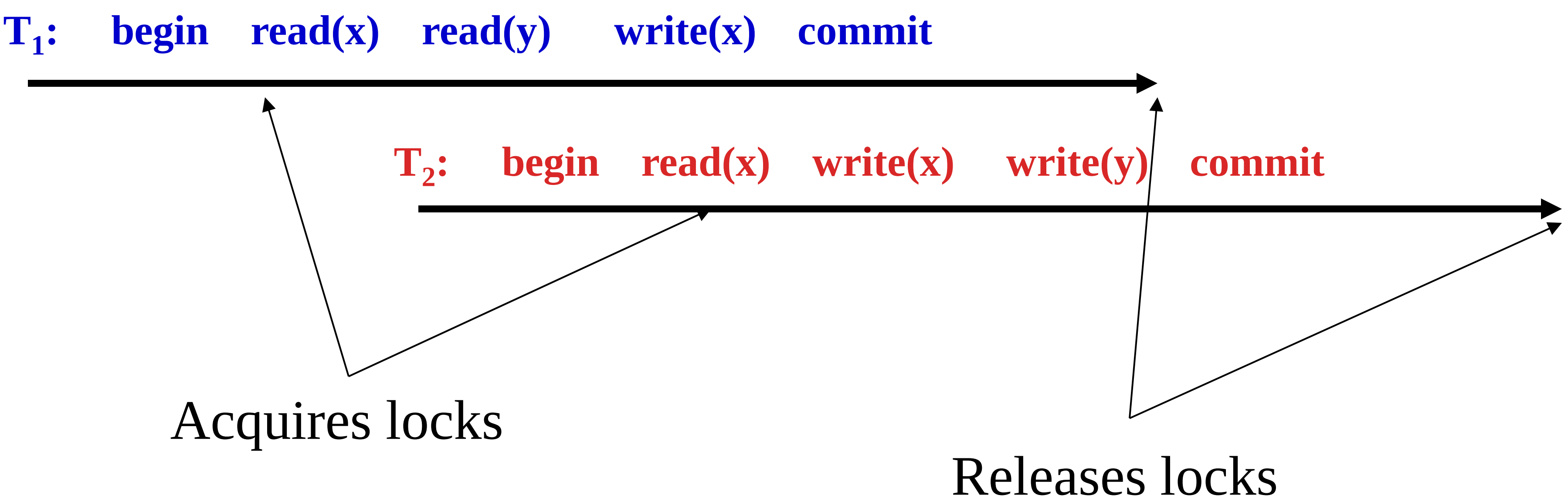
Strict two-phase locking: how it works

- Transaction must have a lock on each data item it will access.
  - Gets a “write lock” if it will (ever) update the item
  - Use “read lock” if it will (only) read the item. Can’t change its mind!
- Obtains all the locks it needs while it runs and hold onto them even if no longer needed
- Releases locks only after making commit/abort decision and only after updates are persistent

Why do we call it "Strict" two phase?

- 2-phase locking: Locks only acquired during the 'growing' phase, only released during the 'shrinking' phase.
- Strict: Locks are only released after the commit decision
  - Read locks don't conflict with each other (hence T' can read x even if T holds a read lock on x)
  - Update locks conflict with everything (are "exclusive")

Strict Two-phase Locking



Notes

- Notice that locks must be kept even if the same objects won't be revisited
  - This can be a problem in long-running applications!
  - Also becomes an issue in systems that crash and then recover
    - Often, they "forget" locks when this happens
    - Called "broken locks". We say that a crash may "break" current locks…

Why does strict 2PL imply serializability?

- Suppose that T' will perform an operation that conflicts with an operation that T has done:
  - T' will update data item X that T read or updated
  - T updated item Y and T' will read or update it
- T must have had a lock on X/Y that conflicts with the lock that T' wants
- T won't release it until it commits or aborts
- So T' will wait until T commits or aborts

Acyclic conflict graph implies serializability

- Can represent conflicts between operations and between locks by a graph (e.g. first T1 reads x and then T2 writes x)
- If this graph is acyclic, can easily show that transactions are serializable
- Two-phase locking produces acyclic conflict graphs

Two-phase locking is “pessimistic”

- Acts to prevent non-serializable schedules from arising: pessimistically assumes conflicts are fairly likely
- Can deadlock, e.g. T1 reads x then writes y; T2 reads y then writes x. This doesn’t always deadlock but it is capable of deadlocking
  - Overcome by aborting if we wait for too long,
  - Or by designing transactions to obtain locks in a known and agreed upon ordering

Contrast: Timestamped approach

- Using a fine-grained clock, assign a "time" to each transaction, uniquely. E.g. T1 is at time 1, T2 is at time 2
- Now data manager tracks temporal history of each data item, responds to requests as if they had occured at time given by timestamp
- At commit stage, make sure that commit is consistent with serializability and, if not, abort

Example of when we abort

- T1 runs, updates x, setting to 3
- T2 runs concurrently but has a larger timestamp. It reads x=3
- T1 eventually aborts
- ... T2 must abort too, since it read a value of x that is no longer a committed value
  - Called a cascaded abort since abort of T1 triggers abort of T2

Pros and cons of approaches

- Locking scheme works best when conflicts between transactions are common and transactions are short-running
- Timestamped scheme works best when conflicts are rare and transactions are relatively long-running
- Weihl has suggested hybrid approaches but these are not common in real systems

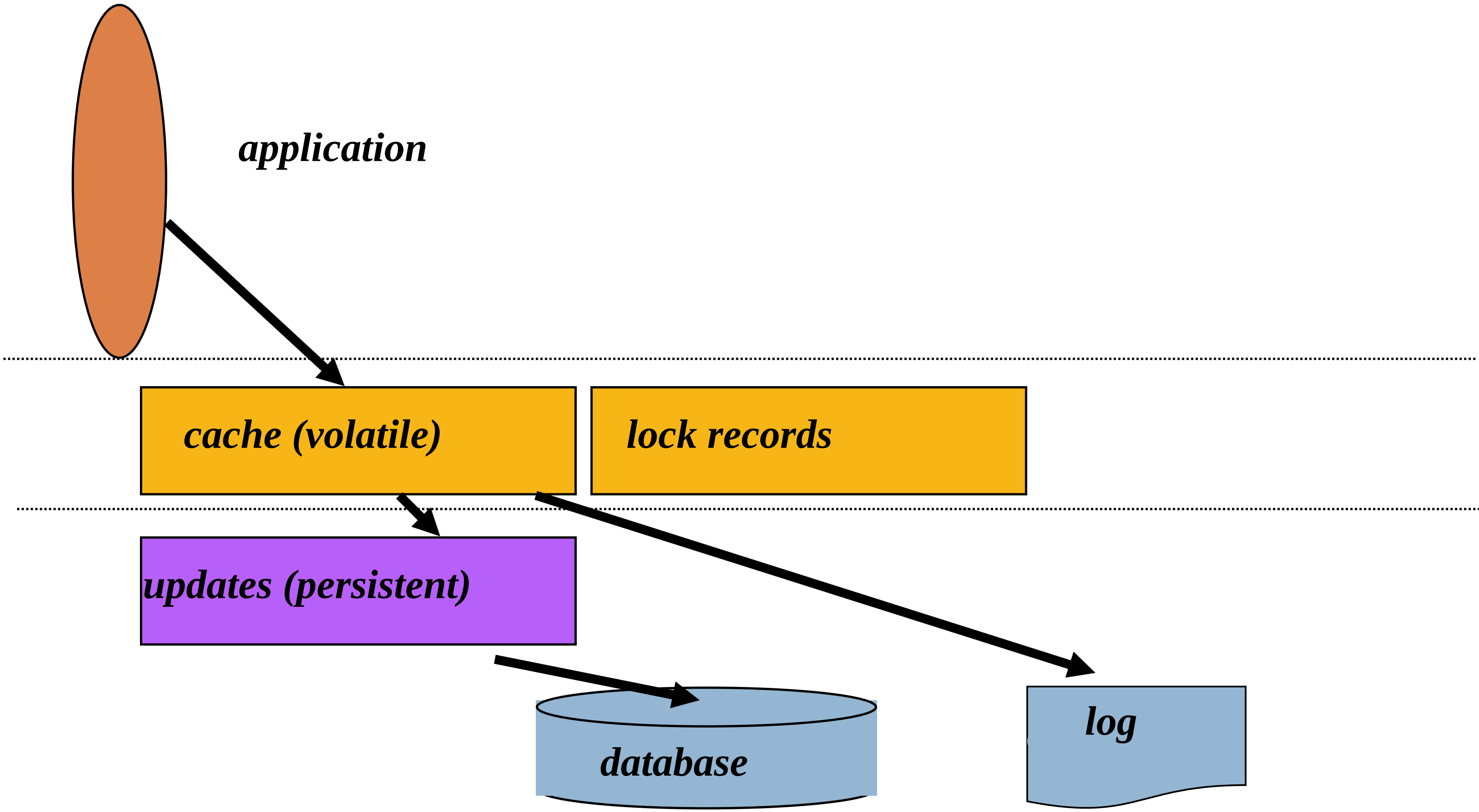
Intentions list concept

- Idea is to separate persistent state of database from the updates that have been done but have yet to commit
- Intensions list may simply be the in-memory cached database state
- Say that transactions intends to commit these updates, if indeed it commits

Role of write-ahead log

- Used to save either old or new state of database to either permit abort by rollback (need old state) or to ensure that commit is all-or-nothing (by being able to repeat updates until all are completed)
- Rule is that log must be written before database is modified
- After commit record is persistently stored and all updates are done, can erase log contents

Structure of a transactional system



Recovery?

- Transactional data manager reboots
- It rescans the log
  - Ignores non-committed transactions
  - Reapplies any updates
  - These must be "idempotent"
    - Can be repeated many times with exactly the same effect as a single time
    - E.g. x := 3, but not x := x.prev+1
- Then clears log records
- (In normal use, log records are deleted once transaction commits)

Transactions in distributed systems

- Notice that client and data manager might not run on same computer
  - Both may not fail at same time
  - Also, either could timeout waiting for the other in normal situations
- When this happens, we normally abort the transaction
  - Exception is a timeout that occurs while commit is being processed
  - If server fails, one effect of crash is to break locks even for read-only access

Transactions in distributed systems

- What if data is on multiple servers?
  - In a non-distributed system, transactions run against a single database system
    - Indeed, many systems structured to use just a single operation – a "one shot" transaction!
  - In distributed systems may want one application to talk to multiple databases

Transactions in distributed systems

- Main issue that arises is that now we can have multiple database servers that are touched by one transaction
- Reasons?
  - Data spread around: each owns subset
  - Could have replicated some data object on multiple servers, e.g. to load-balance read access for large client set
  - Might do this for high availability
- Solve using 2-phase commit protocol!

Unilateral abort

- Any data manager can unilaterally abort a transaction until it has said "prepared"
- Useful if transaction manager seems to have failed
- Also arises if data manager crashes and restarts (hence will have lost any non-persistent intended updates and locks)
- Implication: even a data manager where only reads were done must participate in 2PC protocol!

Transactions on distributed objects

- Idea was proposed by Liskov's Argus group and then became popular again recently
- Each object translates an abstract set of operations into the concrete operations that implement it
- Result is that object invocations may "nest":
  - Library "update" operations, do
  - A series of file read and write operations that do
  - A series of accesses to the disk device

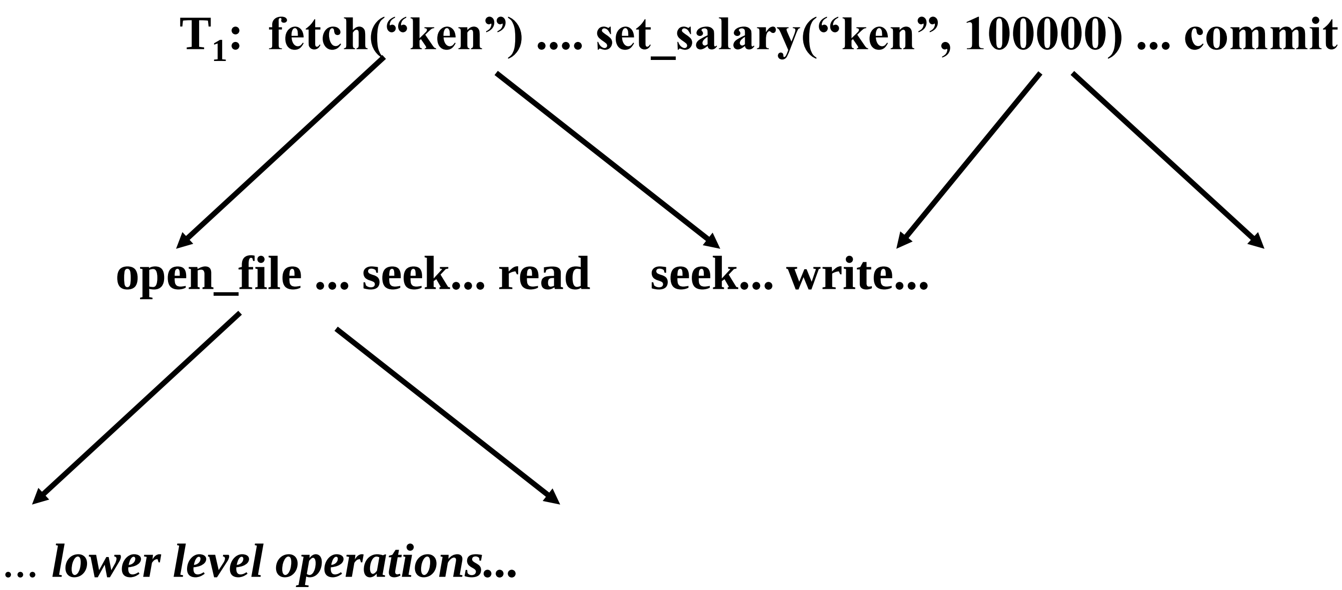
Nested transactions

- Call the traditional style of flat transaction a "top level" transaction
  - Argus short hand: "actions"
- The main program becomes the top level action
- Within it objects run as nested actions

Arguments for nested transactions

- It makes sense to treat each object invocation as a small transaction: begin when the invocation is done, and commit or abort when result is returned
  - Can use abort as a "tool": try something; if it doesn't work just do an abort to back out of it.
  - Turns out we can easily extend transactional model to accommodate nested transactions
- Liskov argues that in this approach we have a simple conceptual framework for distributed computing

Nested transactions: picture



Observations

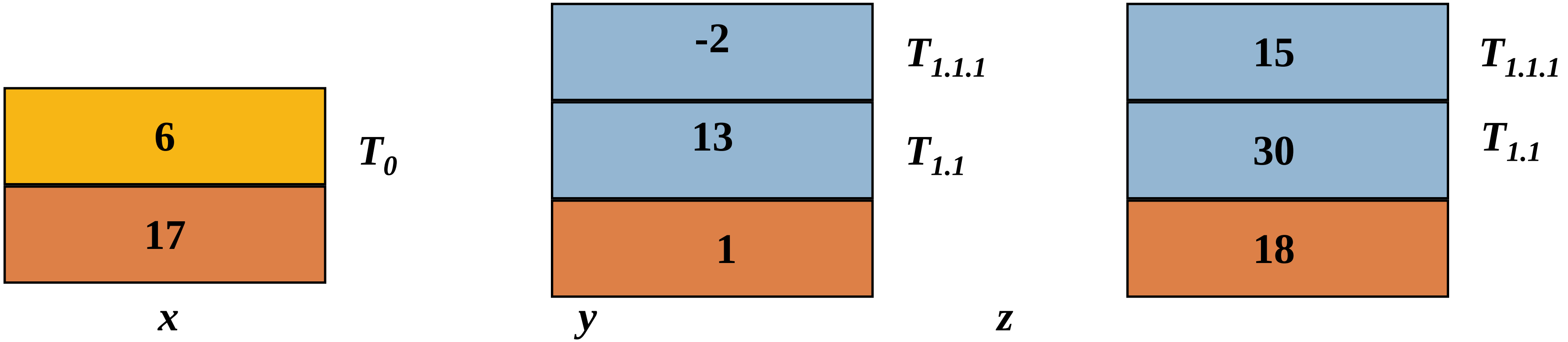
- Can number operations using the obvious notation
  - T1, T1.2.1.....
- Subtransaction commit should make results visible to the parent transaction
- Subtransaction abort should return to state when subtransaction (not parent) was initiated
- Data managers maintain a stack of data versions

Stacking rule

- Abstractly, when subtransaction starts, we push a new copy of each data item on top of the stack for that item
- When subtransaction aborts we pop the stack
- When subtransaction commits we pop two items and push top one back on again
- In practice, can implement this much more efficiently!!!

Data objects viewed as "stacks"

- Transaction T_0 wrote 6 into x
- Transaction T_1 spawned subtransactions that wrote new values for y and z



Locking rules?

- When subtransaction requests lock, it should be able to obtain locks held by its parent
- Subtransaction aborts, locks return to "prior state"
- Subtransaction commits, locks retained by parent
- … Moss has shown that this extended version of 2-phase locking guarantees serializability of nested transactions

Relatively recent developments

- Many cloud-computing solutions favor non-transactional tables to reduce delays even if consistency is much weaker
  - Called the NoSQL movement: "Not SQL"
  - Application must somehow cope with inconsistencies and failure issues. E.g. your problem, not the platform's.

- Also widely used: a model called "Snapshot isolation". Gives a form of consistency for reads and for updates, but not full serializability

Summary

- Transactional model lets us deal with large databases or other large data stores
- Provides a model for achieving high concurrency
- Concurrent transactions won't stumble over one-another because ACID model offers efficient ways to achieve required guarantees