PURDUE UNIVERSITY

CS54200: Distributed Database Systems

Replicated Data

16 January, 2009

Prof. Chris Clifton

Indiana Center for Database Systems

Replicated Data

- Thus far, we have assumed that there is only a single copy of each data item.
- This copy is placed at one of the sites, which is responsible for concurrency control and recovery for that data item.
- However, for a data item that is accessed often from different sites, this could lead to a significant amount of communication.
- Moreover, when a sites fails, all data residing on that site becomes unavailable.

2

Replication

- To increase availability of data, and to reduce communication for remote data, data can be replicated.
- From the user's point of view, replication (like distribution, physical and logical organization of data), should be transparent.
- I.e. the user should not be aware that some (or all) data items are replicated, and should see no difference in performance.
- The user can be a programmer or an end user.

3

1 Copy Serializability

- The correctness definition for replicated databases is therefore that it should behave as though all transactions are executed in a ***serial manner on a single copy database***.
- This is the notion of one copy serializability, I.e. 1SR.
- The user must be given a one copy view of the database.
- How is this achieved?
- Read-only is easy. For writes we must manage carefully!

4

Write-All approach

- This is the obvious first solution:
  - Reads can be satisfied by any copy in the system,
  - Writes must all modify *every* copy of the data item being written.
- This is a very effective solution – it completely eliminates the problem of multiple copies, and gives each txn the correct view. HOWEVER
- It is very poor in terms of performance and progress:
  - Failures have a crippling effect on transactions!

5

Write-All-Available

- Allow a txn to proceed even though failures make it impossible to write all copies of the data.
- Allow the txn to simply write to every site that is available. Those that are down can be ignored.
- Thus some copies of the data may be out of sync, I.e. may not contain the latest updates.

6

Example

- Consider the following execution. Note that multiple copies are marked using the upper case subscripts.

$w_0[x_A]\ w_0[x_B]\ w_0[y_C]\ c_0\ r_1[y_C]\ w_1[x_A]\ c_1\ r_2[x_B]\ w_2[y_C]\ c_2$

- T_2 reads copy x_B from T_0, even though it should have read from T_1.
- Thus the above history is not equivalent to $T_0 T_1 T_2$.
- Is it equivalent to some other serial one-copy history?
- NO! $w_0[y_C] < r_1[y_C] < w_2[y_C]$, there is no other equivalent serial execution.
- This is interesting, because the execution actually seems to be a serial execution of the transactions!!!

7

Example (contd.)

- So what has gone wrong?
- The problem is that the write by T_1 into x, did not update all copies of x – x_B in particular.
- This could only mean that site B must have been down when T_1 wrote x, and must have recovered before T_2 read x.
- I.e. the failures must have been as such:

$w_0[x_A]\ w_0[x_B]\ w_0[y_C]\ c_0\ r_1[y_C]\ fail_B\ w_1[x_A]\ c_1\ Recover_B\ r_2[x_B]\ w_2[y_C]\ c_2$

- Thus the problem is that T_2 read a copy at a site that had failed and upon recovery did not re-sync with the other sites! Fixing this is still not enough!!

8

PURDUE UNIVERSITY

CS54200: Distributed Database Systems

Replicated Data

18 January, 2009

Prof. Chris Clifton

Indiana Center for Database Systems

Assumptions

- Again, we will assume the same model for the database.
- The TM now maps all reads onto a read of some copy, and all writes onto a write on all (available) copies. It uses directories of copies to determine where copies are stored.
- Failures are assumed to be fail stop.
- We begin by ignoring communication failures.
- Thus a copy x_A at a site A is available to site B if A correctly executes each read/write of x_A from site B, and B receives the acknowledgement.

10

Assumptions.

- Therefore site failures are detectable.
- The timing of updating multiple copies can vary:
  - Immediate: as soon as the write is received.
  - Deffered: could delay the updating of copies. Update copies only upon commitment or abortion. Intentions lists can be piggybacked with VOTE_REQ msgs.
- Delayed updating results in
  - Fewer messages
  - Cheaper aborts
  - Delayed commitment
  - Delayed detection of conflicting operations. Can be solved by using a *primary copy* approach.

11

Replicated Data History.

- Let *h( )* be a function that maps
  - $r_i[x] \rightarrow r_i[x_A]$ for some copy x_A of x.
  - $w_i[x] \rightarrow w_i[x_{A1}], \ldots, w_i[x_{Am}]$, for some copies of x
  - $c_i \rightarrow c_i$
  - $a_i \rightarrow a_i$

12

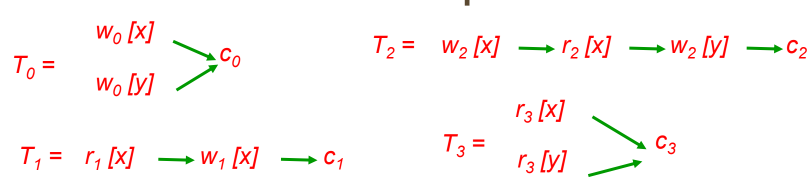
Replicated Data History

- A complete replicated data (RD) history H over $T=\{T_0, \ldots, T_n\}$ is a partial order with ordering relation < where:
  - $H=h(U_{i=0..n}\ T_i)$ for some translation function h;
  - For each T_i and all operations p_i, q_i in T_i, if $p_i<q_i$, then every operation in $h(p_i)$ is related by < to every operation in $h(q_i)$.
  - For every $r_j[x_A]$ there is at least one $w_i[x_A] < r_j[x_A]$
  - *All pairs of conflicting operations are related by <*, where two operations conflict if they operate on the same copy and at least one is a write; and
  - If $w_i[x] < r_j[x]$ and $h(r_j[x])= r_j[x_A]$ then $w_i[x_A]$ must be in $h(w_i[x])$.

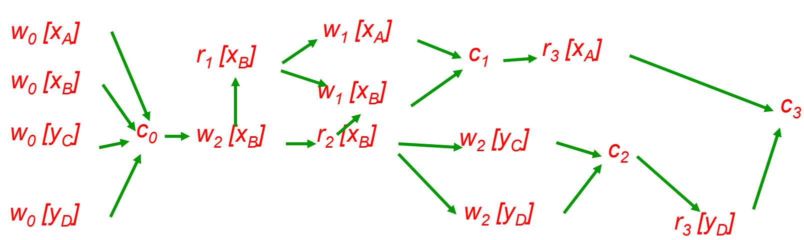
13

Example

Given txns $\{T_0, T_1, T_2, T_3\}$:



The following is an example of an RD history:



14

Reads-From Relationship

- Let *H* be an RD history.
- Txn T_j *reads-x-from* T_i in *H* if for some copy x_A T_j reads-x_A-from T_i , that is, if $w_i[x_A] < r_j[x_A]$ and no $w_k[x_A]$ $(k <> i)$ falls between these operations.
- Since reads-from are unique on copies, and a txn reads only one copy, then reads-from relationships on data items are unique too.

15

Serialization Graph

- Consider only complete histories with committed transactions only.
- I.e. we assume *recoverable* execution.
- What does that mean for replicated data?
- An RD history *H*, is recoverable if whenever T_i reads (any copy) from T_j in *H* and c_i is in *H*, then c_j is in *H* and $c_j < c_i$.
- The Serialization graph is generated as before, except that conflicting operations are now defined on copies rather than data items.

16

Serialization Graph

- Let *H* be an RD history involving transaction T_i. If *SG*(*H*) is acyclic and for some *x*, $w_i[x] <_i r_i[x]$, then T_i reads-*x*-from T_i in *H*.
- ***Proof***:
  - From conditions (2) and (5) on RD histories, $w_i[x] <_i r_i[x]$ implies that for some copy x_A of *x*, $w_i[x_A] < r_i[x_A]$.
  - Suppose, T_i didn't read *x* from T_i in *H*. Then there must exist some $w_k[x_A]$ *(k<>i)* in *H* such that $w_i[x_A] < w_k[x_A] < r_i[x_A]$.
  - But then SG(H) is acyclic.

17

Serializability

- Acyclicity of the serialization graph does NOT guarantee serializability for RD histories.
- A history is serializable if it is equivalent to a 1C history.
- The same order for conflicting operations does not work since the conflicting operation in the RD history and the 1C history are not the same.
- View equivalence is more natural for RD histories since the reads-from-relationships and final writes behave similarly in both types of histories.

18

RD history equivalence

- Given an RD history *H,* define $w_i[x_A]$ to be a *final write for x_A* in *H* if a_i is not in *H* and for all $w_j[x_A]$ in *H* (*j* <>*i*), either a_j is in *H*, or $w_j[x_A] < w_i[x_A]$.
- Two RD histories are equivalent if they are view equivalent, that is, they have the same reads-from relationships and final writes.

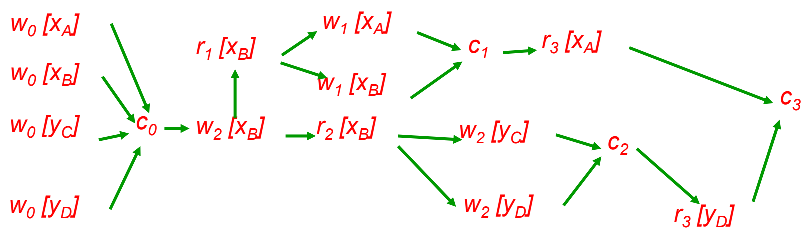
RD history equivalence

- An RD history *H* over *T* is equivalent to a 1C history H_{1C} over *T* if

1. *H* and H_{1C} have the same reads-from relationships on data items (i.e., T_j *reads-x-from* T_i in *H* iff the same holds in H_{1C}), and
2. For each final write $w_i[x]$ in H_{1C}, $w_i[x_A]$ is a final write in *H* for some copy x_A of *x.*

An RD history is *one-copy serializable (1SR)* if it is equivalent to a serial 1C history.

Examples



- Is 1SR, it is equivalent to $T_0\ T_2\ T_1\ T_3$.
- But, $w_0[x_A]\ w_0[x_B]\ w_0[y_C]\ c_0\ r_1[y_C]\ w_1[x_A]\ c_1\ r_2[x_B]\ w_2[y_C]\ c_2$ is not.
- However, it is a serial history!!
- Thus not every serial RD history is 1SR.

21

Final Writes

- Let *H* be an RD history over *T*, with acyclic SG(H). Let H_{1C} be a serial 1C history over *T* such that the order of transactions in H_{1C} is consistent with SG(H). If $w_i[x]$ is a final write for *x* in H_{1C} , then every write, $w_i[x_A]$, by T_i into some copy x_A of *x* is a final write for x_A in *H*.
- ***Proof:***
  - Suppose $w_i[x]$ is a final write for *x* in H_{1C}. Let $w_i[x_A]$ be any write into *x* by T_i in *H*. If $w_i[x_A]$ is not a final write, then there is some $w_j[x_A]$ $(j <> i)$ such that a_j is not in *H* and $w_i[x_A] < w_j[x_A]$.
  - Thus $T_i \rightarrow T_j$ is in SG(H), so T_i precedes T_j in H_{1C}.
  - ➔ a_j is not in H_{1c} and $w_i[x] < w_j[x]$ in H_{1C}, contradicting the choice of $w_i[x]$ as a final write.

22

Serializability

- Thus we can ignore final writes – they must be the same.
- Theorem: Let *H* be an RD history. If *H* has the same reads-from relationships as a serial 1C history H_{1C}, where the *order of transactions in* H_{1C} *is consistent with SG(H),* then *H* is 1SR.

23

PURDUE UNIVERSITY

CS54200: Distributed Database Systems

Replicated Data

20 January, 2009

Prof. Sunil Prabhakar

Indiana Center for Database Systems

Serializability

- Thus we can ignore final writes – they must be the same.
- Theorem: Let H be an RD history. If H has the same reads-from relationships as a serial 1C history H_{1C}, where the order of transactions in H_{1C} is consistent with SG(H), then H is 1SR.

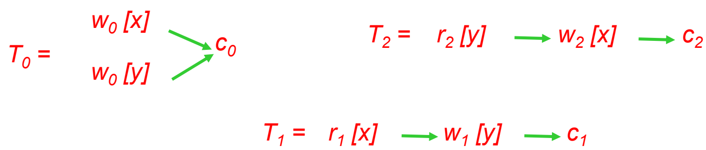
25

Graphs for 1SR histories

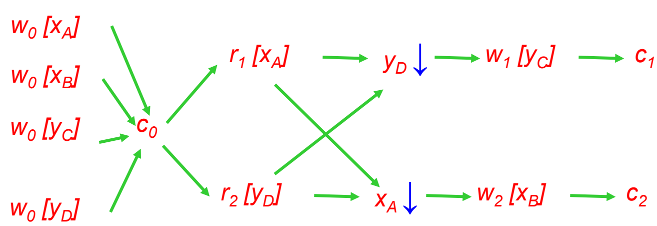
- How can we modify the serialization graphs to identify exactly the set of 1SR histories?
- The problem arises from the failure and recovery of sites:
  - A failed site will not be updated
  - Upon recovery it has inconsistent data.
- How can we capture the effects of these failures and recoveries in the serialization graph?

26

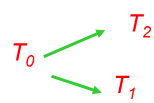
Example



The following RD history can occur with 2PL on copies:



This is not a 1SR history! But SG is acyclic:



27

The problem

- In the example there were no recoveries, thus by ensuring that a recovering site synchronizes before it is accessed, we would still have non-1SR histories!
- We are *failing to capture the conflict at the item level by considering only conflicts at the copy level.*
- Note that two conflicting operations must contain a write which must write all (available) copies. Without failures the conflict is detected.

28

Replicated Data SG

- Try to synchronize two transactions that access a conflicting item.
- Define: n_j *precedes* n_k , i.e., $n_i << n_k$, in a directed graph, if there is a path from n_i to n_k .
- A replicated data serialization graph (RDSG) for *H* is SG(*H*) with enough edges added such that for all data items, *x*:
  1. If T_i and T_k write *x*, then either $T_i << T_k$ or $T_k << T_i$
  2. If T_j *reads-x* from T_i, T_k writes some copy of *x* ($k <> i$, $k <> j$), and $T_i << T_k$, then $T_j << T_k$.

29

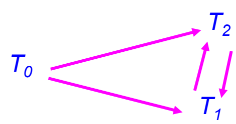
RDSG

- A graph that satisfies condition 1 *induces a write order* for *H*.
- If it satisfies condition 2 it *induces a read order* for *H.*
- Given a history *H*, the *RDSG(H)* is not unique.
- The write order ensures that every pair of txns that write into the same item (even if they don't write the same copy).
- Write and read order ensure that every pair of txns that read and write the same item.

30

Example.

- The example enforces a write order.
- However it does not enforce a read order:
  - Since T_1 reads-x-from T_0, T_2 writes x, and $T_0 \rightarrow T_2$, we add $T_1 \rightarrow T_2$ to RDSG(H);
  - Since T_2 reads-y-from T_0, T_1 writes y, and $T_0 \rightarrow T_1$, we add $T_2 \rightarrow T_1$ to the RDSG(H).



- Now RDSG(H) has a cycle, as required.

31

1SR

- Theorem: Let H be an RD history. If H has an acyclic RDSG, then H is 1SR.
- *Proof:*
  - Let $H_s=T_{i1}, \ldots T_{in}$ be a serial 1C history where $T_{i1}, \ldots, T_{in}$ is a topological sort of RDSG(H).
  - Since RDSG(H) contains SG(H), H is 1SR if H and H_s have the same reads-from relationships.
  - Assume that T_j reads-x-from T_i in H. Suppose, by way of contradiction, that T_j reads-x-from T_k in Hs.
  - If $k=j$, then T_j must read-x-from T_k in H too since SG(H) is acyclic ➔ $k <> j$.

32

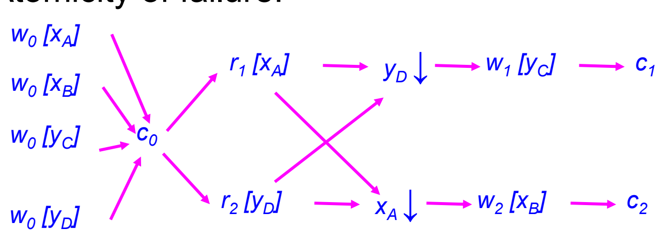
Proof (cont)

- Since T_j reads-x-from T_i in H, $T_i \rightarrow T_j$ is in RDSG(H), so T_i precedes T_j in H_s.
- Since the RDSG induces both a read and write order, we have that either $T_k << T_i$ or $T_j << T_k$.
- Thus either T_k precedes T_i (which precedes Tj) or T_k follows T_j in H_s, both contradict that T_j reads-x-from T_k in H_s.
- Now assume T_j reads-x-from T_i in H_s. By the definition of RD histories and the reads-from relationship, T_j reads-x-from some txn in H, say T_h. By the above, T_j reads-x-from T_h in Hs. Since the reads-from relation is unique, T_h=T_i.

33

Atomicity of Failures and Recovery

- Another alternative, is to ensure that all transactions view failures and recoveries consistently.
- Atomicity of failure:



- T_1 sees the failures as: $yD\downarrow \rightarrow T_1 \rightarrow xA\downarrow$ but
- T_2 sees the failures as: $xA\downarrow \rightarrow T_2 \rightarrow yD\downarrow$

34

Atomicity of Failures

- We want all transactions to *agree on when the failures occurred*.
- There can be no serial ordering of the failures and T_1, T_2 that is consistent with the views of T_1 and T_2.
- We want to synchronize the recognition of failures of sites with the read and write operations that are taking place.
- Certain views of failures may be troublesome and should not be allowed.

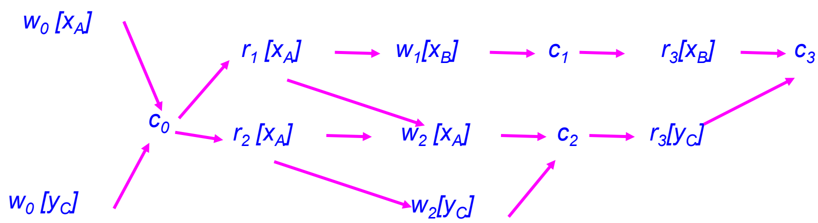
35

Atomicity of Recoveries

- We require that each copy be initialized before it is read a copies txn can be used for this.
- After initialization, all txns need to be informed about the new copy so that they can write it too.
- *This has to be done carefully*:

36

Example



This is an incorrect history. The only equivalent serial history is:

$w_0\,[x_A]$ $w_0\,[y_C]$ c_0 $r_1\,[x_A]$ $w_1[x_B]$ c_1 $r_2\,[x_A]$ $w_2\,[x_A]$ $w_2[y_C]$ c_2 $r_3[x_B]$ $r_3[y_C]$ c_3

Which is not equivalent to $T_0T_1T_2T_3$. T_2 should write x and y and T_3
Should read these values.

37

Atomic Recoveries

- The problem is that T_2 should have updated the new copy of x, xB.
- Since T_1 knew about xB, and executed before T_2.
- In terms of recoveries,
  - The view of T_1 is: $xB\uparrow \rightarrow T_1$
  - The view of T_2 is: $T_2 \rightarrow xB\uparrow$
  - Since T_1 executes before T_2, this is inconsistent!!
- We want all txns to have a consistent view of the recovery of copies.

38

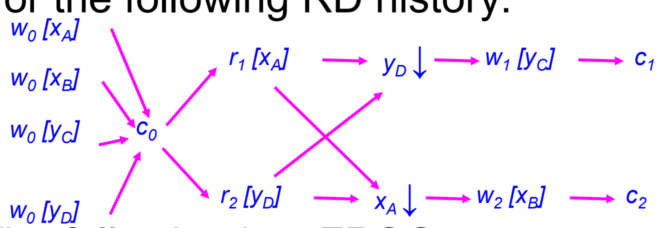
Failure-Recovery SG

- Assume that once a copy fails, it never recovers!!
- Given an RD history H over transactions $\{T_0, \ldots, T_n\}$, a *failure-recovery serialization graph (FRSG)* for H is a directed graph with nodes N and edges E where:
  - $N = \{T_o, \ldots, T_n\} \cup \{create[x_A] \mid x$ is a data item, and x_A is a copy of $x\} \cup \{fail[x_A]\}$
  - $E = \{T_i \rightarrow T_j \mid T_i \rightarrow T_j$ is in $SG(H)\} \cup E1 \cup E2 \cup E3$, where $E1 = \{create[x_A] \rightarrow T_i \mid T_i$ reads or writes $x_A\}$;
    $E2 = \{T_i \rightarrow fail[x_A] \mid T_i$ reads $x_A\}$;
    $E3 = \{T_i \rightarrow create[x_A]$ or $fail[x_A] \rightarrow T_i \mid T_i$ writes some copy of x, but not $x_A\}$.

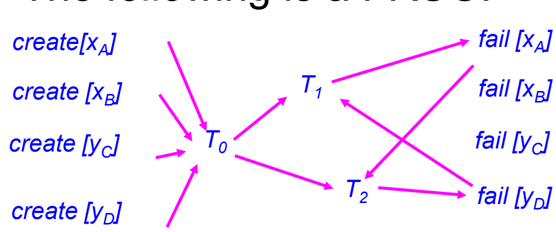
39

Example

- For the following RD history:



- The following is a FRSG:



40

1SR

- Theorem: Let H be an RD history. If H has an acyclic FRSG, then H is 1SR.
- Proof:
  - Let $H_s = T_{i1}, \ldots T_{in}$ be a serial 1C history where $T_{i1}, \ldots, T_{in}$ is a topological sort of FRSG(H).
  - Since FRSG(H) contains SG(H), H is 1SR if H and H_s have the same reads-from relationships.
  - Assume that T_j reads-x_A-from T_i in H. Hence $T_i \rightarrow T_j$ is in FRSG(H), and T_i precedes T_j in Hs.
  - Let T_k be any other transaction that writes x.
  - If T_k writes xA, then since T_j reads-xA-from T_i, either $T_k \rightarrow T_i$ or $T_j \rightarrow T_k$ must be in FRSG(H).

41

Proof (contd.)

- If T_k does not write xA, by defn of FRSG, either $T_k \rightarrow$ *create[xA]* or *fail[xA]* $\rightarrow Tk$.
- In the former case, since *create[xA]* $\rightarrow T_i$, T_k precedes T_i in FRSG(H).
- In the latter case, since $T_j \rightarrow$ *fail[xA]*, T_j precedes T_k in the FRSG(H).
- Hence, if T_k writes x, either T_k precedes T_i or follows T_j in the FRSG and H_s.
- Thus T_j reads-x-from T_i in H_s.
- Now, suppose T_j reads-x-from T_i in H_s. By the defn of RD history, T_j reads-x-from some txn in H, say T_h. By the above, T_j reads-x-from T_h in H_s. Since reads from relationships are unique, $T_h = T_i$.

42

Communication Failures

- Thus far, we have ignored communication failures!
- These can lead to non-serializable executions if network partitions result from the failures.
- Handled by the use of quorums – ensuring that only one of the partitions handles transactions.
- There are several alternatives for enforcing quorums.

43