CS 138: Epidemics and Bayou

Topics

- Client-based consistency
- Epidemic algorithms
- Bayou and Weak Consistency

Room Reservation

- Room database maintained on one or more servers
- Clients use Gossip to make updates
  - everything is linearizable
- Problem solved …

Room Reservation (2)

- 138 TAs schedule room for help session
- 167 TAs also schedule room for help session
- But it's spring break …
  - 138 TAs are on flight to St. Thomas
    - at least one has copy of reservation DB
  - 167 TAs are on flight to Tahiti
    - at least one has copy of reservation DB
  - can't detect conflicts en route
    - cheap airfares — no internet on plane
  - Gossip can't cope

Weak Consistency

- Replicas are eventually consistent with one another
  - assuming no conflicts

Synchronization of Content

- Consensus
  - requires quorum
- Simpler approach
  - each node periodically contacts a random node
    - update it (or vice versa)
  - doesn't require quorum
  - does it work?

Anti-Entropy

- At each synchronization period, server P picks a random server Q and exchanges updates
- Three types:
  - *push*: P $\rightarrow$ Q
  - *pull*: P $\leftarrow$ Q
  - *push-pull*: P $\leftrightarrow$ Q
- Entire databases are exchanged
  - no timestamp information to determine what's new
  - optimization: use checksums to see if they're different

Anti-entropy works as follows: periodically, a server P randomly chooses a server Q and then the two exchange databases. Three modes of anti-entropy are possible. In *push* mode, P pushes its database to Q, which adds to its database everything in P that it doesn't have. In the *pull* mode, the reverse is done. *Push-pull* mode works in both directions.

This discussion comes from "Epidemic Algorithms for Replicated Database Maintenance," by A. Demers, D. Greene, C. Hauser, W. Irish, J. Larson, S. Shenker, H. Sturgis, D. Swinehart, and D. Terry, Proceedings of the ACM SIGACT-SIGOPS 6th Annual Symposium on Principles of Distributed Computing, August, 1987.

Epidemics

- Established theory of how diseases spread by epidemics
  - adapt it
  - primary difference: infection is good

Epidemic Theory

- **Assume a fixed population of size *n***
- **For now assume homogeneous spreading**
  - **anybody can infect anybody else with equal probability**
- **Assume *k* members already infected**
- **Assume infection occurs in rounds**
- **In computer terms:**
  - **a site holding an update it is willing to share is *infective***
  - **a site that has not yet received an update is *susceptible***
  - **a site that has received an update, but unwilling to share is *removed***

We look at the fundamentals of epidemic theory in order to analyze the basic performance of the anti-entropy algorithms. Assume that any server can *infect* any other server with equal probability. Also assume that k members are already infected and infections occur in rounds: at each round, each server randomly picks another server.

Time to Infect

- Number of rounds necessary to infect whole population grows O(log *n*)
  - for push: $\log_2(n) + \ln(n) + O(1)$ (large n)

Push vs. Pull

- Which is better initially?
  - push
- If number of infected members is large; pull is better
  - let p_i be the probability of a site's remaining susceptible after the ith cycle of anti-entropy
    - for *pull*, a site remains susceptible after the i+1st cycle if it was susceptible after the ith cycle and it contacted a susceptible site in the i+1st cycle.

      $p_{i+1} = p_i^2$

      quickly goes to zero for small p_i
    - for *push*, a site remains susceptible after the i+1st cycle if it was susceptible after ith cycle and no infectious site chose to contact it in the i+1st cycle

$$p_{i+1} = p_i(1 - \frac{1}{n})^{n(1-p_i)} \approx \frac{p_i}{e}$$

If we compare the performance of the pull and push approaches; we observe that (for a very large number of servers) the pull approach converges (i.e., infects the entire population) faster than push does. Push-pull performs similar to pull.

Exchange Updates, Not Databases

- Each node keeps list of recent updates (list of “infections”)
  - propagates these to others at each contact
    - receiver adds updates to its list
  - when do items get removed from list?

Rumor Mongering

- Server P randomly selects Q to push updates
- If Q already has seen the updates of P, then P may “lose interest” (become *removed*)
  - … with probability 1/k

A form of non-simple epidemic is called *rumor mongering*.

Rumor Mongering

- **Analysis**

  s: % servers that are susceptible

  i: % servers that are infective

differential equations from epidemic theory: $$\frac{ds}{dt} = -si \qquad \frac{di}{dt} = si - \frac{1}{k}(1-s)i$$

for large n: $$i(s) = \frac{k+1}{k}(1-s) + \frac{1}{k}\log s$$

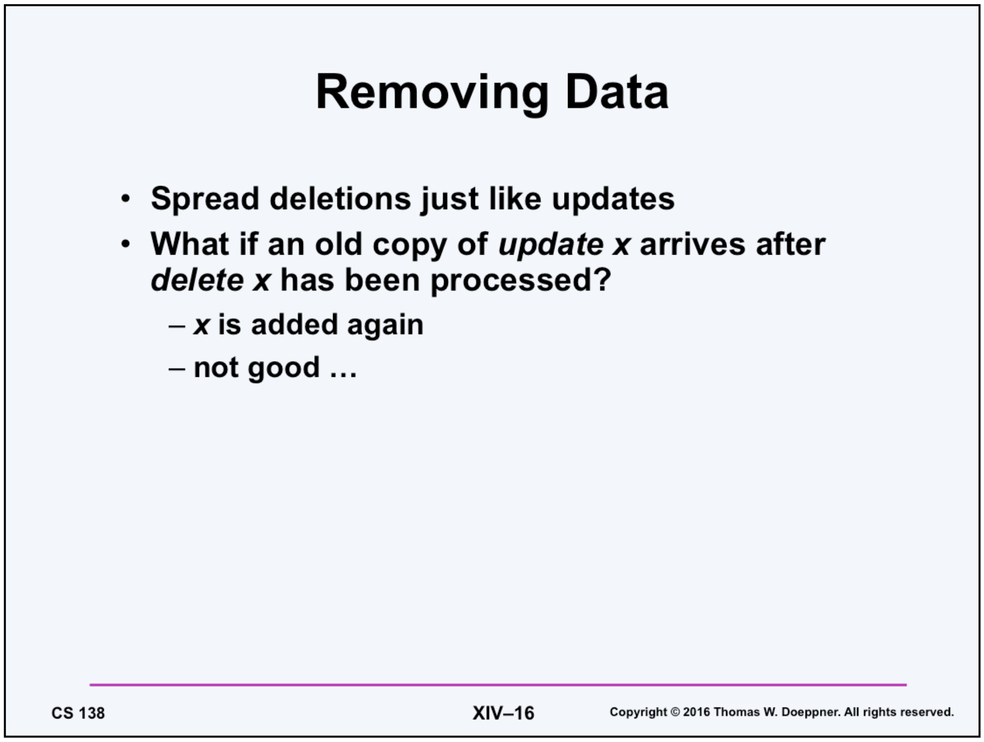
i(s) is zero when: $$s = e^{-(k+1)(1-s)}$$

for k=1, 20% will miss the rumor
for k=2, 6% will miss it

The math is taken from epidemic theory. The final equation tells us how many are still susceptible when there are no more infectious nodes. Thus these will never get the updates.

Rumor Mongering with Anti-Entropy

- Spread updates using rumor mongering
  - some nodes will not get updates
  - but exchanges are cheap
- Run anti-entropy infrequently
  - guarantees all nodes will get updates
  - but exchanges are expensive



Recall that we have no time stamps, so it cannot be determined if an update is new or old.

Death Certificates

- Solution: hold on to fact that x has been deleted
  - propagate *death certificates*
  - like updates, but record a void

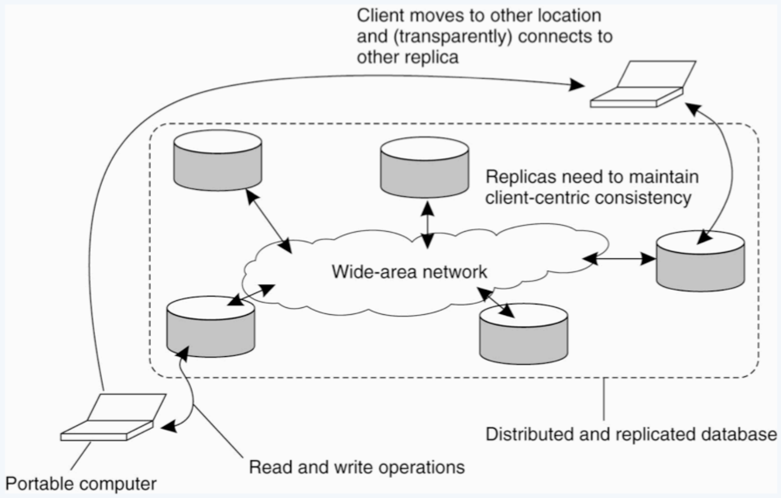
- How long do nodes hold on to death certificates?
  - a finite period
    - never long enough …
- Retain a few *dormant death certificates*
  - will be repropagated as death certificates if old update shows up

Application-specific Conflicts

- Concurrent writes to the same object might not conflict
  - e.g., two updates reserving the same room for different times
- Writes to different objects may conflict
  - e.g., one update for scheduling the projector and the other one the meeting room
- Conventional techniques decide false conflicts or false non-conflicts
- Bayou: Account for application semantics
  - *conflict detection with help of application*

There are many scenarios in which conventional version vector-based techniques fail to detect the conflicts correctly. In some applications, concurrent writes to the same object may not conflict as expected. Furthermore, concurrent writes to different objects may conflict. Bayou handles such cases by having the application define its own notion of conflict.

Bayou



Papers on Bayou include:

"Session Guarantees for Weakly Consistent Replicated Data," Proceedings of the Third International Conference on Parallel and Distributed Information Systems, 1994.

"Managing Update Conflicts in Bayou, a Weakly Connected Replicated Storage System," Proceedings of the fifteenth ACM symposium on Operating systems principles, 1995 (http://delivery.acm.org/10.1145/230000/224070/p172-terry.pdf?key1=224070&key2=3718232721&coll=GUIDE&dl=GUIDE&CFI).

"Flexible Update Propagation for Weakly Consistent Replication," Proceedings of the sixteenth ACM symposium on Operating systems principles, 1997 (http://delivery.acm.org/10.1145/270000/266711/p288-petersen.pdf?key1=266711&key2=2038232721&coll=GUIDE&dl=GUIDE&CFID=86082163&CFTOKEN=97029400).

Conflict Detection & Resolution

- *Dependency check*
  - a condition over the state of the database
  - included in every “write”
    - together with “expected result”
  - shared-calendar example:
    - condition: Is there another meeting at the same room at the same time?
- A *merge procedure* is used if a conflict is detected
  - shared-calendar example:
    - *resolution*: reschedule to alternate time
  - produces new update

Conflict detection is accomplished by using *dependency checks* — each write operation also supplies a dependency check that specifies a simple condition defined over the state of the database. The dependency check also defines what the application expects to see as a result when the condition gets evaluated. If indeed the expected result is observed then Bayou decides that there is no conflict, else it decides that there is a conflict.

If there is a conflict, then a *merge procedure* (i.e., a *conflict resolution procedure*), also supplied by the application, is executed to resolve the conflict. The merge procedure produces a new alternate update that is acceptable by the application and that would not create a conflict with the current database state (i.e., an update for which the dependency check will produce the expected result).

A Bayou "write"

- **Processed at each replica:**

```
Bayou_Write(update,dep_check,mergeproc) {
   IF (DB_EVAL(dep_check.query) ≠
         dep_check.expected_result)
      resolved_update = EXECUTE(mergeproc);
   ELSE
      resolved_update = update;
   DB_EXEC(resolved_update);
}
```


The slide shows the basic format of a Bayou write.

Example: Write and Reconcile in a Shared Calendar

```
Update={insert, Meetings, 12/18/95, 1:30pm, 60min, "Budget Meeting"}

Dependency_check={query="SELECT key FROM Meetings WHERE day=12/18/95 AND
   start<2:30pm AND end>1:30pm", expected_result=EMPTY}

MergeProc:

alternates={ {12/18/95, 3:00pm}, {12/19/95, 9:30am} }


FOREACH a IN alternates {

/* check if feasible, produce newupdate */ }

if(newupdate = {})  /* no feasible alternate */

    newupdate = { insert, ErrorLog, "Update" }

return(newupdate)
```


The slide shows an example Bayou write, including the dependency check and the merge procedure.

Bayou

- Updates propagated via epidemic protocols
  - some combination of rumor mongering and anti-entropy
- Weak consistency
  - requirements given from the client's perspective
  - client can choose desired (weak) consistency model
    - (next several slides)

Monotonic Reads

- **A data store is said to provide monotonic-read consistency if the following condition holds:**
  - **if a process reads the value of a data item x any successive read operation on x by that process will always return that same value or a more recent value**
- **Example (of its not holding)**
  - **you read your calendar at one server, then go to another and don’t see a recent update that was present at the first server, then go to another server and see it, then go to another and don’t see it …**

Note that “process” here means a client who is connecting to multiple servers.

Monotonic Writes

- In a monotonic-write consistent store, the following condition holds:
  - a write operation by a process on a data item x is completed before any successive write operation on x by the same process
- Example
  - you update a header file in a source-code directory on one server, then go to another and update a source-code file; someone else now tries to compile

Read Your Writes

- A data store is said to provide read-your-writes consistency, if the following condition holds
  - the effect of a write operation by a process on data item x will always be seen by a successive read operation on x by the same process
- Example
  - you change your password, then move to another server and your new password hasn't taken effect

Writes Follow Reads

- A data store is said to provide writes-follow-reads consistency, if the following holds:
  - a write operation by a process on a data item x following a previous read operation on x by the same process is guaranteed to take place on the same or a more recent value of x that was read
- Example:
  - consider a loosely connected bulletin-board service (such as Usenet). You would like it to be the case that responses to queries are seen after the queries at all sites

Dealing with the Constraints

- Clients keep track of dependencies
  - read set: set of IDs for writes that are relevant to session reads
  - write set: set of IDs for writes performed in session
- Server S maintains *DB(S, t)*
  - ordered sequence of writes received by server up to time *t*

We sketch an approach to an implementation of the constraints. Our first few ideas aren't entirely practical, but will lead to an approach that is.

Read Your Writes

- Whenever write is accepted by a server, client adds write ID to write set
- Before each read from server S at time t, client must check that

  write set $\subseteq$ DB(S, t)

If a server can't be found that satisfies the restriction of the second bullet, then the application must be notified that read-your-writes cannot be maintained.

Monotonic Reads

- Before each read from server S at time t, client must check that

  read set $\subseteq$ DB(S, t)

- After each read, add to read set the writes that the read depended on

Anti-Entropy Constraints

- Required of servers to handle *monotonic writes* and *writes follow reads*
  - new writes accepted by a server from a client are ordered after existing writes
  - during anti-entropy exchanges:
    - if server S1 sends write W2 to server S2, then any W1 ordered before W2 on S1 is also sent to S2

Writes Follow Reads

- After each read, add to read set the writes that the read depended on
- Before each write at time t, client must check that

  read set $\subseteq$ DB(S, t)

Monotonic Writes

- Before each write at time t, client must check that

  write set $\subseteq$ DB(S, t)
- After each write is accepted by server, client adds write ID to its write set

A Practical Implementation

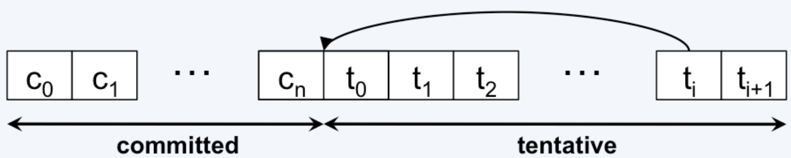
- Implement write IDs as <server, logical time>
- Servers maintain *version vectors* (essentially vector clocks)
  - $V_S[x]$ = logical time of most recent (by logical time) write ID received from server x by server S
- Clients maintain two session vectors, updated like vector clocks
  - read vector: writes relevant to session reads
  - write vector: session writes

Anti-Entropy Implementation

- Each server keeps log of all writes, ordered by write ID
- On anti-entropy exchange (sender S; receiver R):
  - S sends R all writes unknown to R
    - uses version vectors

Ordering

- **Initial write order is tentative**
- **Designated primary server determines total order of writes: *commit sequence number* (CSN)**
  - **write ID = <CSN, server ID, logical time>**
    - **CSN = ∞ initially (while tentative)**
  - **primary propagates updated write IDs**
  - **once received, order is permanent (and total)**



Log Truncation

- **When can it be done?**