Consistency and Replication

• Today:
  
  – Consistency models
    • Data-centric consistency models
    • Client-centric consistency models

Why replicate?

• Data replication versus compute replication

• Data replication: common technique in distributed systems

• Reliability
  – If one replica is unavailable or crashes, use another
  – Protect against corrupted data

• Performance
  – Scale with size of the distributed system (replicated web servers)
  – Scale in geographically distributed systems (web proxies)
Replication Issues

• When to replicate?
• How many replicas to create?
• Where should the replicas located?

• Will return to these issues later (WWW discussion)
• Today: how to maintain consistency?
• Key issue: need to maintain consistency of replicated data
  – If one copy is modified, others become inconsistent

Object Replication

• Approach 1: application is responsible for replication
  – Application needs to handle consistency issues

• Approach 2: system (middleware) handles replication
  – Consistency issues are handled by the middleware
  – Simplifies application development but makes object-specific solutions harder
Replication and Scaling

• Replication and caching used for system scalability
• Multiple copies:
  – Improves performance by reducing access latency
  – But higher network overheads of maintaining consistency
  – Example: object is replicated $N$ times
    • Read frequency $R$, write frequency $W$
    • If $R << W$, high consistency overhead and wasted messages
    • Consistency maintenance is itself an issue
      – What semantics to provide?
      – Tight consistency requires globally synchronized clocks!
• Solution: loosen consistency requirements
  – Variety of consistency semantics possible

Data-Centric Consistency Models

• Consistency model (aka *consistency semantics*)
  – Contract between processes and the data store
    • If processes obey certain rules, data store will work correctly
    – All models attempt to return the results of the last write for a read operation
      • Differ in how “last” write is determined/defined
Strict Consistency

• Any read always returns the result of the most recent write
  – Implicitly assumes the presence of a global clock
  – A write is immediately visible to all processes
    • Difficult to achieve in real systems (network delays can be variable)

Sequential Consistency

• Sequential consistency: weaker than strict consistency
  – Assumes all operations are executed in some sequential order and each process issues operations in program order
    • Any valid interleaving is allowed
    • All agree on the same interleaving
    • Each process preserves its program order
    • Nothing is said about “most recent write”
Linearizability

- Assumes sequential consistency and
  - If TS(x) < TS(y) then OP(x) should precede OP(y) in the sequence
  - Stronger than sequential consistency
  - Difference between linearizability and serializability?
    - Granularity: reads/writes versus transactions

- Example:

<table>
<thead>
<tr>
<th>Process P1</th>
<th>Process P2</th>
<th>Process P3</th>
</tr>
</thead>
<tbody>
<tr>
<td>x = 1;</td>
<td>y = 1;</td>
<td>z = 1;</td>
</tr>
<tr>
<td>print (y, z);</td>
<td>print (x, z);</td>
<td>print (x, y);</td>
</tr>
</tbody>
</table>

Linearizability Example

- Four valid execution sequences for the processes of the previous slide. The vertical axis is time.

- (a) x = 1; print ((y, z)); y = 1; print (x, z); z = 1; print (x, y); Prints: 001011 Signature: 001011
- (b) x = 1; y = 1; print (x, z); print (y, z); z = 1; print (x, y); Prints: 101011 Signature: 101011
- (c) y = 1; z = 1; print (x, y); print (x, z); x = 1; print (y, z); Prints: 010111 Signature: 110101
- (d) y = 1; x = 1; z = 1; print (x, z); print (y, z); print (x, y); Prints: 111111 Signature: 111111
Causal consistency

• Causally related writes must be seen by all processes in the same order.
  – Concurrent writes may be seen in different orders on different machines

<table>
<thead>
<tr>
<th>P1: W(x)a</th>
<th>P2: R(x)a W(x)b</th>
<th>P3: R(x)b R(x)a</th>
<th>P4: R(x)a R(x)b</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Not permitted

<table>
<thead>
<tr>
<th>P1: W(x)a</th>
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<th>P3: R(x)b R(x)a</th>
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</tr>
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<tbody>
<tr>
<td>(b)</td>
<td></td>
<td></td>
<td></td>
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Permitted

Other models

• FIFO consistency: writes from a process are seen by others in the same order. Writes from different processes may be seen in different order (even if causally related)
  – Relaxes causal consistency
  – Simple implementation: tag each write by (Proc ID, seq #)

• Even FIFO consistency may be too strong!
  – Requires all writes from a process be seen in order

• Assume use of critical sections for updates
  – Send final result of critical section everywhere
  – Do not worry about propagating intermediate results
    • Assume presence of synchronization primitives to define semantics
Other Models

Use granularity of critical sections, instead of individual read/write

- Weak consistency
  - Accesses to synchronization variables associated with a data store are sequentially consistent
  - No operation on a synchronization variable is allowed to be performed until all previous writes have been completed everywhere
  - No read or write operation on data items are allowed to be performed until all previous operations to synchronization variables have been performed.

- Entry and release consistency
  - Assume shared data are made consistent at entry or exit points of critical sections

Summary of Data-centric Consistency Models

<table>
<thead>
<tr>
<th>Consistency</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Strict</strong></td>
<td>Absolute time ordering of all shared accesses matters.</td>
</tr>
<tr>
<td><strong>Linearizability</strong></td>
<td>All processes must see all shared accesses in the same order. Accesses are furthermore ordered according to a (nonunique) global timestamp</td>
</tr>
<tr>
<td><strong>Sequential</strong></td>
<td>All processes see all shared accesses in the same order. Accesses are not ordered in time</td>
</tr>
<tr>
<td><strong>Causal</strong></td>
<td>All processes see causally-related shared accesses in the same order.</td>
</tr>
<tr>
<td><strong>FIFO</strong></td>
<td>All processes see writes from each other in the order they were used. Writes from different processes may not always be seen in that order</td>
</tr>
</tbody>
</table>

(a)

<table>
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</thead>
<tbody>
<tr>
<td><strong>Weak</strong></td>
<td>Shared data can be counted on to be consistent only after a synchronization is done</td>
</tr>
<tr>
<td><strong>Release</strong></td>
<td>Shared data are made consistent when a critical region is exited</td>
</tr>
<tr>
<td><strong>Entry</strong></td>
<td>Shared data pertaining to a critical region are made consistent when a critical region is entered.</td>
</tr>
</tbody>
</table>

(b)
Client-centric Consistency Models

- Assume read operations by a single process $P$ at two different local copies of the same data store
  - Four different consistency semantics
- **Monotonic reads**
  - Once read, subsequent reads on that data items return same or more recent values
- **Monotonic writes**
  - A write must be propagated to all replicas before a successive write by the same process
  - Resembles FIFO consistency (writes from same process are processed in same order)
- **Read your writes**: read(x) always returns write(x) by that process
- ** Writes follow reads**: write(x) following read(x) will take place on same or more recent version of x

Eventual Consistency

- Many systems: one or few processes perform updates
  - How frequently should these updates be made available to other read-only processes?
- Examples:
  - DNS: single naming authority per domain
  - Only naming authority allowed updates (no write-write conflicts)
  - How should read-write conflicts (consistency) be addressed?
  - NIS: user information database in Unix systems
    - Only sys-admins update database, users only read data
    - Only user updates are changes to password
Eventual Consistency

- Assume a replicated database with few updaters and many readers
- Eventual consistency: in absence of updates, all replicas converge towards identical copies
  - Only requirement: an update should eventually propagate to all replicas
  - Cheap to implement: no or infrequent write-write conflicts
  - Things work fine so long as user accesses same replica
  - What if they don’t:

Epidemic Protocols

- Used in Bayou system from Xerox PARC
- Bayou: weakly connected replicas
  - Useful in mobile computing (mobile laptops)
  - Useful in wide area distributed databases (weak connectivity)
- Based on theory of epidemics (*spreading infectious diseases*)
  - Upon an update, try to “infect” other replicas as quickly as possible
  - Pair-wise exchange of updates (*like pair-wise spreading of a disease*)
  - Terminology:
    - Infective store: store with an update it is willing to spread
    - Susceptible store: store that is not yet updated
- Many algorithms possible to spread updates
Spreading an Epidemic

• Anti-entropy
  – Server P picks a server Q at random and exchanges updates
  – Three possibilities: only push, only pull, both push and pull
  – Claim: A pure push-based approach does not help spread updates quickly (Why?)
    • Pull or initial push with pull work better
• Rumor mongering (aka gossiping)
  – Upon receiving an update, P tries to push to Q
  – If Q already received the update, stop spreading with prob 1/k
  – Analogous to “hot” gossip items => stop spreading if “cold”
  – Does not guarantee that all replicas receive updates
    • Chances of staying susceptible: \( s = e^{-(k+1)(1-s)} \)

Removing Data

• Deletion of data items is hard in epidemic protocols
• Example: server deletes data item \( x \)
  – No state information is preserved
    • Can’t distinguish between a deleted copy and no copy!
• Solution: death certificates
  – Treat deletes as updates and spread a death certificate
    • Mark copy as deleted but don’t delete
    • Need an eventual clean up
      – Clean up dormant death certificates