Consistency and Replication

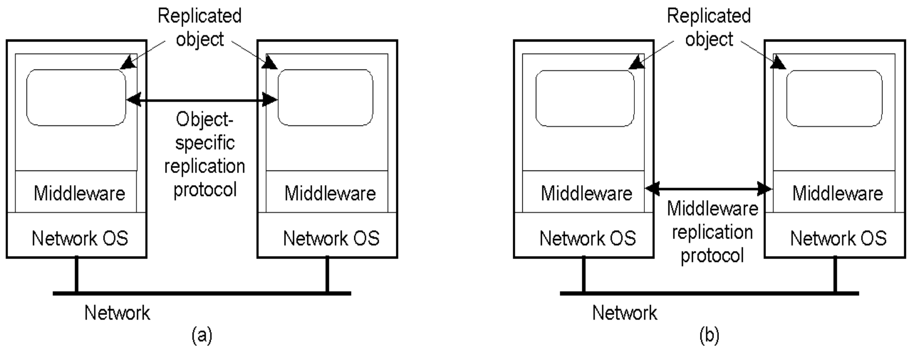
- Today:
  - Introduction
  - Consistency models
    - Data-centric consistency models
    - Client-centric consistency models
  - Thoughts for the mid-term

Why replicate?

- 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)

- Key issue: need to maintain *consistency* of replicated data
  - If one copy is modified, others become inconsistent

Object Replication

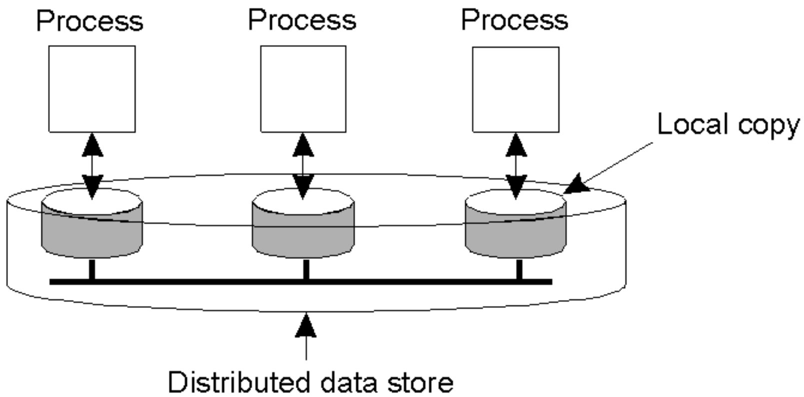


- Approach 1: application is responsible for replication
  - Application needs to handle consistency issues
- Approach 2: system (middleware) handles replication
  - Consistency issues are handled by the middleware
  - Simplifies application development but makes object-specific solutions harder

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 $R \ll W$, 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”

P1:	W(x)a				
P2:		W(x)b			
P3:			R(x)b		R(x)a
P4:				R(x)b	R(x)a

(a)

P1:	W(x)a				
P2:		W(x)b			
P3:			R(x)b		R(x)a
P4:				R(x)a	R(x)b

(b)

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 serializbility?
    - Granularity: reads/writes versus transactions
- Example:

Process P1	**Process P2**	**Process P3**
x = 1; print (y, z);	y = 1; print (x, z);	z = 1; print (x, y);

Linearizability Example

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

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

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

P1: W(x)a				
P2:	R(x)a	W(x)b		
P3:			R(x)b	R(x)a
P4:			R(x)a	R(x)b

(a)

Not permitted

P1: W(x)a			
P2:	W(x)b		
P3:		R(x)b	R(x)a
P4:		R(x)a	R(x)b

(b)

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

- 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

Consistency	Description
Strict	Absolute time ordering of all shared accesses matters.
Linearizability	All processes must see all shared accesses in the same order. Accesses are furthermore ordered according to a (nonunique) global timestamp
Sequential	All processes see all shared accesses in the same order. Accesses are not ordered in time
Causal	All processes see causally-related shared accesses in the same order.
FIFO	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

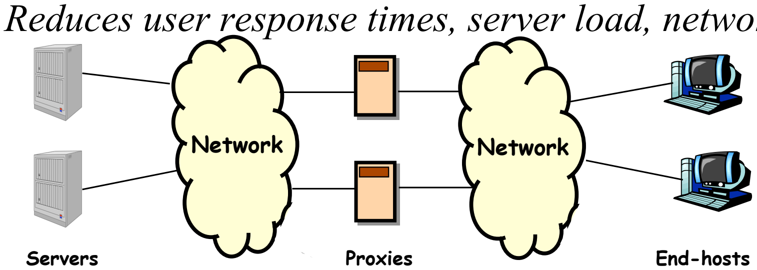
(a)

Consistency	Description
Weak	Shared data can be counted on to be consistent only after a synchronization is done
Release	Shared data are made consistent when a critical region is exited
Entry	Shared data pertaining to a critical region are made consistent when a critical region is entered.

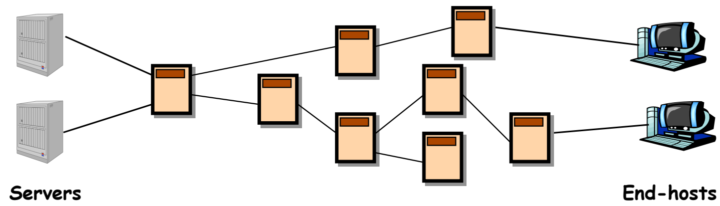
(b)

Caching in WWW: Case Study

- Dramatic growth in world wide web traffic
- Web accesses are non-uniform in nature
  - Create hot-spots of server and network load, increase latency
- *Solution:* employ web proxy caches
  - *Reduces user response times, server load, network load*



Content Distribution Network



- Content distribution network (CDN)
  - Collection of proxies that act as intermediaries between servers and clients
  - Service a client request from "closest" proxy with the object
  - Similar benefits as single proxy environments, but larger scale
  - Example: Akamai CDN - 13,000+ proxies
- Caching in CDN => must maintain cache consistency

Consistency Mechanisms

- Time-to-live (TTL) values
  - Expiration time of cached document
  - Proxy must refresh from server after expiration
    - *Poll:* Use if-modified-since (IMS) HTTP requests
  - Weaker guarantees: document can change before expiration
- Poll every time
  - Poll the server upon request for a cached object
  - Increases response time of requests
  - Provides stronger consistency guarantees

Consistency with Leases

- *Lease:* fixed duration contract between server and proxy
  - Server agrees to notify proxy of all updates to an object over duration *d*
  - "*d*" is the lease duration
  - Lease may be renewed upon expiry
- Properties:
  - Server needs to notify each proxy caching the object of an update
    - Excessive burden for popular objects
  - Leases requires a server to maintain state
    - Overhead can be excessive for large CDNs
  - Leases provide stronger consistency guarantees
  - Push-based approach, server-initiated consistency

Mid-term Exam Comments

- Closed book, closed notes, 90 min
- Lectures 1-14 included on the test
  - Focus on things taught in class (lectures, in-class discussions)
  - Start with lecture notes, read corresponding sections from text
  - Supplementary readings are not *directly* included on the test.
- Exam structure: few short answer questions, mix of subjective and "design" questions

- Good luck!