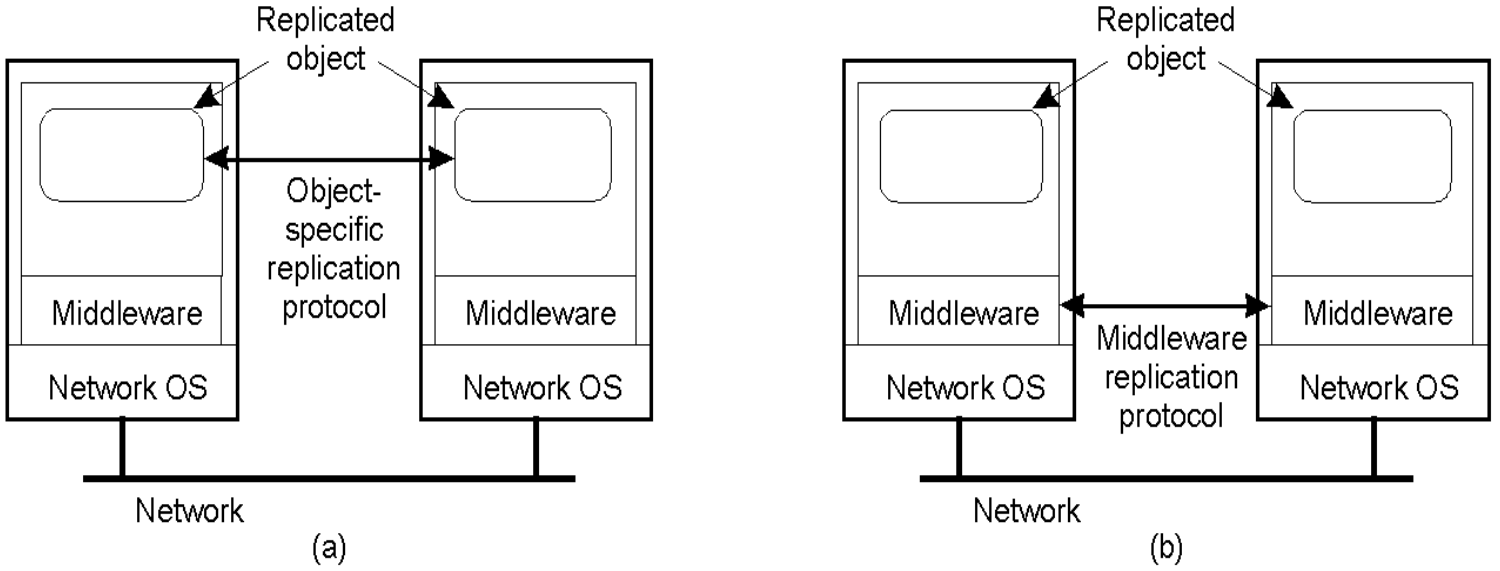
Consistency and Replication

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

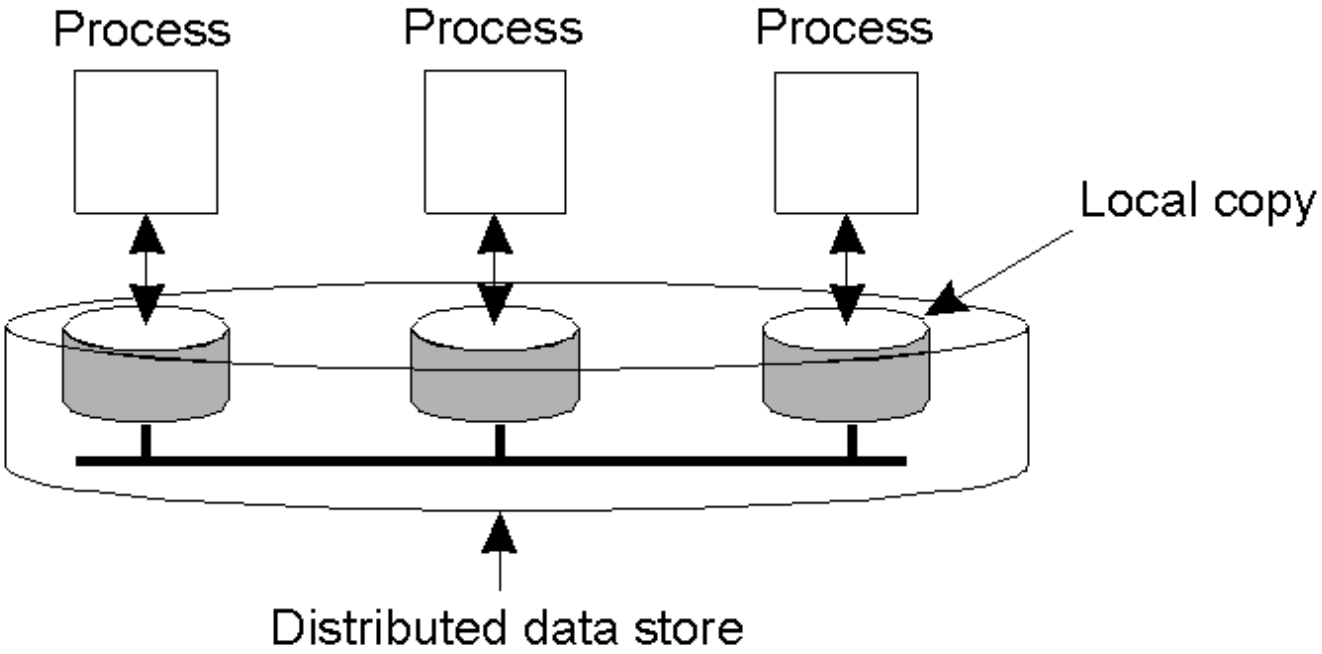


- Approach 1: application is responsible for replication
  - Application needs to handle consistency issues
- Approach 2: system (middleware) handles replication
  - Consistency issues are handled by the middleware
  - Simplifies application development but makes object-specific solutions harder

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<<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

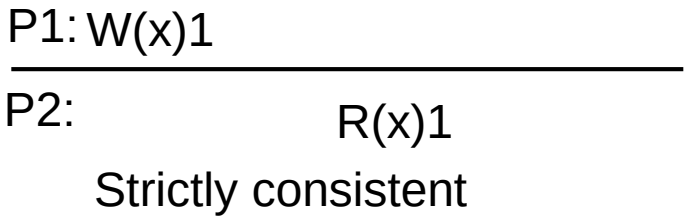
Data-Centric Consistency Models



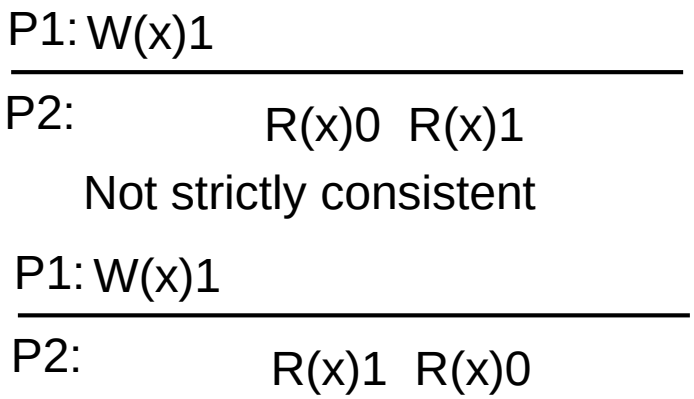
- Consistency model (aka *consistency semantics*)
  - Contract between processes and the data store
    - If processes obey certain rules, data store will work correctly
  - All models attempt to return the results of the last write for a read operation
    - Differ in how “last” write is determined/defined

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)



Strictly consistent

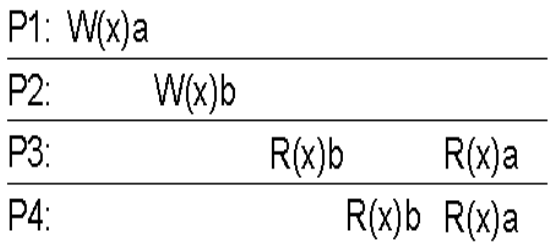


Not strictly consistent

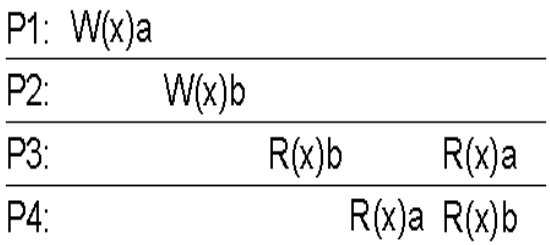
Not valid interleaving

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"



(a) Permitted



(b) Not permitted

All processes must see the same sequence of memory references

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

Linearizability vs. Serializbility

Linearizability is a guarantee about single operations on single objects. It provides a real-time (i.e., wall-clock) guarantee on the behavior of a set of single operations (often reads and writes) on a single object (e.g., distributed register or data item).

In plain English, under linearizability, writes should appear to be instantaneous. Imprecisely, once a write completes, all later reads (where "later" is defined by wall-clock start time) should return the value of that write or the value of a later write. Once a read returns a particular value, all later reads should return that value or the value of a later write.

Linearizability vs. Serializbility

Serializability is a guarantee about transactions, or groups of one or more operations over one or more objects. It guarantees that the execution of a set of transactions (usually containing read and write operations) over multiple items is equivalent to *some* serial execution (total ordering) of the transactions.

Linearizability Example

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

Linearizability Example

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

```
x = 1;
print ((y, z);
y = 1;
print (x, z);
z = 1;
print (x, y);
```

Prints: 001011

Signature: 001011

(a)

```
x = 1;
y = 1;
print (x,z);
print(y, z);
z = 1;
print (x, y);
```

Prints: 101011

Signature: 101011

(b)

```
y = 1;
z = 1;
print (x, y);
print (x, z);
x = 1;
print (y, z);
```

Prints: 010111

Signature: 110101

(c)

```
y = 1;
x = 1;
z = 1;
print (x, z);
print (y, z);
print (x, y);
```

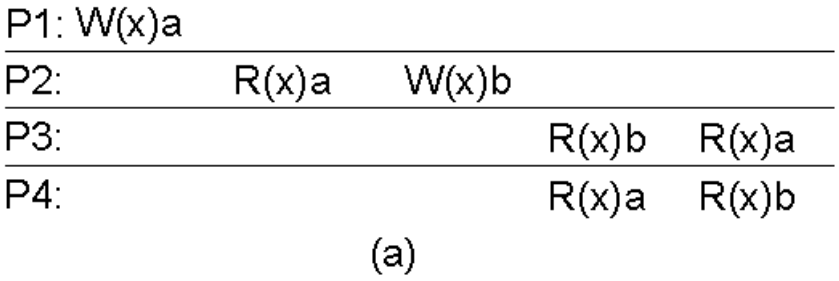
Prints: 111111

Signature: 111111

(d)

Causal consistency

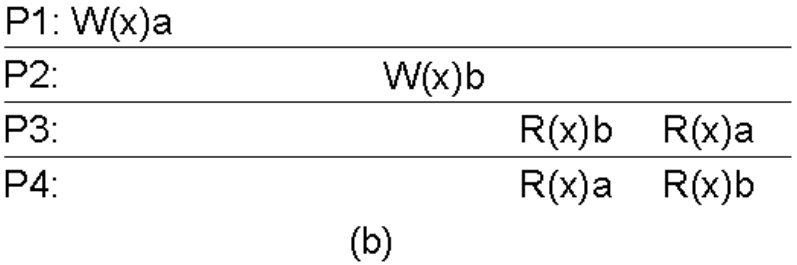
- Causally related writes must be seen by all processes in the same order.
  - Concurrent writes may be seen in different orders on different machines



(a)

Not permitted

W(x)a and W(x)b in causal relation



(b)

Permitted

W(x)a and W(x)b are concurrent

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) Not using synchronization operations

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.

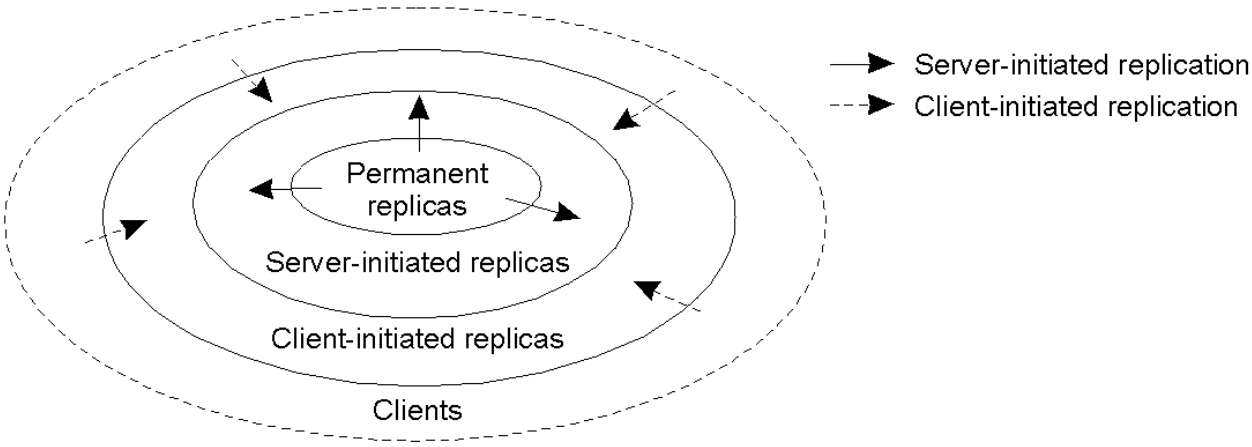
(b) Using synchronization operations

Implementation Issues

- Replica placement
- Use web caching as an illustrative example
- Distribution protocols
  - Invalidate versus updates
  - Push versus Pull
  - Cooperation between replicas

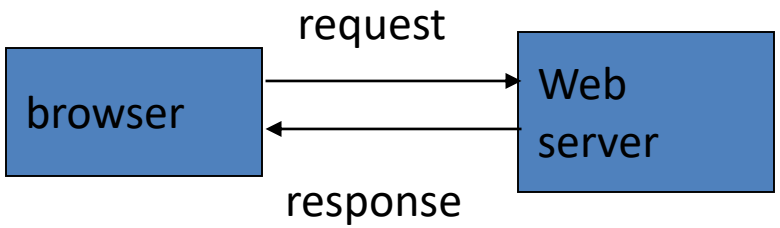
Replica Placement

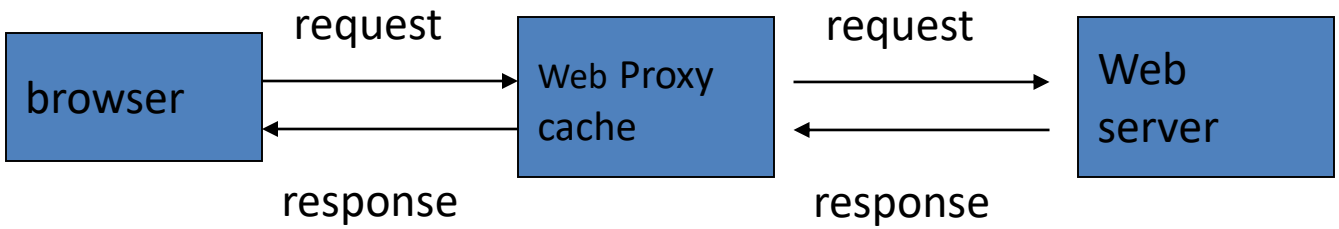
- Permanent replicas (mirroring)
- Server-initiated replicas (push caching)
- Client-initiated replicas (pull/client caching)



Web Caching

- Example of the web to illustrate caching and replication issues
  - Simpler model: clients are read-only, only server updates data



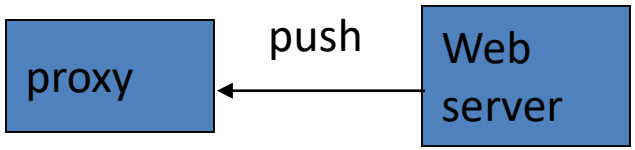


Consistency Issues

- Web pages tend to be updated over time
  - Some objects are static, others are dynamic
  - Different update frequencies (few minutes to few weeks)
- How can a proxy cache maintain consistency of cached data?
  - Send invalidate or update
  - Push versus pull

Push-based Approach

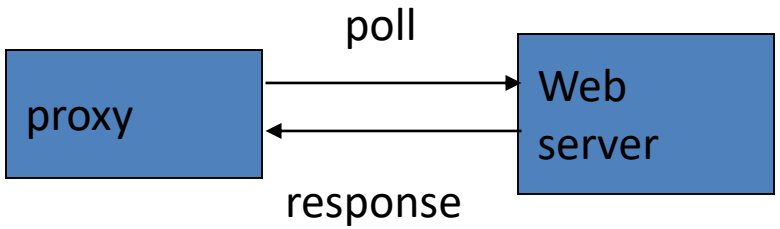
- Server tracks all proxies that have requested objects
- If a web page is modified, notify each proxy
- Notification types
  - Indicate object has changed [invalidate]
  - Send new version of object [update]
- How to decide between invalidate and updates?
  - Pros and cons?
  - One approach: send updates for more frequent objects, invalidate for rest



Push-based Approaches

- Advantages
  - Provide tight consistency [minimal stale data]
  - Proxies can be passive
- Disadvantages
  - Need to maintain state at the server
    - Recall that HTTP is stateless
    - Need mechanisms beyond HTTP
  - State may need to be maintained indefinitely
    - Not resilient to server crashes

Pull-based Approaches



- Proxy is entirely responsible for maintaining consistency
- Proxy periodically polls the server to see if object has changed
  - Use if-modified-since HTTP messages
- Key question: when should a proxy poll?
  - Server-assigned *Time-to-Live (TTL)* values
    - No guarantee if the object will change in the interim

Pull-based Approach: Intelligent Polling

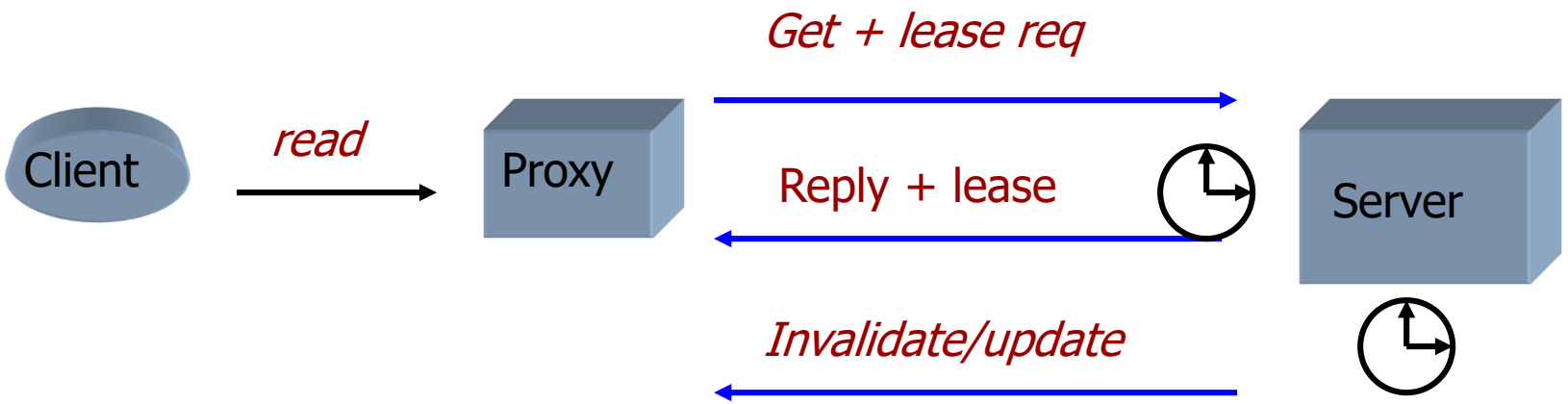
- Proxy can dynamically determine the refresh interval
  - Compute based on past observations
    - Start with a conservative refresh interval
    - Increase interval if object has not changed between two successive polls
    - Decrease interval if object is updated between two polls
    - Adaptive: No prior knowledge of object characteristics needed

Pull-based Approach

- Advantages
  - Implementation using HTTP (If-modified-Since)
  - Server remains stateless
  - Resilient to both server and proxy failures
- Disadvantages
  - Weaker consistency guarantees (objects can change between two polls and proxy will contain stale data until next poll)
    - Strong consistency only if poll before every HTTP response
  - More sophisticated proxies required
  - High message overhead

A Hybrid Approach: Leases

- Lease: duration of time for which server agrees to notify proxy of modification
- Issue lease on first request, send notification until expiry
  - Need to renew lease upon expiry
- Smooth tradeoff between state and messages exchanged
  - Zero duration => polling, Infinite leases => server-push
- Efficiency depends on the *lease duration*



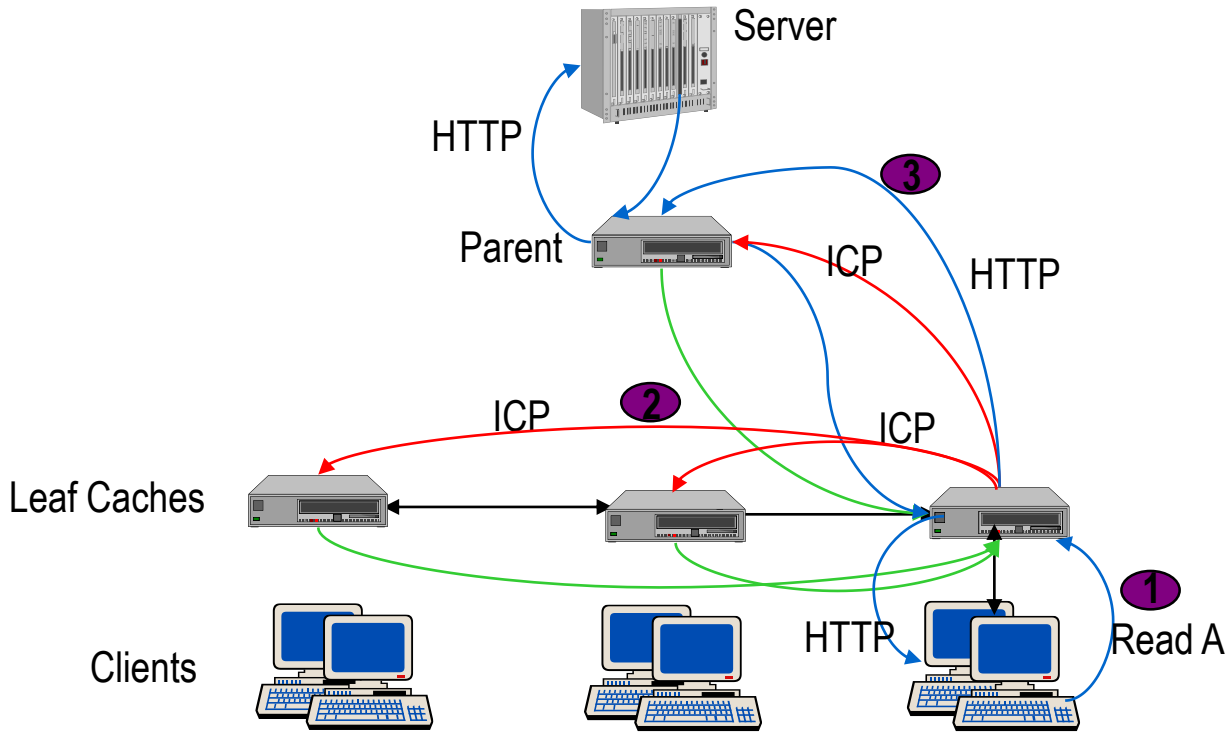
Policies for Leases Duration

- Age-based lease
  - Based on bi-modal nature of object lifetimes
  - Larger the expected lifetime longer the lease
- Renewal-frequency based
  - Based on skewed popularity
  - Proxy at which objects is popular gets longer lease
- Server load based
  - Based on adaptively controlling the state space
  - Shorter leases during heavy load

Cooperative Caching

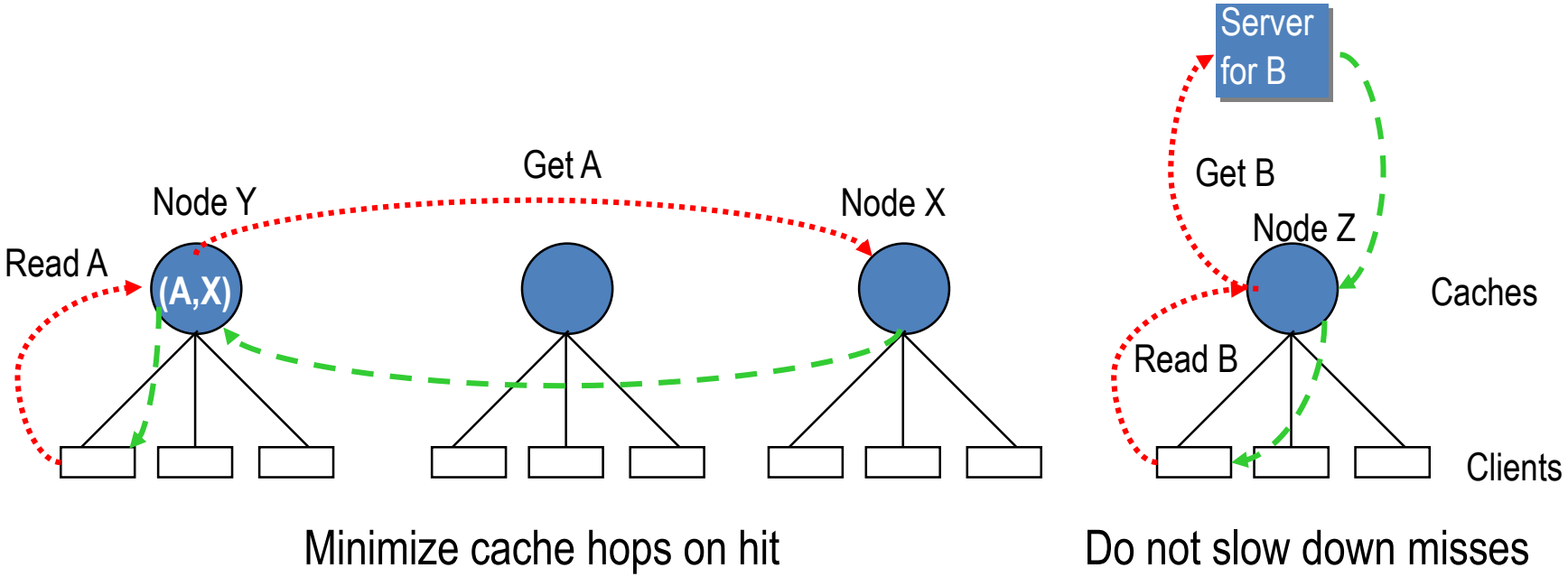
- Caching infrastructure can have multiple web proxies
  - Proxies can be arranged in a hierarchy or other structures
    - Overlay network of proxies: content distribution network
  - Proxies can cooperate with one another
    - Answer client requests
    - Propagate server notifications

Hierarchical Proxy Caching



Examples: Squid, Harvest

Locating and Accessing Data



Properties

- Lookup is local
- Hit at most 2 hops
- Miss at most 2 hops (1 extra on wrong hint)

CDN Issues

- Which proxy answers a client request?
  - Ideally the “closest” proxy
  - Akamai uses a DNS-based approach
- Propagating notifications
  - Can use multicast or application level multicast to reduce overheads (in push-based approaches)
- Active area of research
  - Numerous research papers available