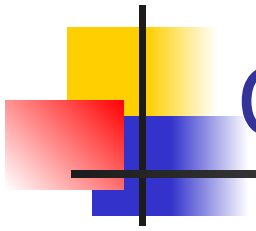
Replication & Consistency

Replication: Creating and using multiple copies of data (or services)

Why replicate?

- Improve system reliability
  - Prevent data loss : i.e. increase data durability
  - Increase data/service availability
    - Note: availability ≠ durability
  - Increase confidence: e.g. deal with byzantine failures
- Improve performance
  - Scaling throughput
  - Reduce access times



Context

Rather trivial

Stateless service replication

- e.g., Web server dealing with page layout (constructed somewhere else), services in application tier in a 3-tier architecture

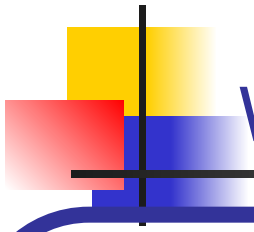
Data replication

- E.g., File system, web site mirrors, browser caches, DNS

Our focus for now

Control replication

- Model: replicated state machine;
- Stateful services (data and control), e.g., critical infrastructure service



What are the issues?

Issue 1. Dealing with data changes

- Consistency models
  - ***What is the semantic*** the system implements?
    [not all applications require 'strict' consistency
- Consistency protocols
  - ***How to implement*** the semantic agreed upon?
    [Tools: *(a)* Operation ordering (delay some operations);
    (b) Operation assignment to replicas]

Issue 2. Replica management

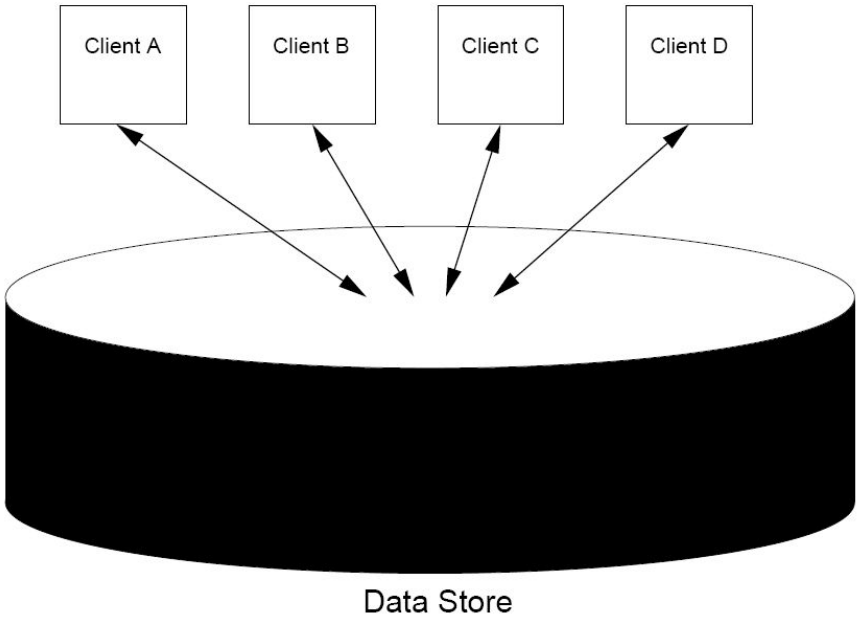
- How many replicas? Where to place them? When to get rid of them?

Issue 3. Request redirection/routing

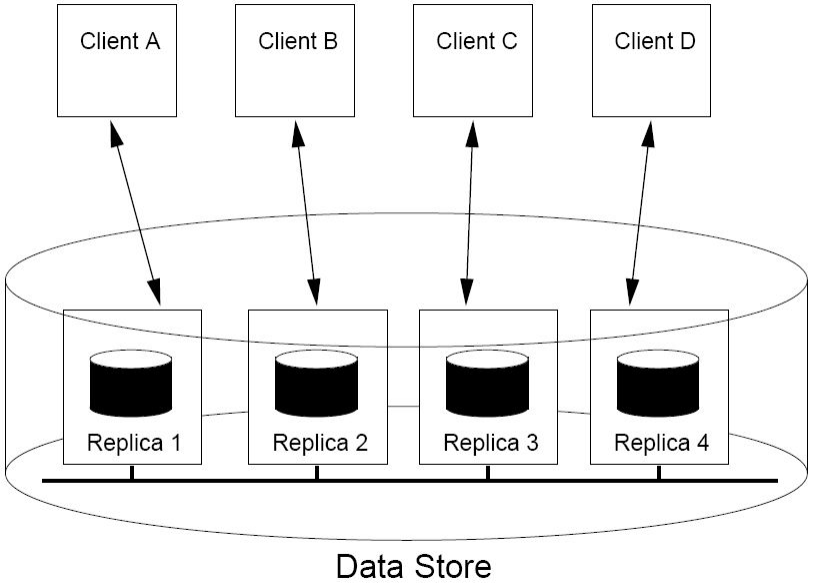
- Which replica should clients use?

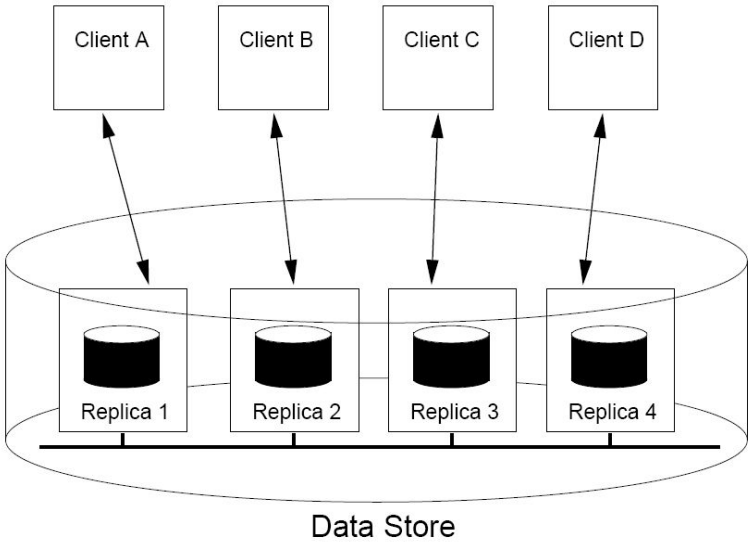
Client's view of the data-store

Ideally 'black box' – i.e., complete 'transparency' over how data is stored and managed



Replica management system view on data store: controls the allocated resources and aims to provide transparency





Consistency model:

Contract between: *(i)* the data store, and

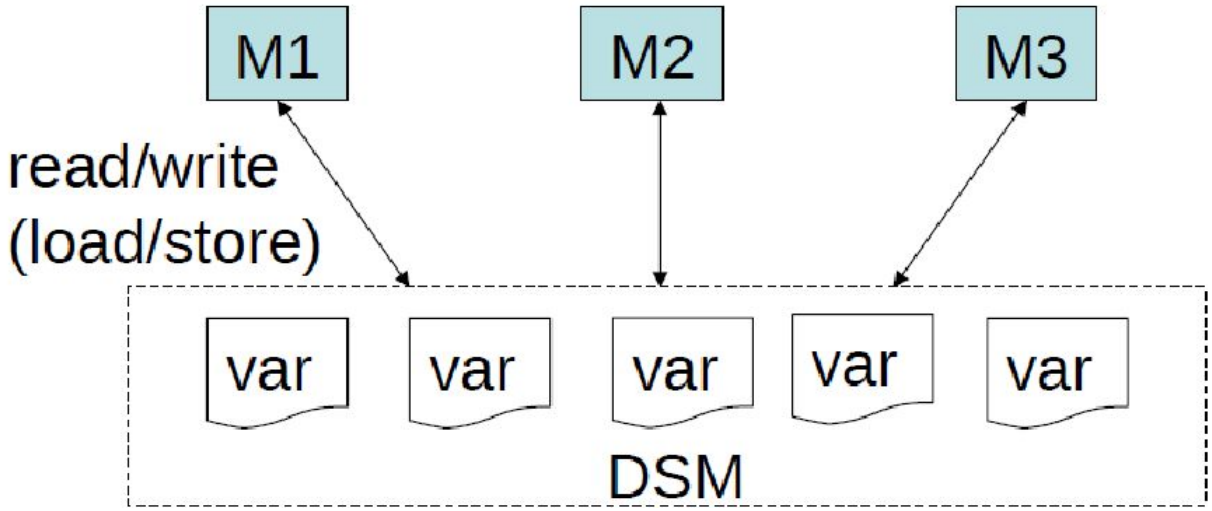
(ii) the clients:

specifies the acceptable result of reads and writes in the presence of concurrent operations, failures, etc.

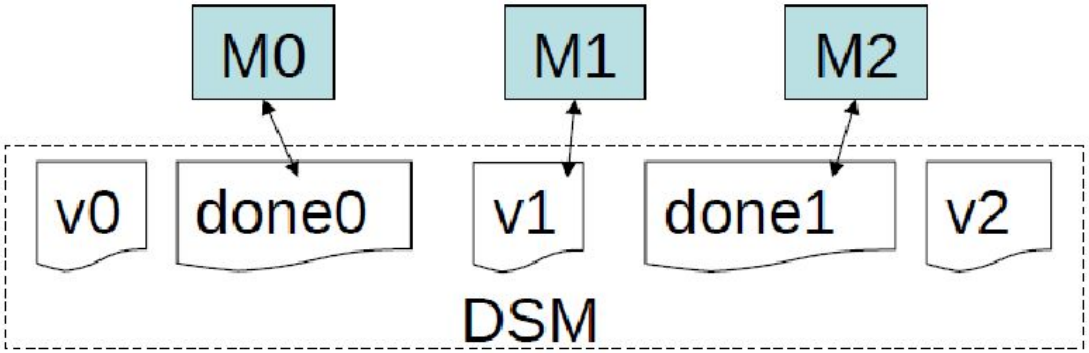
Why do I need one?

An example scenario: Distributed Shared Memory

- Two models for communication in distributed systems:
  - message passing
  - shared memory
- Shared memory is often thought more intuitive to write parallel programs than message passing
  - Each machine can access a common address space



An example scenario: Distributed Shared Memory



M0:

```
v0 = f0();
done0 = 1;
```

M1:

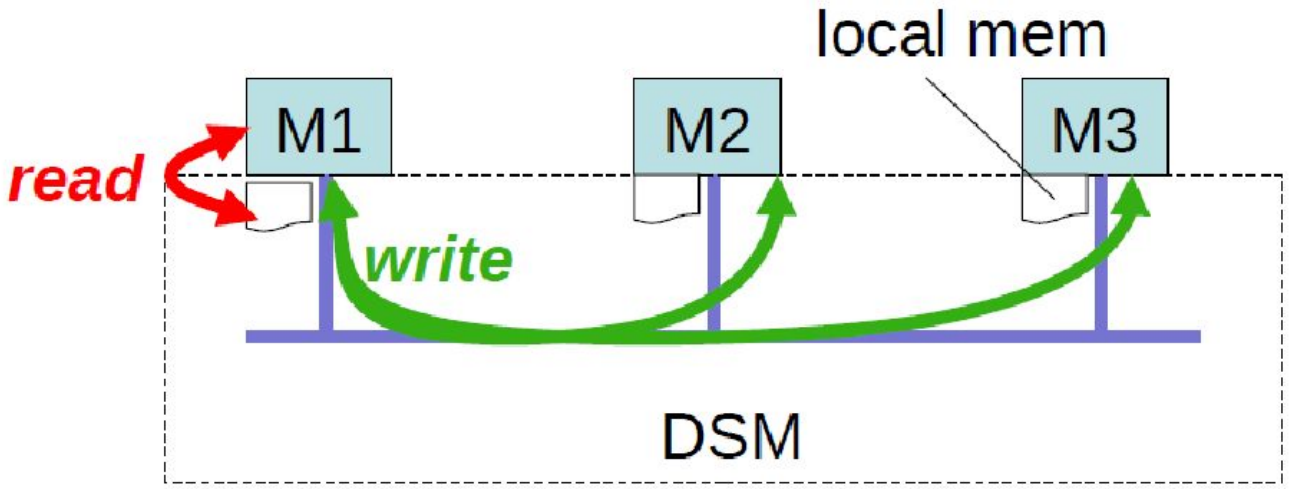
```
while (done0 == 0)
    ;
v1 = f1(v0);
done1 = 1;
```

M2:

```
while (done1 == 0)
    ;
v2 = f2(v0, v1);
```

- What's the intuitive intent?
  - M2 should execute f2() with results from M0 and M1
  - waiting for M1 implies waiting for M0

A naïve DSM implementation:

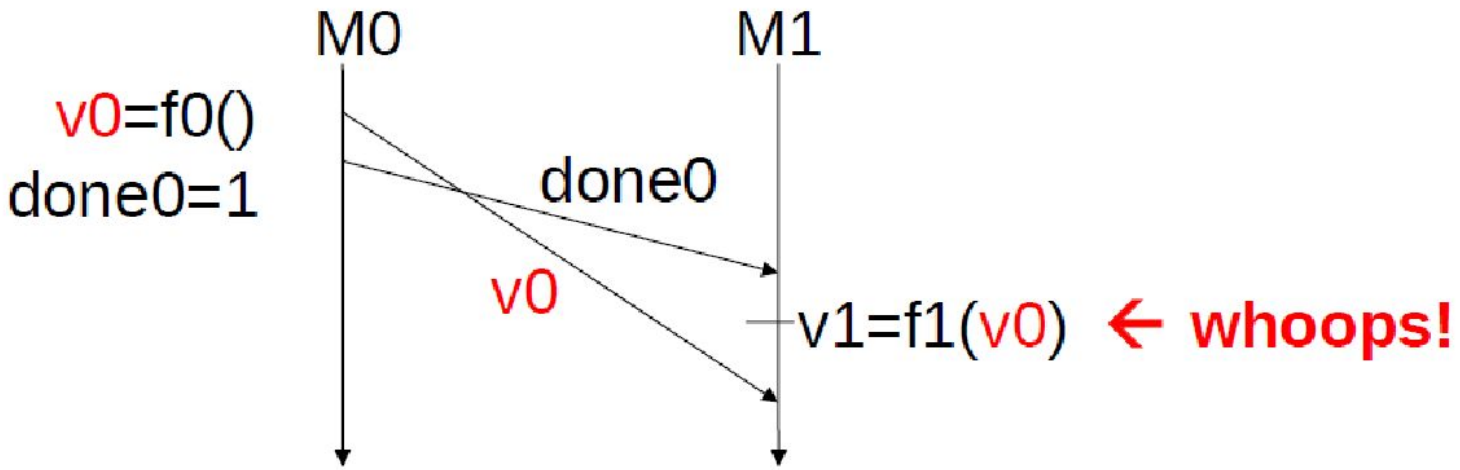


- Each machine has a local copy of all of memory
- Operations:
  - **Read**: from local memory
  - **Write**: send update msg to each host (but **don't wait**)
- Fast: never waits for communication

Question: Does this DSM work well for our application?

Problem 1 with the naïve implementation

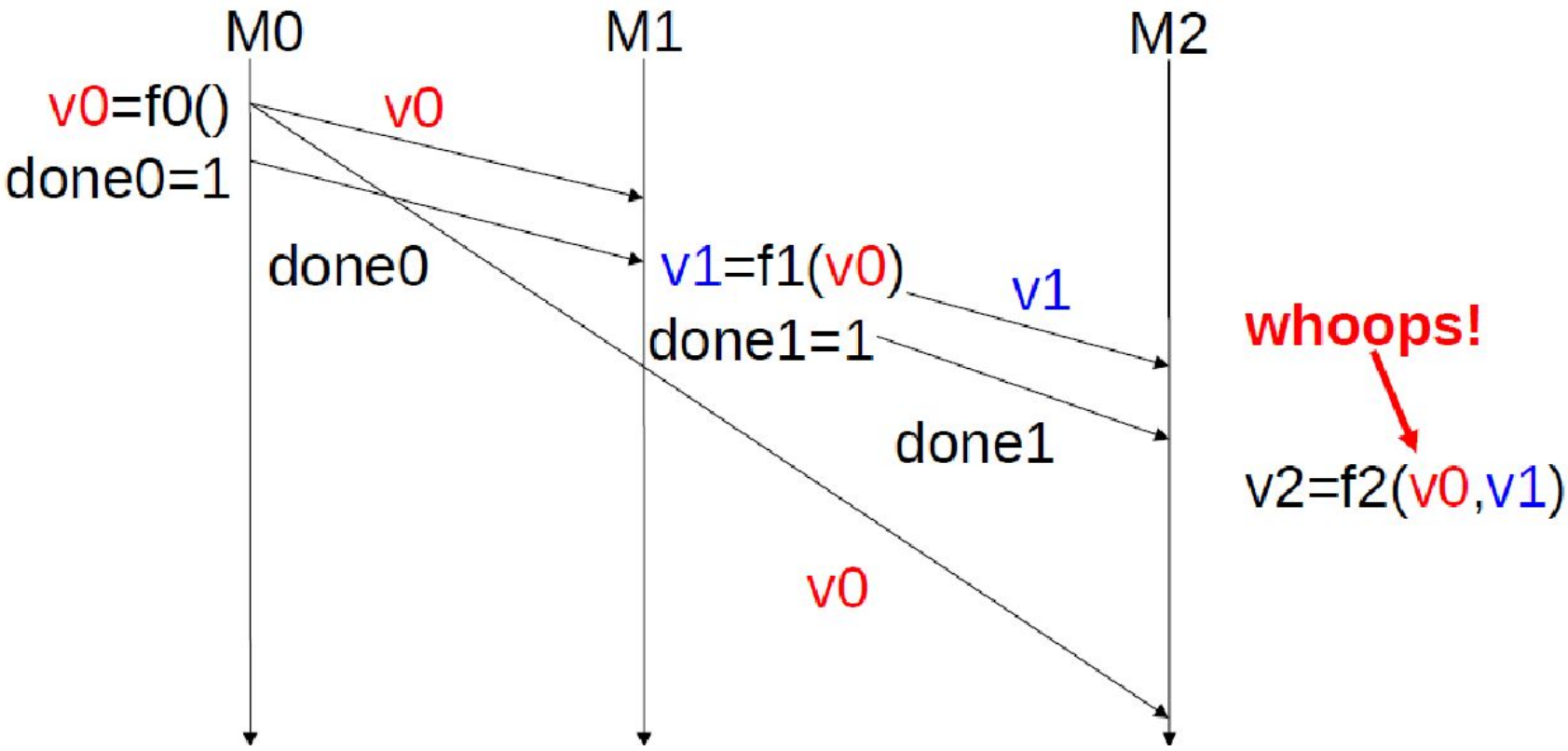
M0's v0=… and done0=… may be interchanged by network, leaving v0 unset but done0=1

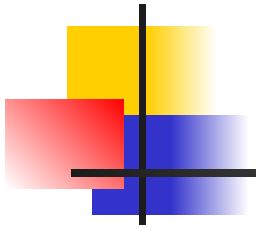


Problem 2 with the naïve implementation

M2 sees M1's writes before M0's writes

- I.e. M2 and M1 disagree on order of M0 and M1 writes



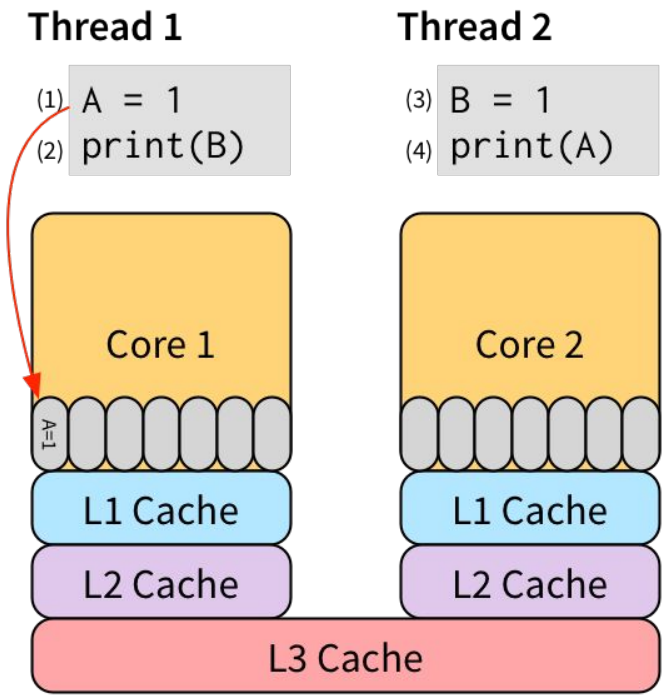


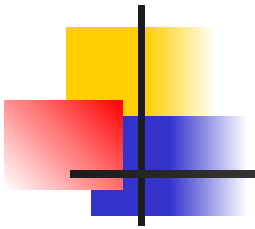
- Naïve DSM is fast but has unexpected behaviour

- Maybe DSM is not “correct”
- … or maybe I should have never expected the application to work in the first place

- the consistency model
  - The “contract” the DSM will obey and the application will rely on

- Do modern multi-processor architectures provide sequential consistency?





Roadmap

- **(1) Consistency models**:
  - contracts between the data store and the clients that specify the [acceptable] result of read/write operation stream in the presence of conflicting operations.
- (2) Consistency protocols
  - How does one implement a consistency model?
  - Tools
    - Operation ordering, delay some
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[high level] one way to provide consistency: ensure that **conflicting** operations are done in the same order everywhere

Conflicting operations: (from the world of transactions):

- **Read–write conflict**: a read operation and a write operation act concurrently
- **Write–write conflict**: two concurrent write operations

Problem: Guaranteeing global ordering on conflicting operations may be costly, reducing scalability

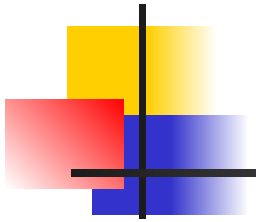
Solution: Weaken the consistency model (adjust consistency requirements) so that hopefully global synchronization can be avoided

Scalability
Performance

□TENSION□

Programmer friendliness

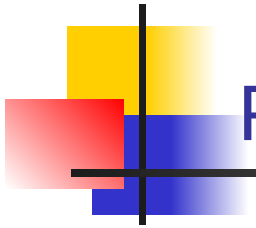
(often implies management overheads)



Consistency model: Contract between the data store and the clients: specifies the [acceptable] results of read and write operations in the presence of concurrent operations.

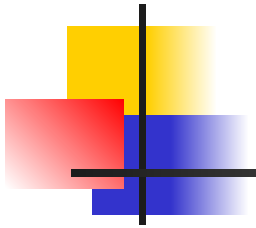
Choices that determine the design space:

- Contract covers all items or subsets (or even each item individually)?
- Contract covers all users or individual users?
- Contract covers sets of operations (e.g., transactions, for databases; or multiple ops on the same object, for files)



Recap

- Why are replication (and caching) needed?
  - For performance, scalability, fault tolerance (availability, durability), ability to operate while disconnected
- When do consistency concerns arise?
  - With replication and caching (our focus)
  - Concurrent (sets of) operations on shared data
    - e.g., databases, filesystems

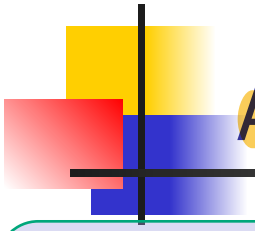


The space to cover is huge – so the 'consistency' as contract terminology appears in lots of contexts.

E.g., what type of consistency do distributed filesystems provide?

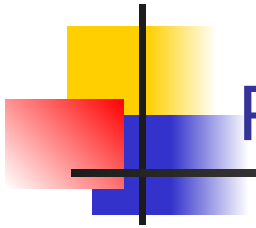
- session consistency (AFS)
  - aka. – open-to-close consistency
- 'close-to-open' consistency (NFS > v2.4.10)?

GFS: see discussion here



ACID properties

- Atomic: All or nothing
  - State shows either all the effects of a transaction, or none of them:
- Consistent (think of it as Correct): Guarantees basic properties
  - A transaction moves the database from a state where integrity holds, to another where integrity holds (eg: constraints)
- Isolated: Each transaction runs as if alone
  - Effect of concurrent transactions is the same as transactions running one after another (ie looks like batch mode)
- Durable: Cannot be undone
  - Once a transaction has committed, it can not be undone in spite of failures.



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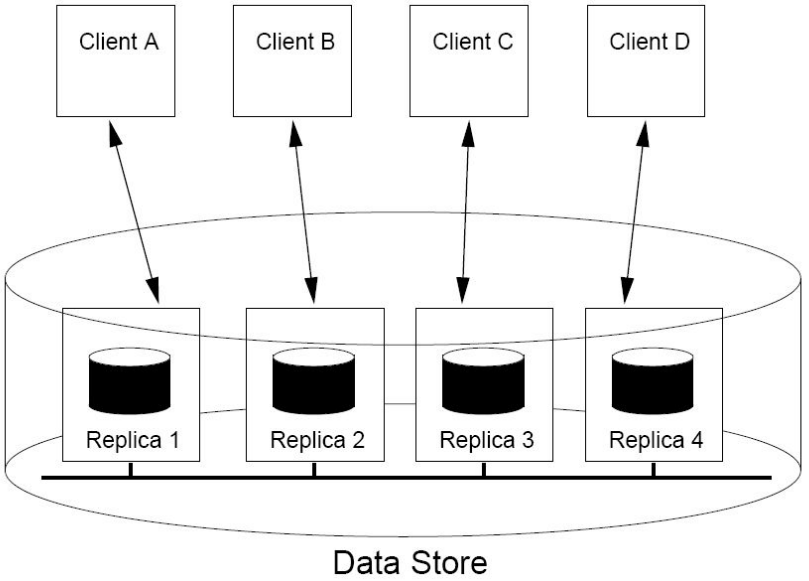
Consistency models (for replicated data)

- Data centric: Assume a global, data-store view (i.e., across all clients)
  - Models based on ordering of operations
    - Constraints on operation ordering at the data-store level
  - Eventual consistency
  - Continuous consistency
    - Limit the deviation between replicas
- Client centric
  - Assume client-independent views of the datastore
  - Constraints on operation ordering for each client independently



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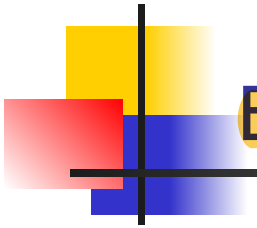
- Strict
- Strong (Linearizability)
- Sequential
- Causal
- Eventual

Weaker Consistency Models



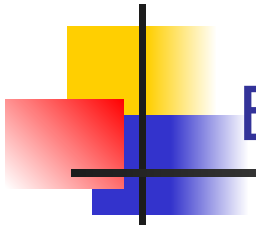
Eventual Consistency

Original idea: If single point to insert updates (no write-write conflicts), and no updates take place for a long enough period time, make sure all replicas will gradually (i.e., eventually) become consistent.

Where does this work well?

- Mostly read-only workloads, and
- No concurrent updates
  - e.g., updates have only one source, or all updates performed through a master replica
- Clients can operate with out-of-date data

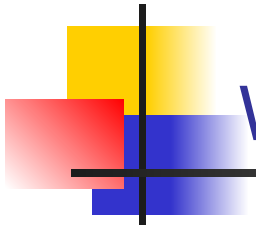
Two-word summary: best-effort



Eventual Consistency (II)

No constraint on operation ordering

- Allow stale reads, but ensure that reads will eventually reflect previously written values
  - Even if this takes very long …
- Don’t order concurrent writes as they are executed
  - which might create conflicts later: which write was first?
  - Used by Amazon’s Dynamo …
    - with a mechanism for read reconciliation based on vector clocks



Why / Why NOT Eventual consistency

- [+] Support disconnected operations or network partitions
  - [for some apps] Better to read a stale value than nothing
  - [for some apps] Better to save writes somewhere than nothing
- [+] Support for increased parallelism
  - Though that's not what people have typically used this for
- [-] Potentially anomalous application behavior – Stale reads and conflicting writes…

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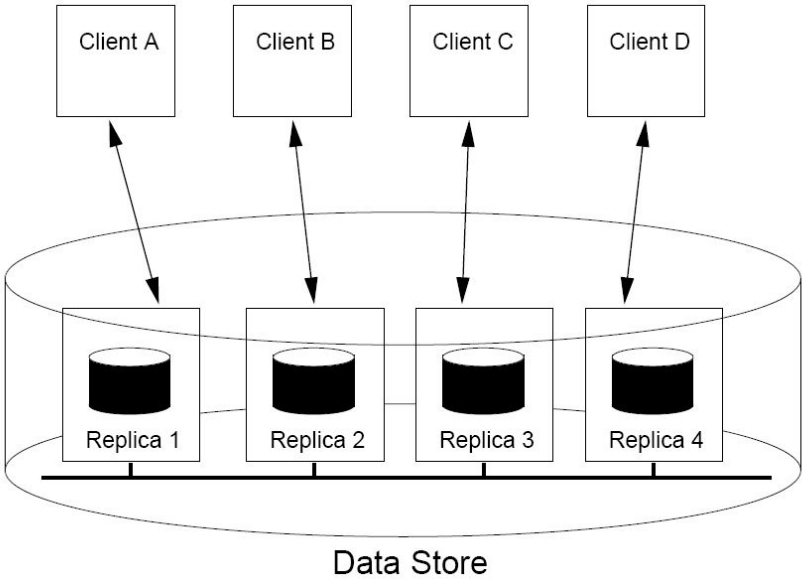

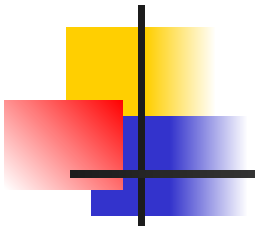

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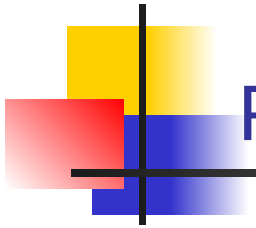

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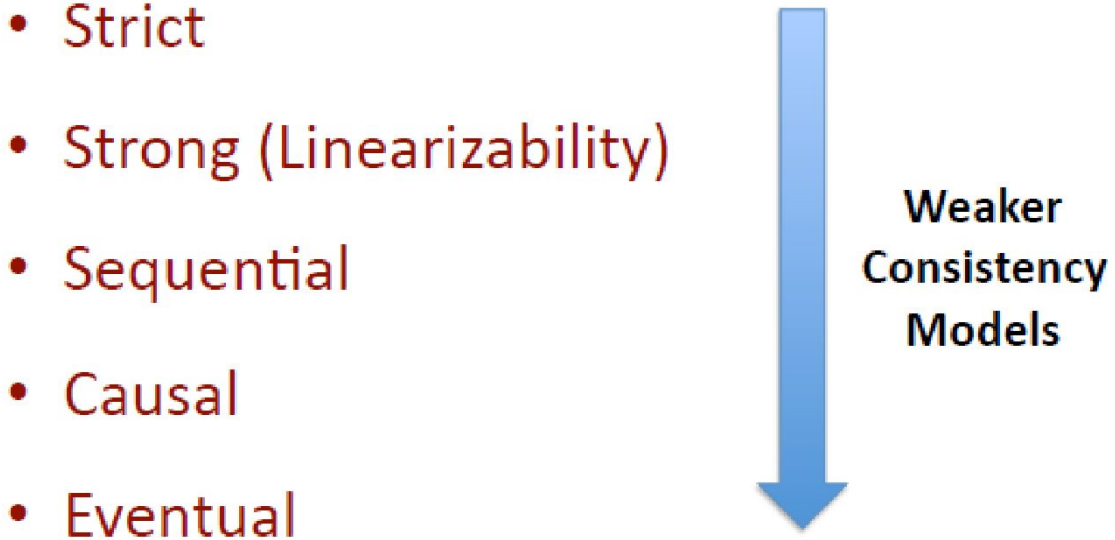
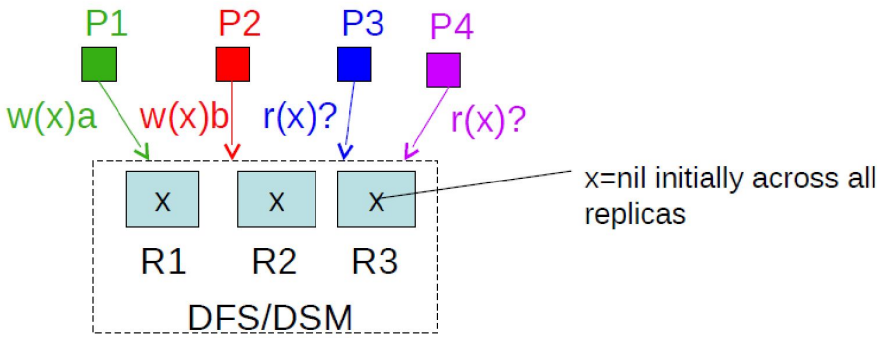
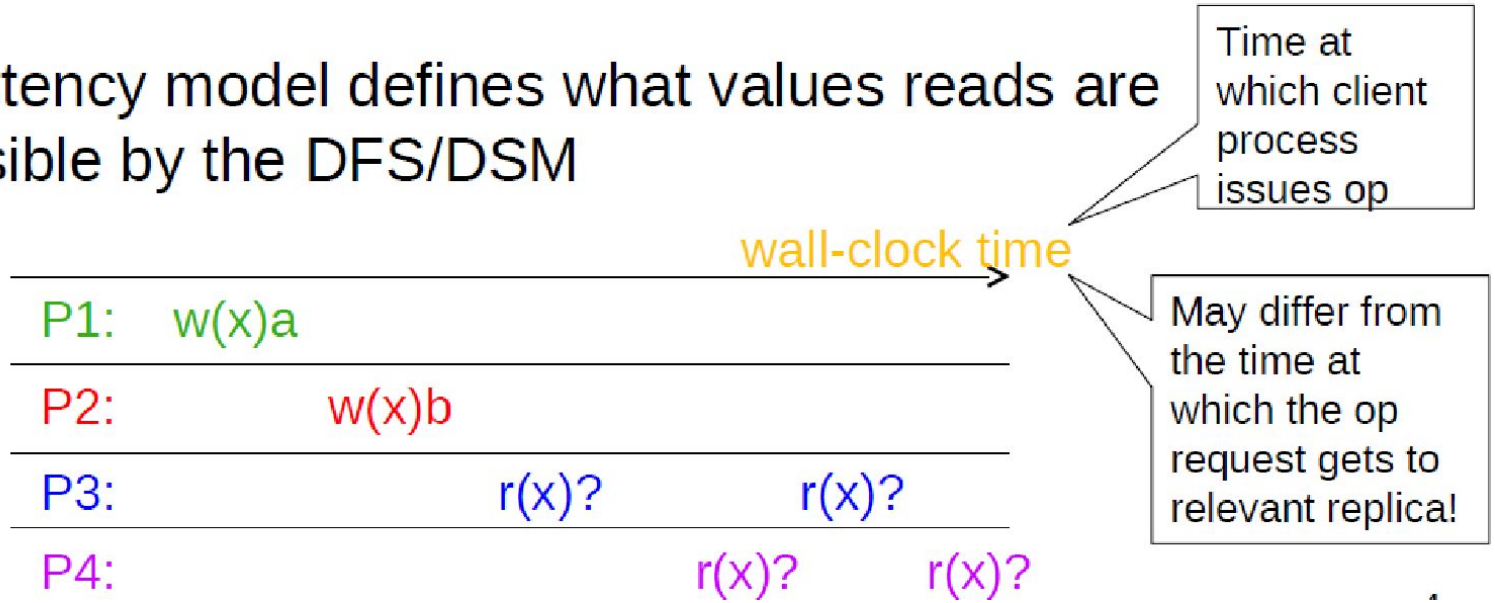


Notations:

- Read: $R_i(x)$ a -- client ***i*** reads ***a*** from location ***x***
- Write: $W_i(x)$ b -- client ***i*** writes ***b*** at location ***x***

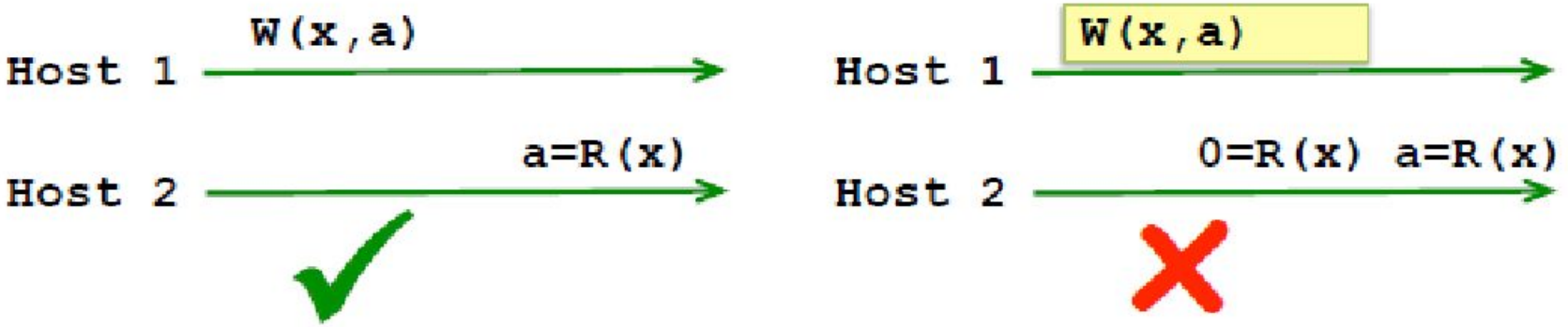


Consistency model defines what values reads are admissible by the DFS/DSM

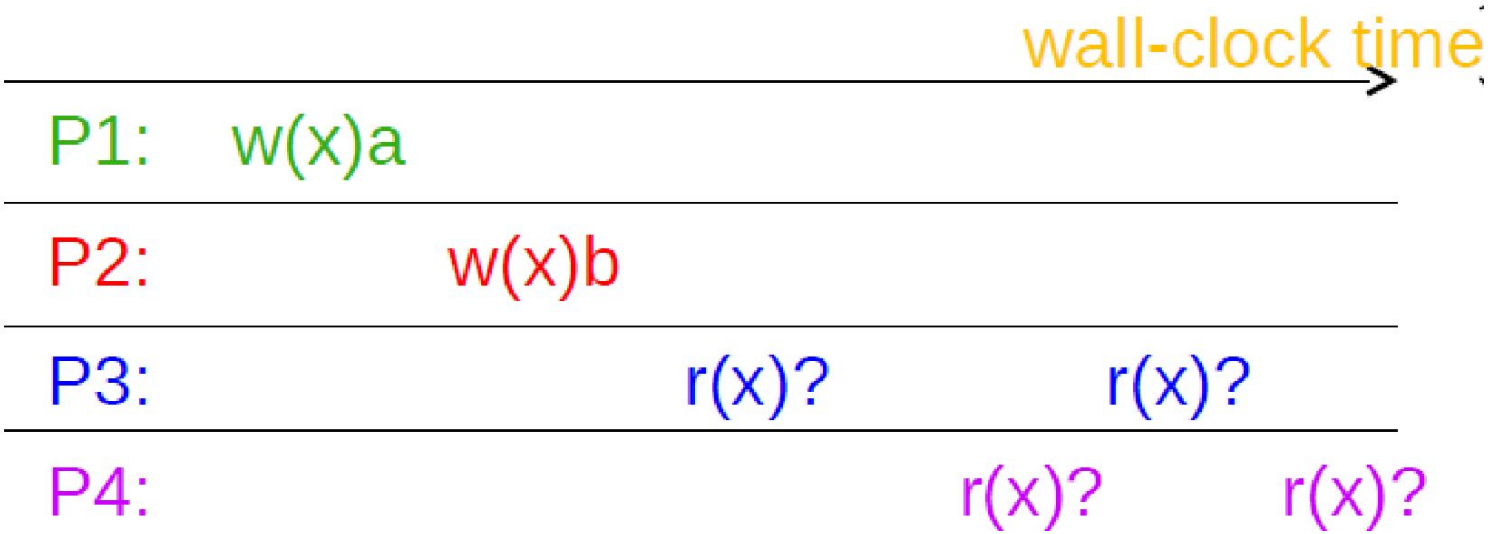


Strict Consistency

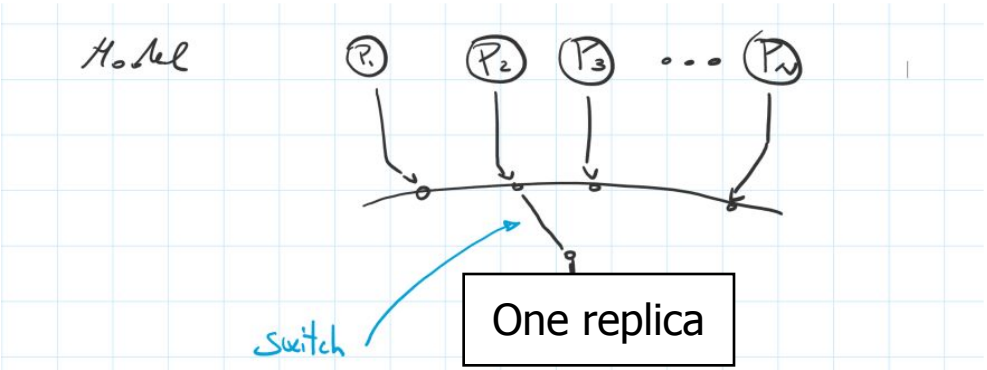
- Strongest consistency model we'll consider
  - Any read on a data item X returns value corresponding to result of the most recent write on X
- Need an absolute global time
  - "Most recent" needs to be unambiguous
  - Corresponds to when operation was issued
  - Impossible to implement in practice on multiprocessors



What do reads return with 'strict consistency'



Sequential Consistency



[the technical definition]The result o
- operations were executed in some
- the operations of each individual process appear in the order in which they are issued.

[an intuitive definition]: a system is sequentially consistent if a system with no replication and *synchronous* operations could have produced any of its traces.

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

(a)

Are there other outputs a sequential system could produce? Can you list all of them?

Give an example of a trace that is sequentially consistent but not strictly

strict vs. sequential consistency

- In sequential consistency, the [physical time] ordering of events does NOT matter.
  - (except for events in the same process)

- All that is required for sequential:
  - All processors see the same ordering of operations
    - (regardless of whether this is the order that the operations actually occurred)
      - except operations in the same process which must preserve their actual ordering.

Sequential Consistency (example)

3 processes (P1, P2, P3) and 3 (replicated) variables X, Y, Z initialized to 0

Process1:	Process 2	Process 3
X ☐ 1	Y ☐ 1	Z ☐ 1
Read (Y, Z)	Read (X, Z)	Read (X, Y)

Parallel

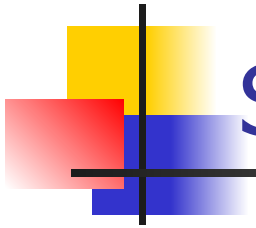
Sequential

Collect output: $print_{P1}$ (Y^{P1}, Z^{P1});
$print_{P2}$ (X^{P2}, Z^{P2});
$print_{P3}$ (X^{P3}, Y^{P3})

Is output: 11 11 11 possible if you assume sequential consistency?

What about: 00 00 00?

What about: 00 10 10?



Sequential vs. Eventual Consistency

One view:

- Sequential: pessimistic concurrency handling
  - Decide on update order as they are executed
- Eventual: optimistic concurrency handling
  - Let updates happen, worry about deciding their order later
  - May raise conflicts
    - Think about when you code offline for a while – you may need to resolve conflicts with other team members when you commit
    - Resolving conflicts is not that difficult with code, but it's really hard in general (e.g., think about resolving conflicts when you've updated an image)

Linearizability (linerarizable consistency)
(aka. **external** consistency)
(aka. **strong** consistency)

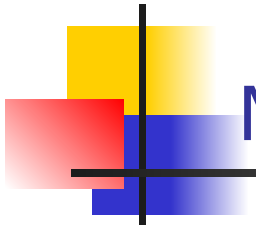
The result of any execution is the same **as if**

- (1) operations by all processes were executed in some sequential order, and
- (2) this order reflects
  - (2′) [sequential consistency] the order in each individual process
  - (2″) [linearizability] the order in which the operations execute in real time*

$$\text{strict} \subset \text{linearizable} \subset \text{sequential}$$

* assume operations are synchronous (then non-overlapping operations can be ordered), or assume some loosely synch clocks to get order

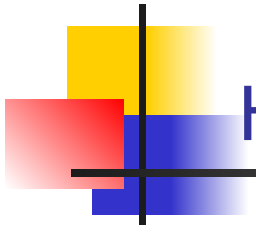
** operation effects are visible to subsequent, non-overlapping operations in other processes



More examples

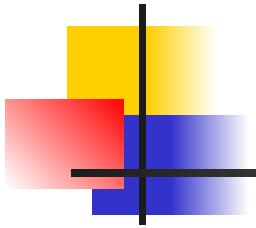
- Give an example of a trace that is generated by a system that is:
  - (a) NOT sequential
  - (b) sequential but NOT linearizable
  - (c) linearizabe but NOT strictly consistent

- If the DSM is sequentially consistent does the code in the example before (slide 10) 'work'?
  - Yes.



Harder Problem

- Give an example of a trace of a system that demonstrates that sequential consistency is not composable
  - i.e., when having data items (or data stores) that are each (independently) kept sequentially consistent, their composition as a set need not be so



Datastore X

P1: W(x)a R(x)a

P2: W(x)b

Let's assume that no matter how far further on gets in time the result is still R(x)a (same assumption below for R(y)b)

Traces observed on datastores X and Y <u>independently</u> do not violate sequential consistency

Datastore Y

P1: W(y)a

P2: W(y)b R(y)b

Combined datastore X and Y

P1: W(x)a W(y)a R(x)a

P2: W(y)b W(x)b R(y)b

<u>Combined</u> trace on X <u>and</u> Y violates sequential consistency for the combined store (see next slide) for argument

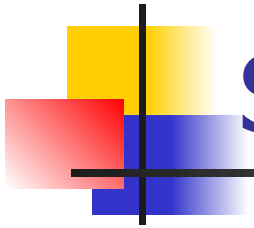
The original trace

Writes Have Propagated

P1:	W(x)a		W(y)a				R(x)a		
P2:		W(y)b	W(x)b				R(y)b		

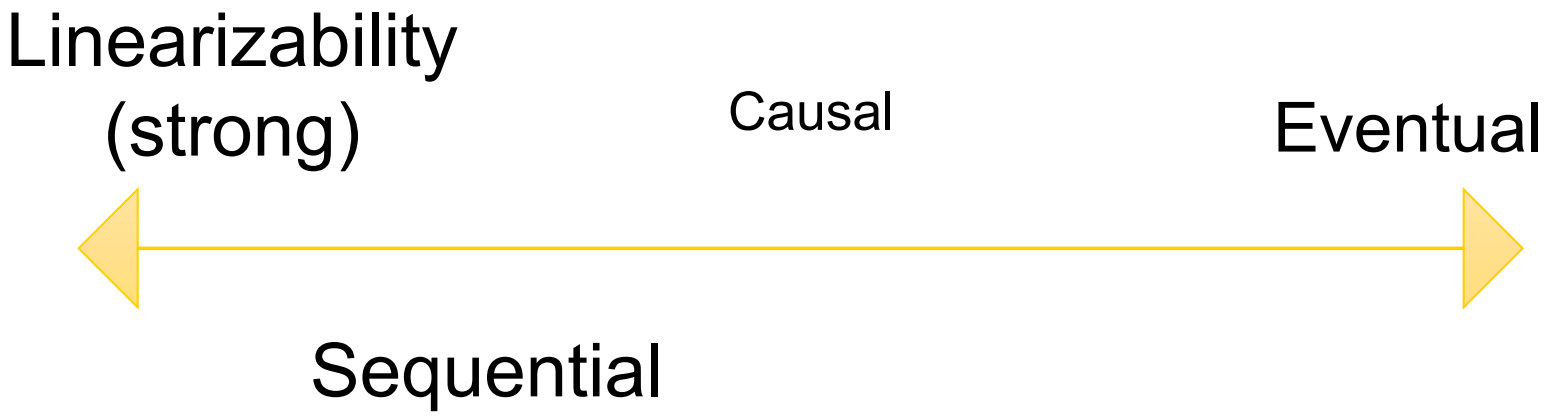
The possible ways of sequencing the operations

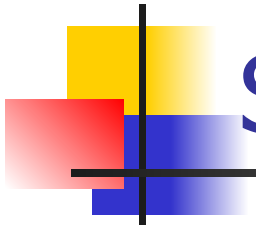
	W(x)a	W(y)a	W(y)b	W(x)b				x=b	y=b
	W(x)a	W(y)a	W(x)b	W(y)b	not possible - would violate ordering in P2				
	W(x)a	W(y)b	W(y)a	W(x)b				x=b	y=a
	W(x)a	W(y)b	W(x)b	W(y)a				x=b	y=a
	W(x)a	W(x)b	...	...	not possible - would violate ordering in P2				
	W(y)a	...	...	...	not possible - would violate ordering in P1				
	W(y)b	W(x)a	W(y)a	W(x)b				x=b	y=a
	W(y)b	W(x)a	W(x)b	W(y)a				x=b	y=a
	W(y)b	W(y)a	...	...	not possible				
	W(y)b	W(x)b	W(x)a	W(y)a				x=a	y=a
	W(y)b	W(x)b	W(y)a	W(x)a	not possible				
	W(x)b	...	...	...	not possible				



So far …

- Consistency models:
  - contract between the data store and the clients that specify the [acceptable/possible] results of read/write operations in a stream in the presence of conflicting operations.





So far …

- Consistency models:
  - contract between the data store and the clients that specify the [acceptable/possible] results of read/write operations in a stream in the presence of conflicting operations.

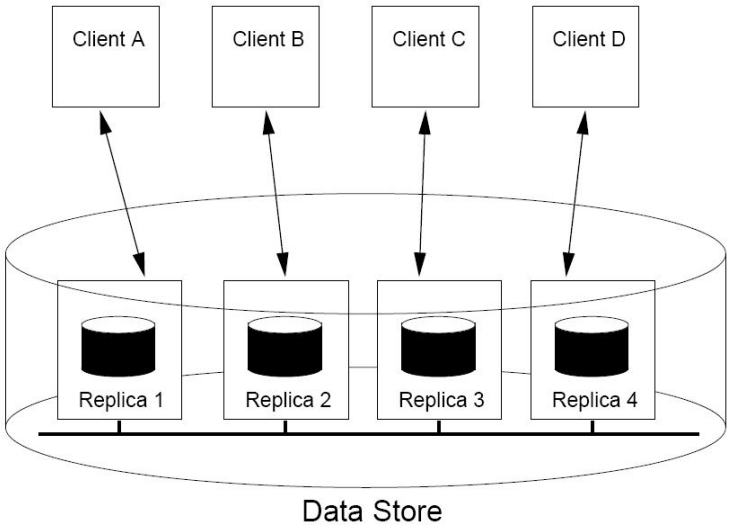
- Consistency protocols
  - How does one implement a consistency model?
  - Tools to exploit
    - Operation ordering, delay some
    - Operation assignment to replicas

Consistency protocols

Question: How does one design a protocol to implement the desired consistency model?

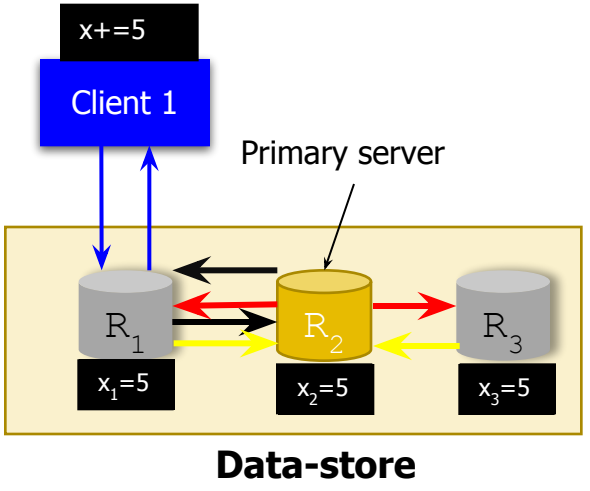
[focus] **Sequential consistency**

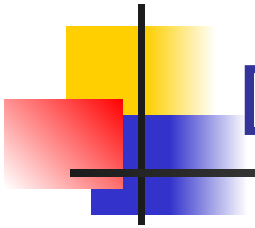
- Primary / backup
- Chain replication
- Quorum protocols



A protocol for primary-backup

- Overview (note that many variants are possible!):
  - All write operations are forwarded to the primary replica
    - Write operations are synchronous (i.e., blocking)
  - Read operations to any replica
- Approach for write ops
  - Client connects to some replica R_C
  - If the client issues write operation to R_C:
    - R_C forwards the request to the primary replica R_P
    - R_P updates its local value
    - R_P forwards the update to other replicas R_i
    - Other replicas R_i update, and send an ACK back to R_P
  - After R_P receives all ACKs, it informs R_C that the write operation is completed
  - R_C acknowledges the client, which in return completes the write operation





Discussion (I)

- Protocol provides a simple way to implement sequential consistency
  - Writes are performed in the same order on all replicas
  - Guarantees that clients on node A see the most recent write operations initiated at A
- However, latency is high
  - Writes block until all the replicas are updated
- Use: distributed databases and file systems that require fault-tolerance
  - Replicas are placed on the same LAN to reduce latency

Discussion (II)

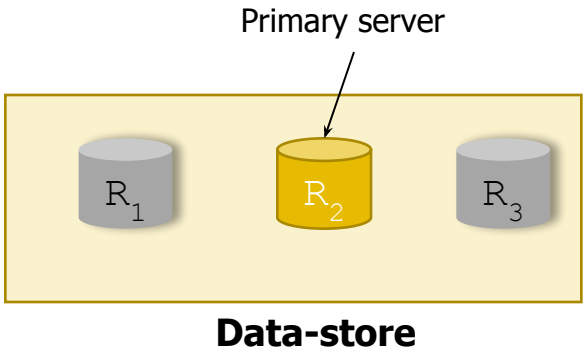
Q: Could a non-blocking strategy be applied?

(And maintain the same consistency properties?)

- Writes return immediately after touching a replica? Writes return after touching primary? What assumptions would you make? What properties result?

Q: How to deal with failures?

- Of backup replicas
- Of the primary?

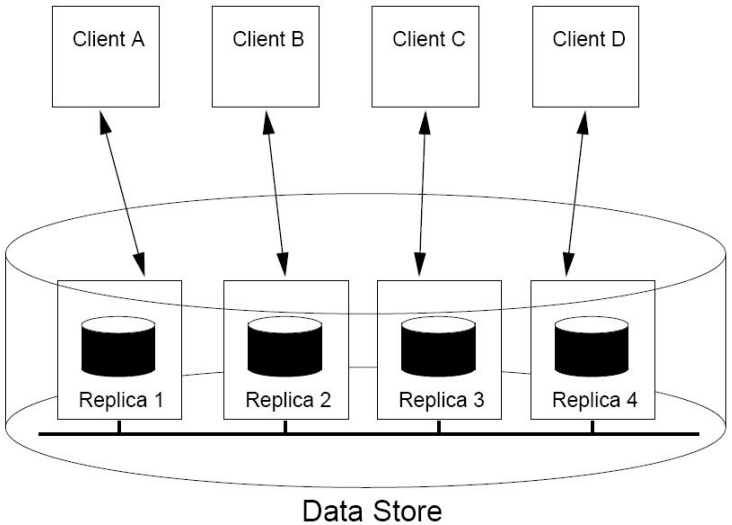


Consistency protocols

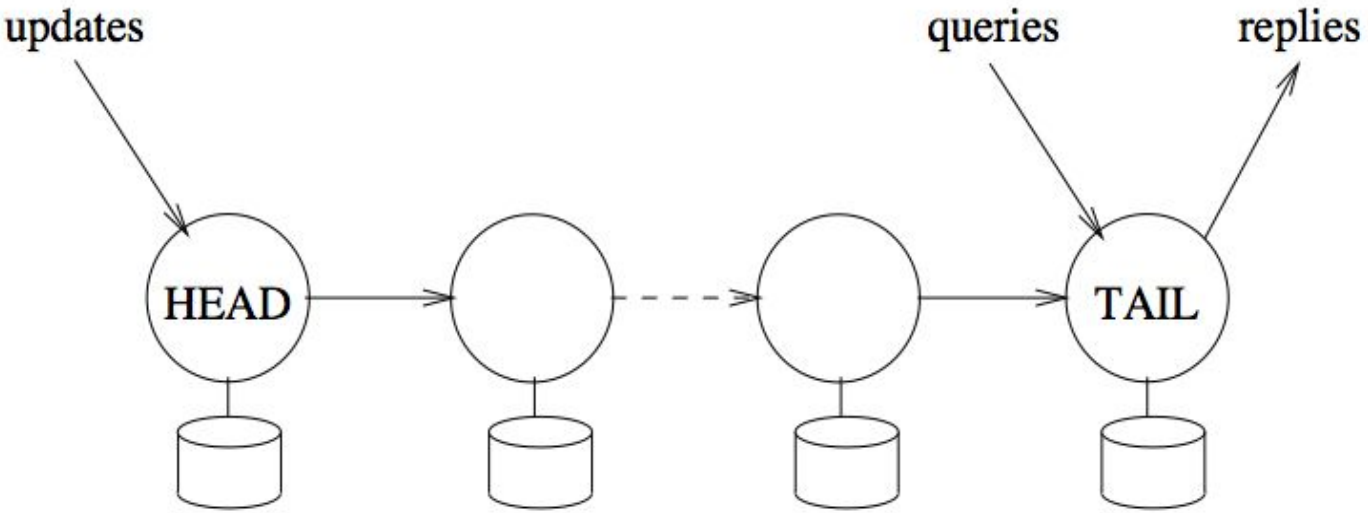
Question: How does one design a protocols to implement the desired consistency model**?**

Sequential consistency

- Primary / backup
- Chain replication
- Quorum protocols



Chain replication



Consistency protocols

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Sequential consistency

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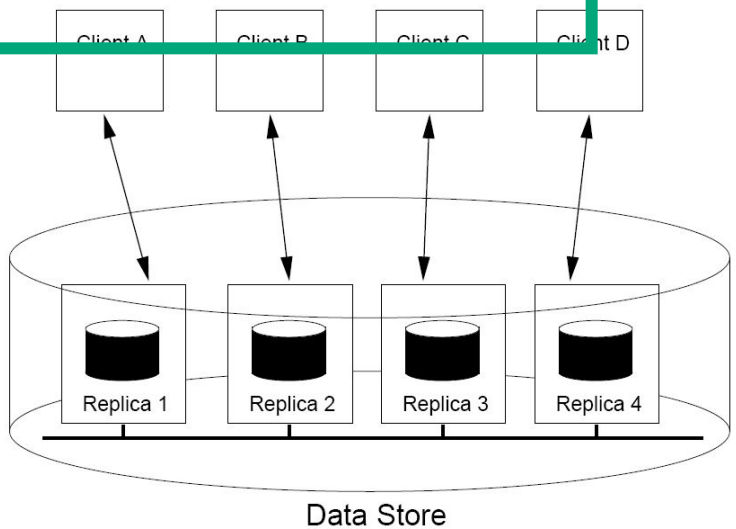


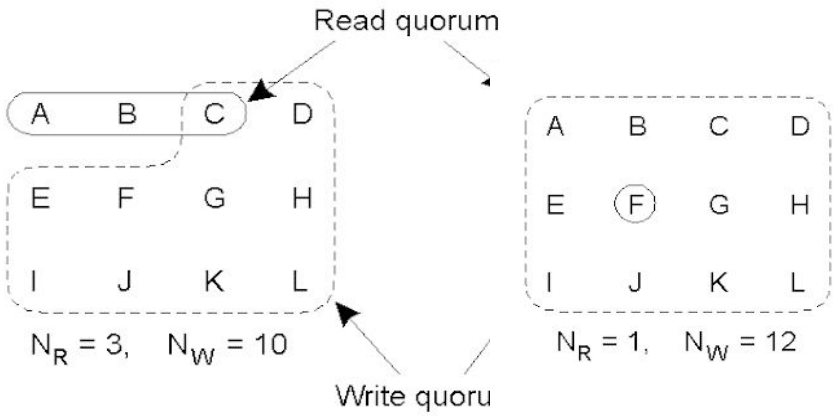
Replicated writes: Quorums

Problem (with primary-backup scheme): some replicas may not be available all the time / may be slow

- leads to low availability (for writes) / high response time

Solution: quorum-based protocols: Ensure that each operation is carried on *enough* replicas (not *all*)

- a majority 'vote' is established before each operation
- distinguish a **read quorum** and a **write quorum**:



What's a valid quorum configuration?

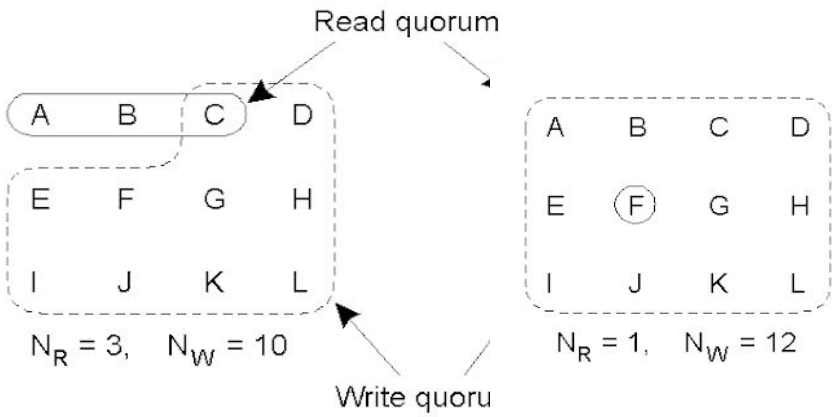
Two basic rules for correctness

- A read quorum should "intersect" any prior write quorum at >= 1 processes

$$Q_r + Q_w > N$$

- A write quorum should intersect any other write quorum

$Q_w + Q_w > N$ results in $Q_w > N/2$



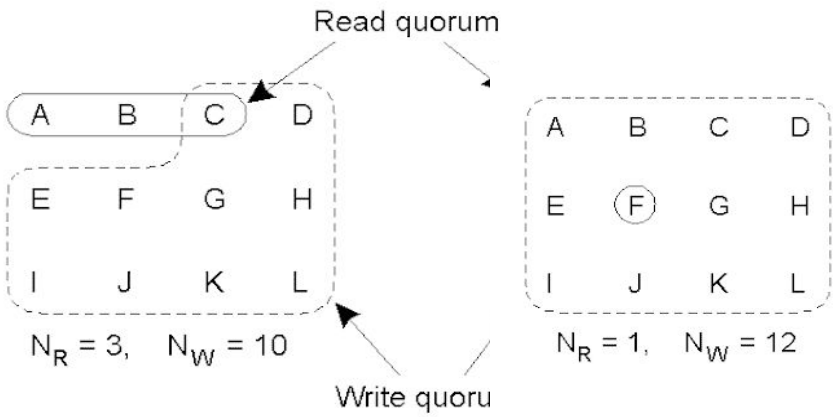
Quorums: Mechanics for read operations

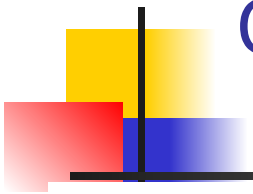
Setup: Replicas have "versions"

- Versions are numbered (timestamped)
- Timestamps must increase monotonically (process id to break ties)

Read operations:

- Client send RPCs until Q_r processes reply
- Then use the replica with the largest timestamp (the most recently updated replica)





Quorums: Mechanics write operations

Setup: Replicas have "versions",

- Versions are numbered (e.g., logically timestamped)
- Timestamps must increase monotonically

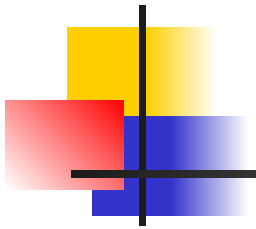
Writes:

- Need to determine next version number.
- Need a protocol to protect from concurrent writes
  - Need to make sure all replicas are updated atomically

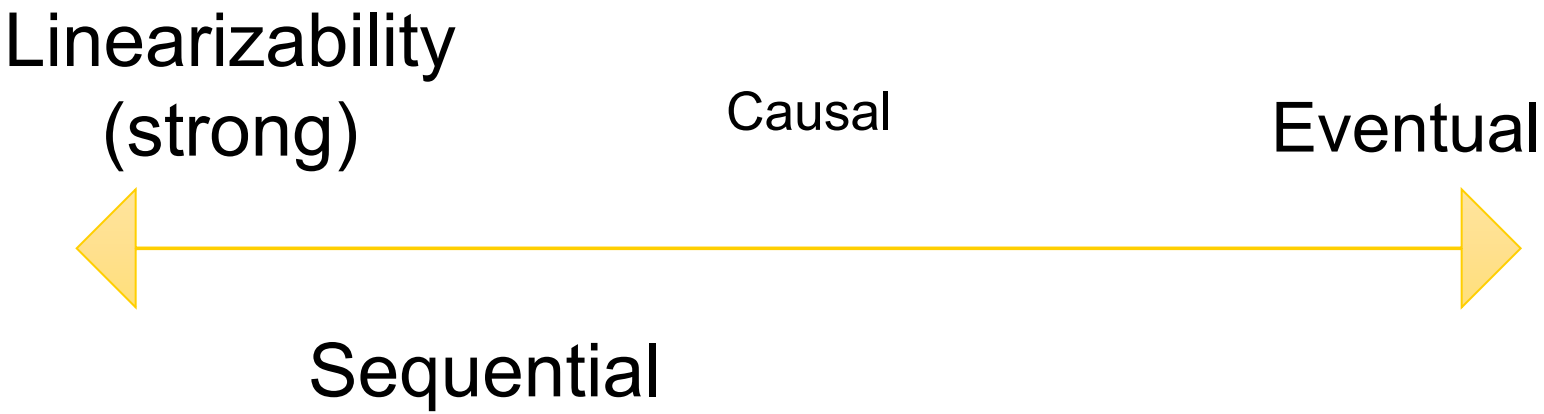
Quorum based protocols: Write algorithm

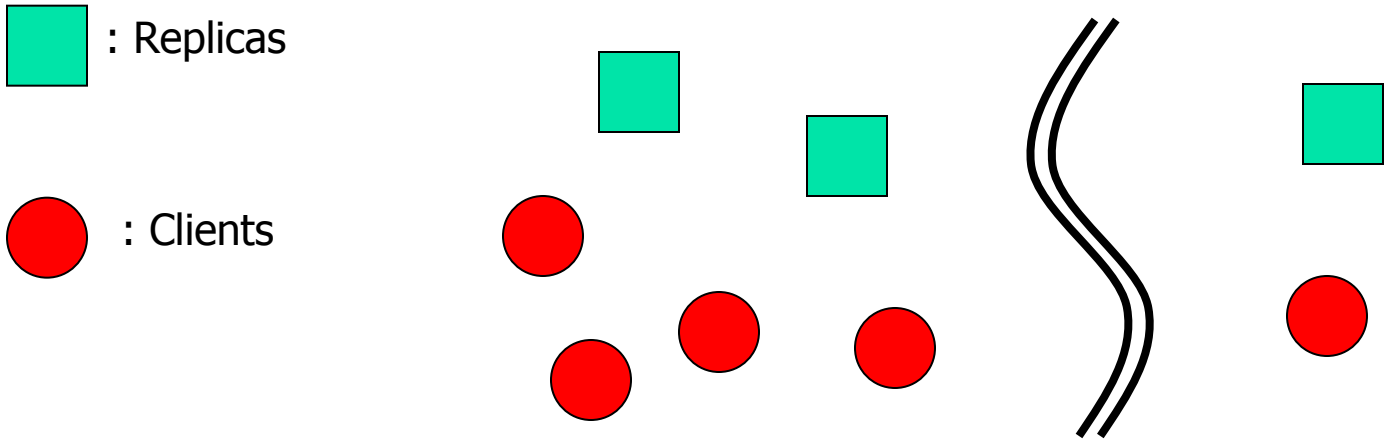
(similar to two-phase commit)

- Client: Contacts all replica hosts and propose the write.
  - "I would like to execute write W_j on data-item I"
- Replica:
  - Locks the replica against other writes (may fail).
  - Puts the request in a queue of pending writes
  - Sends back: ACK, proposed version-number (e.g., logical clock) , pID
- Client:
  - If $< Q_w$ replies: send ABORT to all participants
  - If $\geq Q_w$ replies:
    - new_replica_number = max [versions] + 1
    - Send (COMMIT, new_replica_number)
- Replica:
  - Commit, unlock



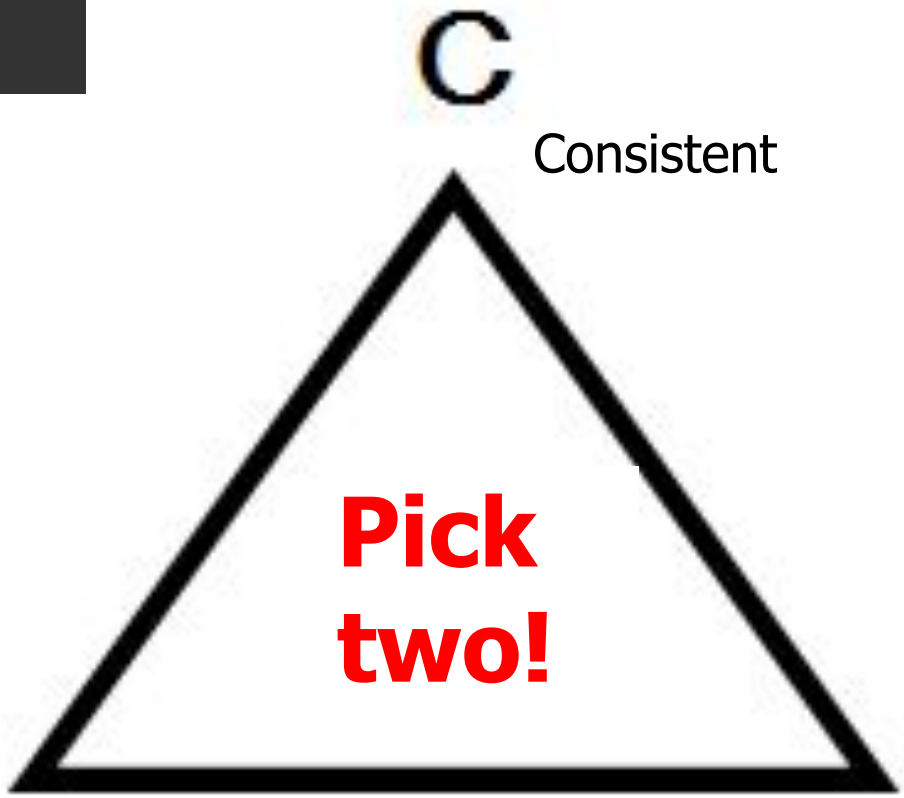
Wrapping up:
a note on trade-offs





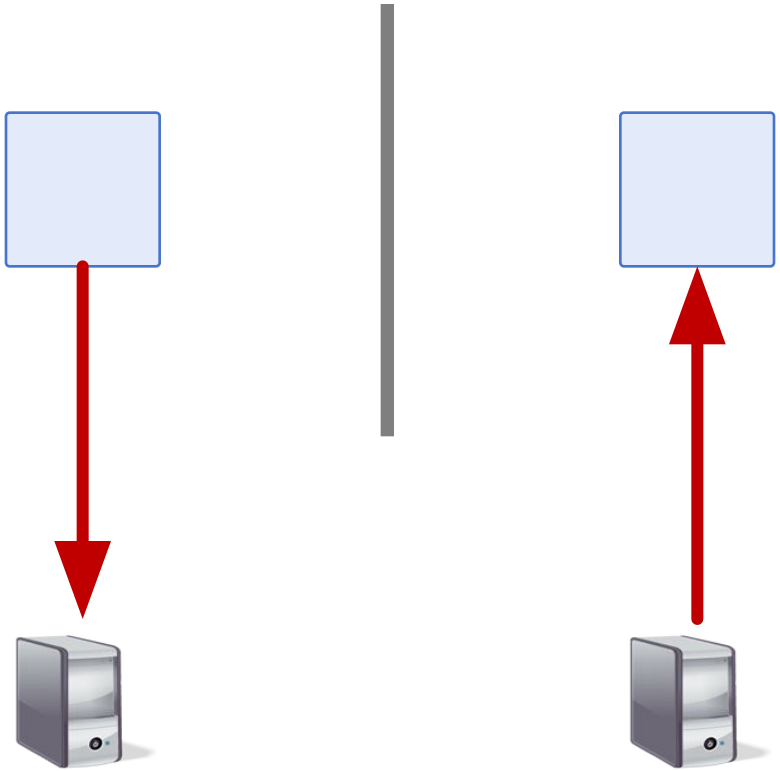
C+PT (-A)	Option 1:	accept reads	accept reads
	Option 2:	accept reads	reject writes
A+PT (-C)		accept writes	reject reads
		accept reads + writes	accept reads + writes
		'inconsistent' results	'inconsistent' results

CAP Theorem



CAP Twelve Years After – How the "Rules" Have Changed, IEEE Spectrum 2012 [link]
Brewer's conjecture and the feasibility of consistent, available, partition-tolerant web services, SIGACT News 33(2): 51-59 (2002)

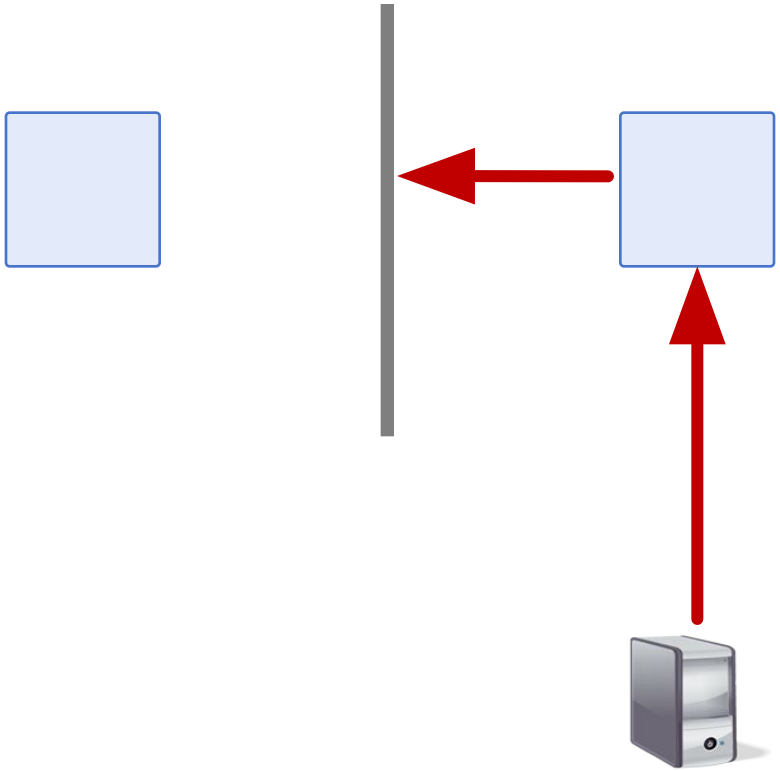
CAP Theorem: Proof



Not consistent

Gilbert, Seth, and Nancy Lynch. "Brewer's conjecture and the feasibility of consistent, available, partition-tolerant web services." ACM SIGACT News 33.2 (2002): 51-59.

CAP Theorem: Proof



Not available

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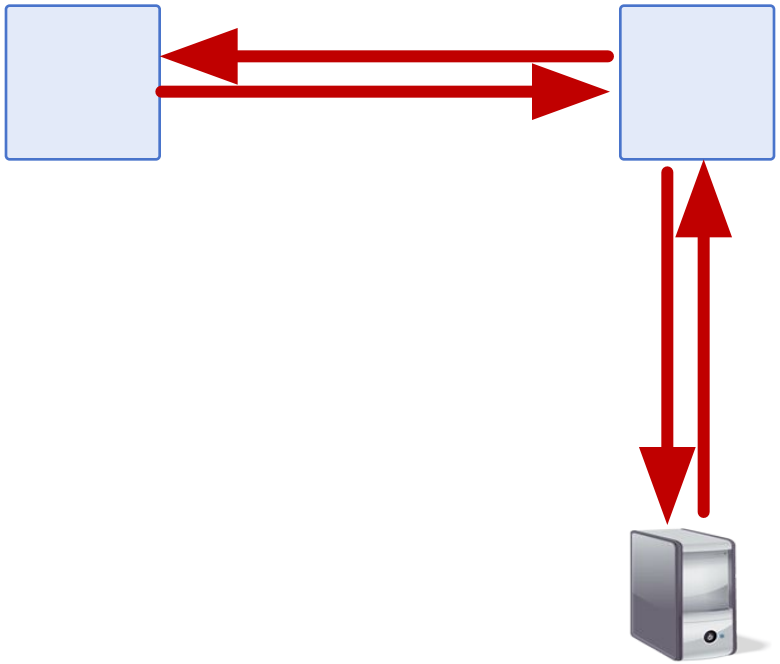
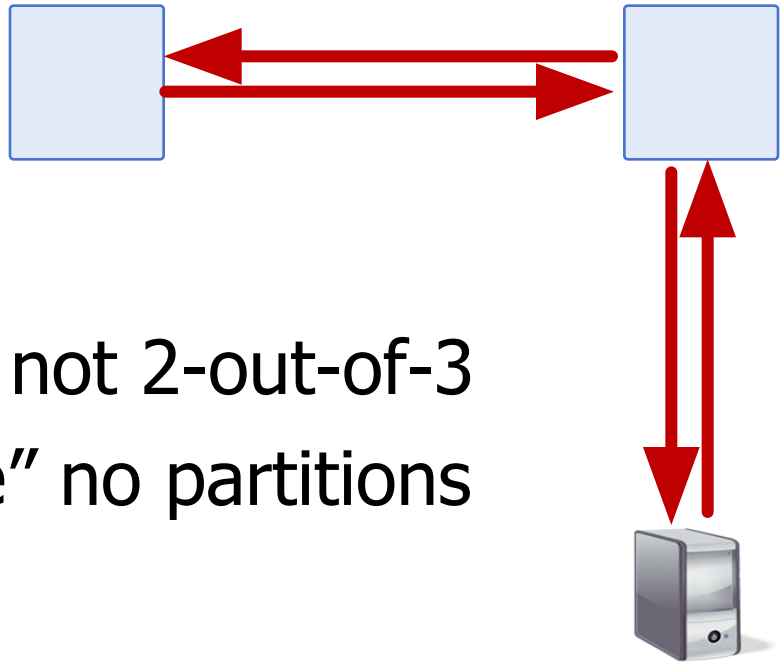


Not partition tolerant

Gilbert, Seth, and Nancy Lynch. "Brewer's conjecture and the feasibility of consistent, available, partition-tolerant web services." ACM SIGACT News 33.2 (2002): 51-59.

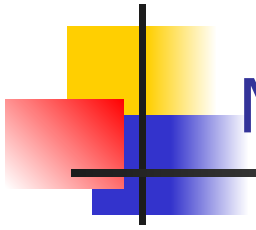
CAP Theorem: AP or CP



Not partition tolerant

Criticism: It's not 2-out-of-3

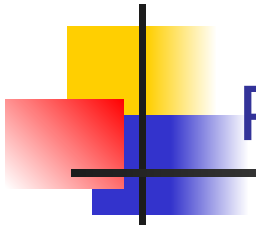
- Can't "choose" no partitions
- So: AP or CP



More tradeoffs: Latency vs. Consistency

- Low-latency: Speak to fewer than quorum of nodes?
  - Primary-backup: write N, read 1
  - General: |W| + |R| > N

- L and C are fundamentally at odds
  - "C" = linearizability, sequential

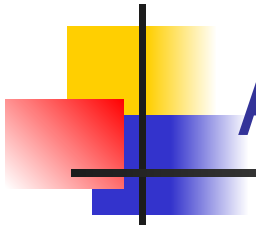


PAC / ELC

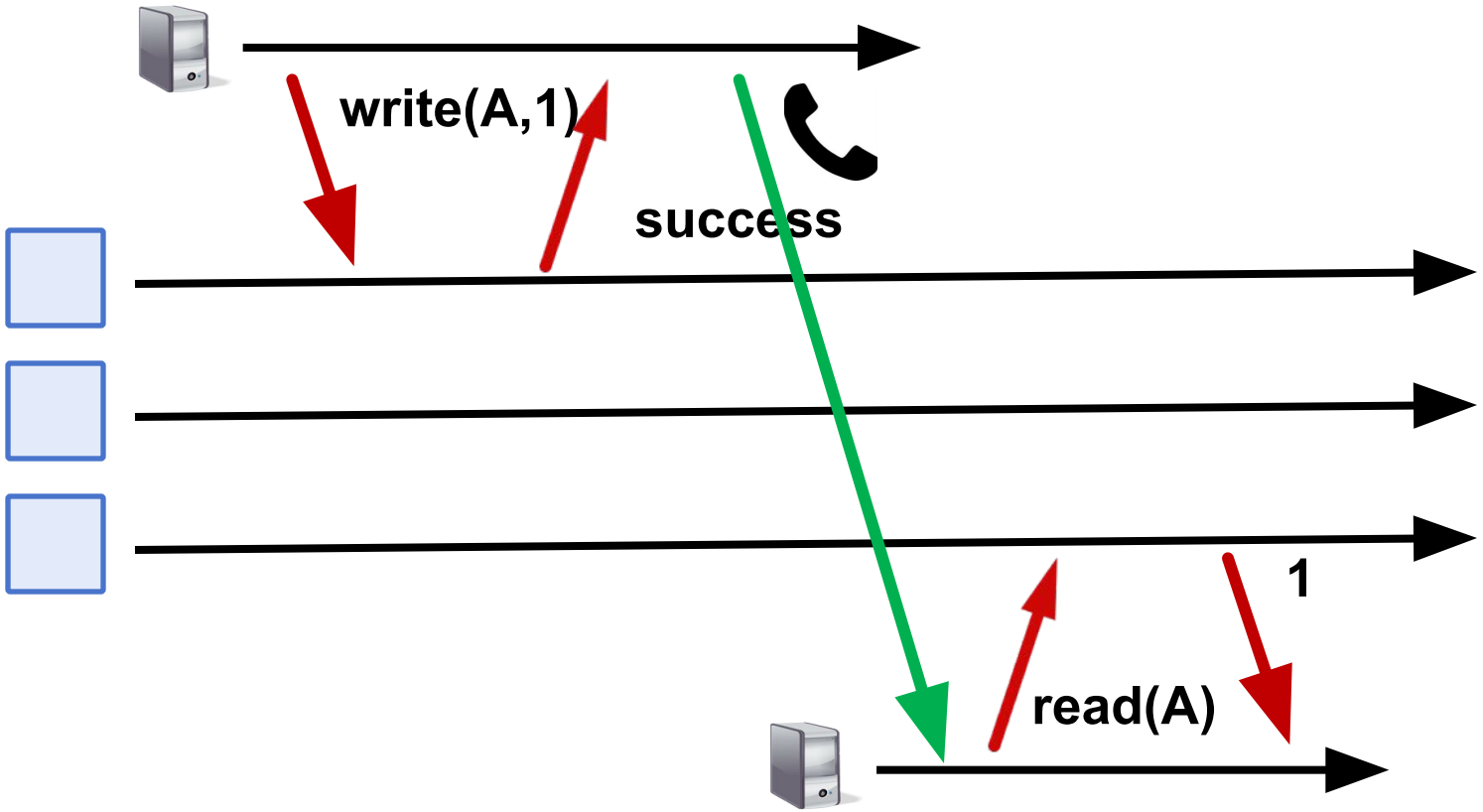
- If there is a partition (**P**):
  - How does system tradeoff A and C?
- **E**lse (no partition)
  - How does system tradeoff L and C?

- Is there a useful system that switches?
  - Dynamo: PA/EL
  - "ACID" dbs: PC/EC

http://dbmsmusings.blogspot.com/2010/04/problems-with-cap-and-yahoos-little.html

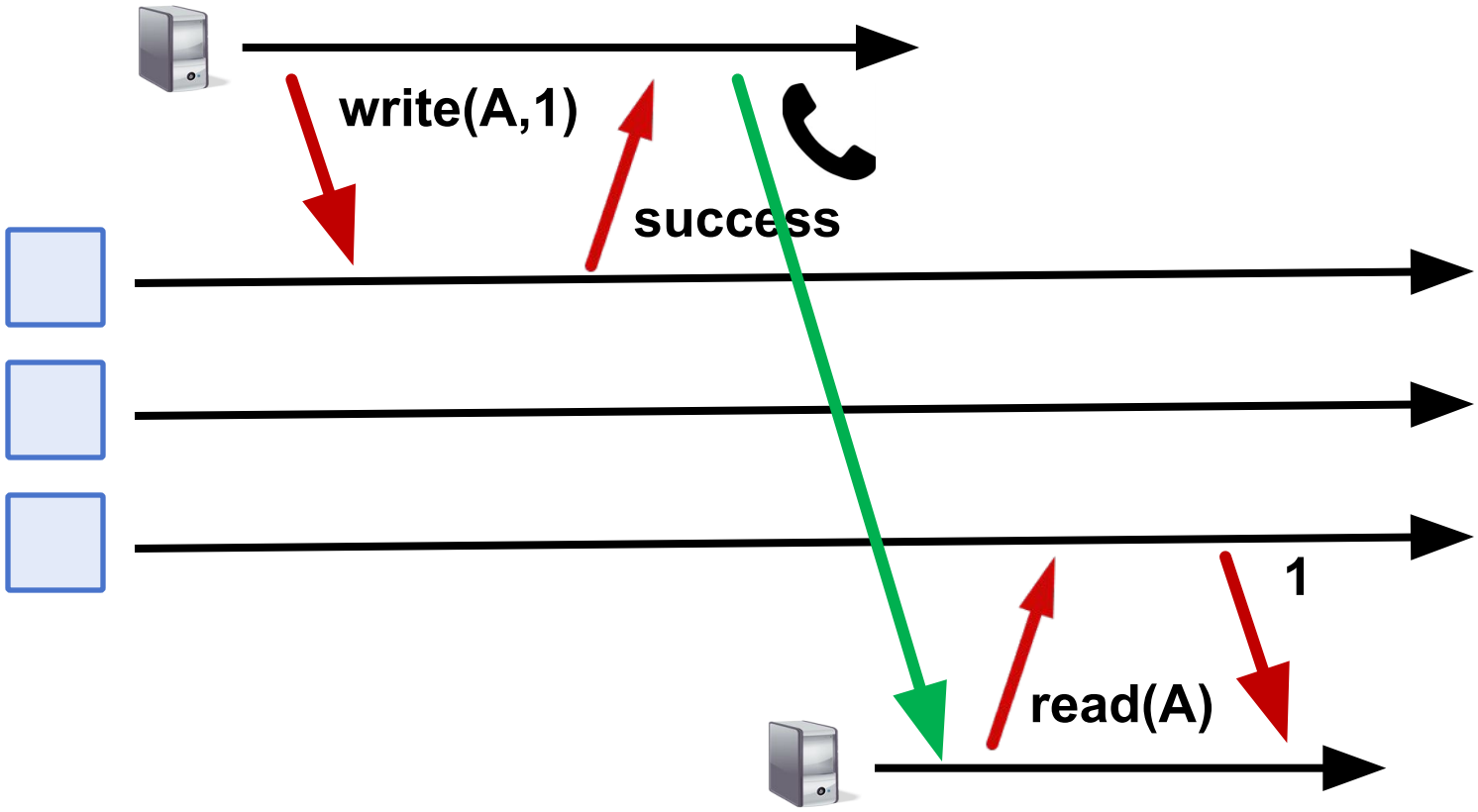


A brief review / discussion

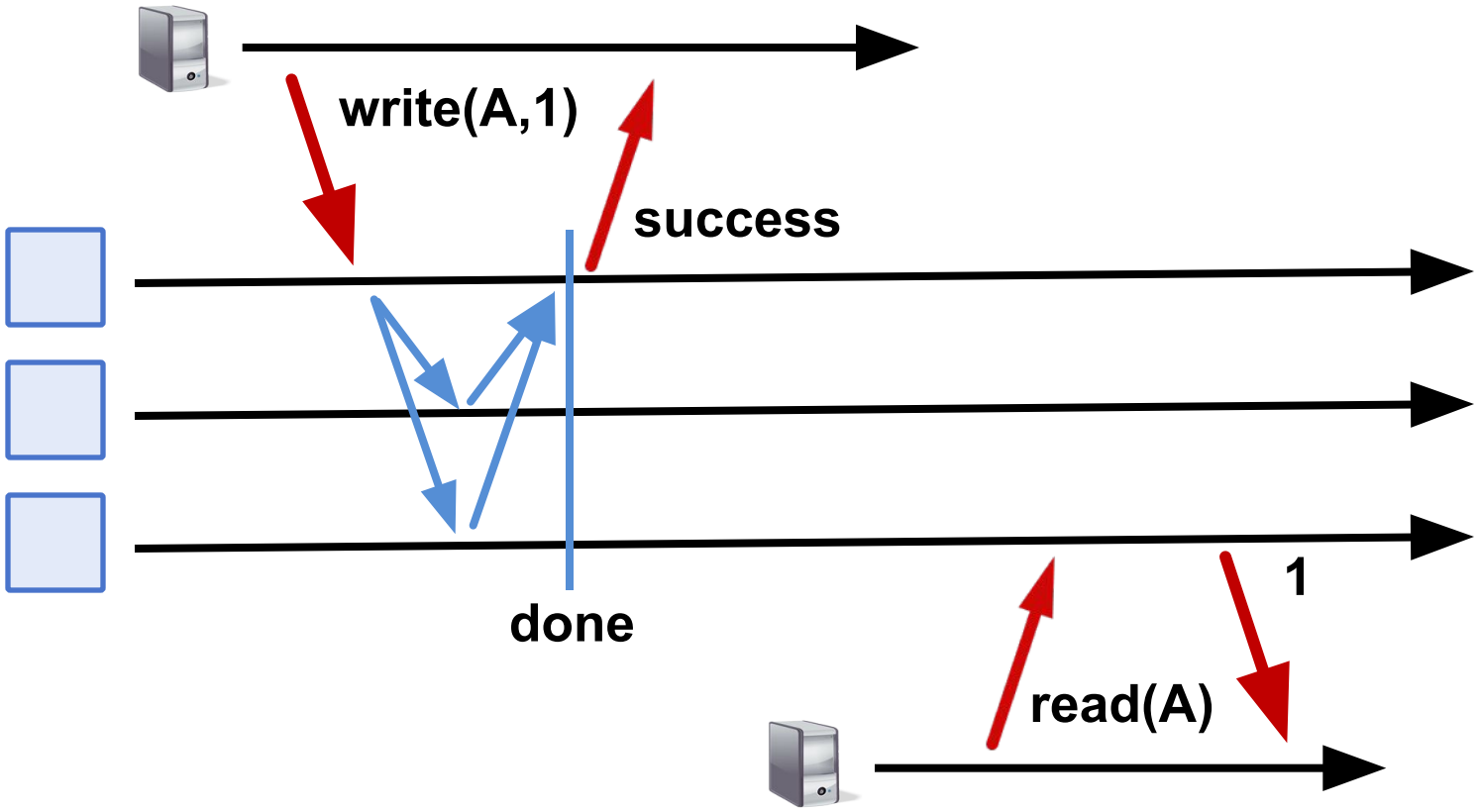


Phone call: *happens-before* relationship,
through "out-of-band" communication

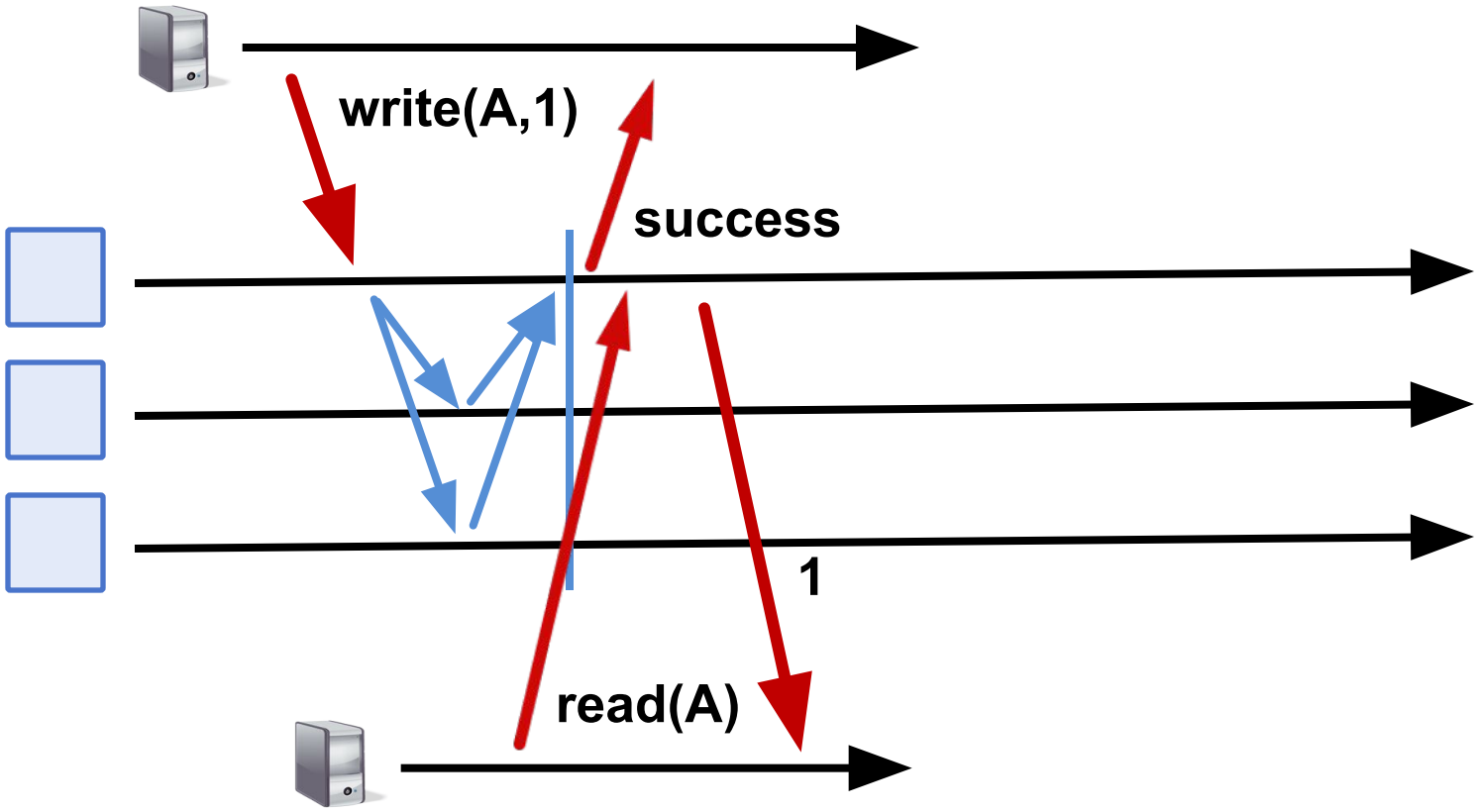
Which consistency model would guarantee the expected r(A)1 outcome?



One cool trick: Delay responding to writes/ops until properly performed on all replicas



- Isn't sufficient to return value of third node:
  It doesn't know precisely when op is "globally" committed

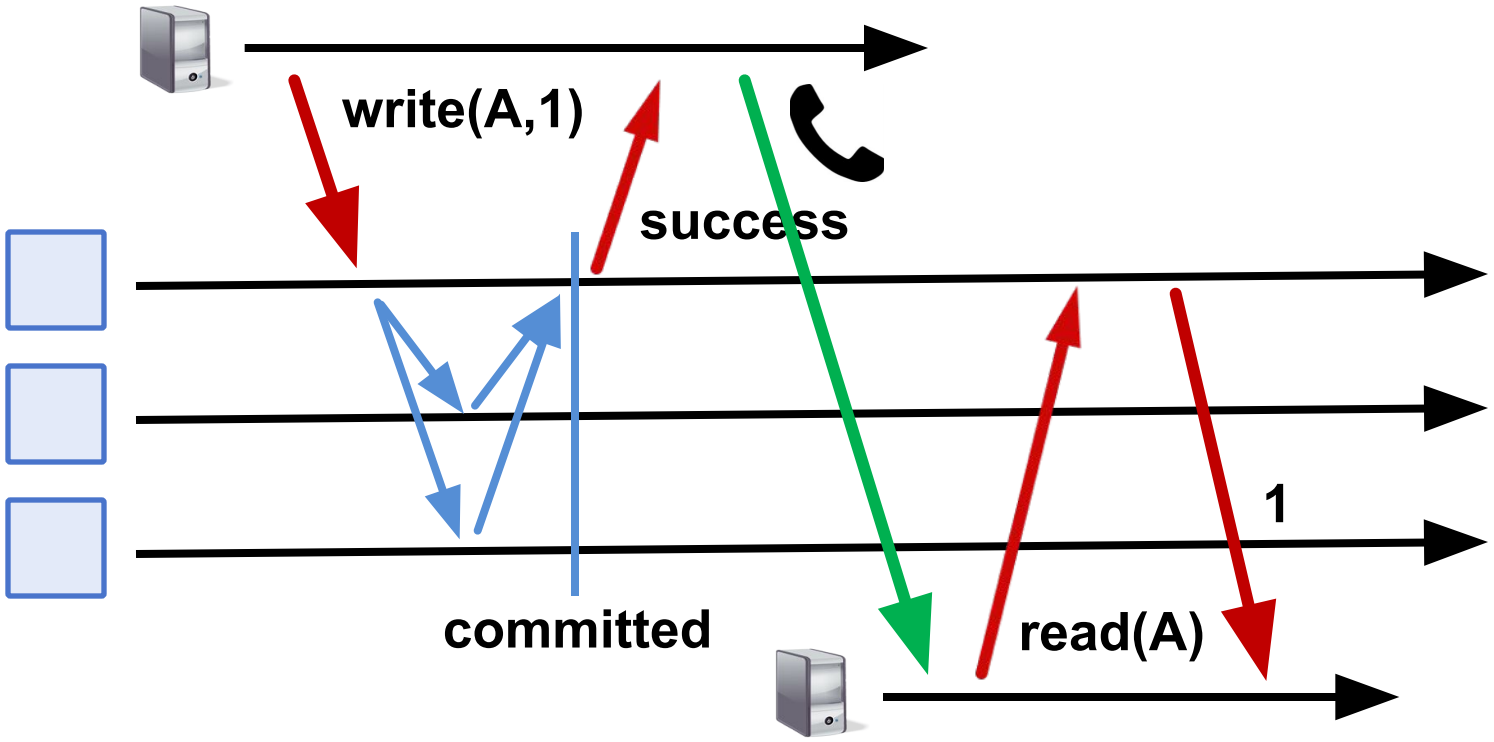


Potential solutions to order all operations via: (1) leader/primary, (2) consensus, or (3) physical time (a la Spanner)

Strong consistency = linearizability

- Linearizability (Herlihy and Wang 1991)
  1. All servers execute all ops in *some* identical sequential order
  2. Global ordering preserves each client's own local ordering
  3. Global ordering preserves real-time guarantee
     - All ops receive global time-stamp using a sync'd clock
     - If $ts_{op1}(x) < ts_{op2}(y)$, OP1(x) precedes OP2(y) in sequence
- Once write completes, all later reads (by wall-clock start time) should return value of that write or value of later write.
- Once read returns particular value, all later reads should return that value or value of later write.

Intuition: Real-time ordering

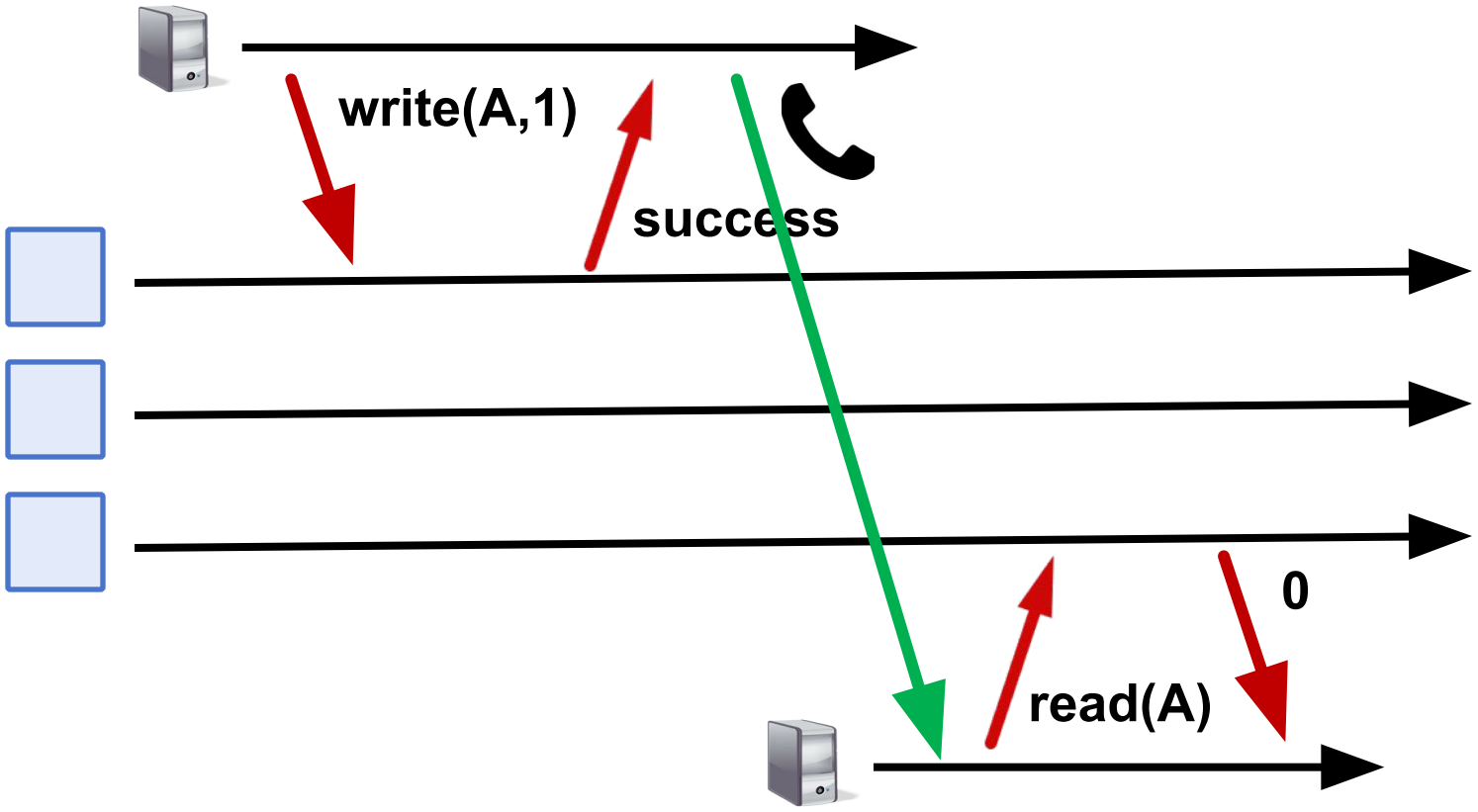


- Once write completes, all later reads (by wall-clock start time) should return value of that write or value of later write.
- Once read returns particular value, all later reads should return that value or value of later write.

Weaker: Sequential consistency

- Sequential = Linearizability – real-time ordering
  1. All servers execute all ops in *some* identical sequential order
  2. Global ordering preserves each client's own local ordering
- With concurrent ops, "reordering" of ops (w.r.t. real-time ordering) acceptable, but all servers must see same order
  - e.g., linearizability cares about time
    sequential consistency cares about program order

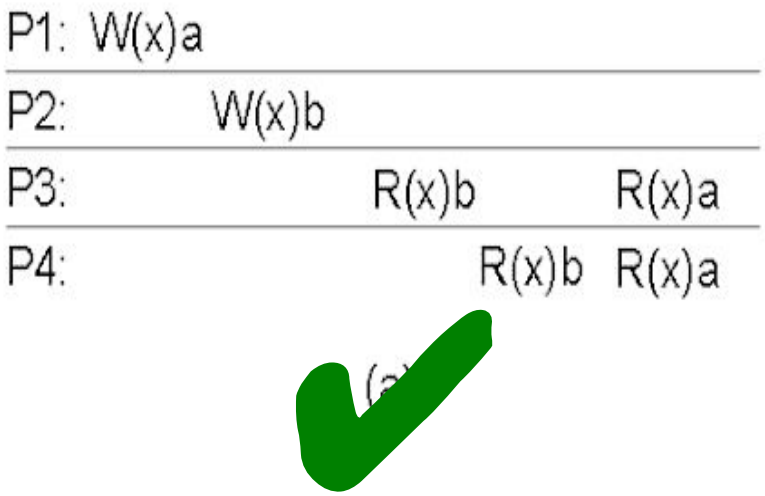
Sequential Consistency

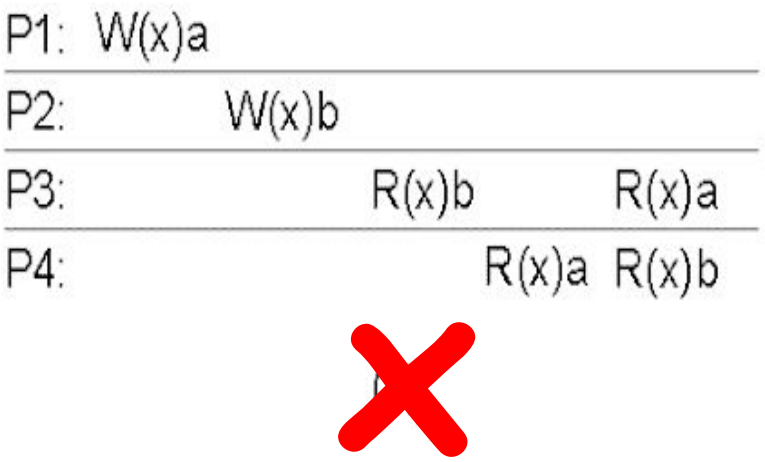


In this example, system orders read(A) before write(A,1)

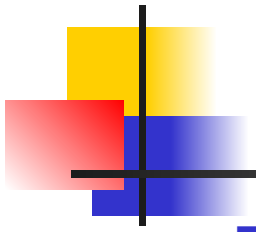
[a sequential concurrency contract would allow this]

Valid Sequential Consistency?

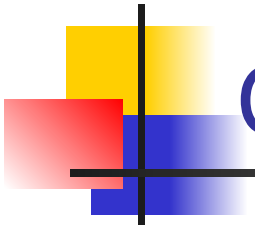




- Why? Because P3 and P4 don't agree on order of ops. Doesn't matter when events took place on diff machine, as long as proc's AGREE on order.
- What if P1 did both W(x)a and W(x)b?
  - Neither valid, as (a) doesn't preserve local ordering



- We stopped here



Causal consistency

- Remember causality notion from Lamport (logical) clocks?
  - That's what causal consistency enforces
- Causal consistency: Any execution is the same as if all causally-related read/write ops were executed in an order that reflects their causality
  - All concurrent ops may be seen in different orders
- Therefore:
  - Reads are fresh only w.r.t. the writes they are causally dependent on
  - causally-related writes are ordered by all replicas in the same way, BUT
  - concurrent writes may be committed in different orders by different replicas, and hence read in different orders by different applications

Causal Consistency (1)

"Causally related" relationship (notation '□'):

- A read is causally related to the write that provided the data for the read.
- A write is causally related to a read that happened before this write *in the same process*.
- Relationship is transitive: If write1 → read, and read → write2, then write1 → write2.

Def: concurrent ops == NOT causally related

Causal Consistency (Example)

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

Note: $W_1(x)a \rightarrow W_2(x)b$, but *not* $W_2(x)b \rightarrow W_1(x)c$

- Is this sequence is allowed with a causally-consistent store?
- Is this sequence allowed with sequentially consistent store?

Causal Consistency: (More Examples)

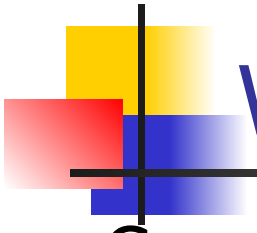
P1: W(x)a				
P2:	R(x)a	W(x)b		
P3:			R(x)b	R(x)a
P4:			R(x)a	R(x)b

SecC: no
CauC: no

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

SecC: no
CauC: yes

- Which sequence is allowed with a causally-consistent store?
- Which sequence allowed with sequentially consistent store?



Why Causal Consistency?

- Causal consistency is strictly weaker than sequential consistency (and can give weird results (as you've seen)
  - strict $\subset$ linearizabile $\subset$ sequential $\subset$ causal
- BUT causal also offers more possibilities for concurrency:
  - Concurrent operations (which are not causally-dependent) can be executed in different orders by different replicas
  - In contrast, with sequential consistency, you need to enforce a global ordering of all operations
- Hence, one can get better performance than with sequential

From what I know, not very popular in industry So, we're not gonna focus on it any more

Consistency protocols

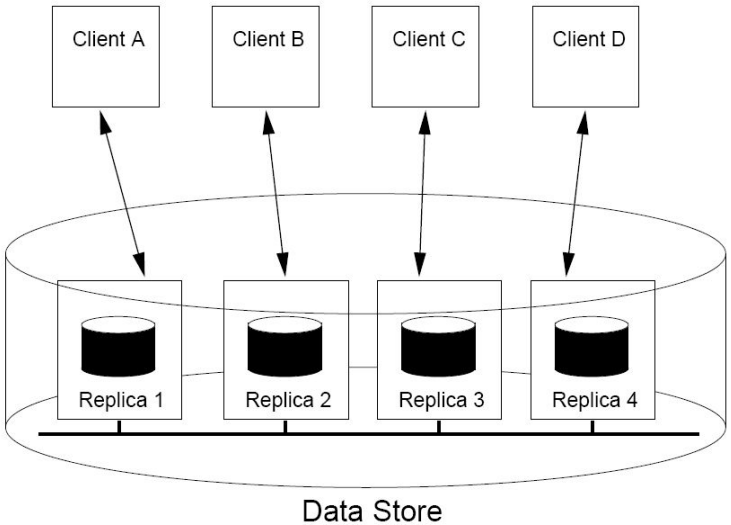
Question: How does one design a protocols to implement the desired consistency model**?**

Sequential consistency

- Group with total ordering
- Primary / backup
- Chain replication
- Quorum protocols

Causal consistency

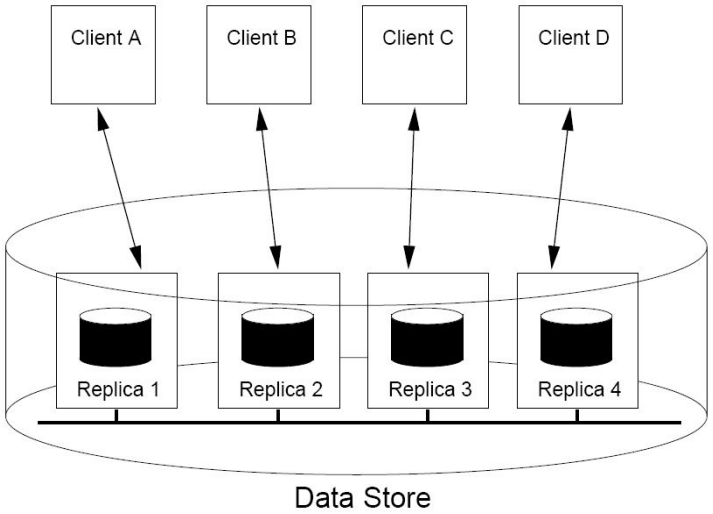
- Group with causal ordering

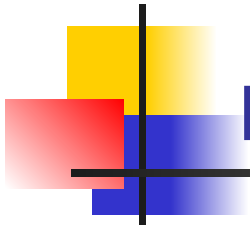


Many Other Consistency Models Exist ...

- Data centric: Assume a global, data-store view (i.e., across all clients)
  - Models based on ordering of operations
    - Constraints on operation ordering at the data-store level
  - Continuous consistency
    - Limit the deviation between replicas

- Client centric
  - Assume client-independent views of the datastore
  - Constraints on operation ordering for each client independently



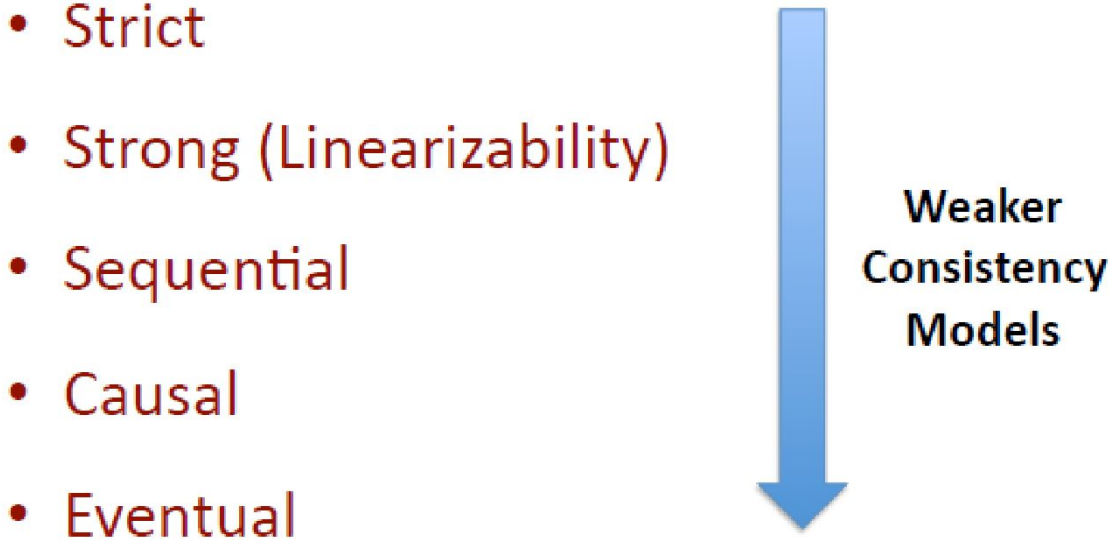


Many Other Consistency Models Exist

- Other standard consistency models
  - … take a look at next slides here
  - read Tanenbaum 7.3

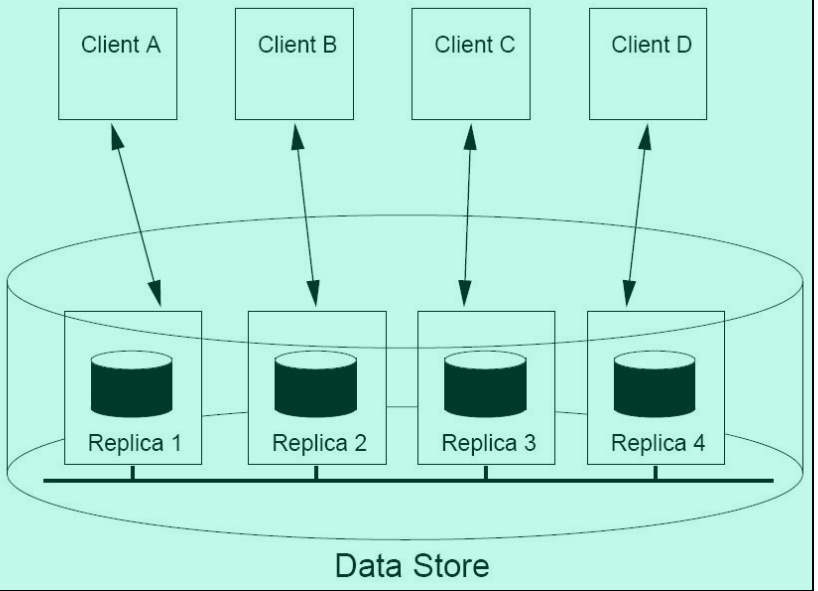
Consistency models

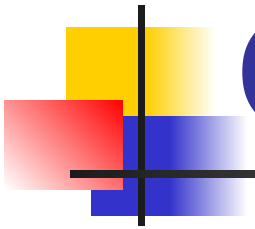
- Data centric: Assume a global, data-store view (i.e., across all clients)
  - Models based on ordering of operations
    - Constraints on operation ordering at the data-store level
  - Eventual consistency
  - Continuous consistency



Consistency models

- Data centric: Assume a global, data-store view (i.e., across all clients)
  - Models based on ordering of operations
    - Constraints on operation ordering at the data-store level
  - Continuous consistency
    - Limit the deviation between replicas
  - Eventual consistency
- Client centric
  - Assume client-independent views of the datastore
  - Constraints on operation ordering for each client independently

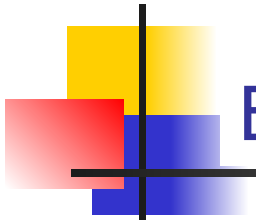




Client-centric Consistency Models

Goal: Avoid system-wide consistency, by concentrating on what each client independently wants

(instead of maintaining a global view)



Example: Consistency for Mobile Users

Example: Distributed database to which a user has access through her notebook.

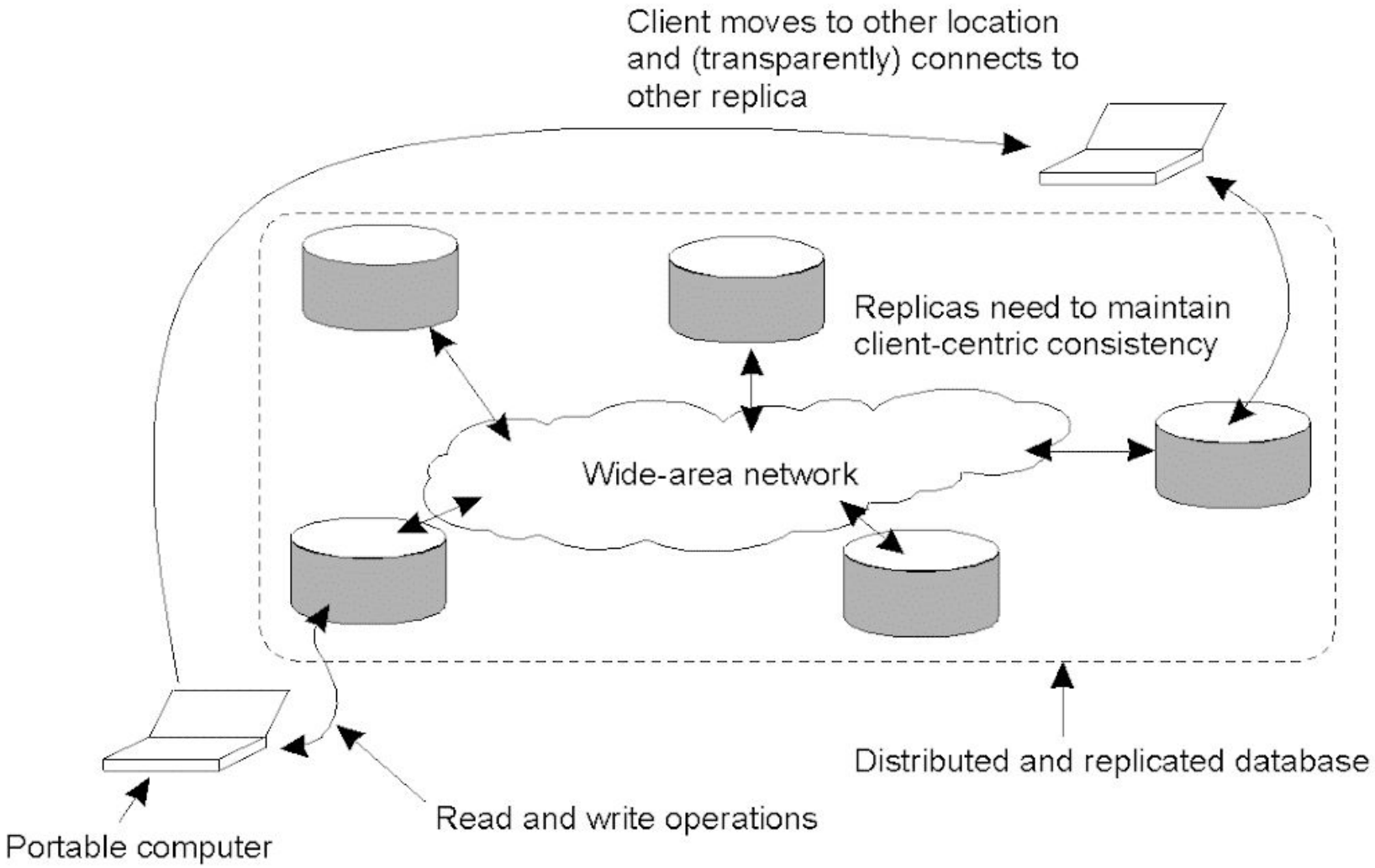
- Notebook acts as a front end to the database.

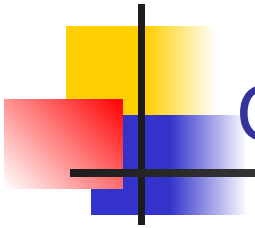
- At location *A* user accesses the database with reads/updates
- At location *B* user continues work, but unless it accesses the same server as the one at location *A*, she may detect inconsistencies:
  - updates at *A* may not have yet been propagated to *B*
  - user may be reading newer entries than the ones available at *A:*
  - user updates at *B* may eventually conflict with those at *A*

Note: The only thing the user really needs is that the entries updated and/or read at *A*, are available at *B* the way she left them in *A*.

- **Idea**: the database will appear to be consistent **to the user**

Example - Consistency for Mobile Users





Client-centric Consistency

Idea: Guarantee a degree of data access consistency for a single client/process point of view.

Notations:

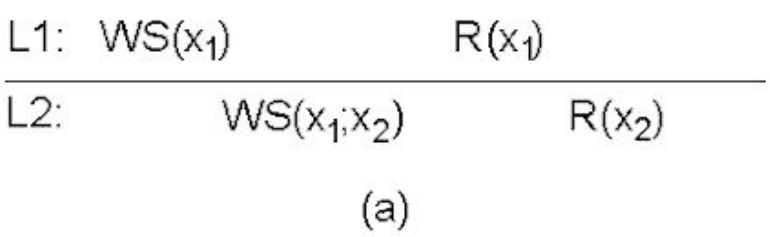
- $x_i[t]$ ☐ Value of data item *x* at time *t* at local replica L_i
- $WS(x_i [t])$ ☐ working set (all write operations) at L_i up to time t on data item *x*
- $WS(x_i [t]; x_j [t])$ ☐ indicates that it is known that $WS(x_i [t])$ is included in $WS(x_j [t])$

Shorthand: we do not use [t] (it's implied)

Monotonic-Read Consistency

Intuition: Client "sees" the same or newer version of data.

Definition: *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 or a more recent value.*



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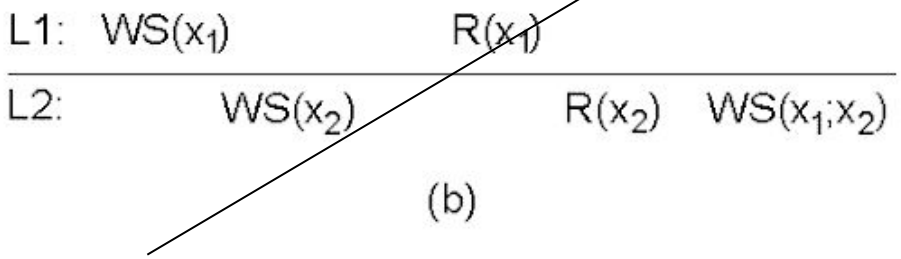

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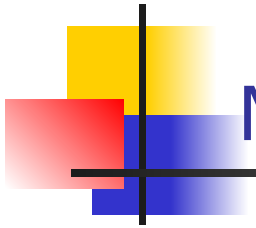


Monotonic reads – Examples

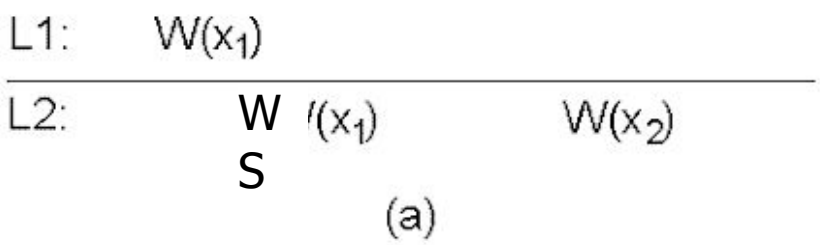
- A personalized news webpage
- Reading (not modifying) incoming e-mail while you are on the move.
  - Each time you connect to a different e-mail server, that server fetches (at least) all the updates from the server you previously visited.
- Reading personal calendar updates from different servers.
  - Monotonic Reads guarantees that the user sees always more recent updates, no matter from which server the reading takes place.

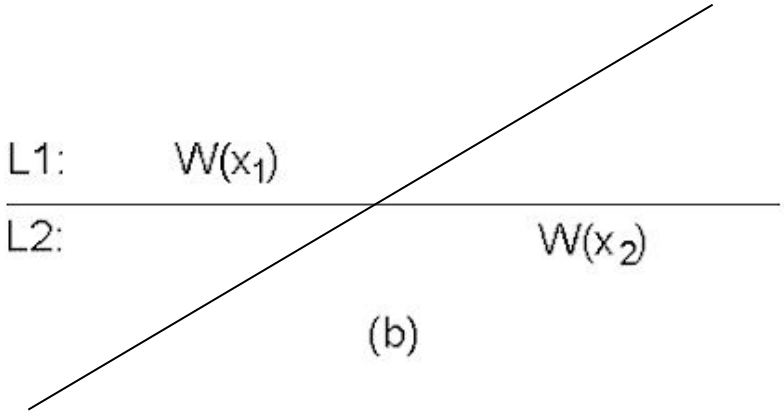
(All the above assume read-only)

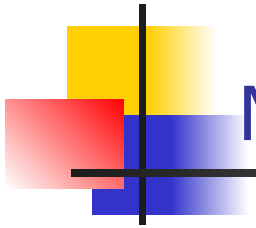
Monotonic-Write Consistency

Intuition: A write happens on a replica only if it's brought up to date with preceding write operations on same data (but possibly at different replicas)

Definition: *A write operation by a process on a data item x is completed (on all replicas) before any successive write operation on x by the same process.*







Monotonic writes – Examples

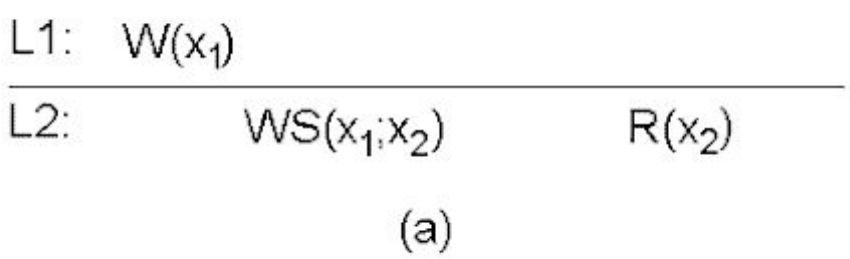
- Updating a program at server *S*2, and ensuring that all components on which compilation and linking depend, are also placed at *S*2.

- Maintaining versions of replicated files in the correct order everywhere (propagate the previous version to the server where the newest version is installed).

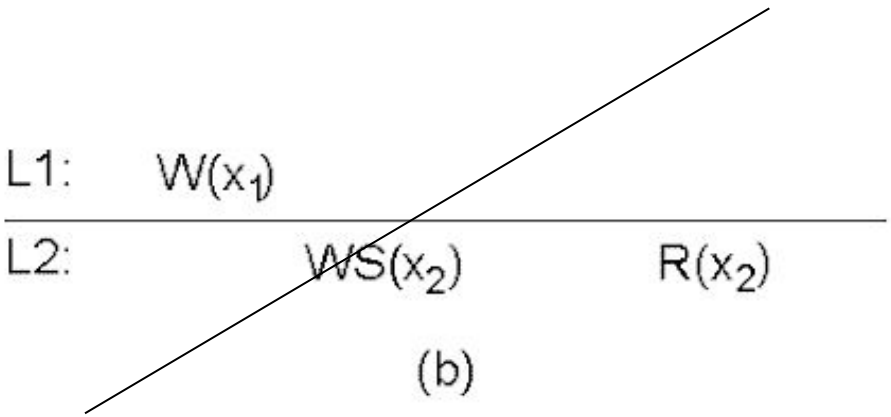
Read-Your-Writes Consistency

Intuition: All previous writes are always completed before any successive read

Definition: *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.*



(a)



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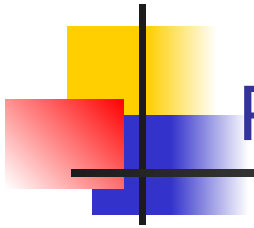


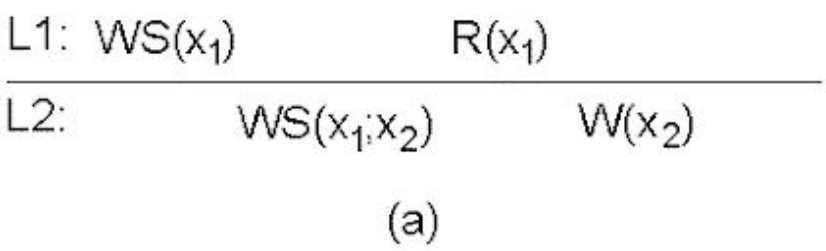
Read-Your-Writes - Examples

- Updating your Web page and guaranteeing that your Web browser shows the newest version instead of its cached copy.
- Password database

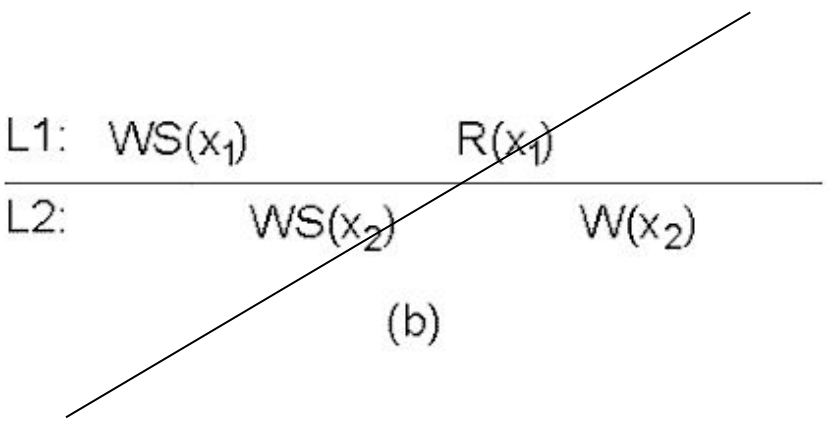
Writes-Follow-Reads Consistency

Intuition: Any successive write operation on x will be performed on a copy of x that is same or more recent than the last read.

Definition: *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.*



(a)



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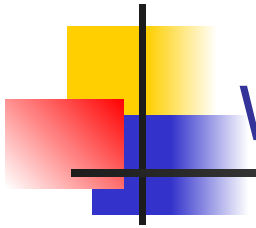
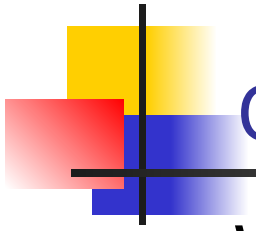


Writes-Follow-Reads - Examples

- See reactions to posted articles only if you have the original posting
  - a read “pulls in” the corresponding write operation.



Quiz like questions

What is the crucial difference between data-centric and client-centric consistency models?

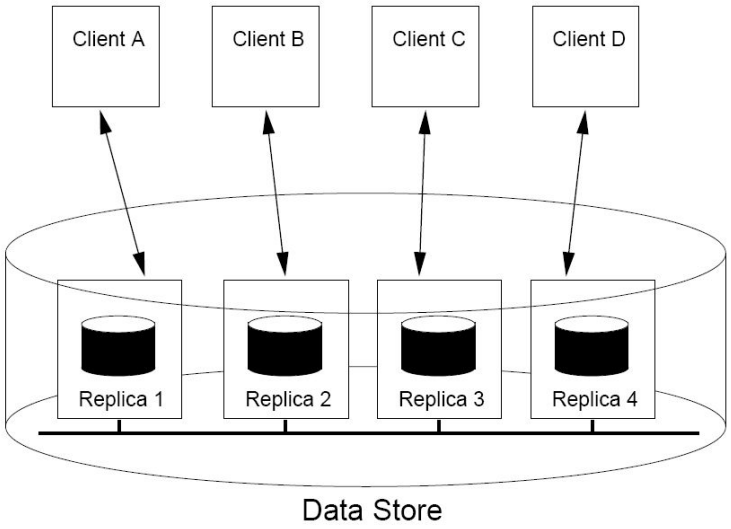
Where does the ‘eventual consistency’ model fit in this taxonomy: is it data-centric or client-centric?

Consider a system that combines read-your-writes consistency with writes-follow-reads consistency (that is, it provides both). Is this system also sequentially consistent?

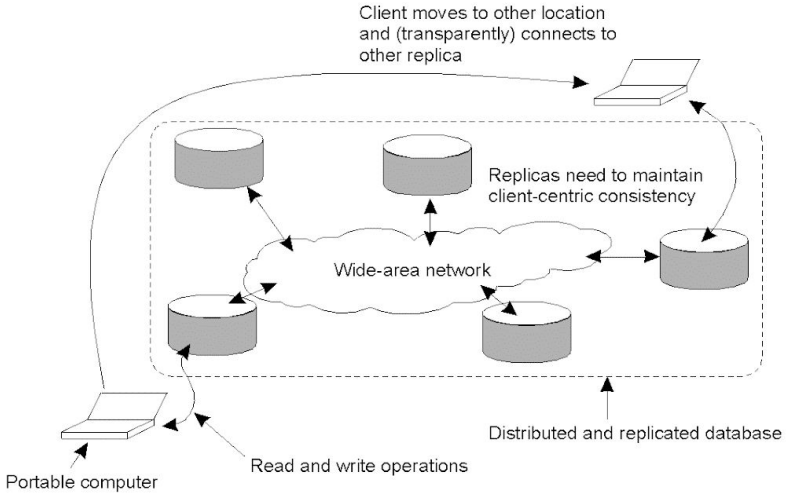
Question: How does one design the protocols to implement the desired consistency model**?**

- Data centric
  - Constraints on operation ordering at the data-store level
    - Sequential consistency.
  - Continuous consistency: limit the deviation between replicas

- Client centric
  - Constraints on operation ordering for each client independently



Reminder: Monotonic-Rea



Definition: *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 or a more recent value.*

Intuition: Client "sees" the same or a newer version of the data.

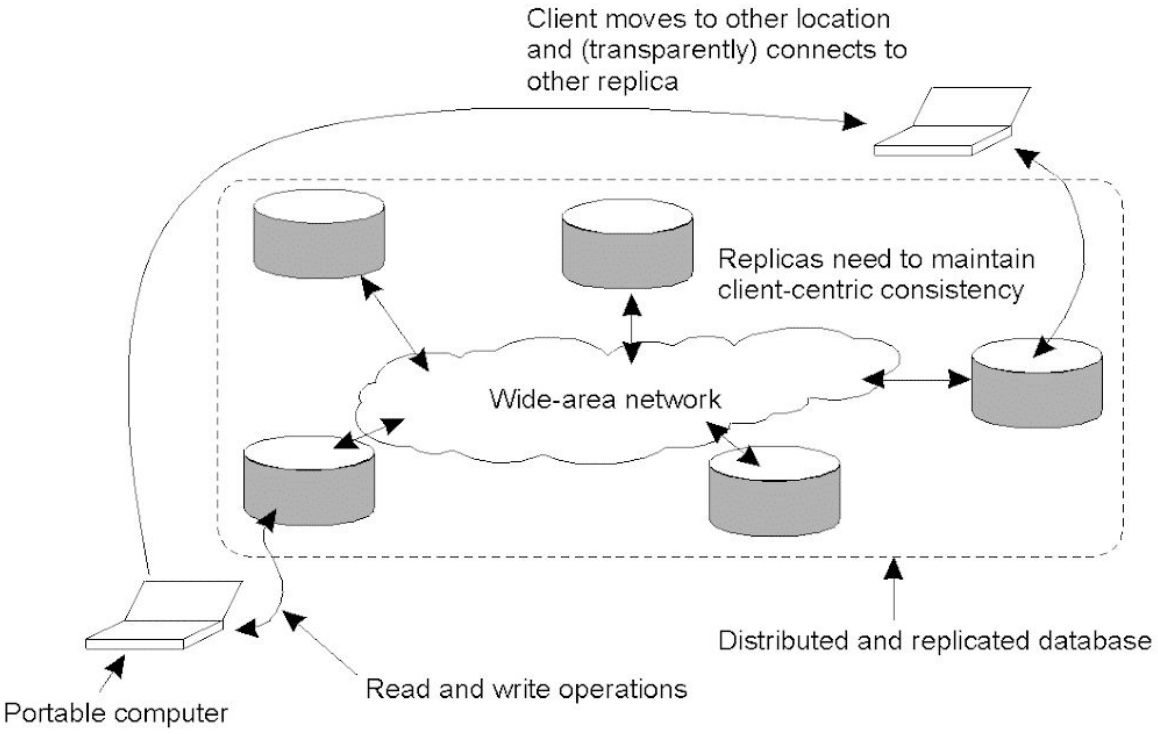
How would you implement this?

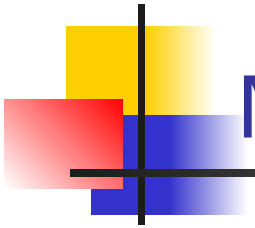
Implementation of monotonic-read consistency

Key intuition: client carries state to identify the last operation(s)

Protocol sketch:

- Globally unique ID
- The client keeps t
  - *ReadSet:* the write far on various obj
- When a client laur
  - Client sends the *R*
  - The server checks performed.
    - [If necessary] F
  - Executes the read operation.





More quiz-like questions

Sketch a protocol design for the following consistency model

- Monotonic-writes
- Read-your-writes
- Writes-follow-reads

Write the pseudo-code

Consistency models

- Data centric: Assume a global, data-store view (i.e., across all clients)
  - Models based on ordering of operations
    - Constraints on operation ordering at the data-store level
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  - Continuous consistency
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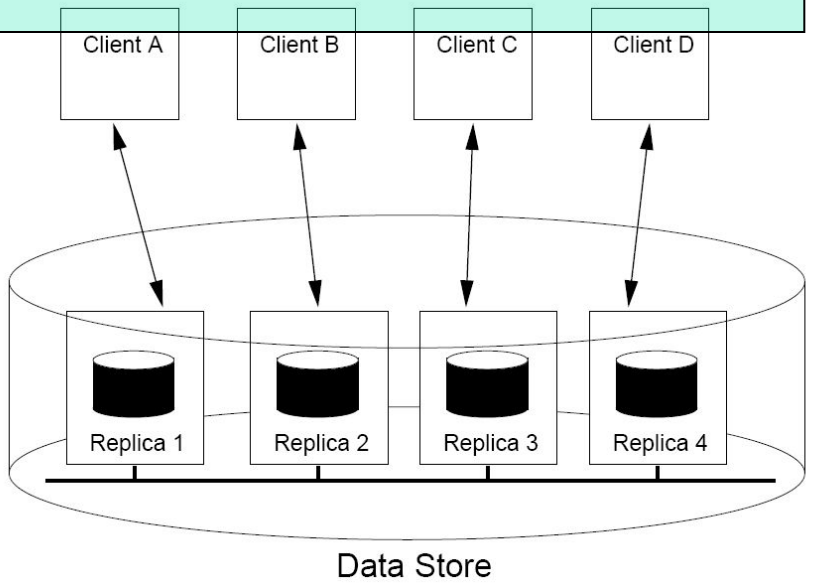
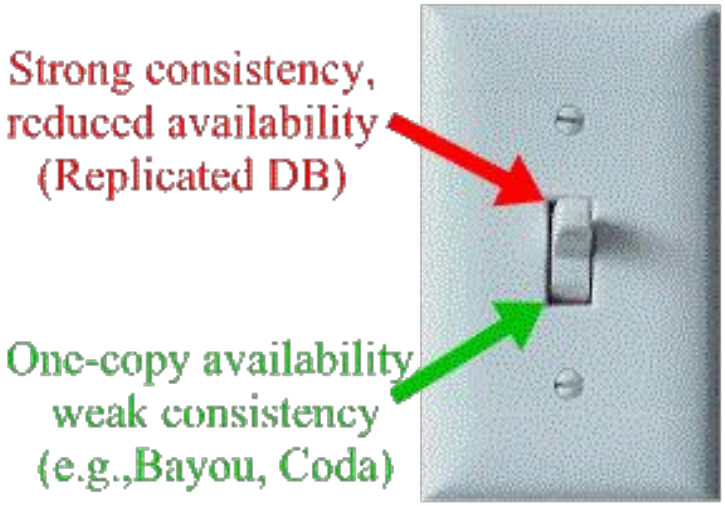


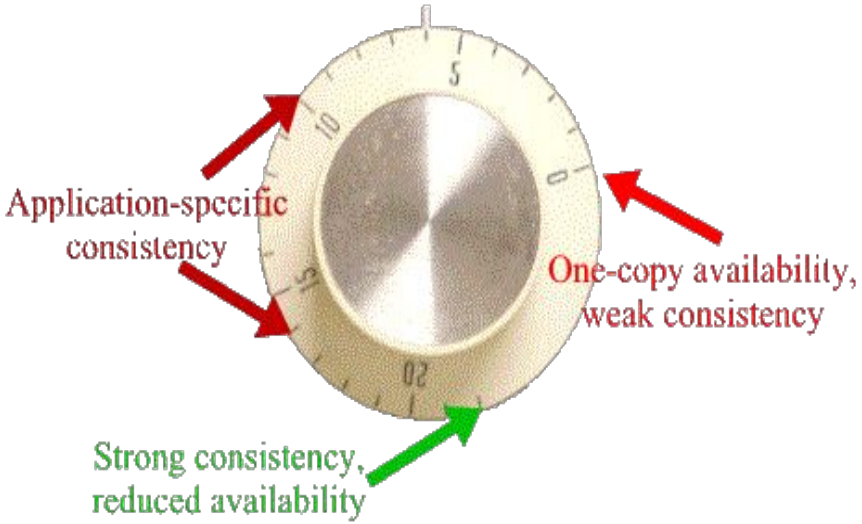
Continuous Consistency

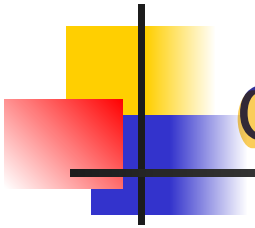
Obs1: We can talk a about a degree of consistency

- Goal: Limit the deviation between replicas

Metaphor: Knob vs. switch







Continuous Consistency

Obs1: We can talk a about a degree of consistency

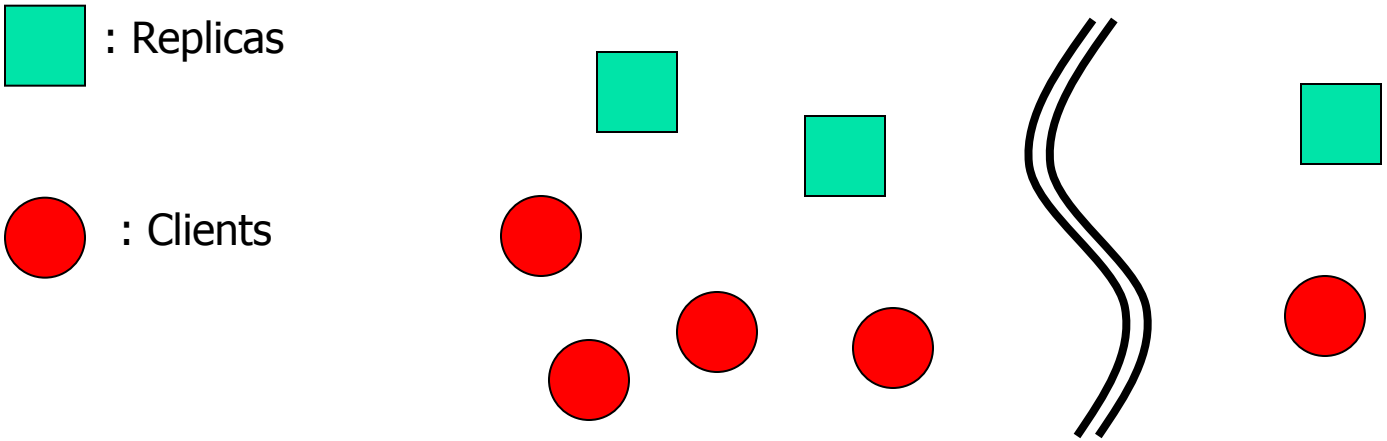
- Goal: Limit the deviation between replicas

Obs2: Multiple metrics to measure deviation are possible

- replicas may differ in their numerical value
- replicas may differ in their relative staleness
- replicas may differ with respect to (number and order) of performed update operations

conit: consitency unit ☐ specifies the data unit over which consistency is to be enforced.

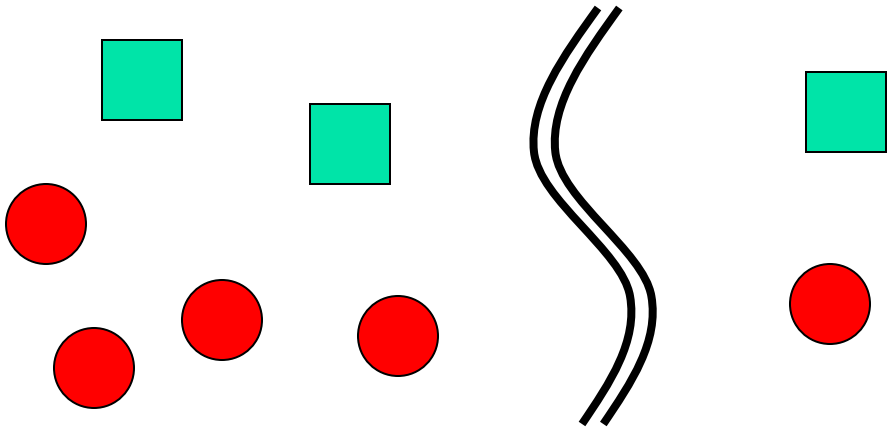
Limitations of Consistency Mechanisms Based on Request Ordering



Option 1:	**accept reads**	**accept reads**
	reject writes	**reject writes**
Option 2:	**accept reads**	**reject reads**
	accept writes	**reject writes**

Effects of Continuous Consistency

Policy: each replica can buffer up to 5 writes

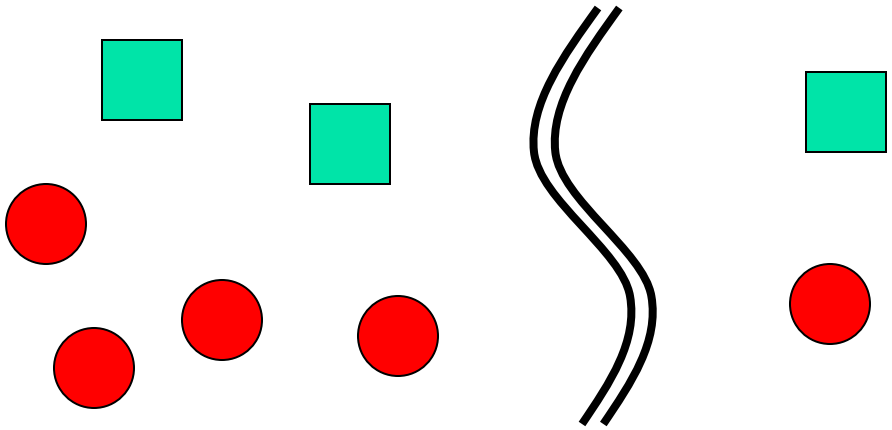


Option 1: accept reads, reject writes — accept reads, reject writes

New Option 1: accept reads, accept first 10 writes — accept reads, accept first 5 writes

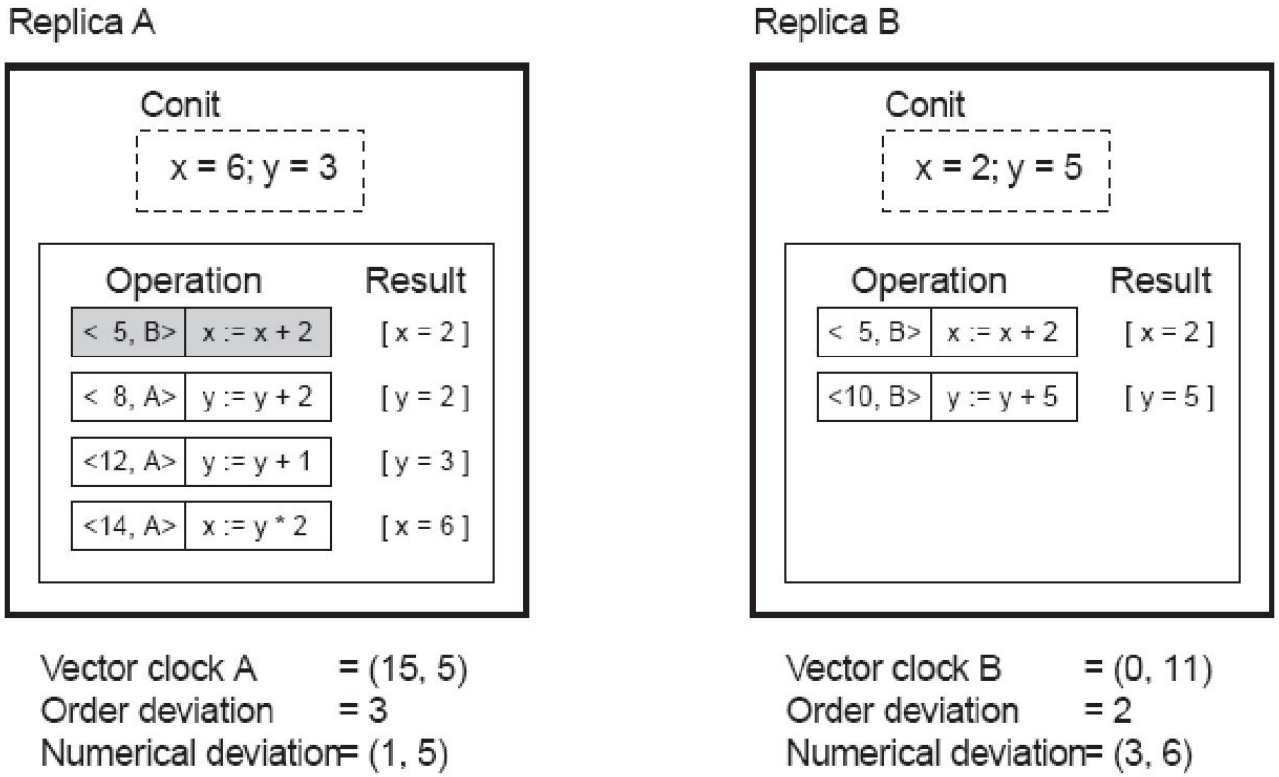
Effects of Continuous Consistency

Policy: each replica can buffer up to 5 writes



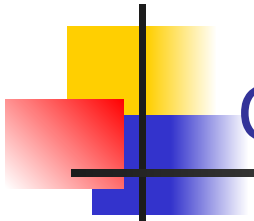
Option 2: reads	accept reads	reject
writes	accept writes	reject
New Option 2: reads	accept reads	accept first few
writes	accept writes	accept first 5

Example



Conit: contains the variables *x* and *y*:

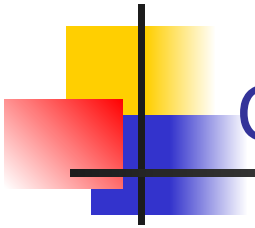
- Each replica maintains a **vector clock**
- *B* sends *A* operation [<5,*B*>: *x* := *x* + 2]; *A* has made this operation **permanent** (cannot be rolled back)
- *A* has three **pending** operations ☐ order deviation = 3



Consistency **protocols**

Question: How does one design the protocols to implement the desired consistency model**?**

- Data centric
  - Constraints on operation ordering at the data-store level
    - Sequential consistency.
  - **Continuous consistency: limit the deviation between replicas**



Continuous Consistency

Obs1: We can talk a about a degree of consistency

- Goal: Limit the deviation between replicas

Obs2: Multiple metrics to measure deviation

- replicas may differ in their numerical value
- replicas may differ in their relative staleness
- replicas may differ with respect to (number and order) of performed update operations

Continuous Consistency: Bounding Numerical Errors (I)

Setup: consider a conit (data item) *x* and let *weight(W(x))* denote the numerical change in its value after a write *W*.

- [for simplicity] Assume that for all *W(x), weight*(*W*) > 0

- *W* is initially forwarded to one of the *N* replicas: the *origin*(*W*).

- *TW*[*i, j*] are the writes executed by server S_i that originated from S_j
  $TW[i, j]=\Sigma \{weight(W)|\ origin(W)=S_j\ \&\ W\ \ in\ \ log(S_i)\}$

Note: Actual value of *x*: v_i *:* value of *x* at replica *i*

$$v(t) = v_{init} + \sum_{k=1}^{N} TW[k,k]$$

$$v_i = v_{init} + \sum_{k=1}^{N} TW[i,k]$$

Continuous Consistency: Bounding Numerical Errors (II)

Reminder: *TW*[*i*, *j*] writes executed by server S_i originated at S_j

Actual value of *x*:

$$v(t) = v_{init} + \sum_{k=1}^{N} TW[k,k]$$

v_i : value of *x* at replica *i*

$$v_i = v_{init} + \sum_{k=1}^{N} TW[i,k]$$

Goal: need to ensure that $v(t) - v_i < d$ for every S_i.

Continuous Consistency: Bounding Numerical Errors (II)

Reminder: $TW[i, j]$ writes executed by server S_i originated at S_j

Actual value of x:

$$v(t) = v_{init} + \sum_{k=1}^{N} TW[k,k]$$

v_i : value of x at replica i

$$v_i = v_{init} + \sum_{k=1}^{N} TW[i,k]$$

Goal: need to ensure that $v(t) - v_i < d$ for every S_i.

Approach: Let every server S_k maintain a **view** $TW_k[i, j]$ for what S_k believes is the value of $TW[i, j]$.

- This information can be piggybacked when an update is propagated.

Note: $0 \le TW_k[i, j] \le TW[i, j] \le TW[j, j]$

Reminder: $TW[i, j]$ writes executed by server S_i originated at S_j

Actual value of x:

$$v(t) = v_{init} + \sum_{k=1}^{N} TW[k,k]$$

v_i : value of x at replica i

$$v_i = v_{init} + \sum_{k=1}^{N} TW[i,k]$$

Goal: need to ensure that $\sum_{\substack{k=1 \\ k \neq i}}^{N} (TW[k,k] - TW[i,k]) < d$

then, as an approximate bound: $TW[k,k] - TW[i,k] < \frac{d}{N-1}$

for all k

Approach: Let every server S_k maintain a **view** $TW_k[i, j]$ for what S_k believes is the value of $TW[i, j]$.

- This information can be piggybacked when an update is propagated.

Note1: $0 \leq TW_k[i, j] \leq TW[i, j] \leq TW[j, j]$

Note2: $TW_k[i, k]$: view at node K about updates inserted at k and propagated to I

Reminder: $TW[i, j]$ writes executed by server S_i originated at S_j

Actual value of x: v_i : value of x at replica i

$$v(t) = v_{init} + \sum_{k=1}^{N} TW[k,k] \qquad v_i = v_{init} + \sum_{k=1}^{N} TW[i,k]$$

Goal: need to ensure that $v(t) - v_i < d$ for every S_i.

Approach: Let every server S_k maintain a **view** $TW_k[i, j]$ for what S_k believes is the value of $TW[i, j]$.

- This information can be piggybacked when an update is propagated.

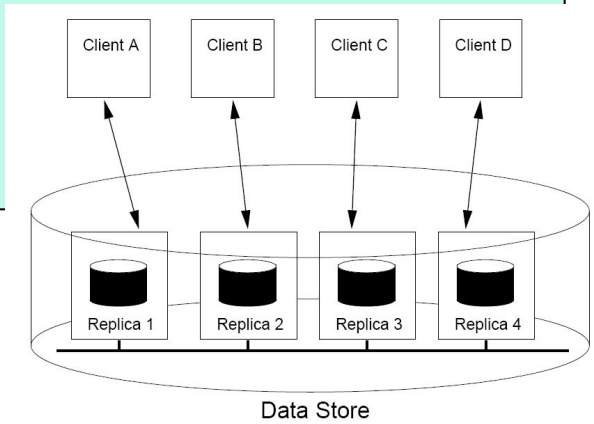
Solution: S_k sends operations from its log to S_i when it sees that $TW_k[i, k]$ is getting too far from $TW[k, k]$,

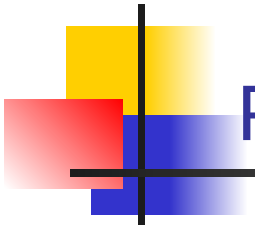
- in particular, when $TW[k, k] - TW_k[i, k] > d/(N - 1)$.

Note: Staleness can be done analogously, by essentially keeping track of what has been seen last from S_k

Consistency models: contracts between the data store and the clients

- Data centric: solutions at the data store level
  - Continuous consistency
    - limit the deviation between replicas, or
  - Eventual consistency
  - Models based on ordering of operations
    - Constraints on operation ordering at the data-store level
- Client centric
  - Assume client-independent views of the datastore
  - Constraints on operation ordering for each client independently





Rodamap

Issue 1. Dealing with data changes

- Consistency models
  - What is the semantic the system implements
  - (luckily) applications do not always require strict consistency
- Consistency protocols
  - How to implement the semantic agreed upon?

Issue 2. Replica management

- How many replicas?
- Where to place them?
- When to get rid of them?

Issue 3. Redirection/Routing

- Which replica should clients use?

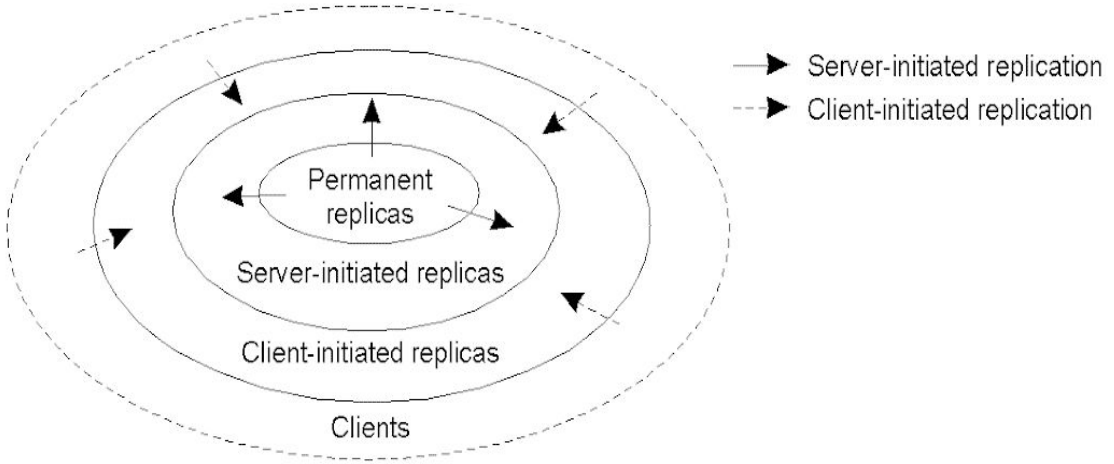
Replica server placement

Problem: Figure out what the best *K* places are out of *N* possible locations.

- Select best location out of *N – j, j:0..K-1* for which the average distance to clients is minimal. Then choose the next best server.
  - (Note: The first chosen location minimizes the average distance to all clients.)
  - Computationally expensive.
- Select the *k* largest autonomous system and place a server at the best-connected host.
  - Computationally expensive.
- Position nodes in a *d*-dimensional geometric space, where distance reflects latency. Identify the *K* regions with highest density and place a server in every one.
  - Computationally cheap.

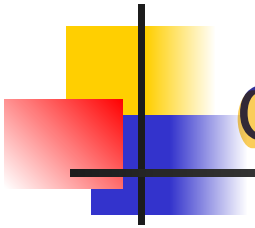
Content replicat

Model: We consider
(don't worry whether t



Distinguish different processes: A process is capable of hosting a replica of an object :

- Permanent replicas: Process/machine always having a replica (the discussion so far!)
- Server-initiated replica: Process that can dynamically host a replica on request of another server in the data store
- Client-initiated replica: Process that can dynamically host a replica on request of a client (**client caches**)

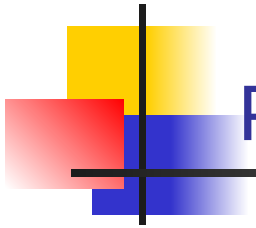


Client initiated replicas (caches)

Issue: What do I propagate when content is dynamic?
State vs. operations

- Propagate only notification/invalidation of update (often used for web caches)
- Transfer data from one copy to another (often for caching in distributed databases)
- Propagate the update operation to other copies (similar to active replication)

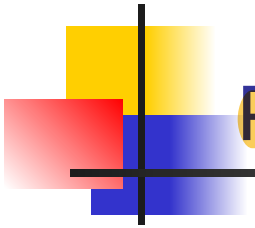
Note: No single approach is the best, but depends highly on (1) available bandwidth and read-to-write ratio at replicas; (2) consistency model



Propagating updates (1/2)

- Pushing updates: server-initiated approach, in which the update is propagated regardless of whether the target asked for it.
- Pulling updates: client-initiated approach, in which client requests to be updated.

Issue	**Push-based**	**Pull-based**
State of server	List of client replicas and caches	None
Messages sent	Update message (and possibly fetch update later)	Poll and update
Response time at client	Immediate (or fetch-update time)	Fetch-update time



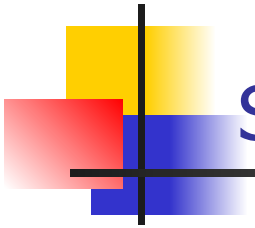
Propagating updates: Leases (2/2)

Observation: We can *dynamically* switch between pull and push using **leases**:

- *Lease: A contract in which the server promises to push updates to the client until the lease expires.*

Additional Technique: Make lease expiration time dependent on system's behavior (adaptive leases):

- **Age-based leases**: An object that hasn't changed for a long time, will not change in the near future, so provide a long-lasting lease
- **Renewal-frequency based leases**: The more often a client requests a specific object, the longer the expiration time for that client (for that object) will be
- **State-based leases**: The more loaded a server is, the shorter the expiration times become



Summary

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- Consistency models
  - What is the semantic the system implements
  - (luckily) applications do not always require strict consistency
- Consistency protocols
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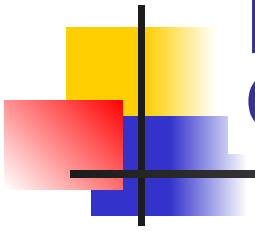
- When to get rid of them?

Issue 3. Client Side Caching

- How to deal with client initiated replication



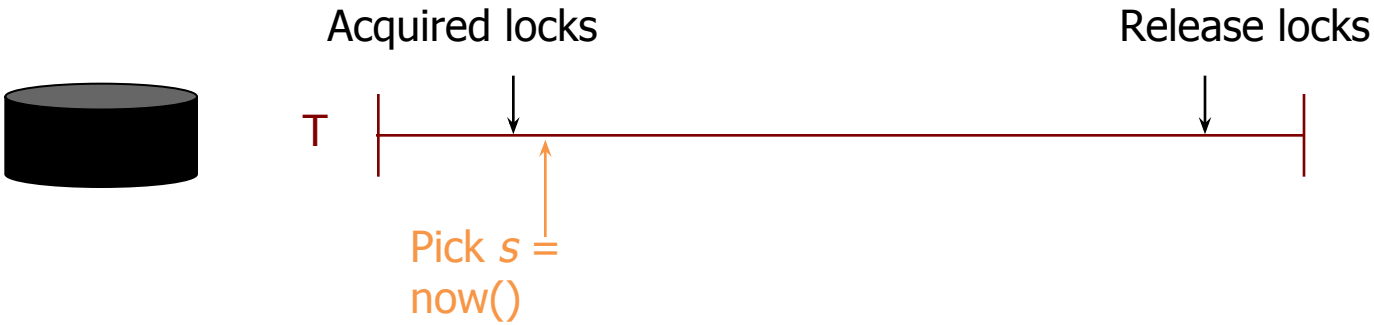
[Intuition for] Google's spanner (much simplified)

- Goal: provide linearizability (external consistency)
- Context: slightly different
  - distributed transactions (rather than replication)

- Key issue: how to execute transactions and assign timestamps such that
  - "order reflects the order in which the transactions *appear* to execute to an external observer (e.g., an application)."
- Key innovation:
  - Atomic clocks and reasoning about time uncertainty.

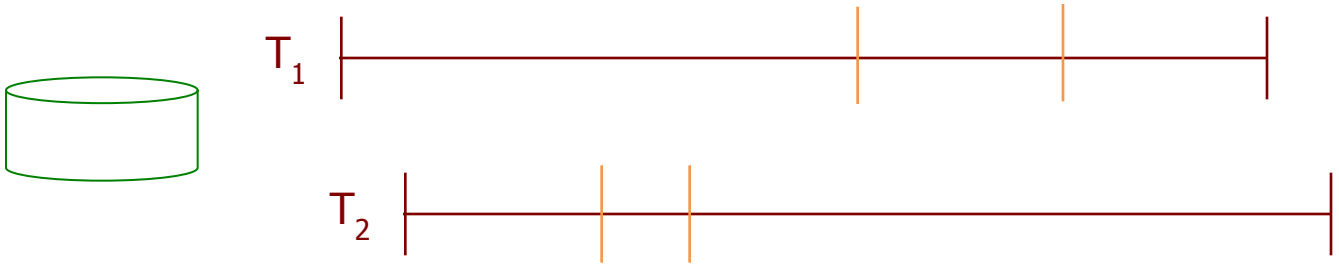
[Google's spanner] Timestamps, Global Clock

- Strict two-phase locking for write transactions
- Assign timestamp while locks are held

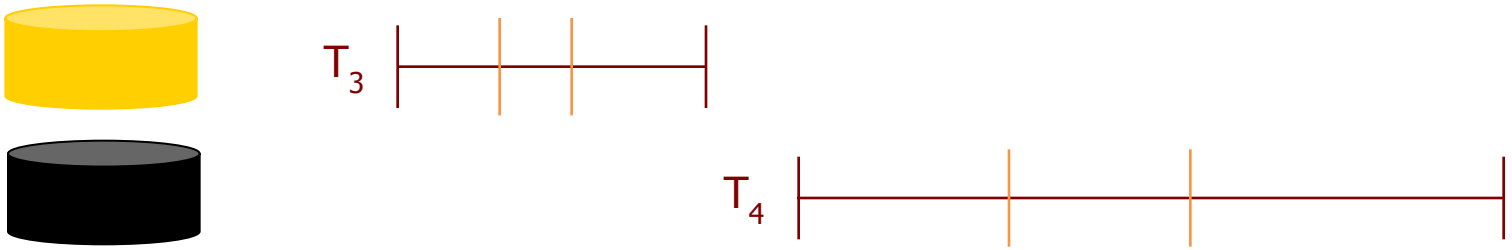


Timestamp Invariants

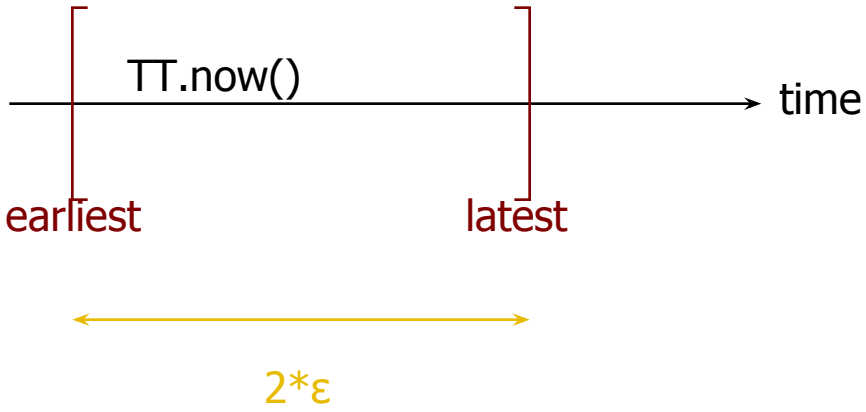
- Timestamp order == commit order



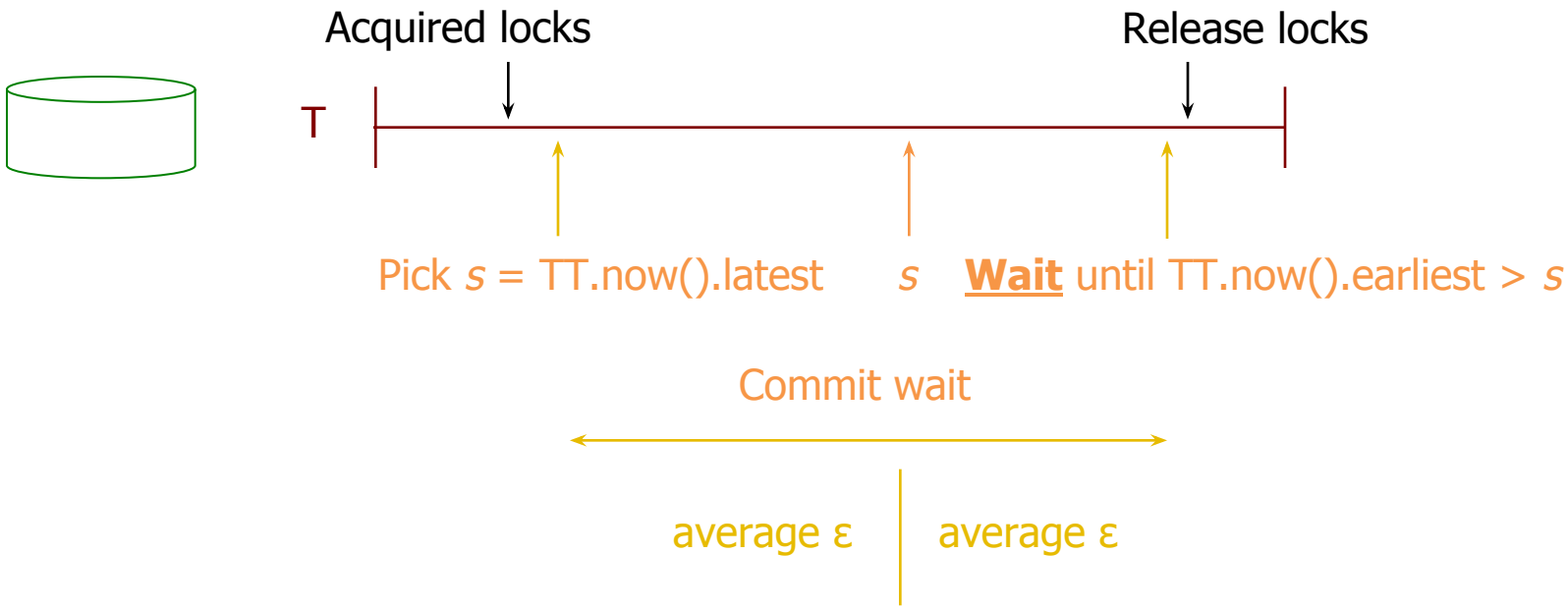
- Timestamp order respects global wall-time order



- TrueTime: "Global wall-clock time" with bounded uncertainty



Timestamps and TrueTime



1. Each processor issues requests in the order specified by the program
   - Do not issue the next request unless the previous one has finished

2. Requests to an individual memory location are served from a single FIFO queue
   - Writes occur in a single order
   - Once a read observes the effect of a write, it's ordered behind that write