Distributed Systems
CS6421
Consistency and Replication

Prof. Tim Wood and Prof. Roozbeh Haghnazar

Includes material adapted from Van Steen and Tanenbaum's Distributed Systems book

Final Project

Questions?

- Design Document
  - Proposed Design
  - UML Diagrams describing architecture and communication
  - Work timeline with breakdown by team member

- Schedule meetings with us!

- Timeline
  - Milestone 0: Form a Team - 10/12
  - Milestone 1: Select a Topic - 10/19
  - Milestone 2: Literature Survey - 10/29
  - **Milestone 3: Design Document - 11/5**
  - Milestone 4: Final Presentation - 12/14

https://gwdistsys20.github.io/project/

Last Time…

- Fault Tolerance
  - Types of Failures
  - Two Generals Problem
  - Fault Tolerance Algorithms
  - Centralized FT: Raft/Paxos

This Time…

- Replication and Consistency
  - Why replicate
  - What is consistency?
  - Consistency Models
  - Quorum Replication

Next Time: Exam!

DistSys Challenges

- **Heterogeneity**
- Openness
- **Security**
- **Failure Handling**
- Concurrency
- **Quality of Service**
- **Scalability**
- **Transparency**

Any questions about these? You will need to relate your project to them and they will be on the exam!

Problem

- Given that synchronization and locking is so difficult, do we really need it in a distributed system?

- Is there a better way?

Reasons for Replication

- Data are replicated to increase the reliability of a system.
- Replication for performance
    - Scaling in numbers
    - Scaling in geographical area
- Caveat
    - Gain in performance
    - Cost of increased bandwidth for maintaining replication

Reasons for Replication

- Reliability.
- Performance.

- Replication is the solution.

How do we keep them up-to-date?
How do we keep them consistent?

More on Replication

- Replicas allows remote sites to continue working in the event of local failures.
- It is also possible to protect against data corruption.
- Replicas allow data to reside close to where it is used.
- This directly supports the distributed systems goal of enhanced *scalability*.
- Even a large number of replicated “local” systems can improve performance: think of clusters.

- So, what’s the catch?

- It is not easy to keep all those replicas *consistent*.

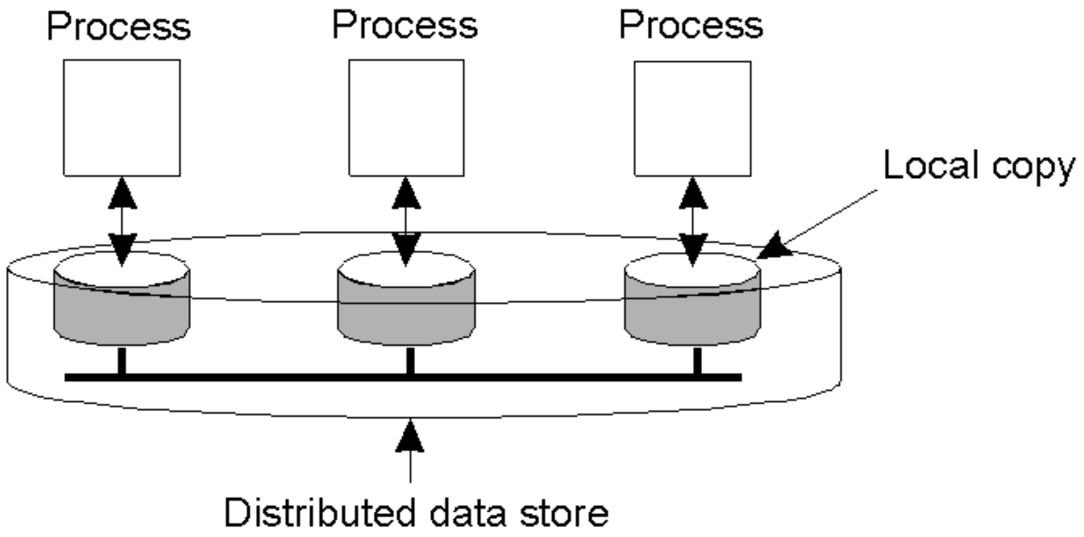
CONSISTENCY MODELS

- What is a consistency model?
  - It is an agreement and contract between a distributed data store and related processes.

- Data-Centric
  - Continuous
  - Consistent ordering of operation
    - Sequential
    - Causal
- Client-Centric

Data-Centric Consistency Models

- A data-store can be read from or written to by any process in a distributed system.
- A local copy of the data-store (replica) can support "fast reads".
- However, a write to a local replica needs to be propagated to *all* remote replicas.



CONTINUOUS CONSISTENCY

- There are different ways for applications to specify what inconsistencies they can tolerate.
- Yu and Vahdat [2002] take a general approach by distinguishing three independent axes for defining inconsistencies:
  - deviation in numerical **values** between replicas
  - deviation in **staleness** between replicas
  - deviation with respect to the **ordering** of update operations
- They refer to these deviations as forming ***continuous consistency*** ranges.

EXAMPLE OF NUMERICAL DEVIATIONS

Company	Stock price
Apple	$1100.00

+0.02
+0.03

Company	Stock price
Apple	$1100.00

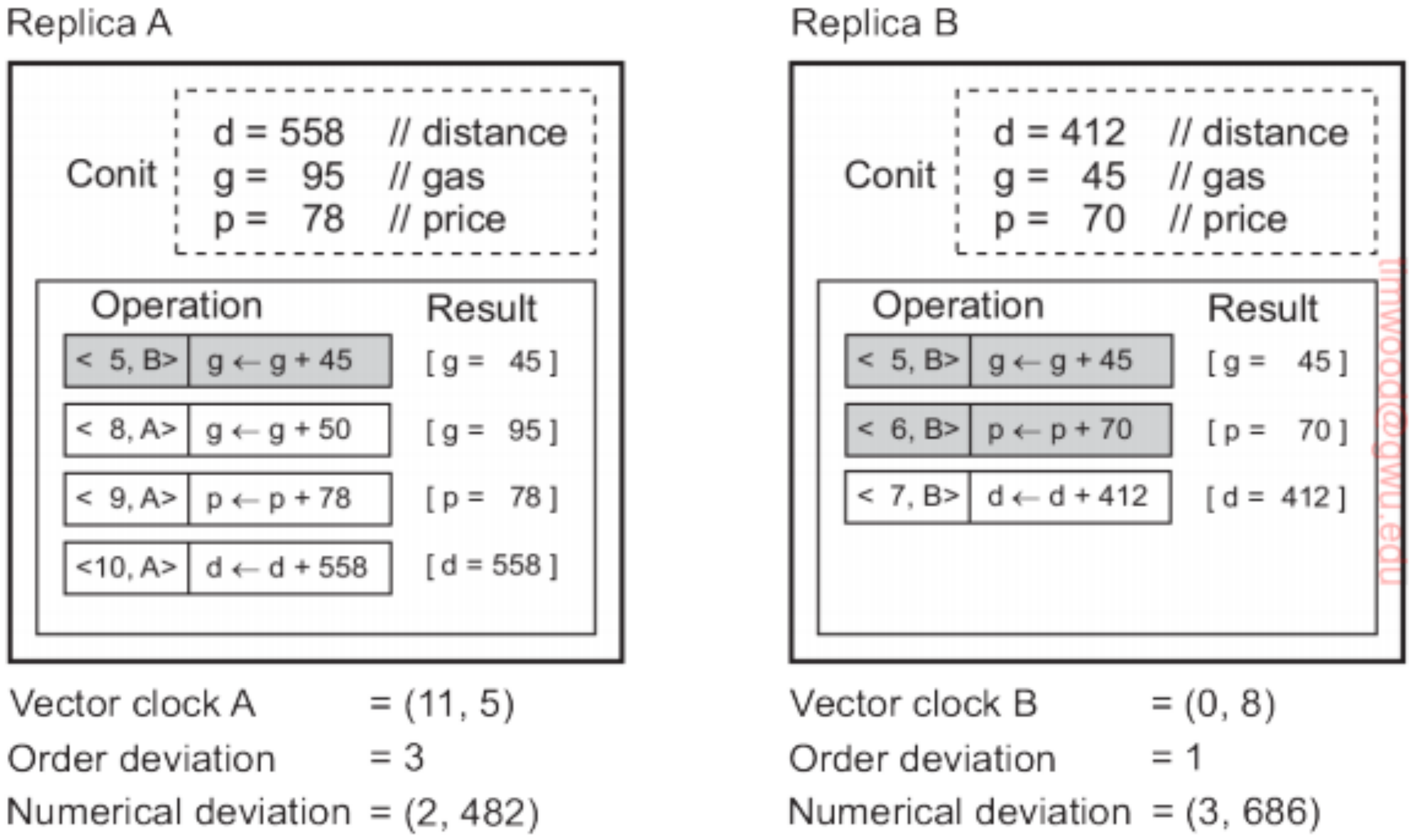
+0.03

Company	Stock price
Apple	$1100.00

+0.03

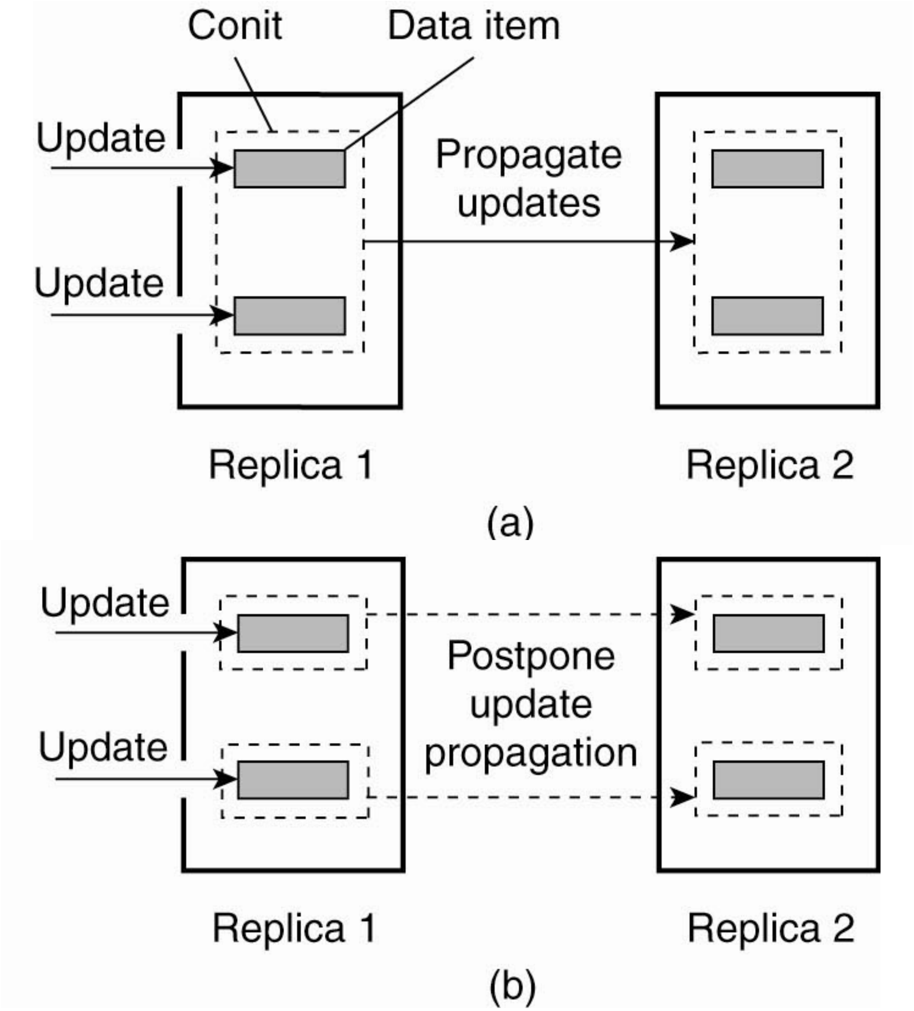
Continuous Consistency

- Each replica server maintains a two-dimensional vector clock



CONTINUOUS CONSISTENCY

- Choosing the appropriate granularity for a conit.
  - (a) Two updates lead to update propagation.
  - (b) No update propagation is needed



Consistent ordering of operations

- Sequential consistency
- Causal consistency
- Grouping operations

Consistency Models

Consistency versus coherence

- A consistency model describes what can be expected when multiple processes concurrently operate on a set of data. The set is then said to be consistent if it adheres to the rules described by the model.

- Where data consistency is concerned with a set of data items, coherence models describe what can be expected to hold for only a single data item [Cantin et al., 2005].

- In this case, we assume that a data item is replicated; it is said to be coherent when the various copies abide to the rules as defined by its associated consistency model.

Consistency Model Diagram Notation

$W_i(x)a$ – a write by process ‘i’ to item ‘x’ with a value of ‘a’. That is, ‘x’ is set to ‘a’.

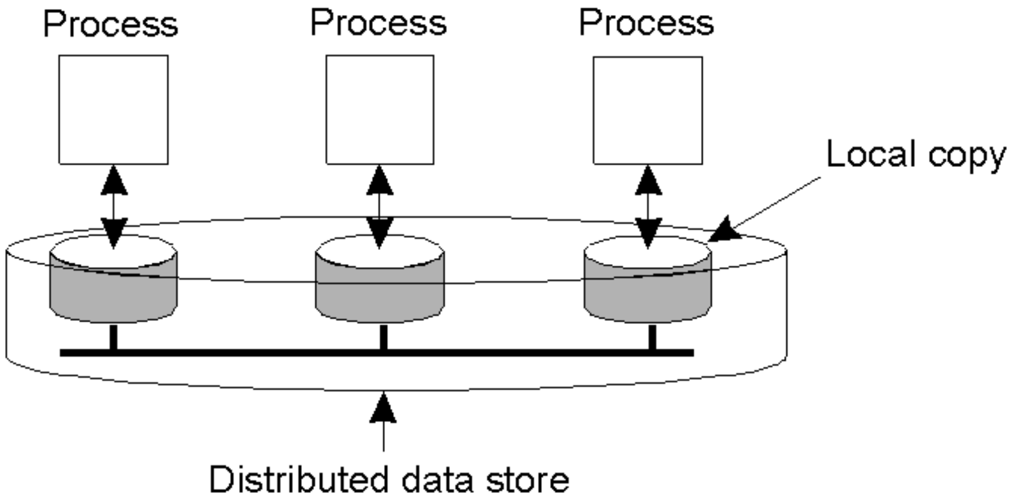
$R_i(x)b$ – a read by process ‘i’ from item ‘x’ producing the value ‘b’. That is, reading ‘x’ returns ‘b’.

Time moves from left to right in all diagrams.

Set x=a

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

Read x
Got b



Sequential Consistency

- The result of any execution is the same as if the operations of **all processes** were executed in some sequential order, and
- The operations of each individual process appear in this sequence in the order specified by its program.

Any ordering of reads/writes is fine, but all processes must see the same ordering

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

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

Which are sequentially consistent?

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P3:			R(x)b	R(x)a
P4:			R(x)a	R(x)b

Which are sequentially consistent?

Causal Consistency

- Writes that are potentially causally related must be seen by all processes in the same order.
- Concurrent writes may be seen in a different order by different processes.

Reading a value means your future writes may be causally related to that operation!

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

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

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

Causal Consistency

- Writes that are potentially causally related must be seen by all processes in the same order.
- Concurrent writes may be seen in a different order by different processes.

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

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

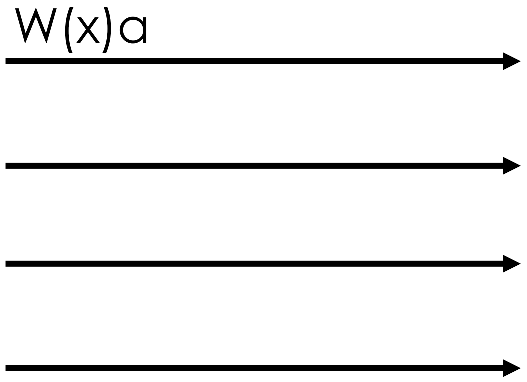
P1:	W(x)a				
P2:			W(x)b		R(x)c
P3:		W(x)c		R(x)b	R(x)a
P4:				R(x)a	R(x)b

Reading a value means your future writes may be causally related to that operation!

Consistency Problems

Breakout rooms with project group

- For each timeline, specify if it achieves Sequential, Causal, or neither



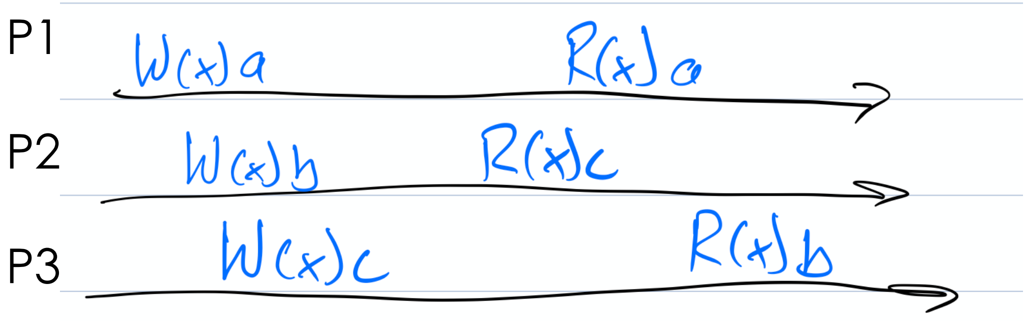
Writes that are potentially causally related must be seen by all processes in the same order. Concurrent writes may be seen in a different order by different processes.

- The result of any execution is the same as if the operations of **all processes** were executed in some sequential order, and

Group Problems

Is each timeline **Sequential**, **Causal**, or **Neither**?

A



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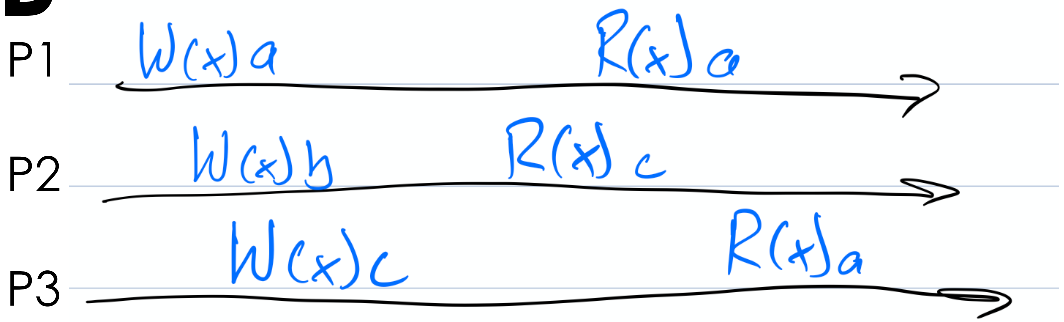

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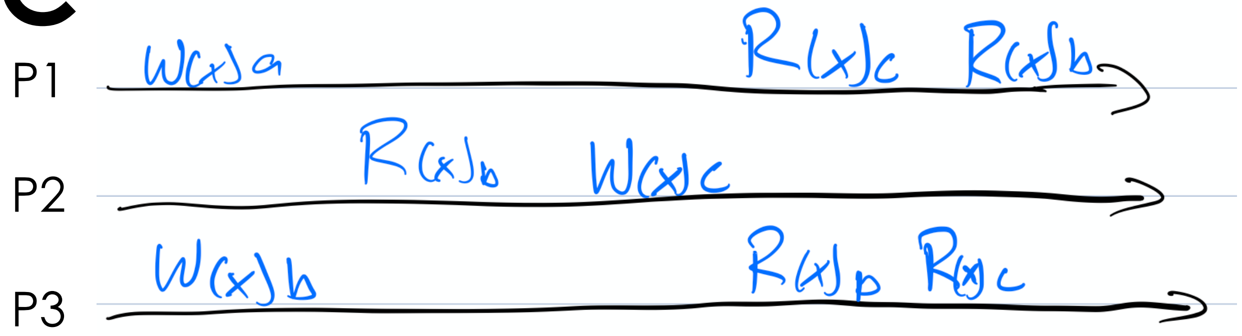

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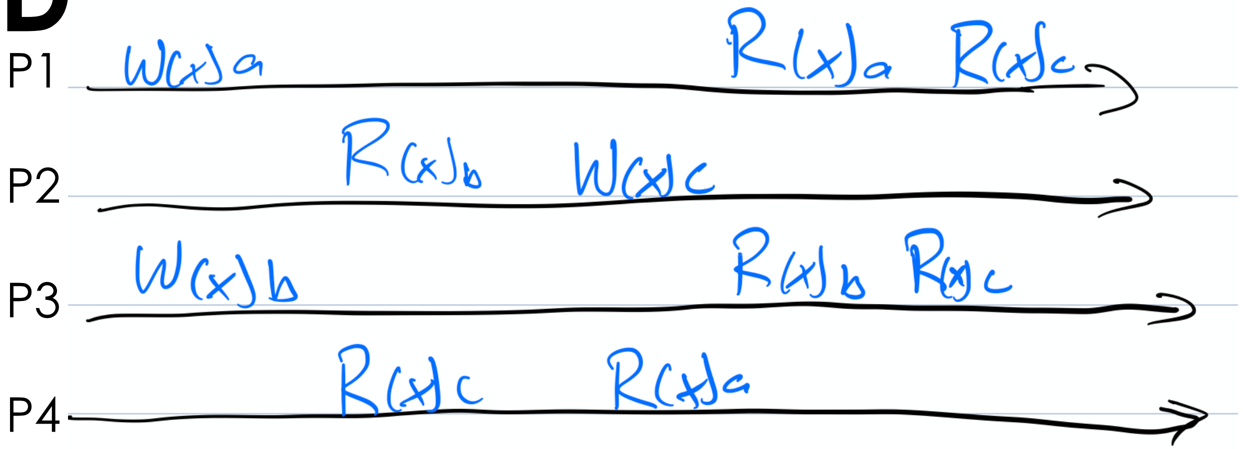
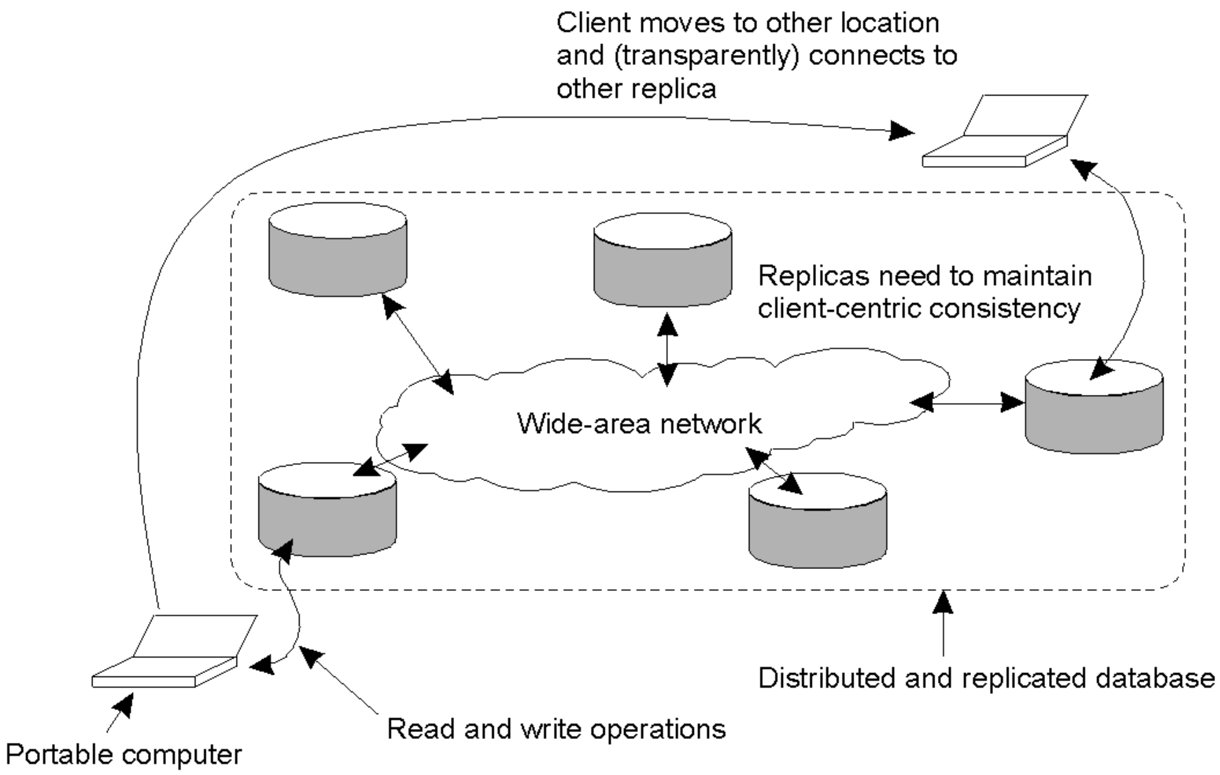


Eventual consistency

- The only requirement is that all replicas will *eventually* be the same.
- All updates must be guaranteed to propagate to all replicas … *eventually*!
- This works well if every client always updates the same replica.
- Things are a little difficult if the clients are *mobile*.

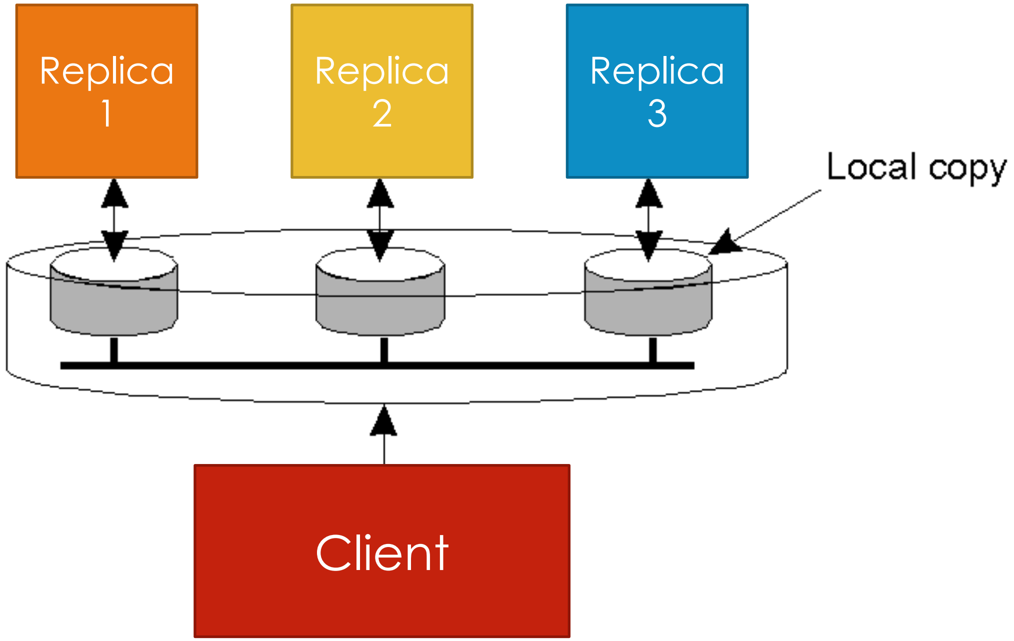
Eventual Consistency: Mobile Problems

- The principle of a mobile user accessing different replicas of a distributed database.
- When the system can guarantee that a single client sees accesses to the data-store in a consistent way, we then say that "client-centric consistency" holds.



Client-Centric Consistency Models

- **Monotonic Reads**: Reads never go backwards
- **Monotonic Writes**: Writes never go backwards
- **Read your Writes**: My own writes must be visible
- **Writes follow reads**: If a write is based on a read, it must happen after it



What does the client see?

Client-Centric Consistency Models

- **Monotonic Reads**: If a process reads the value of a data item *X*, any subsequent read operation on *X* by that process will always return that same value or a more recent value

Example

Automatically reading your personal calendar updates from different servers. Monotonic Reads guarantees that the user sees all updates, no matter from which server the automatic reading takes place.

Example

Reading (not modifying) incoming 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.

Client-Centric Consistency Models

- **Monotonic Writes**: A write operation by a process on a data item *X* is completed before any successive write operation on *X* by the same process.

Example

Updating a program at server S_2, and ensuring that all components on which compilation and linking depends, are also placed at S_2.

Example

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

Client-Centric Consistency Models

- **Read your Writes**: The effect of a write operation by a process on data item *X*, will always be seen by a successive read operation on *X* by the same process.

Example

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

Client-Centric Consistency Models

- **Writes follow reads**: A write operation by a process on a data item *X* following a previous read operation on *X* by the same process, is guaranteed to take place on the same or a more recent value of *X* that was read.

Example

If I read and then comment on an article, nobody should see my comment until after they see the article

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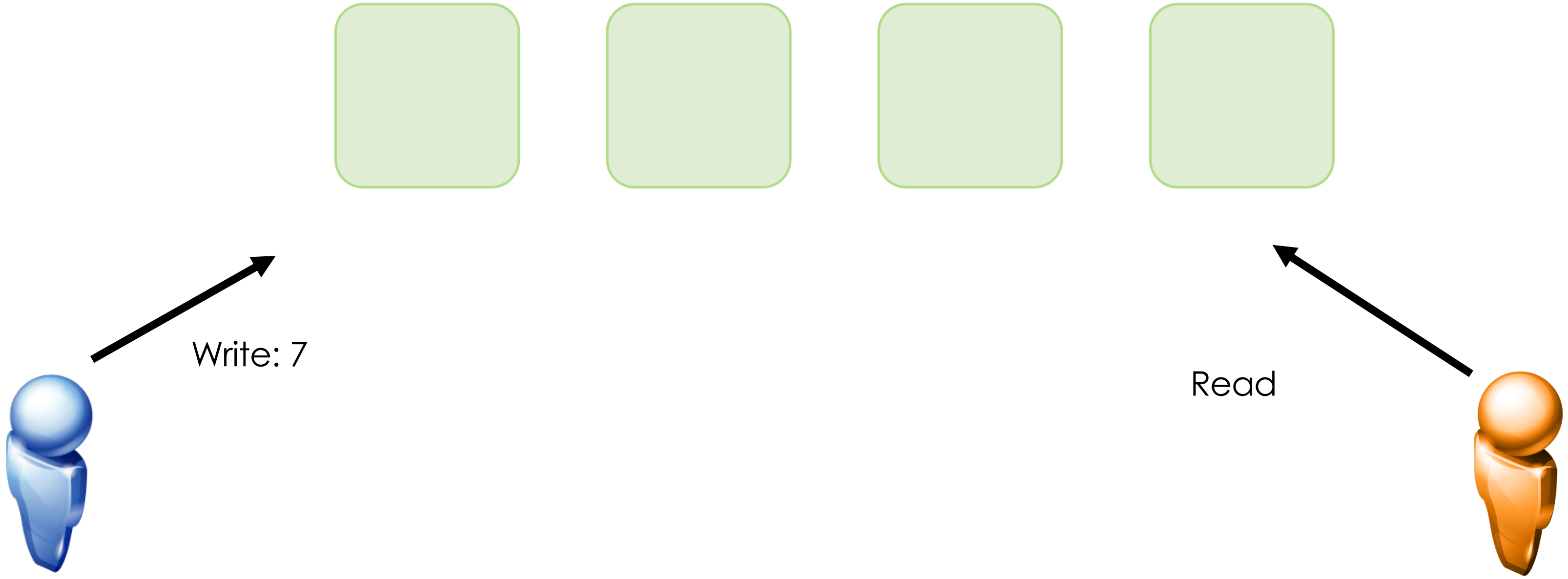
Quorum Replication

Quorum Based Systems

- Quorum: a set of responses that agree with each other of a particular size
- Crash fault tolerance: Need a quorum of **1**
  - **f** others can fail (thus need f+1 total replicas)
- Data fault tolerance: Need a quorum **f+1**
  - **f** others can fail (thus need 2f+1 total replicas)
  - Need a majority to determine correctness

Quorum

- 4 Replicas
  - Some nodes might be temporarily offline
- How many replicas to send to for a read or write?
  - Must wait for a response from each one



Dynamo DB

- Object Store from Amazon
  - Technical paper at SOSP 2007 conference (top OS conference)
- Stores **N** replicas of all objects
  - But a replica could be out of date!
  - Might be saved across multiple data centers
  - Gradually pushes updates to all replicas to keep in sync
- When you read, how many copies, **R**, should you read from before accepting a response?
- When you write, how many copies, **W**, should you write to before confirming the write?

DYNAMO DB

- Read and Write Quorum size: how will the system behave?
- R=1
- W = 1
- R = N/2+1
- R=1, W = N
- R=N, W=1

Dynamo DB

- Read and Write Quorum size:

- R=1 — fastest read performance, no consistency guarantees
- W = 1 — fast writes, reads may no be consistent
- R = N/2+1 (reading from majority)
- R=1, W = N - slow writes, but reads are consistent
- R=N, W=1 - slow reads, fast writes, consistent
- Standard: N=3, R=2, W=2
  - Ensures overlap

QUORUM

- How do N, R, and W affect:
- **Performance:**
- **Consistency:**
- **Durability:**
- **Availability:**

DynamoDB lets the user tune these for their needs

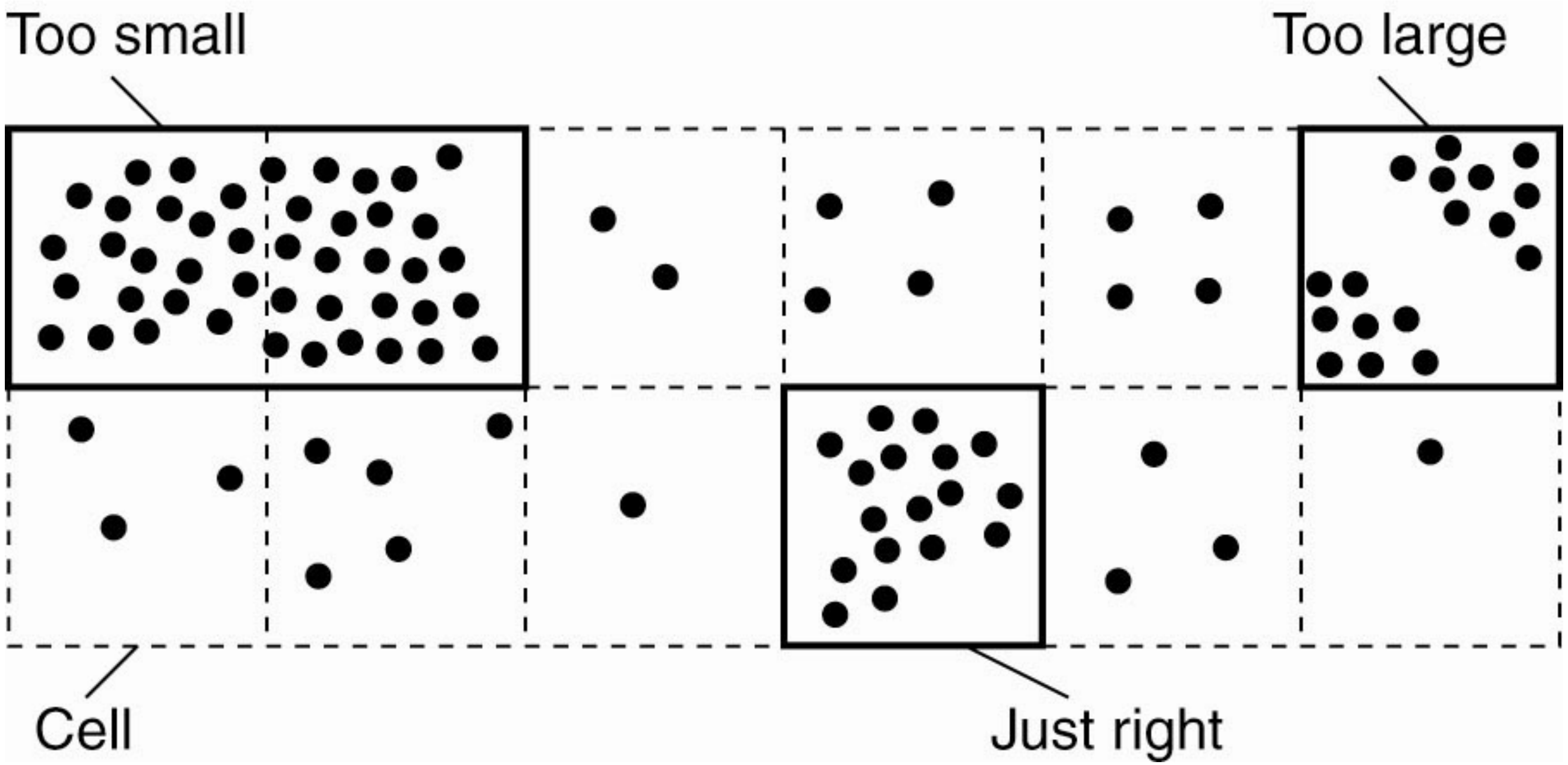
QUORUM

- How do N, R, and W affect:
- **Performance:**
  - low R or W -> higher performance
  - for a fixed R or W: higher N gives higher performance
  - higher N means more synchronization traffic
- **Consistency:**
  - R + W > N — guarantees consistency
  - R+w << N — much less likely to be consistent
- **Durability:**
  - N=1 vs N=100, more N = more durability
- **Availability:**
  - Higher N or W => higher availability

Replica management

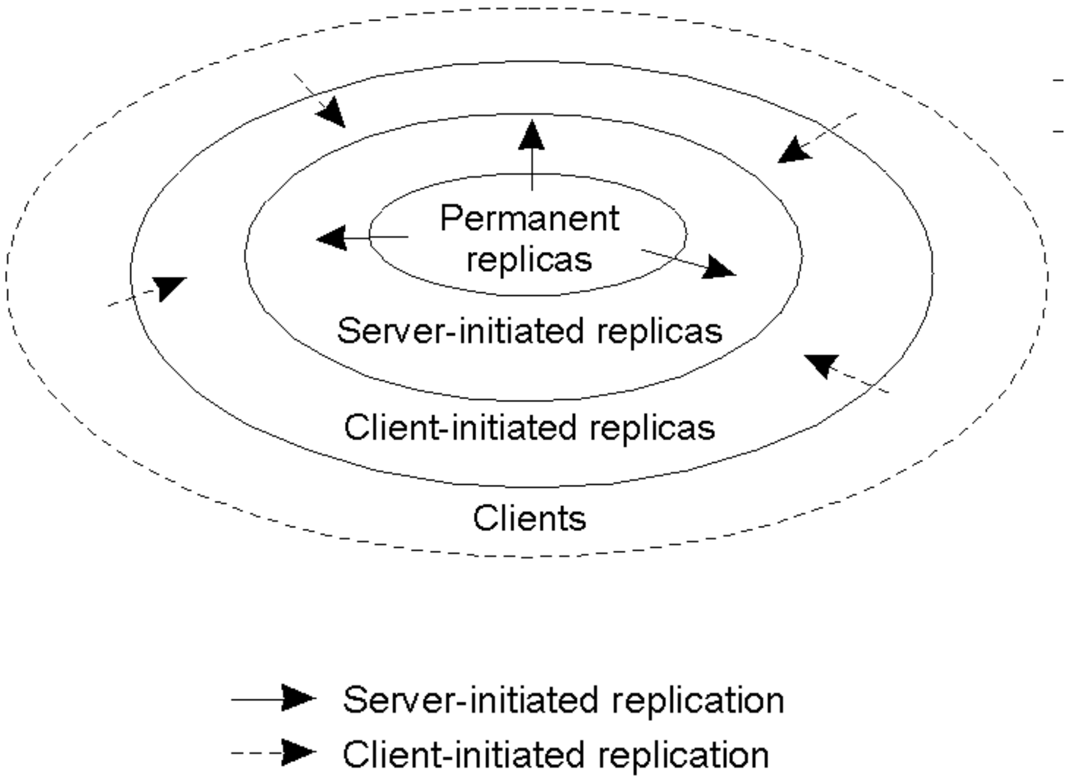
- A key issue for any distributed system that supports replication is to decide **where**, **when**, and by **whom** replicas should be placed, and subsequently which mechanisms to use for keeping the replicas consistent.
- The placement problem itself should be split into two subproblems:
  - placing replica servers
  - placing content

Finding the best server location



Content replication and placement

1. ***Permanent replicas***: tend to be small in number, organized as COWs (Clusters of Workstations) or mirrored systems.
2. ***Server-initiated replicas***: used to enhance performance at the initiation of the owner of the data-store. Typically used by web hosting companies to geographically locate replicas close to where they are needed most. (Often referred to as "push caches").
3. ***Client-initiated replicas***: created as a result of client requests – think of browser caches. Works well assuming, of course, that the cached data does not go *stale* too soon.



Exam

Exam Details – 11/12

- Exam will be during class Thursday November 12, 6:10-8:40PM
- Exam will be on Blackboard
- Exam will be open book and open notes as follows:
  - The Van Steen & Tanenbaum book
  - The slides presented in class
  - Any notes you wrote (typed/handwritten)
- You may **NOT** use any external websites
- You may **NOT** communicate with any other students/people outside class
- Sample questions are on website