Consistency Models

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Distributed Systems
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Overview

- Strong consistency models
- CAP rule and base methodology
- Partition-tolerant consistency models

Data consistency model

- Recall, a data consistency model describes the expected behavior from a storage system when clients access data
  - When clients issue get()/put(), what values can get() read?
- Benefits of consistency model
  - Allows reasoning about concurrency and failures
  - Abstracts network, node and timing models, replication
  - Helps with correct implement of applications, storage systems
- Now, we will see that consistency models make tradeoffs in application complexity, performance, availability
  - Informally: how system designer makes life harder for programmer, to make system faster …

Linearizability redux

- Linearizability: all processes execute operations in some total order, while preserving real-time ordering
  - Operations appear to occur instantaneously, consistent with program order, at some point in between invocation & response
- Linearizability provides strong consistency
  - All clients see same order of writes
  - All clients read latest data
- Strong consistency is intuitive for programmers
  - Same behavior as a machine processing one request at a time
  - Hides network, node, timing complexities in distributed systems

Issues with linearizability

- For linearizability, every read and write request involves communicating with a majority (quorum) of replicas
- Problem 1: low performance, high latency
  - With 5 replicas, every operation needs to communicate with 3 replicas
  - With leader-based algorithms, leader becomes bottleneck
- Problem 2: low availability
  - If a replica has stale data, it cannot serve any requests
  - If a replica is partitioned, it cannot serve any requests
  - If a majority of replicas are down, system is unavailable
- Takeaway: linearizability provides strong consistency but limits performance and availability

How to improve performance & availability?

- We need to allow accesses that may violate the strong consistency guarantees provided by linearizability

- Say a set of geographically distributed web servers cache data from a backend database server
  - Each data item may have copies (replicas) at the web servers
  - Ensuring that a response always returns the latest copy requires synchronization between all the caches and the database
  - Instead, a web server could directly return its cached item
  - This may occasionally return stale data, but it is faster, and it allows availability even when the database is unavailable or highly loaded

- Takeaway: need weaker consistency models for higher performance and availability

Sequential consistency

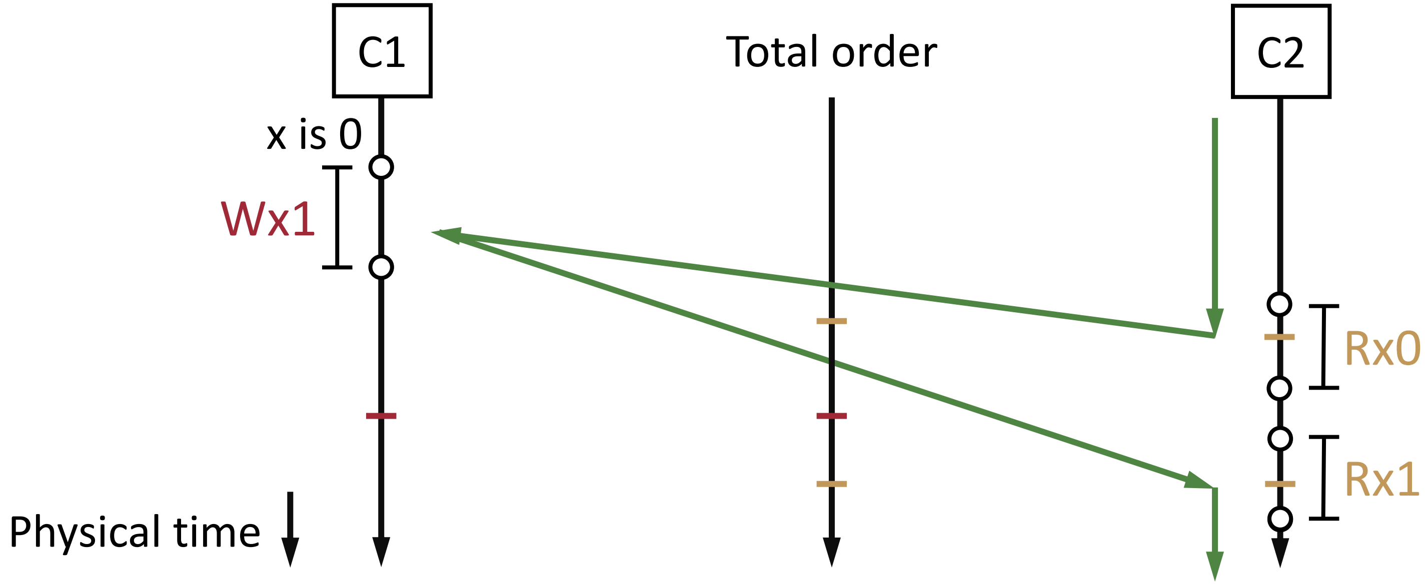
- Sequential consistency weakens linearizability by not providing any real-time guarantees

- Sequential consistency: all processes execute operations in some total order~~, while preserving real-time ordering~~
  - Operations appear to occur instantaneously, consistent with program order~~, at some point in between invocation & response~~

- Provides better performance than linearizability because operations across processes can be reordered (provided there is some total order)

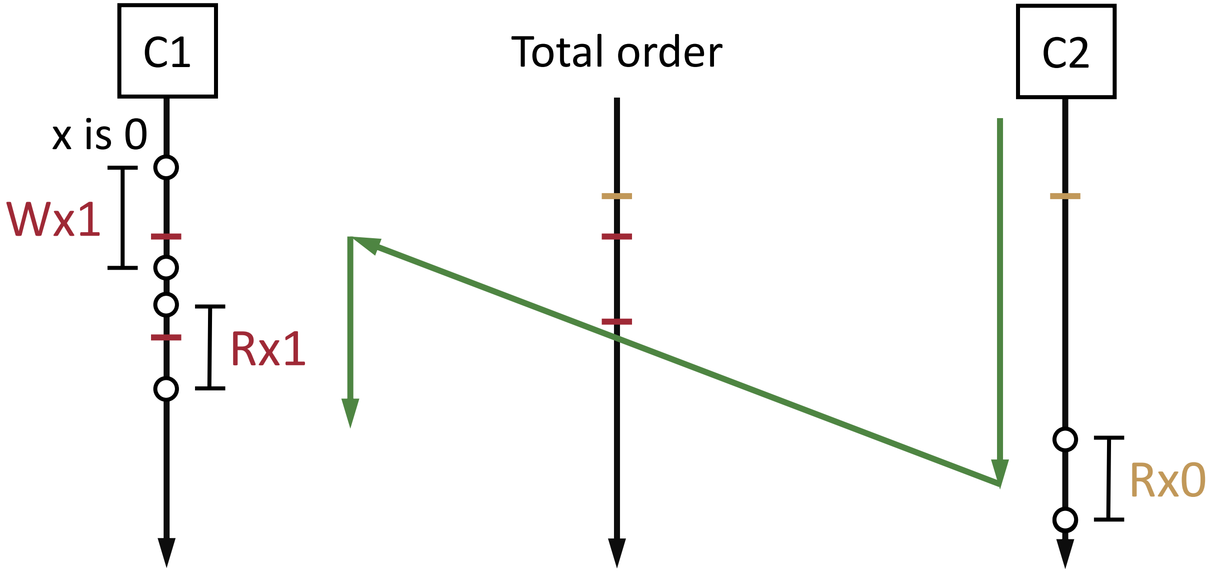
Sequential consistency - Example 1

- Sequentially consistent
- Writes may appear to be delayed



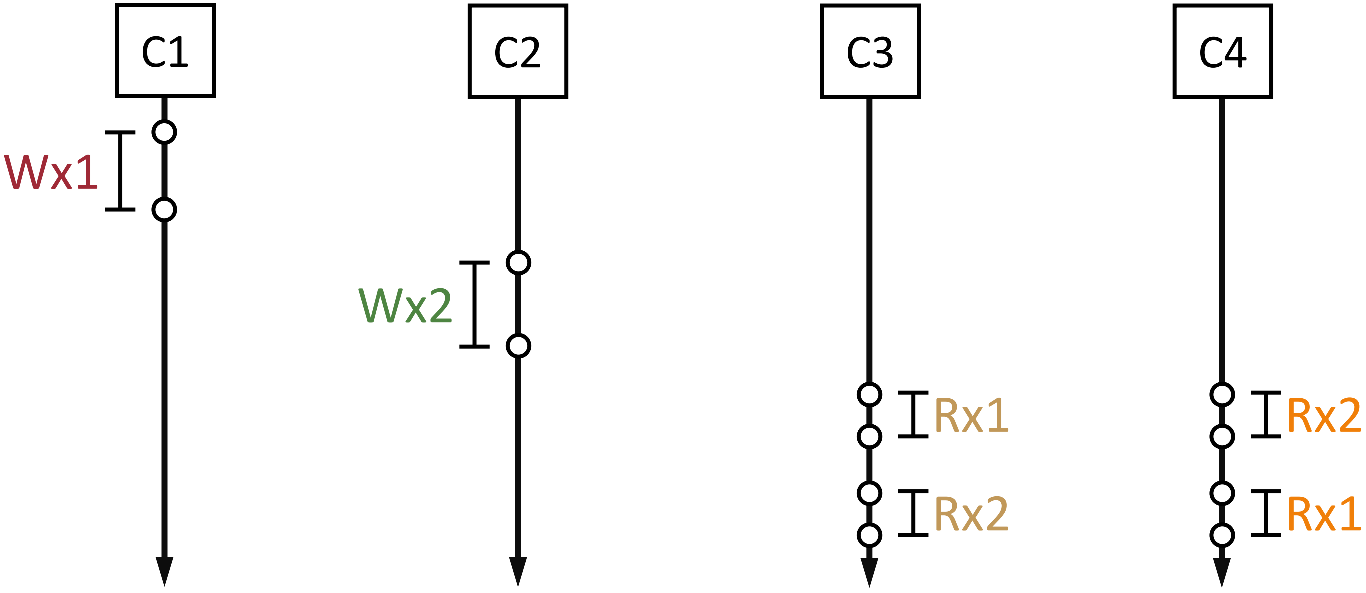
Sequential consistency - Example 2

- Sequentially consistent
- Reads may return stale data



Sequential consistency - Example 3

- Not sequentially consistent
- There is no possible total ordering of operations



Understanding sequential consistency

- There is a total ordering of operations, but
  - A write may be ordered much after its response (delayed write)
  - A read may return arbitrarily stale data (stale read)
- However, sequential consistency is still a strong model
  - Still ensures total order of operations
  - Once A observes data from B, A cannot observe B's prior state
- As we will see, Zookeeper provides consistency in between sequential consistency and linearizability
  - Improves performance, availability compared to linearizability, particularly for read-heavy workloads
- Problem: total order still limits availability

CAP Rule and Base Methodology

Amazon, Google Experiments (2006)

- Amazon found that every 100ms in added page load time cost them 1% in sales
  - Today, would lose over 5 billion!
- Google took 0.4s to generate a web page with 10 results, 0.9s to generate a page with 30 results
  - However, 0.5s delay caused a 20% drop in traffic!
- Conclusion: performance at scale determines revenue
  - And revenue shapes technology
  - An arms race began to improve cloud performance, availability

A sprint to render your web page!

In the Cloud, Not Every Subsystem Needs the Strongest Guarantees

- Brewer argued that strong consistency delays response
  - For example, conflicting database updates
    can be forced into an agreed order,
    but this takes time and involves
    node-node communication,
    and with a network partition,
    the system provides no availability

- But cloud services make money only when they always provide fast response, so they must relax consistency

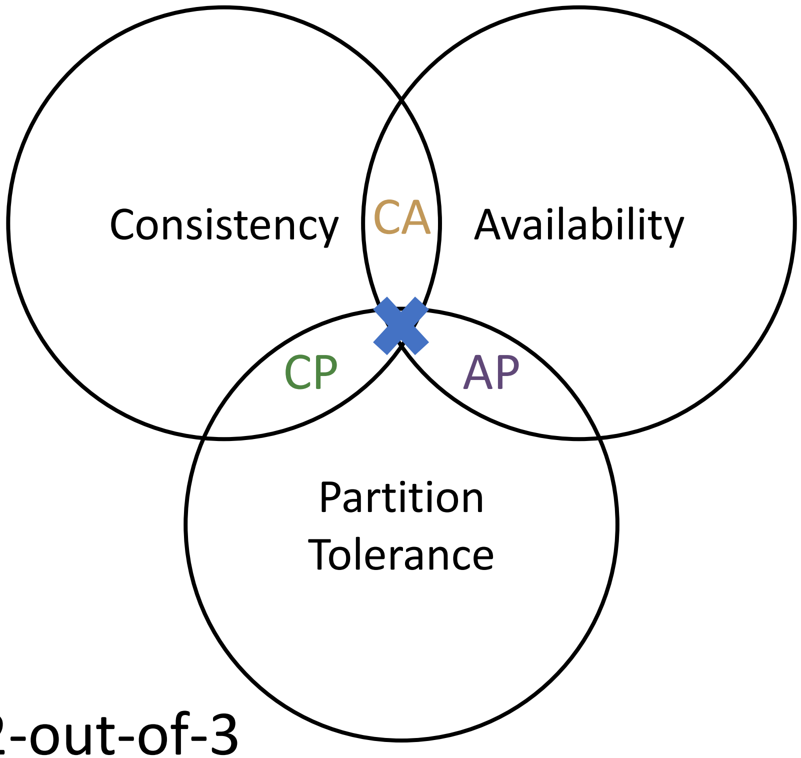
Examples of relaxing consistency

- Cache data in the application tier and serve it even when back-end database servers are unavailable, though cached data may be potentially stale
- Store a copy of data periodically (e.g., nightly) and use this read-only (potentially stale) data for analysis
- Allow delayed updates by enqueuing update tasks for later processing to amortize processing costs
- Guess the effects of updates and fix conflicts later, e.g., buy an item, eventually told it was sold out, get refund

CAP

- Brewer captured tradeoff between speed of response and consistency by postulating a rule that connects consistency, availability and partition tolerance (CAP)
- Consistency: Updates performed in some system-selected order by all replicas. Queries return most up-to-date values. Users see a single system.
- Availability: System responds to every user request, even when some nodes are down.
- Partition Tolerant: System can tolerate network failures between subsystems. E.g., machines are partitioned into separate subnets, and switch between the subnet fails.

Cap Rule



- You cannot achieve all three together:
  - Consistency
  - Availability
  - Partition-Tolerance
- Popular interpretation: choose 2-out-of-3
  - CA: Assumes partitions don't occur, not realistic
  - CP: poor availability, users unhappy
  - AP: hard to program, possibly confusing to users
- None of these options are appealing!

CAP rule in practice

- Partitions do occur, so systems must tolerate partitions
  - You cannot not choose partition tolerance …
  - But you can design systems to make them rare
- When there are no partitions,
  provide both consistency and availability
- When there is a partition, systems need to choose between consistency, availability
  - E.g., design systems that are best suited for application's consistency and availability needs
- When partition is fixed, restore consistency & availability
  - E.g., reconcile inconsistent replicas

BASE methodology

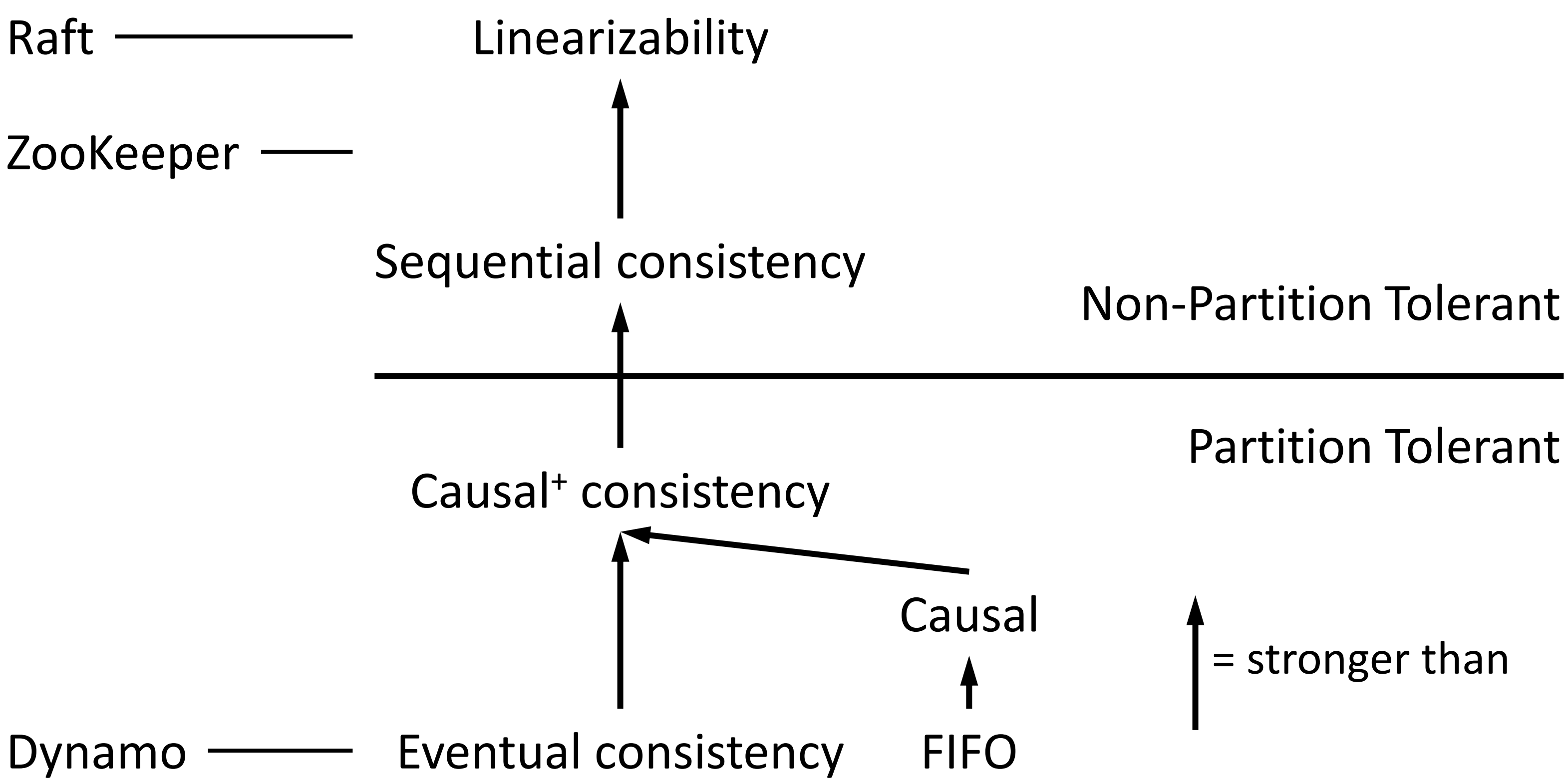
- BASE: set of rules for implementing CAP-based solutions
- Invented at eBay, adopted by Amazon, others
  - Basic Availability: provide continuous availability, despite failures or temporary inconsistency
  - Soft State: use state that can be regenerated (e.g., cached data) for efficiency
  - Eventual Consistency: assuming no further updates to an item, all users will eventually see the same value of the item
- Soft state and eventual consistency help recovery from failures, network partitions, data inconsistency, etc.

BASE example

- For example, if product photos rarely change, cache them, do not check for staleness with each cache access, let them expire after a few days or weeks
  - Avoids all cache refresh traffic
  - If a photo does change, you do see a stale photo, but this is rare
- BASE = "CAP in practice"
  = "Use CAP. You can clean up later."
- BASE encourages developers to think about when they need or do not need consistency

Partition-Tolerant Consistency Models

Consistency hierarchy



Eventual consistency

- All nodes execute operations (e.g., get, put) in any order
  - Allows partition tolerance
- Assuming no new updates to a data item, all accesses to that item will eventually return the last updated value

  $\Rightarrow$ Replicas must synchronize to converge to same state eventually
- Used in optimistically replicated systems
  - Weakest "reasonable" form of consistency for replicated data
  - Provides high availability and partition tolerance
  - But eventual convergence is not suitable for all apps
  - Later, we will look at Dynamo, an example of such a system

Understanding eventual consistency

- Reads, writes are performed at a replica without synchronizing with other replicas, so replicas may diverge
- Conceptually, updates are totally ordered "immediately", but replicas establish/learn the total order eventually when they synchronize updates with each other later
- Why is this model partition tolerant?

Understanding eventual consistency

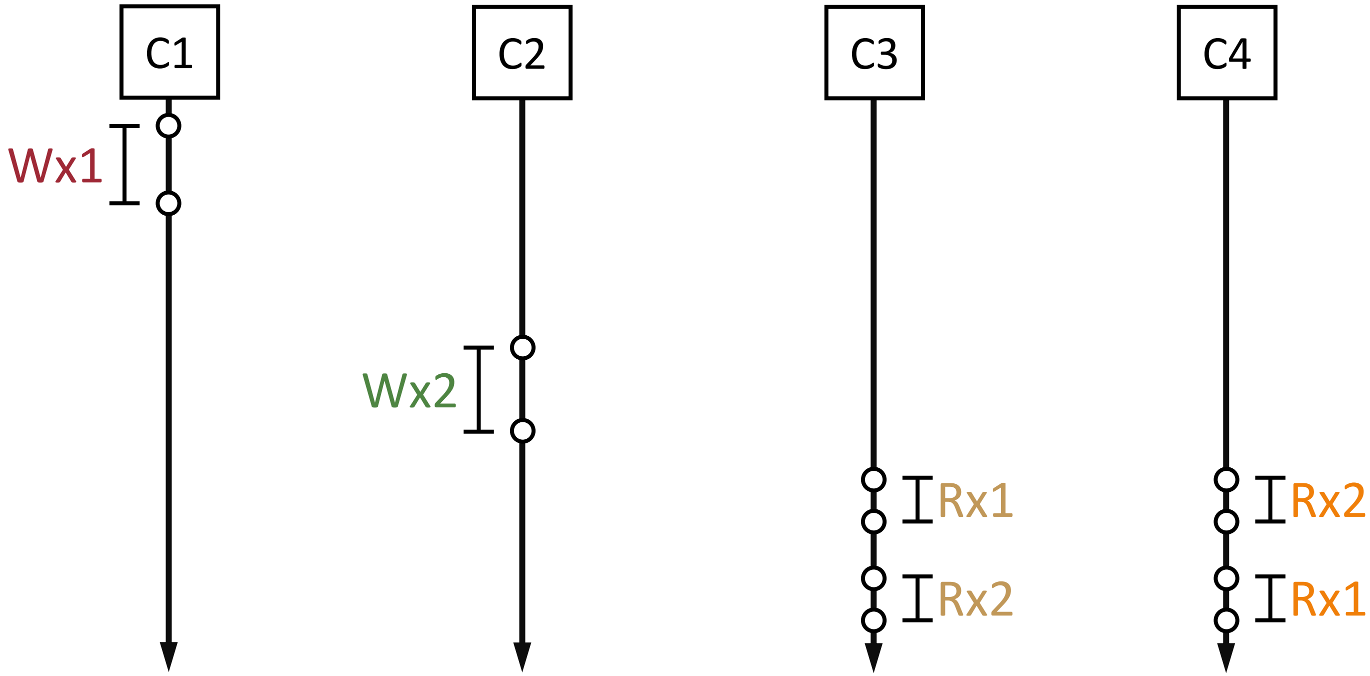
- Applications need to handle out-of-order writes
  - Say total order of two updates is Wx1, Wx2
  - Initially, a replica receives Wx2 (out-of-order)
  - Application tentatively reads Rx2
  - During synchronization, when replica receives Wx1, Wx2 may need to be rolled back, invalidating application’s Rx2 read
    - E.g., Wx1 is sale of last item of x, Wx2 is no longer possible
  - Application needs to be able to handle such tentative reads

Causal+ consistency

- Causal consistency: all processes execute operations in an order that satisfies causality (happens-before)
  - Say Client 1 writes WxA, Client 2 reads RxA and then writes WyB
  - Then, WxA -> WyB (happens-before)
  - All processes should observe WxA and then WyB
- Implications
  - High availability: allows partition tolerance since causally related operations cannot occur across partitions
  - No guarantee of convergence: replicas can apply two non-causally-related events in different orders
- Causal^{+}: data is eventually consistent also

Understanding causal consistency

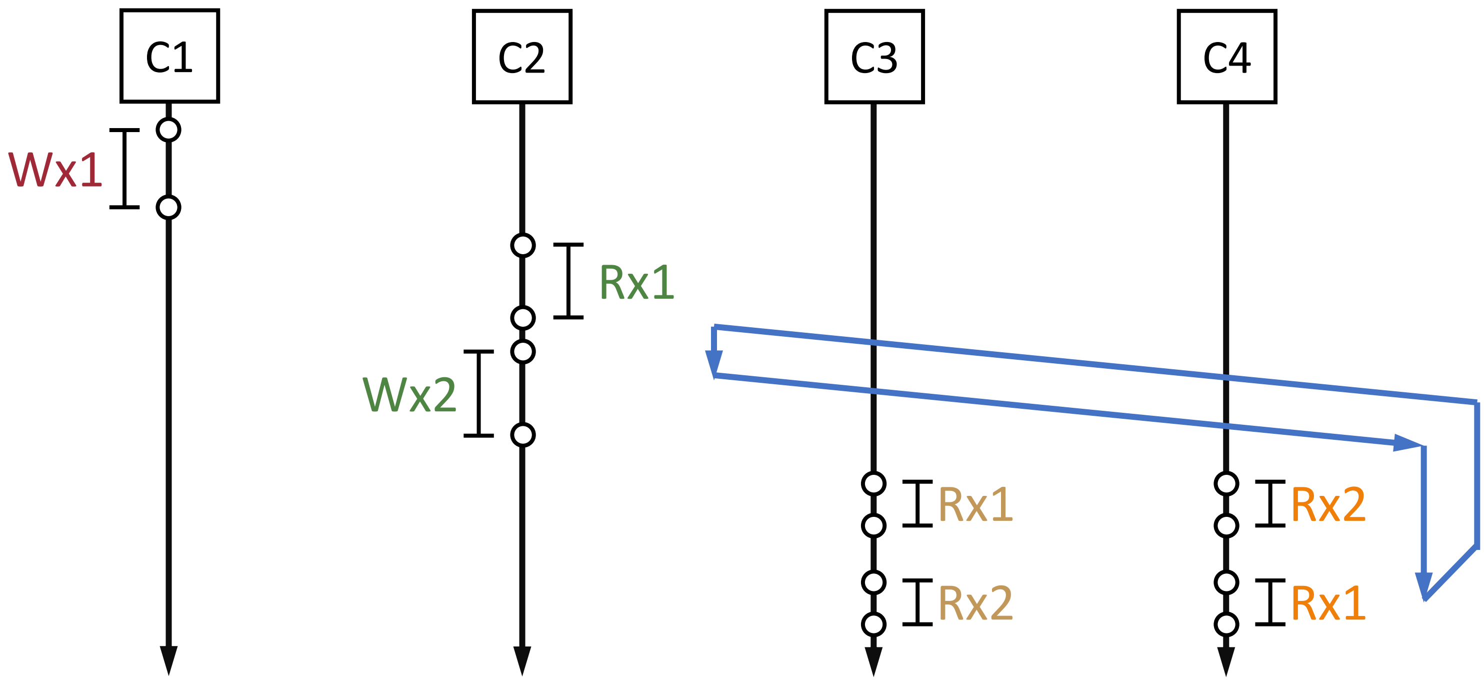
- With causal consistency, there should be no cyclic dependencies among operations
- Are these operations causally consistent?
  - Yes: no dependency between Wx1 and Wx2, C3 and C4 can observe them in either order



Understanding causal consistency

- With causal consistency, there should be no cyclic dependencies among operations

- Are these operations causally consistent?
  - No: Wx1 happens before Wx2,
    C4 should not observe Rx2 and then Rx1



Session (client-centric) guarantees

- We have focused on consistency guarantees provided by a system to all users
- Session guarantees describe consistency guarantees provided by a system to a single client
  - No guarantees are made about accesses from different clients
- Motivation from mobile computing
  - Consider a mobile client that is connected to a replica
  - Client travels to another continent, connects to another replica
  - What guarantees can the client expect when it accesses its data?

Session (client-centric) guarantees

- Causal consistency ensures four session guarantees
  - Read-your-writes: a process's read can only be served by replicas that have applied all previous writes of the process
  - Monotonic writes: a process's write is only applied on replicas that have applied all previous writes of the process
  - Monotonic reads: a process's read can only be served by replicas that have applied all previous writes observed (read) by the process (i.e., reads don't go backwards)
  - Writes-follow-reads: a process's write is only applied on replicas that have applied all previous writes observed (read) by the process (i.e., causal writes)
- These guarantees become important when client sessions switch replicas (otherwise, trivially satisfied)

FIFO consistency

- FIFO consistency ensures the first three session guarantees: read-your-writes, monotonic writes and monotonic reads
- Writes across processes that are causally related may be performed in any order

Comparing consistency models

- Consider a message board, e.g., Piazza
  - A user posts a new message
  - Users reply to the post

Linearizability	Users sees the post and all replies in same real-time order
Sequential	Users sees the post and a prefix of all replies in same order, replies may not be real-time order
Causal	Users sees the post before replies, but may see replies in different order
FIFO	Users read messages from each user in order but not across users, so may see replies before post

Conclusions

- Strong consistency models such as linearizability and sequential consistency ensure total order of operations
  - Pros: Make it easier to write applications
  - Cons: Limit performance and availability under partitions
- CAP rule and base methodology
  - In the cloud, fast response and partition tolerance is critical
  - Base: continuous availability, cache data, eventual consistency
- Causal and eventual consistency models
  - Pros: Provide partition tolerance
  - Cons: Make it harder to write applications, e.g., users can see temporarily inconsistent data, replicas need reconciliation