# CSE 486/586 Distributed Systems
# Consistency --- 2

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## Recap: Linearizability

- Linearizability
  - Should provide the behavior of a single client and a single copy
  - A read operation returns the most recent write, regardless of the clients according to their original actual-time order.
- Complication
  - In the presence of concurrency, read/write operations overlap.



## Linearizability Examples

- Example 1

a.write(x)
a.read() -> x
a.read() -> x

- Example 2

a.write(x)
a.read() -> 0
a.read() -> x
a.read() -> x

If this were a.read() -> 0, it wouldn't support linearizability.



## Linearizability Examples

- Example 3

a.write(x)
a.read() -> x
a.read() -> x
a.read() -> y
a.write(y)



## Linearizability

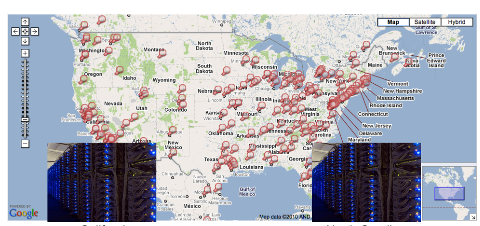
- Linearizability is all about client-side perception.
  - The same goes for all consistency models for that matter.
- If you write a program that works with a linearizable storage, *it works as you expect it to work*.
- There's no surprise.



## Implementing Linearizability

- Will this be difficult to implement? Any strategy?

You (NY): x.write(5)
Friend (CA): x.write(2), read(x) → 5



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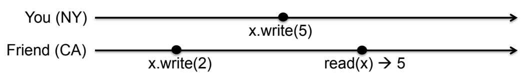
## Implementing Linearizability

- Will this be difficult to implement?
  - It depends on what you want to provide.




- How about:
  - All clients send all read/write to CA datacenter.
  - CA datacenter propagates to NC datacenter.
  - A request never returns until all propagation is done.
  - Correctness (linearizability)? yes
  - Performance? No

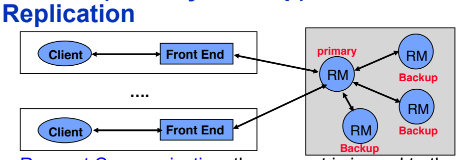


## Implementing Linearizability

- Importance of latency
  - Amazon: every 100ms of latency costs them 1% in sales.
  - Google: an extra .5 seconds in search page generation time dropped traffic by 20%.
- Linearizability typically requires *complete* synchronization of multiple copies before a write operation returns.
  - So that any read over any copy can return the most recent write.
  - No room for asynchronous writes (i.e., a write operation returns before all updates are propagated.)
- It makes less sense in a global setting.
  - Inter-datecenter latency: ~10s ms to ~100s ms
- It might still makes sense in a local setting (e.g., within a single data center).



## Passive (Primary-Backup) Replication

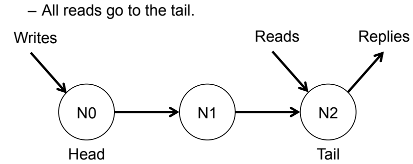



- Request Communication: the request is issued to the primary RM and carries a unique request id.
- Coordination: Primary takes requests atomically, in order, checks id (resends response if not new id.)
- Execution: Primary executes & stores the response
- Agreement: If update, primary sends updated state/ result, req-id and response to all backup RMs (1-phase commit enough).
- Response: primary sends result to the front end



## Chain Replication

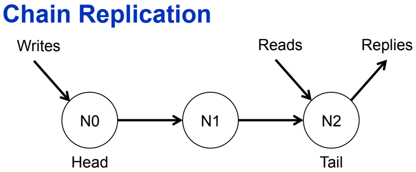
- One technique to provide linearizability with better performance
  - All writes go to the head.
  - All reads go to the tail.




- Linearizability?
  - Clear-cut cases: straightforward
  - Overlapping ops?



## Chain Replication




- What ordering does this have for overlapping ops?
  - We have freedom to impose an order.
  - Case 1: A write is at either N0 or N1, and a read is at N2. The ordering we're imposing is read then write.
  - Case 2: A write is at N2 and a read is also at N2. The ordering we're imposing is write then read.
- Linearizability
  - Once a write becomes visible (at the tail), all following reads get the write result.



## CSE 486/586 Administrivia

- PA3 deadline: 4/8 (Friday)

## Relaxing the Guarantees

- Do we need linearizability?


- Does it matter if I see some posts some time later?
- Does everyone need to see these in this particular order?



## Relaxing the Guarantees

- Linearizability advantages
  - It behaves as expected.
  - There's really no surprise.
  - Application developers do not need any additional logic.
- Linearizability disadvantages
  - It's difficult to provide high-performance (low latency).
  - It might be more than what is necessary.
- Relaxed consistency guarantees
  - Sequential consistency
  - Causal consistency
  - Eventual consistency
- It is still all about client-side perception.
  - When a read occurs, what do you return?



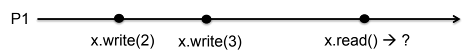
## Sequential Consistency

- A little weaker than linearizability, but still quite strong
  - Essentially linearizability, except that it allows writes from other processes to show up later.
- How can we achieve it?
  - Preserving the single-client, single-copy semantics
  - …while allowing writes from other processes to become visible later.
- The single-client semantics
  - Processing all requests as if they were coming from a single client (in a single stream of ops).
  - Again, this meets our basic expectation---it's easiest to understand for an app developer if all requests appear to be processed one at a time.
- Let's consider the single-copy semantics with a few examples.



## Single-Copy Semantics

- Consider the following single process.

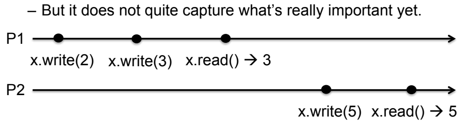



- What do you expect to read?
  - 3, not 2
  - Why even consider 2? E.g., if there were two copies not synchronized correctly, two writes could be applied to different copies.
- Why 3 then?
  - It's the program order.
- Single-copy semantics
  - When a storage system preserves a process's program order, the process will believe that there's a single copy.



## Single-Copy Semantics

- But we need to make it work with multiple processes.
  - When a storage system preserves each and every process's program order, they will all think that there's a single copy.
- Simple example
  - But it does not quite capture what's really important yet.

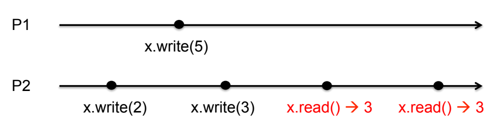



- Single-copy semantics
  - A storage system preserves each and every process's program order.
  - It gives an illusion to every process that they're working with a single copy. But the example's writes all show up in time.



## Delayed Write Visibility

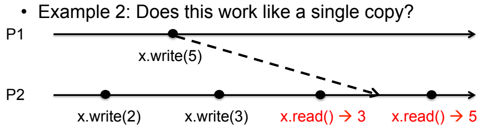
- How do we reconcile program order preservation with the writes from other processes showing up later?
  - A write from a different process should still be applied and synchronized as a single copy.
- Example 1: Does this work like a single copy (P2 never reads P1's write)?




- Yes! (This is what happens with linearizability.)
- It's just that P1's writes are showing up in time.

## Delayed Write Visibility

- How do we reconcile program order preservation with the writes from other processes showing up later?
  - A write from a different process should still be applied and synchronized as a single copy.
- Example 2: Does this work like a single copy?

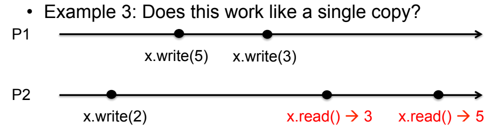



- Yes! (This does not happen with linearizability.)
- It's just that P1's writes are showing up later.
  - It's like x.write(5) happens between the two reads at P2.
  - It's also like P1 and P2's operations are interleaved and processed like the arrow shows.



## Delayed Write Visibility

- How do we reconcile program order preservation with the writes from other processes showing up later?
  - A write from a different process should still be applied and synchronized as a single copy.
- Example 3: Does this work like a single copy?




- No!
- If your storage behaves like this, you don't know if you're preserving P1's program order.
  - If later P1 has a read, it might return 5, which is wrong.



## Sequential Consistency

- Combining all three
  - Single-client semantics
  - Single-copy semantics
  - Delayed write visibility
- Single-client semantics
  - All requests appear to come from a single client with a single interleaving of all requests.
  - I.e., all requests appear be processed one at a time.
- Single-copy semantics
  - In the single interleaving, all program orders of all processes are preserved.
- Delayed write visibility
  - In the single interleaving, all program orders are only logically preserved.



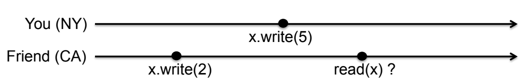
## Sequential Consistency

- Your storage *appears* to process all requests in a single interleaved ordering (single client), where…
  - …each and every process's program order is preserved (single copy),
  - …and each process's program order is only *logically preserved*, i.e., it doesn't need to preserve its actual-time ordering (delayed write visibility).
- It works as if all clients are reading out of a single copy.
  - This meets the expectation from a (isolated) client, working with a single copy.
  - Linearizability meets the expectation of all clients even if they all know what others are doing.
  - Both sequential consistency and linearizability provide an illusion of a single copy.



## Sequential Consistency vs. Linearizability

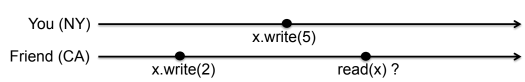
- Both should behave as if there were only a single copy, and a single client.
  - It's just that SC doesn't preserve the actual-time order, but just the program order of each client.
- Difference

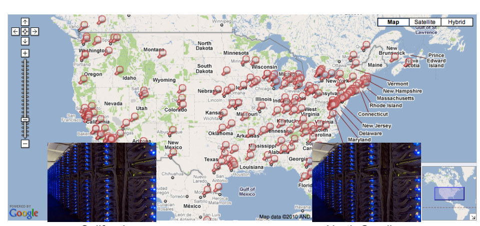



  - Linearizability: Once a write is returned, the system is obligated to make the result visible to all clients based on actual time. I.e., the system has to return 5 in the example.
  - Sequential consistency: Even if a write is returned, the system is not obligated to make the result visible to other clients immediately. I.e., the system can still return 2 in the example.



## Sequential Consistency



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## Sequential Consistency Examples

- Example 1: Can a sequentially consistent storage show this behavior? (I.e., can you come up with an interleaving that behaves like a single copy?)
  - P1: a.write(A)
  - P2: a.write(B)
  - P3: a.read()->B a.read()->A
  - P4: a.read()->B a.read()->A
- Example 2
  - P1: a.write(A)
  - P2: a.write(B)
  - P3: a.read()->B a.read()->A
  - P4: a.read()->A a.read()->B



## Implementing Sequential Consistency

- In what implementation would the following happen?
  - P1: a.write(A)
  - P2: a.write(B)
  - P3: a.read()->B a.read()->A
  - P4: a.read()->A a.read()->B
- Possibility
  - P3 and P4 use different copies.
  - In P3's copy, P2's write arrives first and gets applied.
  - In P4's copy, P1's write arrives first and gets applied.
  - Writes are applied in different orders across copies.
  - This doesn't provide sequential consistency.



## Implementing Sequential Consistency

- When implementing a consistency model, we need to think about how to handle writes and how to handle reads
- Handling writes
  - Single-client, single-copy: Write synchronization happens (or writes are applied) in the same order everywhere across different copies, while preserving each process's logical write order.
  - Delayed write visibility: The synchronization does not have to be complete at the time of return from a write operation. (I.e., actual writes on different copies can be done at different times.)
- Handling reads
  - Single-client, single-copy: A read from a process should be done on a copy that already has applied the process's latest write. And all reads should be processed by the program order.

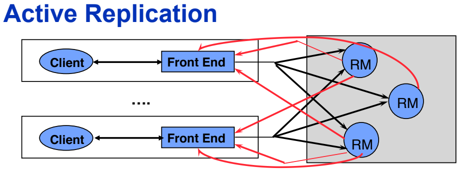


## Implementing Sequential Consistency

- Typical implementation
  - You're not obligated to make the most recent write (according to actual time) visible (i.e., applied to all copies) right away.
  - But you are obligated to apply all writes in the same order for all copies. This order should be FIFO-total.



## Active Replication




- A front end FIFO-orders all reads and writes.
- A read can be done completely with any single replica.
- Writes are totally-ordered and asynchronous (after at least one write completes, it returns).
  - Total ordering doesn't guarantee when to deliver events, i.e., writes can happen at different times at different replicas.
- Sequential consistency, not linearizability
  - Read/write ops from the same client will be ordered at the front end (program order preservation).
  - Writes are applied in the same order by total ordering (single copy).
  - No guarantee that a read will read the most recent write based on actual time.



## Two More Consistency Models

- Even more relaxed
  - We don't even care about providing an illusion of a single copy.
- Causal consistency
  - We care about ordering causally related write operations correctly.
- Eventual consistency
  - As long as we can say all replicas converge to the same copy eventually, we're fine.

## Summary

- Linearizability
  - The ordering of operations is determined by time.
  - Primary-backup can provide linearizability.
  - Chain replication can also provide linearizability.
- Sequential consistency
  - The ordering of operations preserves the program order of each client.
  - Active replication can provide sequential consistency.



## Acknowledgements

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