Consistency Models

COS 418: Distributed Systems
Lecture 15

Mike Freedman

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Consistency Models

- Contract between a distributed system and the applications that run on it
- A consistency model is a set of guarantees made by the distributed system

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Linearizability

- All replicas execute operations in some total order
- That total order preserves the real-time ordering between operations
  - If operation A completes before operation B begins, then A is ordered before B in real-time
  - If neither A nor B completes before the other begins, then there is no real-time order. But there must be *some* total order.

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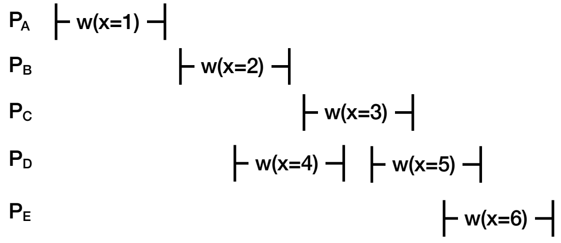
Real-Time Ordering Examples



P_A ├ w(x=1) ┤

P_B ├ w(x=2) ┤

P_C ├ w(x=3) ┤

P_D ├ w(x=4) ┤ ├ w(x=5) ┤

P_E ├ w(x=6) ┤

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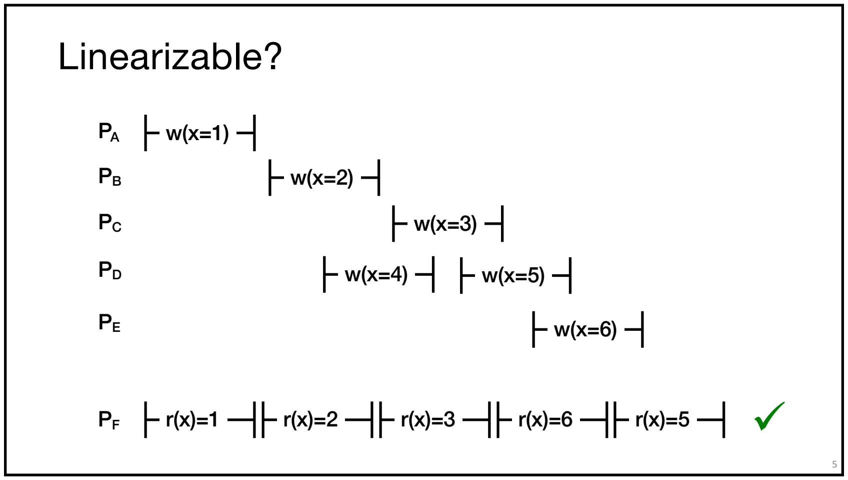

Linearizable?

P_A ├ w(x=1) ┤

P_B ├ w(x=2) ┤

P_C ├ w(x=3) ┤

P_D ├ w(x=4) ┤ ├ w(x=5) ┤

P_E ├ w(x=6) ┤

P_F ├ r(x)=1 ┤├ r(x)=2 ┤├ r(x)=3 ┤├ r(x)=6 ┤├ r(x)=5 ┤ ✓

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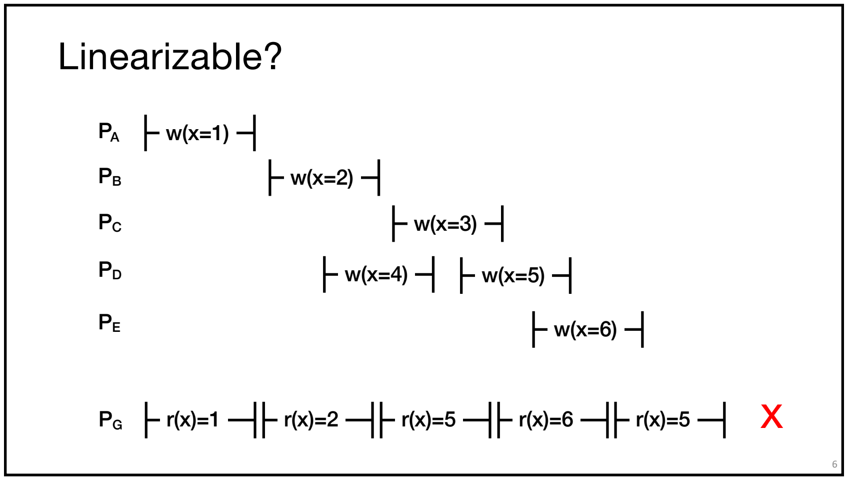

Linearizable?

P_A ├ w(x=1) ┤

P_B ├ w(x=2) ┤

P_C ├ w(x=3) ┤

P_D ├ w(x=4) ┤ ├ w(x=5) ┤

P_E ├ w(x=6) ┤

P_G ├ r(x)=1 ┤├ r(x)=2 ┤├ r(x)=5 ┤├ r(x)=6 ┤├ r(x)=5 ┤ X

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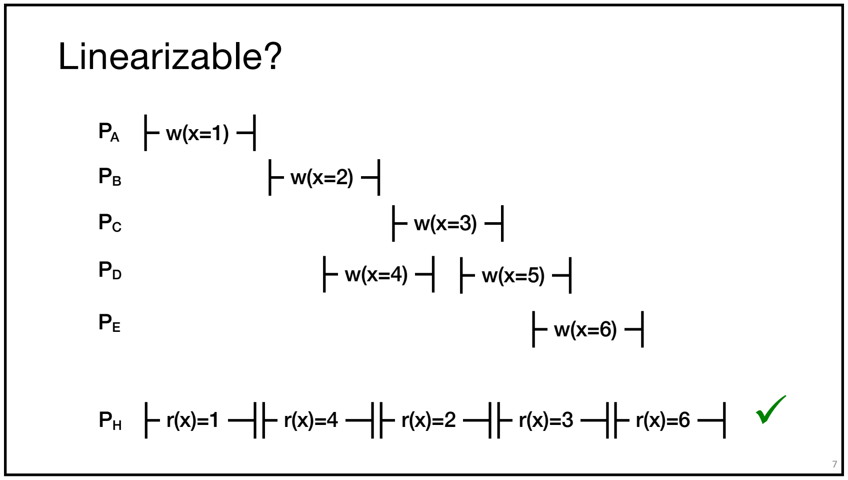

Linearizable?

P_A ├ w(x=1) ┤

P_B ├ w(x=2) ┤

P_C ├ w(x=3) ┤

P_D ├ w(x=4) ┤ ├ w(x=5) ┤

P_E ├ w(x=6) ┤

P_H ├ r(x)=1 ┤├ r(x)=4 ┤├ r(x)=2 ┤├ r(x)=3 ┤├ r(x)=6 ┤ ✓

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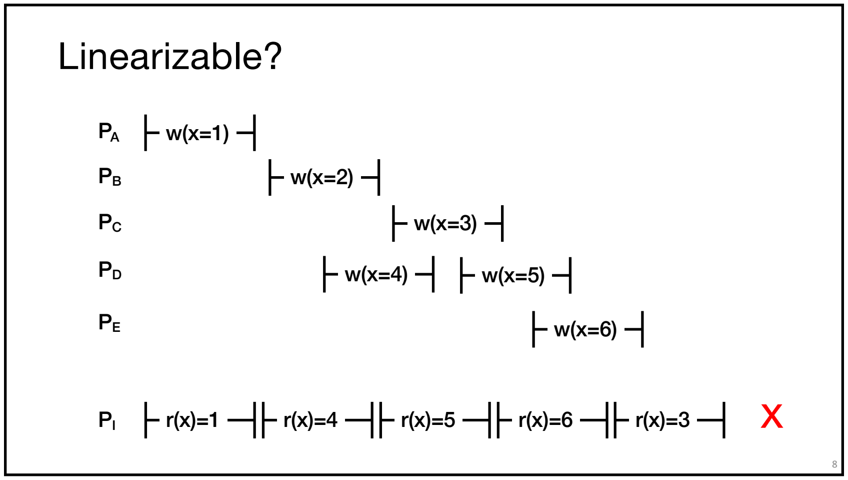

Linearizable?

P_A ├ w(x=1) ┤

P_B ├ w(x=2) ┤

P_C ├ w(x=3) ┤

P_D ├ w(x=4) ┤ ├ w(x=5) ┤

P_E ├ w(x=6) ┤

P_I ├ r(x)=1 ┤├ r(x)=4 ┤├ r(x)=5 ┤├ r(x)=6 ┤├ r(x)=3 ┤ X

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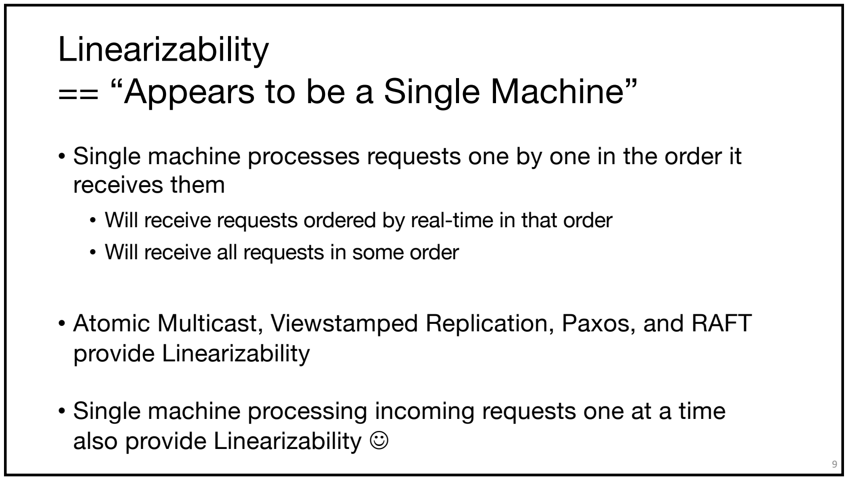

Linearizability == “Appears to be a Single Machine”

- Single machine processes requests one by one in the order it receives them
  - Will receive requests ordered by real-time in that order
  - Will receive all requests in some order
- Atomic Multicast, Viewstamped Replication, Paxos, and RAFT provide Linearizability
- Single machine processing incoming requests one at a time also provide Linearizability ☺

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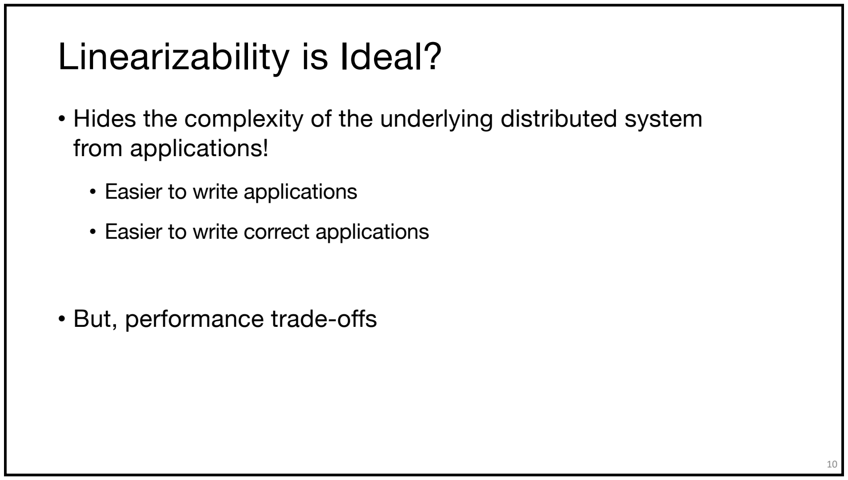

Linearizability is Ideal?

- Hides the complexity of the underlying distributed system from applications!
  - Easier to write applications
  - Easier to write correct applications
- But, performance trade-offs

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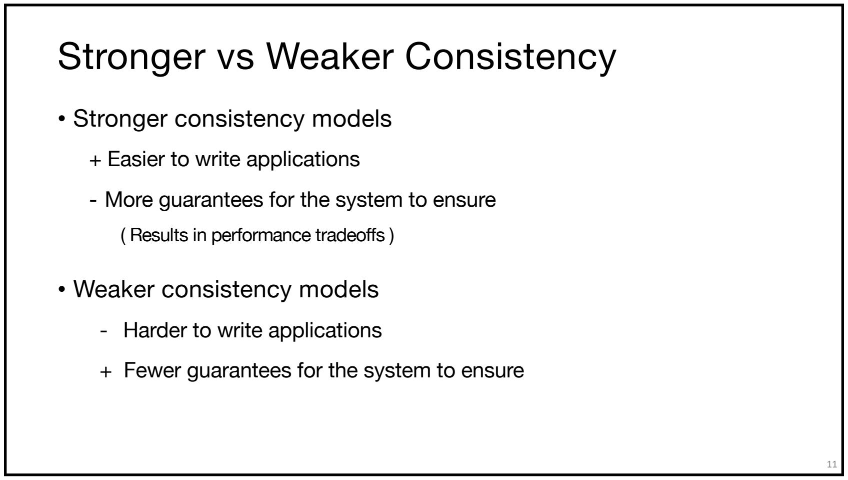

Stronger vs Weaker Consistency

- Stronger consistency models

  + Easier to write applications

  - More guarantees for the system to ensure

  (Results in performance tradeoffs)
- Weaker consistency models

  - Harder to write applications

  + Fewer guarantees for the system to ensure

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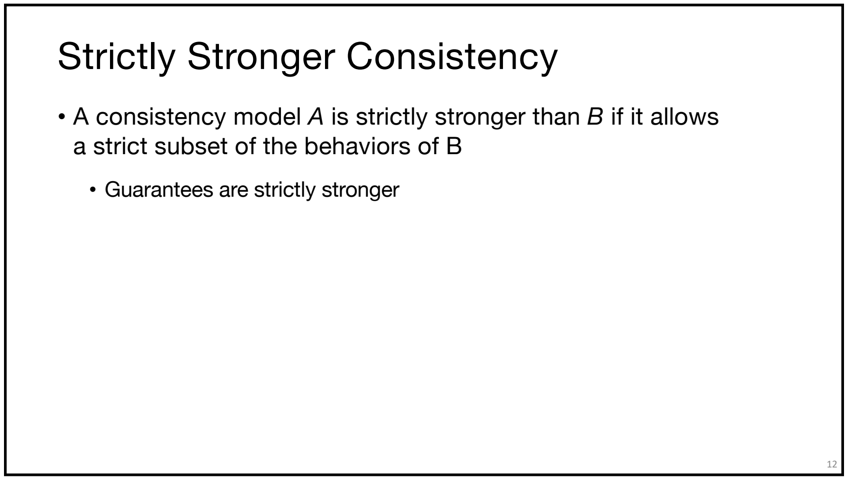

Strictly Stronger Consistency

- A consistency model *A* is strictly stronger than *B* if it allows a strict subset of the behaviors of B
  - Guarantees are strictly stronger

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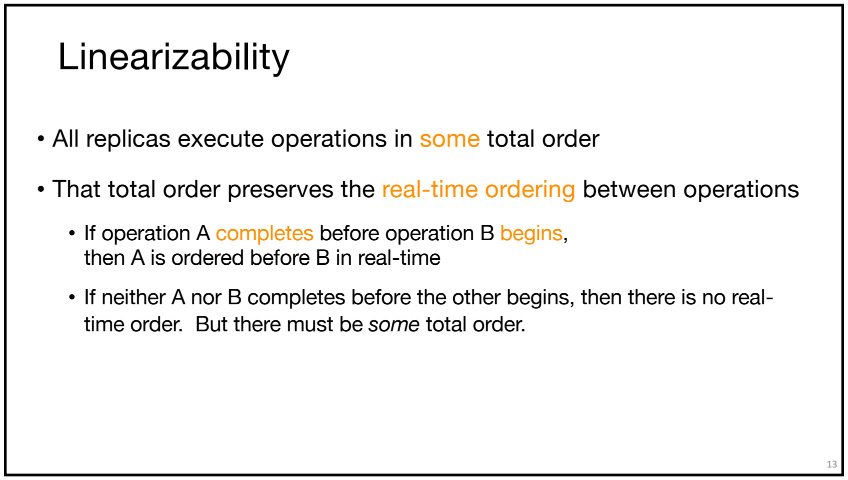

Linearizability

- All replicas execute operations in some total order
- That total order preserves the real-time ordering between operations
  - If operation A completes before operation B begins, then A is ordered before B in real-time
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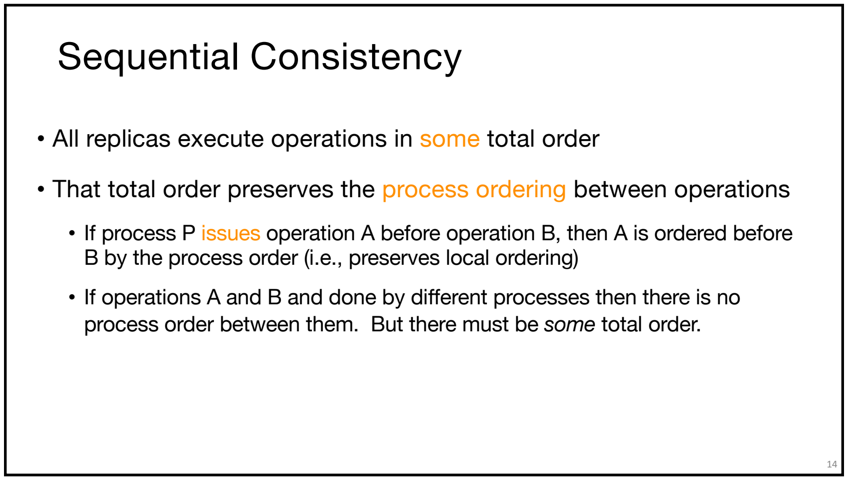

Sequential Consistency

- All replicas execute operations in some total order
- That total order preserves the process ordering between operations
  - If process P issues operation A before operation B, then A is ordered before B by the process order (i.e., preserves local ordering)
  - If operations A and B and done by different processes then there is no process order between them. But there must be *some* total order.

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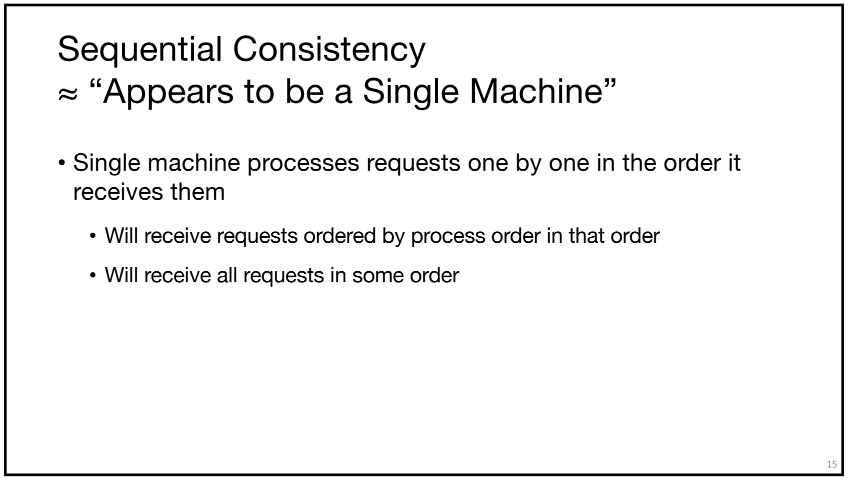

Sequential Consistency ≈ "Appears to be a Single Machine"

- Single machine processes requests one by one in the order it receives them
  - Will receive requests ordered by process order in that order
  - Will receive all requests in some order

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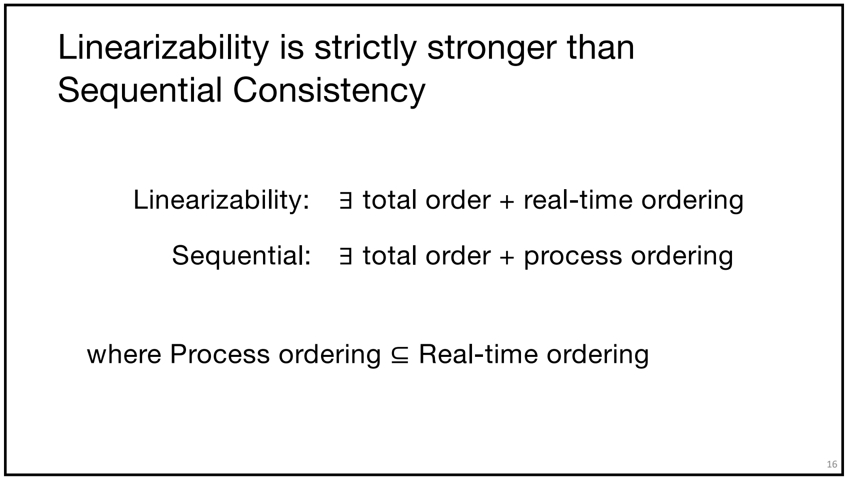

Linearizability is strictly stronger than Sequential Consistency

Linearizability: ∃ total order + real-time ordering

Sequential: ∃ total order + process ordering

where Process ordering ⊆ Real-time ordering

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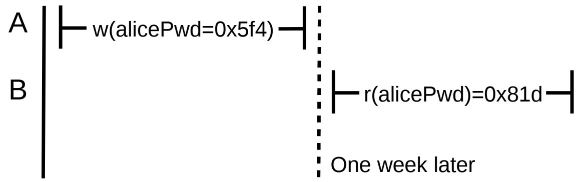
Sequential But Not Linearizable



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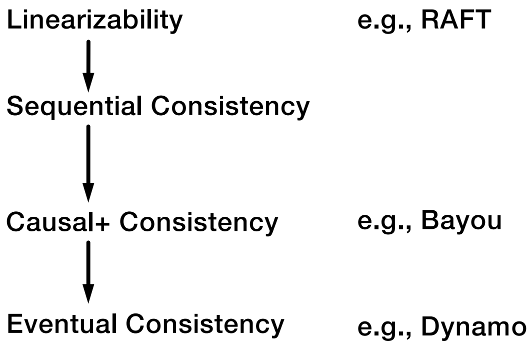
Consistency Hierarchy


Linearizability e.g., RAFT
Sequential Consistency
Causal+ Consistency e.g., Bayou
Eventual Consistency e.g., Dynamo

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Causal+ Consistency

- Partially orders all operations, does not totally order them
  - Does not look like a single machine
- Guarantees
  - For each process, ∃ an order of all writes + that process's reads
  - Order respects the happens-before (→) ordering of operations
  - + replicas converge to the same state
    - Skip details, makes it stronger than eventual consistency

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Causal Consistency

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

Concurrent: Ops not causally related

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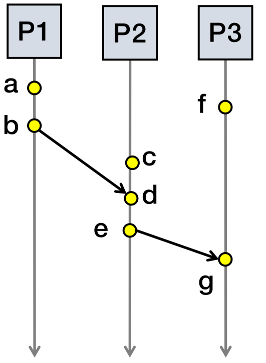
Causal Consistency

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

Concurrent: Ops not causally related



Physical time ↓

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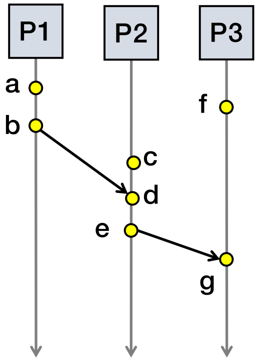
Causal Consistency

Operations	Concurrent?
a, b	
b, f	
c, f	
e, f	
e, g	
a, c	
a, e	



Physical time ↓

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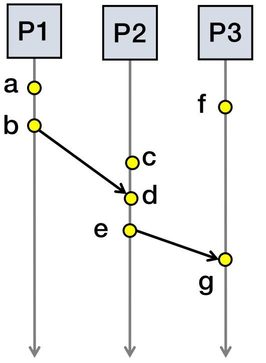
Causal Consistency

Operations	Concurrent?
a, b	N
b, f	Y
c, f	Y
e, f	Y
e, g	N
a, c	Y
a, e	N



Physical time ↓

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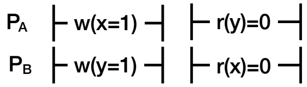
Causal+ But Not Sequential



√ Casual+

Happens Before Order

w(x=1) → r(y)=0

w(y=1) → r(x)=0

P_A Order: w(x=1), r(y=0), w(y=1)

P_B Order: w(y=1), r(x=0), w(x=1)

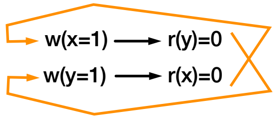
X Sequential

Process Ordering

w(x=1) → r(y)=0

w(y=1) → r(x)=0

No Total Order



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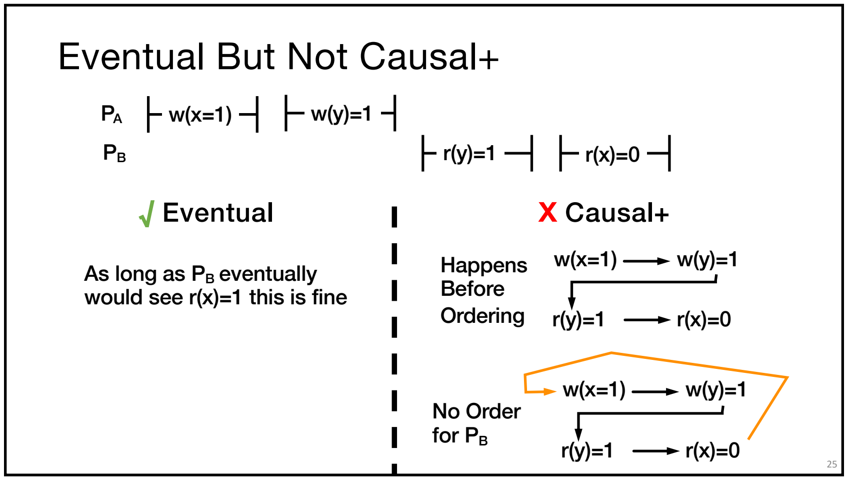

Eventual But Not Causal+

P_A ├ w(x=1) ┤ ├ w(y)=1 ┤

P_B ├ r(y)=1 ┤ ├ r(x)=0 ┤

√ Eventual

As long as P_B eventually would see r(x)=1 this is fine

X Causal+

Happens Before Ordering

w(x=1) → w(y)=1

r(y)=1 → r(x)=0

No Order for P_B

w(x=1) → w(y)=1

r(y)=1 → r(x)=0

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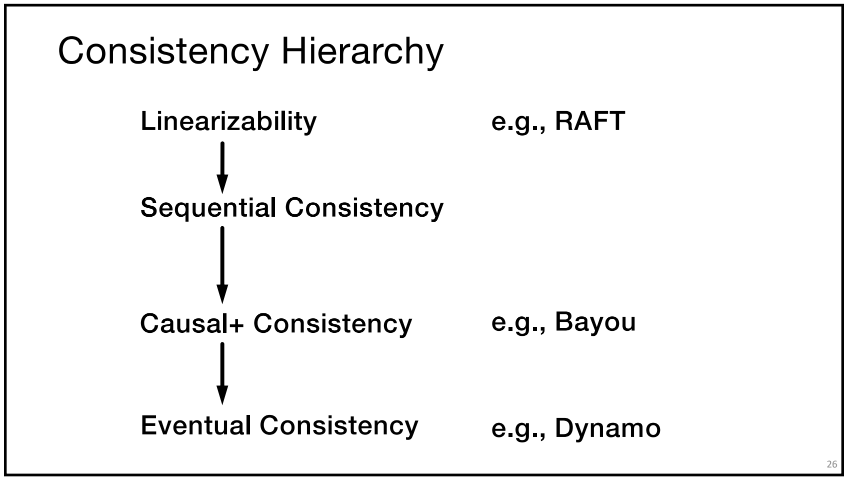

Consistency Hierarchy

Linearizability — e.g., RAFT

↓

Sequential Consistency

↓

Causal+ Consistency — e.g., Bayou

↓

Eventual Consistency — e.g., Dynamo

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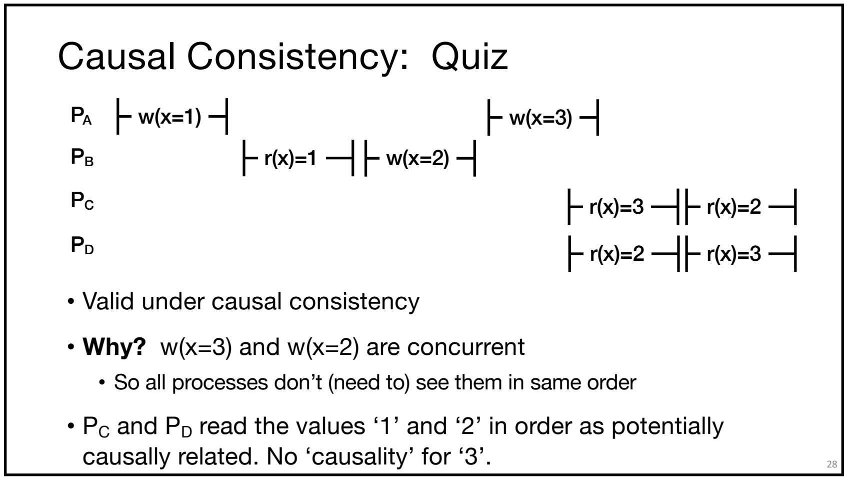

Causal Consistency: Quiz

P_A ├ w(x=1) ┤ ├ w(x=3) ┤

P_B ├ r(x)=1 ┤├ w(x=2) ┤

P_C ├ r(x)=3 ┤├ r(x)=2 ┤

P_D ├ r(x)=2 ┤├ r(x)=3 ┤

- Valid under causal consistency
- **Why?** w(x=3) and w(x=2) are concurrent
  - So all processes don't (need to) see them in same order
- P_C and P_D read the values '1' and '2' in order as potentially causally related. No 'causality' for '3'.

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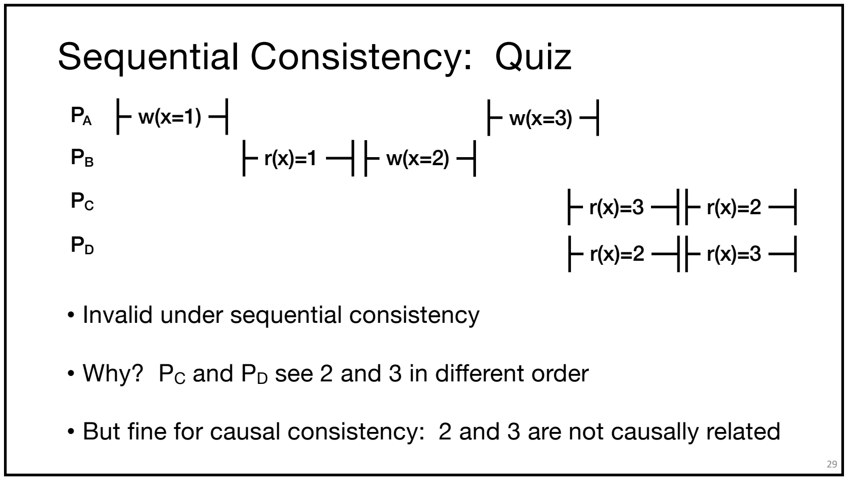

Sequential Consistency: Quiz

P_A ├ w(x=1) ┤ ├ w(x=3) ┤

P_B ├ r(x)=1 ┤├ w(x=2) ┤

P_C ├ r(x)=3 ┤├ r(x)=2 ┤

P_D ├ r(x)=2 ┤├ r(x)=3 ┤

- Invalid under sequential consistency
- Why? P_C and P_D see 2 and 3 in different order
- But fine for causal consistency: 2 and 3 are not causally related

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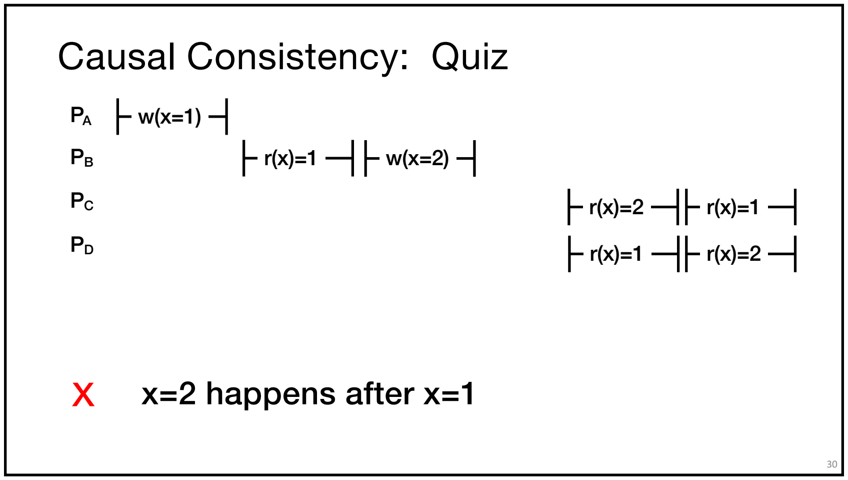

Causal Consistency: Quiz

P_A ├ w(x=1) ┤

P_B ├ r(x)=1 ┤├ w(x=2) ┤

P_C ├ r(x)=2 ┤├ r(x)=1 ┤

P_D ├ r(x)=1 ┤├ r(x)=2 ┤

X x=2 happens after x=1

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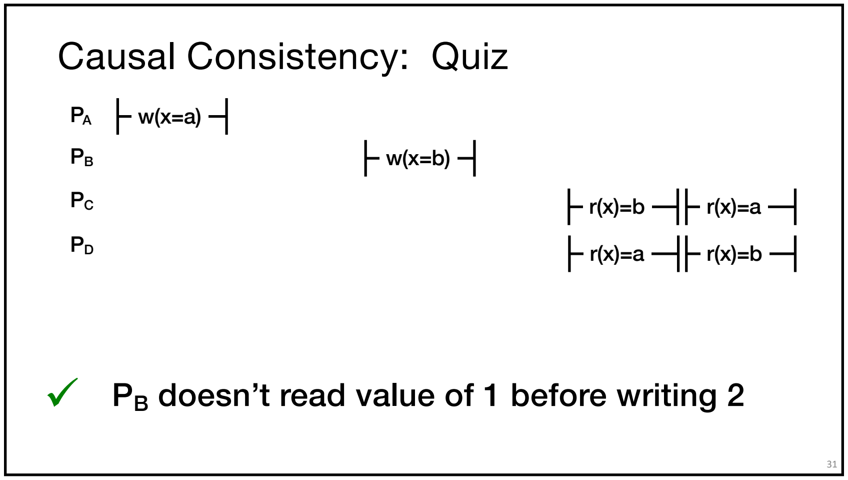

Causal Consistency: Quiz

P_A ├ w(x=a) ┤

P_B ├ w(x=b) ┤

P_C ├ r(x)=b ┤├ r(x)=a ┤

P_D ├ r(x)=a ┤├ r(x)=b ┤

✓ P_B doesn't read value of 1 before writing 2

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