# Consistency Models

COS 418/518: (Advanced) Distributed Systems
Lecture 13

Michael Freedman & Wyatt Lloyd

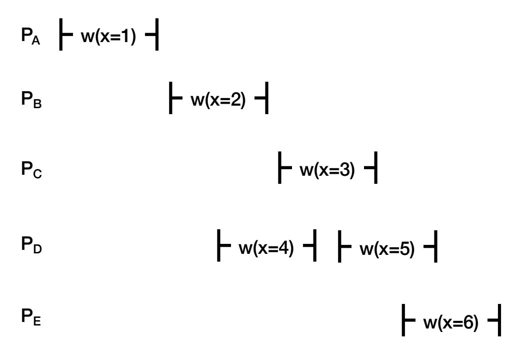
## Consistency Models

- 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

## 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)

## Real-Time Ordering Examples



# 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 ┤ ✓

# 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

# 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 ┤ ✓

# 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

## 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 ☺

## 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

## 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

## 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

## 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 order before B by the process order
  - 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)

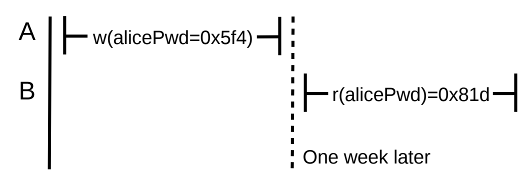
## Sequential Consistency ≈ "Appears to be a Single Machine"

- 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

## Linearizability is strictly stronger than Sequential Consistency

- Linearizability: $\exists$ total order + real-time ordering
- Sequential: $\exists$ total order + process ordering
  - Process ordering $\subseteq$ Real-time ordering

## Sequential But Not Linearizable



# Consistency Hierarchy

Linearizability — e.g., RAFT

↓

Sequential Consistency

↓

Causal+ Consistency — e.g., Bayou

↓

Eventual Consistency — e.g., Dynamo

# 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

# Causal Consistency

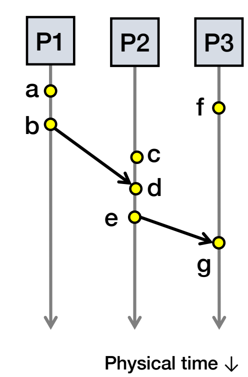
1. Writes that are potentially causally related must be seen by all processes in same order.
2. Concurrent writes may be seen in a different order on different processes.

- Concurrent: Ops not causally related

# Causal Consistency

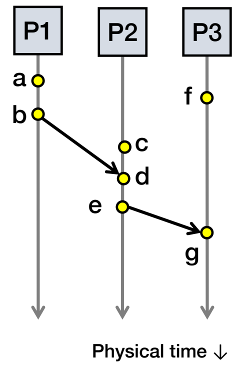
1. Writes that are potentially causally related must be seen by all processes in same order.
2. Concurrent writes may be seen in a different order on different processes.

- Concurrent: Ops not causally related



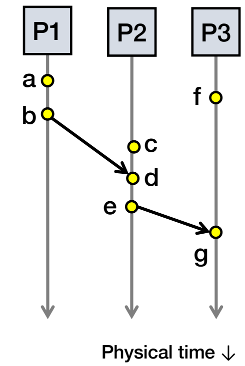
# Causal Consistency

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




# 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 |




# Causal+ But Not Sequential

$P_A$ ├ w(x=1) ┤ ├ r(y)=0 ┤

$P_B$ ├ w(y=1) ┤ ├ r(x)=0 ┤

√ 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: w(x=1) → r(y)=0; w(y=1) → r(x)=0

# 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

## Consistency Hierarchy

Linearizability — e.g., RAFT

↓

Sequential Consistency

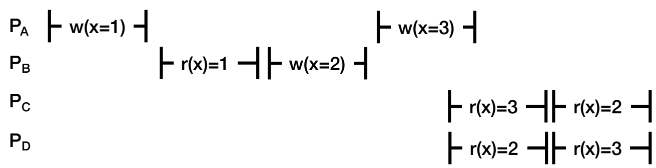
↓

Causal+ Consistency — e.g., Bayou

↓

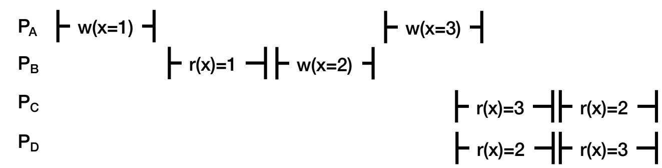
Eventual Consistency — e.g., Dynamo

## Causal Consistency: Quiz




- Valid under causal consistency
- **Why?** x=3 and 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'.

## Sequential Consistency: Quiz




- 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

## Causal Consistency

$P_A$ ├ 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

## Causal Consistency

$P_A$ ├ 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