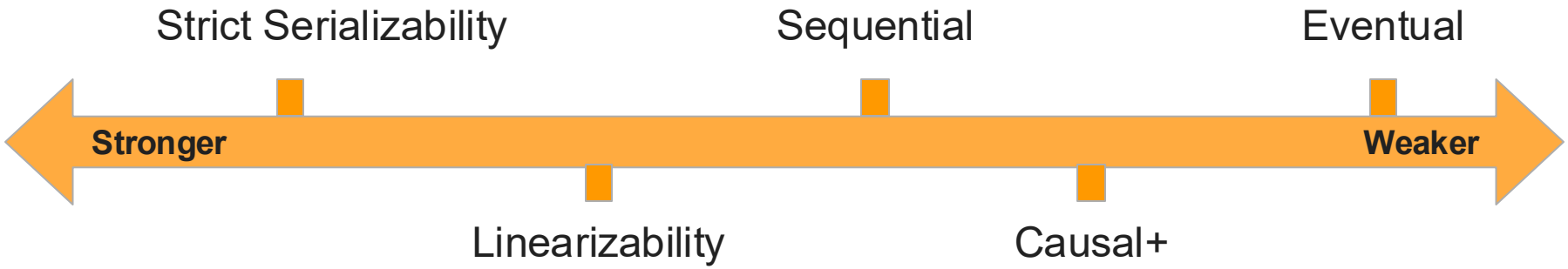
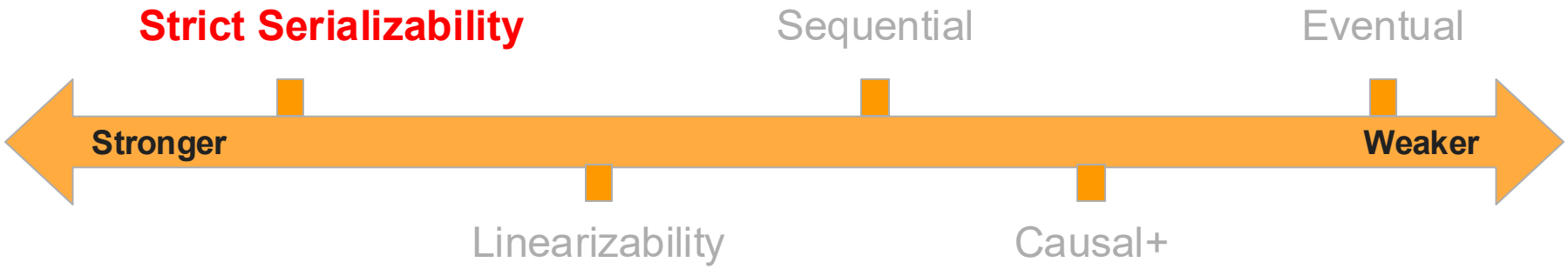
Consistency

November 2025

Consistency Models



Consistency Models



Strict Serializability

- Transactions: operations that span multiple objects (e.g., keys in KV store) *atomically* commit (or abort).
- Total order: There exists some legal total ordering of transactions.
    - Legal (intuitively defined for strict serializability): in the total ordering, read operations “see” the latest write operation.
- Preserves real-time commit order: if *txn A* commits before *txn B* begins, then *txn A* occurs before *txn B* in the total order.
    - Write ops in a committed txn are visible to all future txns’ read ops.
    - Intuition: once a read “sees” a txn and commits, all future reads must also “see” that txn.

Strict Serializability

Pros: applications can easily reason about correctness of transactions.
Cons: strict serializability imposes high read and write latencies on system.

Strict Serializability Example

Strictly Serializable? **Yes**

P1: {W(x)b, W(y)b}

P2: {W(x)a}

P3: {R(x)a} {R(x)b}

P4: {R(x)b} {R(y)b}

Strictly Serializable? **No**

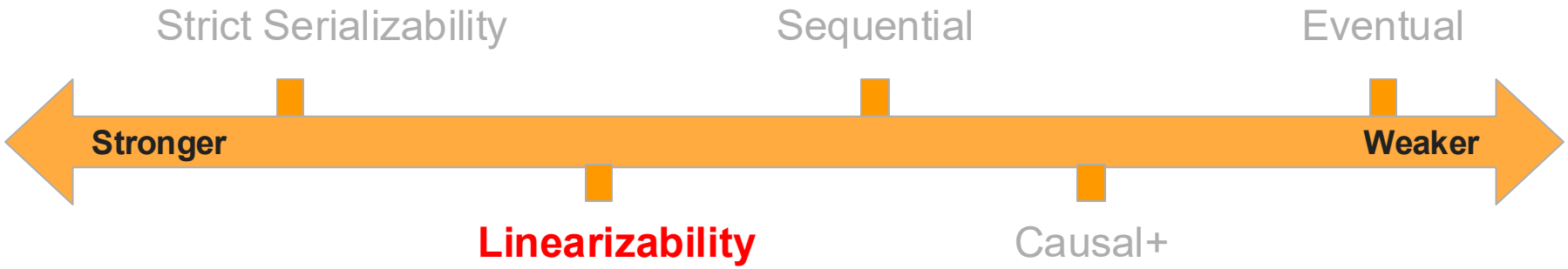
P1: {W(x)b, W(y)b}

P2: {W(x)a}

P3: {R(y)b} {R(x)a}

P4: {R(x)b} {R(y)b}

Consistency Models



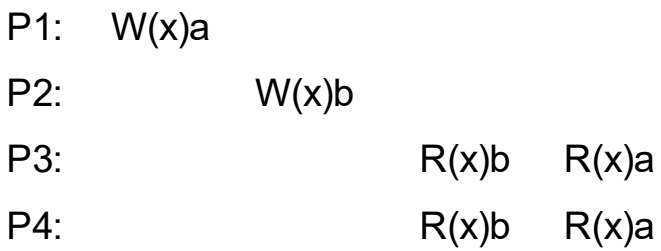
Linearizability

- Total order: There exists some legal total order of **operations (not txns)**.
- Difference from *strict serializability*?
  - Single-object operations! No transactions!
- Preserves real-time ordering: if an operation *A* completes before operation *B* begins, then op A occurs before op *B* in the total order.
  - A completed write op is visible to all future read ops.
  - Intuition: once a read “sees” a new write, all future reads must also “see” that write.

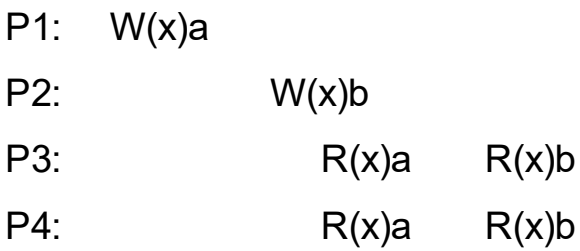
Pros: Easy to reason about correctness
Cons: High read and write latencies

Linearizability Example

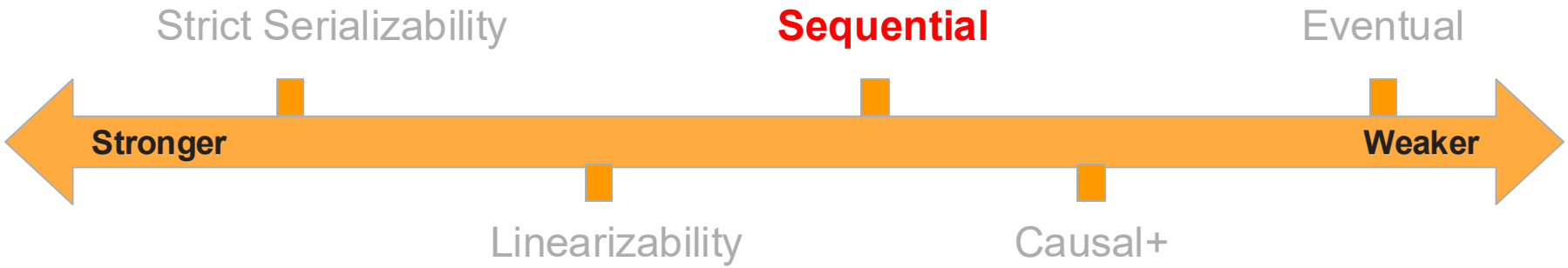
Linearizable? **No**



Linearizable? **Yes**



Consistency Models



Sequential Consistency

- Total order: there exists some legal total order of operations.
- Preserves **process ordering**: total order respects order of each process's operations.
- Difference from *linearizability*?
  - Order of ops across processes not determined by real-time

Pros: Can allow more orderings than linearizability → better performance
Cons: Many possible sequential executions → increased application complexity

Sequential Consistency Example

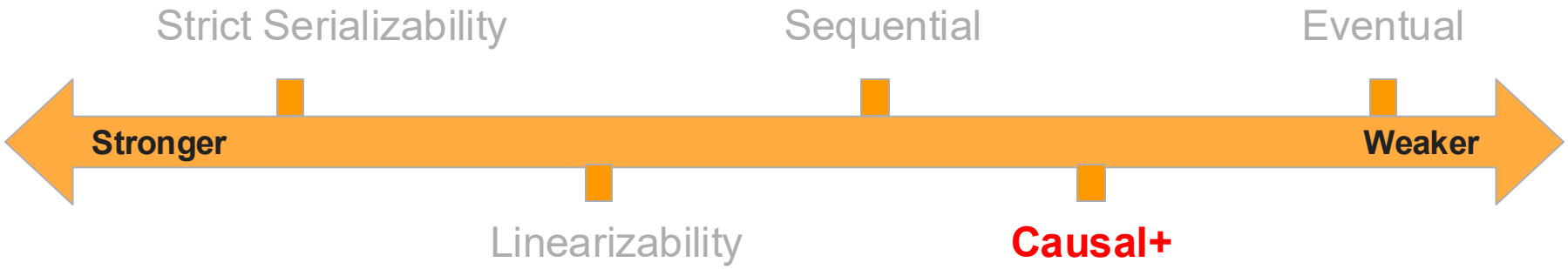
Sequentially Consistent? **Yes**

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

Sequentially Consistent? **No**

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

Consistency Models

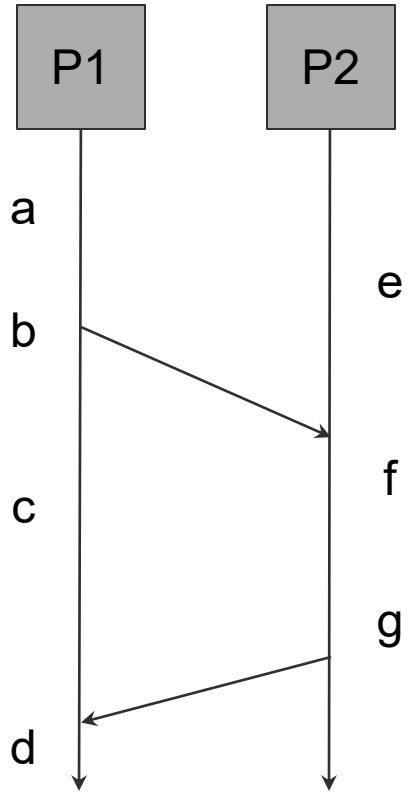


Causal+ Consistency

- Partial order: order causally related ops the same way across all processes
- +: replicas' total order eventually converges.
- Difference from *sequential consistency*?
  - Only causally related ops need to be ordered: **no guaranteed total order.**
  - Concurrent ops may be ordered differently across different processes.

Pros: preserves causality while improving efficiency.
Cons: harder to reason about concurrency.

Ops	Concurrent
a,b	**No**
a,e	**Yes**
a,g	**No**
c,e	**Yes**
c,d	**No**
d,g	**No**
d,f	**No**
e,g	**No**
a,d	**No**



Causal+ Consistency Example

Causally+ Consistent? Yes

P1: W(x)a

P2: W(x)b

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

P4: R(x)a

Causally+ Consistent? No

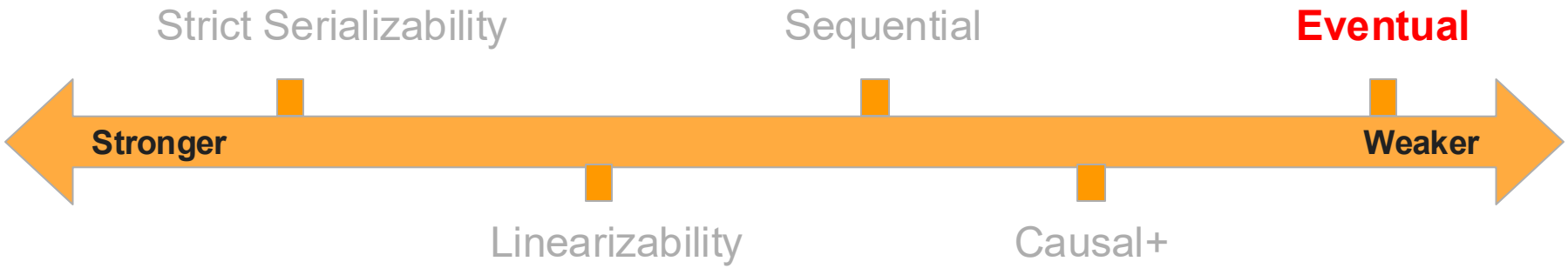
P1: W(x)a

P2: R(x)a W(x)b

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

P4: R(x)a

Consistency Models



Eventual Consistency

- Eventual convergence: If no more writes, all replicas *eventually* agree.
- Difference from *causal consistency*?
  - Does not preserve causal relationships
  - Is the “+” in causal+.
- Frequently used with application conflict resolution, anti-entropy

Pros: highly available; think Bayou.
Cons: no safety guarantees, need conflict resolution.

In a nutshell...

Strict Serializability: total order + real time guarantees over *transactions*

Linearizability: total order + real time guarantees over *operations*

Sequential Consistency: total order + process order

Causal+ Consistency: causally ordered + replicas eventually converge

Eventual Consistency: eventually, everyone should agree on state

Exercise 1:

P1: {W(x) 1, W(y) 2} {R(y) 4}

P2: {W(x) 1, R(y) 4}

P3: {W(x) 0, W(y) 4}

P4: {R(x) 0} {R(x) 1}

Consistency Model:

Strictly Serializable	Yes
Linearizable	Yes
Sequential	Yes
Causal+	Yes
Eventual	Yes

Exercise 2:

P1:	W(x) 1			R(y) 4
P2:		R(x) 1		R(y) 4
P3:		R(x) 1	W(y) 4	
P4:		R(x) 1		R(y) 4

Consistency Model:

Linearizable	**Yes**
Sequential	**Yes**
Causal+	**Yes**
Eventual	**Yes**

Exercise 3:

P1:	W(x) 3				W(y) 7	
P2:		W(x) 1				
P3:			R(x) 1	R(x) 3		R(y) 7
P4:			R(x) 1	R(x) 3		R(y) 7
P5:			R(x) 1	R(x) 3		R(y) 7

Consistency Model:

Linearizable	**No**
Sequential	**Yes**
Causal+	**Yes**
Eventual	**Yes**

Exercise 4:

P1:	W(x) 3				W(y) 7	
P2:		W(x) 1				
P3:			R(x) 1	R(x) 3		R(y) 7
P4:			R(x) 3	R(x) 1		R(y) 7
P5:			R(x) 1	R(x) 3		R(y) 7

Consistency Model:

Linearizable	**No**
Sequential	**No**
Causal+	**Yes**
Eventual	**Yes**

Exercise 5:

P1:	W(x) 1					
P2:		W(x) 3				
P3:			W(x) 7			
P4:				R(x) 3	R(x) 7	R(x) 1
P5:				R(x) 3	R(x) 1	R(x) 7

Consistency Model:

Linearizable	**No**
Sequential	**No**
Causal+	**Yes**
Eventual	**Yes**

Exercise 6:

P1:	W(x) 1							
P2:		W(x) 3						
P3:			R(x) 3	W(x) 7				
P4:					R(x) 3	R(x) 7	R(x) 1	
P5:					R(x) 3	R(x) 1	R(x) 7	

Consistency Model:

Linearizable	**No**
Sequential	**No**
Causal+	**Yes**
Eventual	**Yes**

Exercise 7:

P1:	W(x) 1							
P2:		R(x) 1	W(x) 3					
P3:				R(x) 3	W(x) 7			
P4:						R(x) 3	R(x) 7	R(x) 1
P5:						R(x) 3	R(x) 1	R(x) 7

Consistency Model:

Linearizable	**No**
Sequential	**No**
Causal+	**No**
Eventual	**Yes**