Consistency

11/15/2019
Consistency Models

- Strict Serializability
- Linearizability
- Sequential
- Causal+
- Eventual
Consistency Models

- Strict Serializability
- Linearizability
- Sequential
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- Eventual

Stronger to Weaker
Strict Serializability

- **Transactions**: Operations can span multiple objects (e.g., keys in KV store)
- **Total order**: There exists some legal total ordering of transactions.
  - **Legal**: In the total ordering, a read operation sees the latest write operation.
- **Preserves real-time ordering**: Any transaction $A$ that completes before transaction $B$ begins, occurs before $B$ in the total order.
- **Properties**:
  - Writes in a completed transaction appear to all future reads
  - Once a read sees transaction and completes, all future reads must see new transaction

**Pros**: Easily reason about correctness of transactions

**Cons**: High read and write latencies
Strict Serializability Example

<table>
<thead>
<tr>
<th>严格的串行可串行化？</th>
<th>是</th>
<th>严格的串行可串行化？</th>
<th>否</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1:</td>
<td>{W(x)b, W(y)b}</td>
<td>P1:</td>
<td>{W(x)b, W(y)b}</td>
</tr>
<tr>
<td>P2:</td>
<td>{W(x)a}</td>
<td>P2:</td>
<td>{W(x)a}</td>
</tr>
<tr>
<td>P3:</td>
<td>{R(x)a}</td>
<td>P3:</td>
<td>{R(y)b}</td>
</tr>
<tr>
<td>P4:</td>
<td>{R(x)b}</td>
<td>P4:</td>
<td>{R(x)b}</td>
</tr>
</tbody>
</table>
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Stronger

Weaker
Linearizability

- **Total order**: There exists some legal total order of operations
- **Preserves real-time ordering**: Any operation $A$ that completes before operation $B$ begins, occurs before $B$ in the total order.
- **Difference from strict serializability?**
  - Single-object operations! No transactions!
- **Properties**
  - A completed write appears to all future reads
  - Once a read sees a new value, all future reads must return the new value (until new write)

**Pros**: Easy to reason about correctness

**Cons**: High read and write latencies
## Linearizability Example

<table>
<thead>
<tr>
<th>Linearizable?</th>
<th>No</th>
<th>Linearizable?</th>
<th>Yes</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1: W(x)a</td>
<td></td>
<td>P1: W(x)a</td>
<td></td>
</tr>
<tr>
<td>P2: W(x)b</td>
<td></td>
<td>P2: W(x)b</td>
<td></td>
</tr>
<tr>
<td>P3: R(x)b R(x)a</td>
<td></td>
<td>P3: R(x)a R(x)b</td>
<td></td>
</tr>
<tr>
<td>P4: R(x)b R(x)a</td>
<td></td>
<td>P4: R(x)a R(x)b</td>
<td></td>
</tr>
</tbody>
</table>
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Stronger at the left, Weaker at the right.
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

<table>
<thead>
<tr>
<th>P1:</th>
<th>W(x)a</th>
<th>P1:</th>
<th>W(x)a</th>
</tr>
</thead>
<tbody>
<tr>
<td>P2:</td>
<td>W(x)b</td>
<td>P2:</td>
<td>W(x)b</td>
</tr>
<tr>
<td>P3:</td>
<td>R(x)b R(x)a</td>
<td>P3:</td>
<td>R(x)b R(x)a</td>
</tr>
<tr>
<td>P4:</td>
<td>R(x)b R(x)a</td>
<td>P4:</td>
<td>R(x)a R(x)b</td>
</tr>
</tbody>
</table>

Sequentially Consistent? Yes

Sequentially Consistent? No
Consistency Models

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Consistency models range from stronger to weaker.
Causal+ Consistency

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

**Pros**: Preserves causality while improving efficiency

**Cons**: Need to reason about concurrency
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

Strict Serializability → Linearizability → Causal → Sequential → Eventual

Stronger → Linearizability → Causal → Sequential → Eventual → Weaker
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 Dynamo

**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\} \quad \{R(y) 4\}

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

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

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

Consistency Model:

- Strictly Serializable: Yes
- Linearizable: Yes
- Sequential: Yes
- Causal+: Yes
- Eventual: Yes
Exercise 2:

Consistency Model:
- Linearizable: Yes
- Sequential: Yes
- Causal+: Yes
- Eventual: Yes

P1: \( W(x) \ 1 \quad R(y) \ 4 \)

P2: \( R(x) \ 1 \quad R(y) \ 4 \)

P3: \( R(x) \ 1 \quad W(y) \ 4 \)

P4: \( R(x) \ 1 \quad R(y) \ 4 \)
Exercise 3:

<table>
<thead>
<tr>
<th></th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
<th>P5</th>
<th>Consistency Model:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>W(x) 3</td>
<td>W(x) 1</td>
<td>R(x) 1</td>
<td>R(x) 1</td>
<td>R(x) 1</td>
<td>Linearizable</td>
</tr>
<tr>
<td></td>
<td>W(y) 7</td>
<td></td>
<td>R(x) 3</td>
<td>R(x) 3</td>
<td>R(x) 3</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>R(y) 7</td>
<td>R(y) 7</td>
<td>R(y) 7</td>
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<td>Causal+</td>
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<td>Eventual</td>
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<td></td>
<td>Yes</td>
</tr>
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</table>
Exercise 4:

Consistency Model:
- Linearizable: No
- Sequential: No
- Causal+: Yes
- Eventual: Yes

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
Exercise 5:

<table>
<thead>
<tr>
<th></th>
<th>P1: W(x) 1</th>
<th>P2: W(x) 3</th>
<th>P3: W(x) 7</th>
<th>P4: R(x) 3 R(x) 7 R(x) 1</th>
<th>P5: R(x) 3 R(x) 1 R(x) 7</th>
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**Consistency Model:**

- Linearizable: No
- Sequential: No
- Causal+: Yes
- Eventual: Yes
Exercise 6:

<p>| | | |</p>
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<td>W(x) 7</td>
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<td>P4:</td>
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<td>P5:</td>
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<td>R(x) 1</td>
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Consistency Model:

- Linearizable: No
- Sequential: No
- Causal+: Yes
- Eventual: Yes
Exercise 7:

Consistency Model:

- Linearizable: No
- Sequential: No
- Causal+: No
- Eventual: Yes

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<th>W(x) 1</th>
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