CAP Theorem and Consistency Models

COS 418: Distributed Systems
Lecture 12

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Outline

1. Network Partitions
2. Linearizability
3. CAP Theorem
4. Consistency Hierarchy
Network Partitions Divide Systems
Network Partitions Divide Systems
How Can We Handle Partitions?

• Atomic Multicast?
• Bayou?
• Viewstamped Replication?
• Chord?
• Paxos?
• Dynamo?
• RAFT?
How About This Set of Partitions?
Fundamental Tradeoff?

• Replicas appear to be a single machine, but lose availability during a network partition

• OR

• All replicas remain available during a network partition but do not appear to be a single machine
CAP Theorem Preview

• You cannot achieve all three of:
  1. Consistency
  2. Availability
  3. Partition-Tolerance

• Partition Tolerance => Partitions Can Happen
• Availability => All Sides of Partition Continue
• Consistency => Replicas Act Like Single Machine
  • Specifically, Linearizability
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1. Network Partitions
2. Linearizability
3. CAP Theorem
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Linearizability [Herlihy and Wing 1990]

- 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
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
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, e.g., CAP
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CAP Conjecture [Brewer 00]

• From keynote lecture by Eric Brewer (2000)
  • History: Eric started Inktomi, early Internet search site based around “commodity” clusters of computers
  • Using CAP to justify “BASE” model: Basically Available, Soft-state services with Eventual consistency

• Popular interpretation: 2-out-of-3
  • Consistency (Linearizability)
  • Availability
  • Partition Tolerance: Arbitrary crash/network failures
Assume to contradict that Algorithm $A$ provides all of CAP
**CAP Theorem**  [Gilbert Lynch 02]

Assume to contradict that Algorithm A provides all of CAP
CAP Theorem [Gilbert Lynch 02]

Assume to contradict that Algorithm A provides all of CAP

Write eventually returns (from A)

Partition Possible (from P)
CAP Theorem [Gilbert Lynch 02]

Assume to contradict that Algorithm A provides all of CAP

Write eventually returns (from A)

Read begins after write completes
Read eventually returns (from A)

Partition Possible (from P)
**CAP Theorem** [Gilbert Lynch 02]

Assume to contradict that Algorithm A provides all of CAP

- **Partition Possible (from P)**
- **Write eventually returns (from A)**
- **Read eventually returns (from A)**
- **Not consistent (C) => contradiction!**

Write eventaully returns

Read begins after write completes

Partition Possible (from P)
Cannot “choose” no partitions
  • 2-out-of-3 interpretation doesn’t make sense
  • Instead, availability OR consistency?

i.e., fundamental tradeoff between availability and consistency
  • When designing system must choose one or the other, both are not possible
CAP Interpretation Part 2

• It is a theorem, with a proof, that you understand!

• Cannot “beat” CAP Theorem

• Can engineer systems to make partitions extremely rare, however, and then just take the rare hit to availability (or consistency)
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1. Network Partitions

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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

• e.g., Linearizability
  • Guarantees a total order of operations
  • Guarantees the real-time ordering is respected
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

• Linearizability is strictly stronger than Sequential Consistency
  • Linearizability: ∃ total order + real-time ordering
  • Sequential: ∃ total order + process ordering
    • Process ordering ⊆ Real-time ordering
Sequential But Not Linearizable
Consistency Hierarchy

Linearizability
  ↓
Sequential Consistency
  ↓
Causal+ Consistency
  ↓
Eventual Consistency
  ↓
e.g., RAFT
  ↓
e.g., Bayou
  ↓
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+ But Not Sequential

\[ P_A \vdash w(x=1) \quad \vdash r(y)=0 \]
\[ P_B \vdash w(y=1) \quad \vdash r(x)=0 \]

√ 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+

$P_A \vdash w(x=1) \vdash w(y)=1 \vdash$ $r(y)=1 \vdash r(x)=0$ $w(y)=1$ $r(x)=0$ $w(x=1)$ $w(y)=1$ $r(x)=0$ $\sqrt{\text{Eventual}}$

$P_B$  $\vdash r(y)=1 \vdash r(x)=0$

$\checkmark$ Eventual

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

$\times$ Causal+

Happens Before Ordering

No Order for $P_B$

$\vdash w(x=1) \rightarrow w(y)=1$

$\vdash r(y)=1 \rightarrow r(x)=0$

$\vdash w(x=1) \rightarrow w(y)=1$

$\vdash r(y)=1 \rightarrow r(x)=0$
Consistency Hierarchy

Linearizability → Sequential Consistency → Causal+ Consistency → Eventual Consistency

- e.g., RAFT
- e.g., Bayou
- e.g., Dynamo

CAP
Consistency Hierarchy

- Linearizability  
  - e.g., RAFT

- Sequential Consistency

- Causal+ Consistency  
  - e.g., Bayou

- Eventual Consistency  
  - e.g., Dynamo

CAP  
PRAM 1988  
(Princeton)
PRAM [Lipton Sandberg 88] [Attiya Welch 94]

- $d$ is the worst-case delay in the network over all pairs of processes

- Sequentially consistent system

- read time + write time $\geq d$

- Fundamental tradeoff between consistency and latency!
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