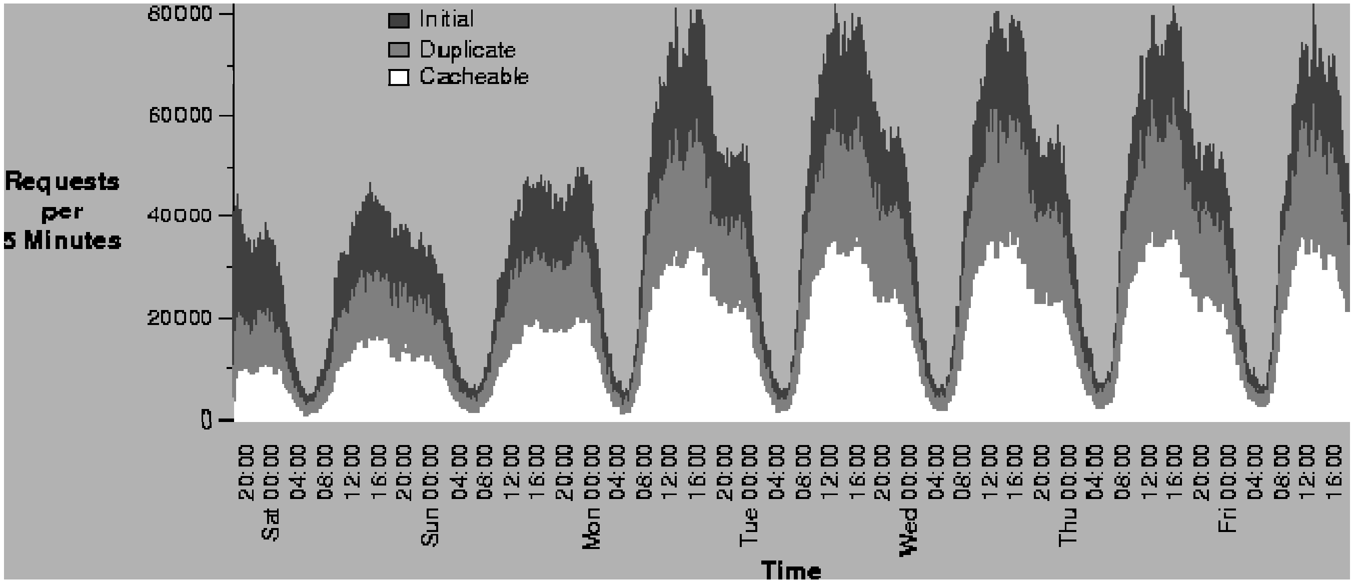
CAP Theorem



Organization-Based Analysis of Web-Object Sharing and Caching
Alec Wolma et al.

CAP Theorem Introduction

- It is **impossible** for a replicated **read-write store** in an asynchronous network to maintain the following **three guarantees simultaneously**:
  - **C**onsistency
  - **A**vailability
  - **P**artition-Tolerance

atomic register

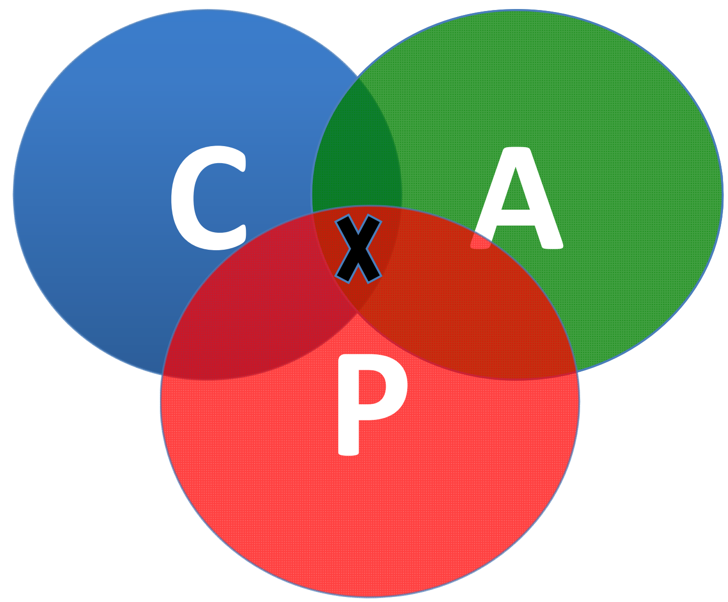
- Initially, conjectured by Eric Brewer in 1998, later proven by Lynch et al.
- Describes *tradeoffs* involved in distributed system design

Definition of Atomic Register

- Models **replicated read-write store**:
  - set(X) sets value of register to X
  - get() returns the value of register
- Register is replicated and distributed, must maintain consistency and availability across all replicas
- Models many distributed system types
  - Key-value store
  - Distributed cache

C-A-P: Choose <u>two</u> out of <u>three</u>*

- <u>C</u>onsistency:
  - All read requests should read the latest value (or return an error)
- <u>A</u>vailability:
  - All requests should return successfully
- <u>P</u>artition-tolerance:
  - The system can tolerate arbitrary number of communication failures



- Traditional view
  - Today, more a **spectrum**

Definition of Consistency

- Refers to **replication consistency**
  - Not related to *A* – ***C*** – *I D properties* for transactions

- Ideally means **strict consistency**
  - As we know, this is by and large impossible in a distributed system

- Thus, here, assumes **linearizability**

- This usually means replication across sites should be done **eagerly**

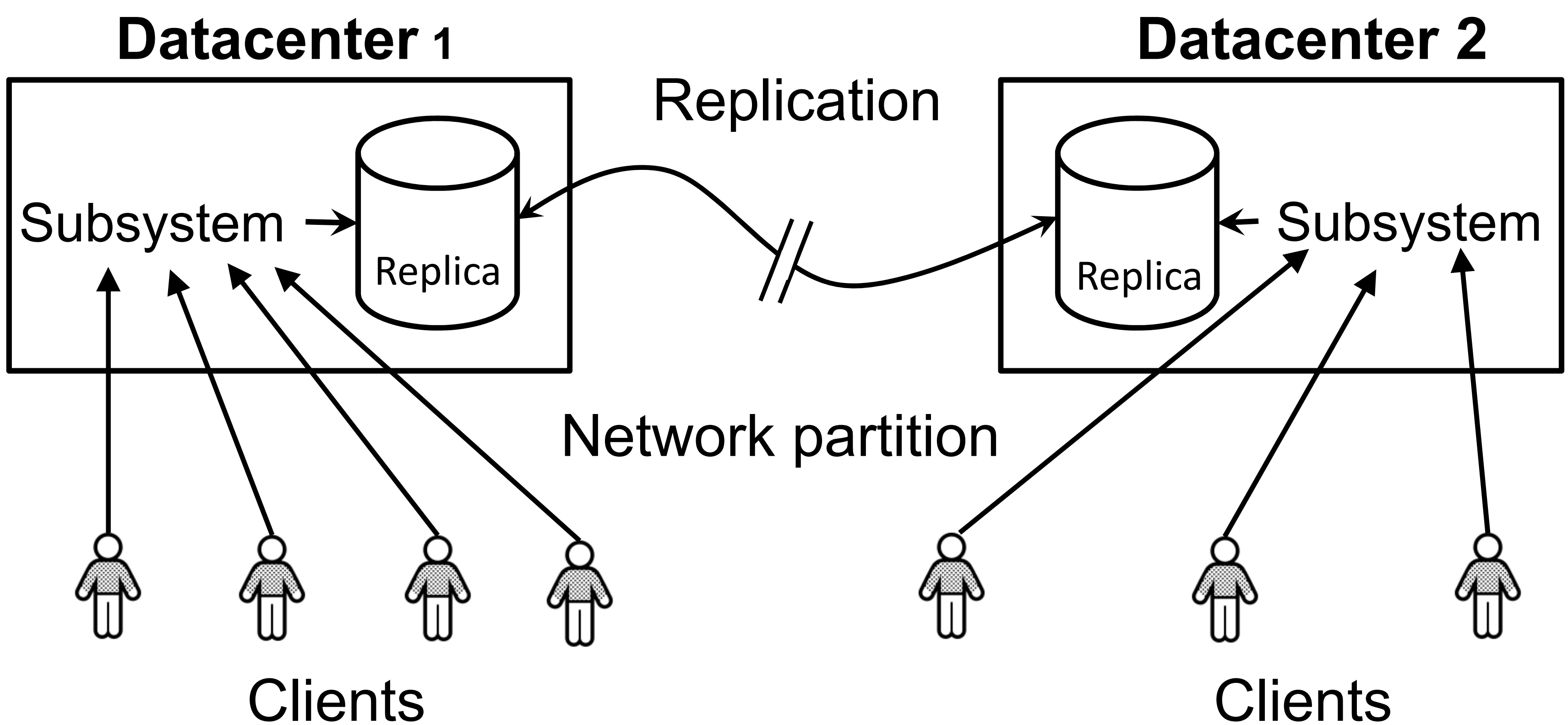
Definition of Availability

- **Every request** received by a non-failed node must result in a **non-error response**
  - **Non-triviality requirement**: a system which always responds with errors is **not available**
- Assumes a **crash failure** model for nodes
  - **Functioning nodes** must continue to operate even if there are **failed nodes** in system
- No requirement on **latency**: response can be very slow but must eventually come through
- Both a **weak and strong** definition: no latency guarantee, but 100% response success

Definition of Partition-Tolerance

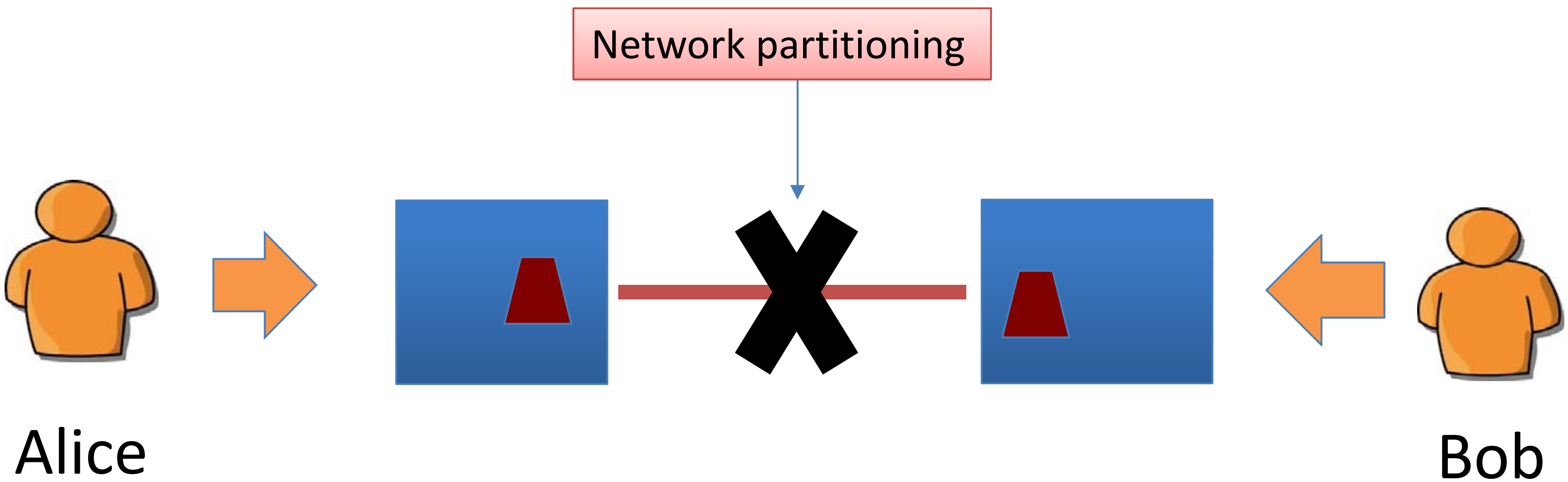
- Asynchronous system model
- Message loss (failure model)
- Partition means total communication loss between partitioned subsystems
- System **continues request processing** even if a network partition causes communication loss between subsystems
- If the system requires a **stronger system model**, or a **weaker failure model**, then it is **not partition-tolerant**
- No guarantee that **partitions recover**, but it doesn't mean they are **always present** either

Definition of Partition-Tolerance



Illustrating Example

Hotel Booking: are we double-booking the same room?



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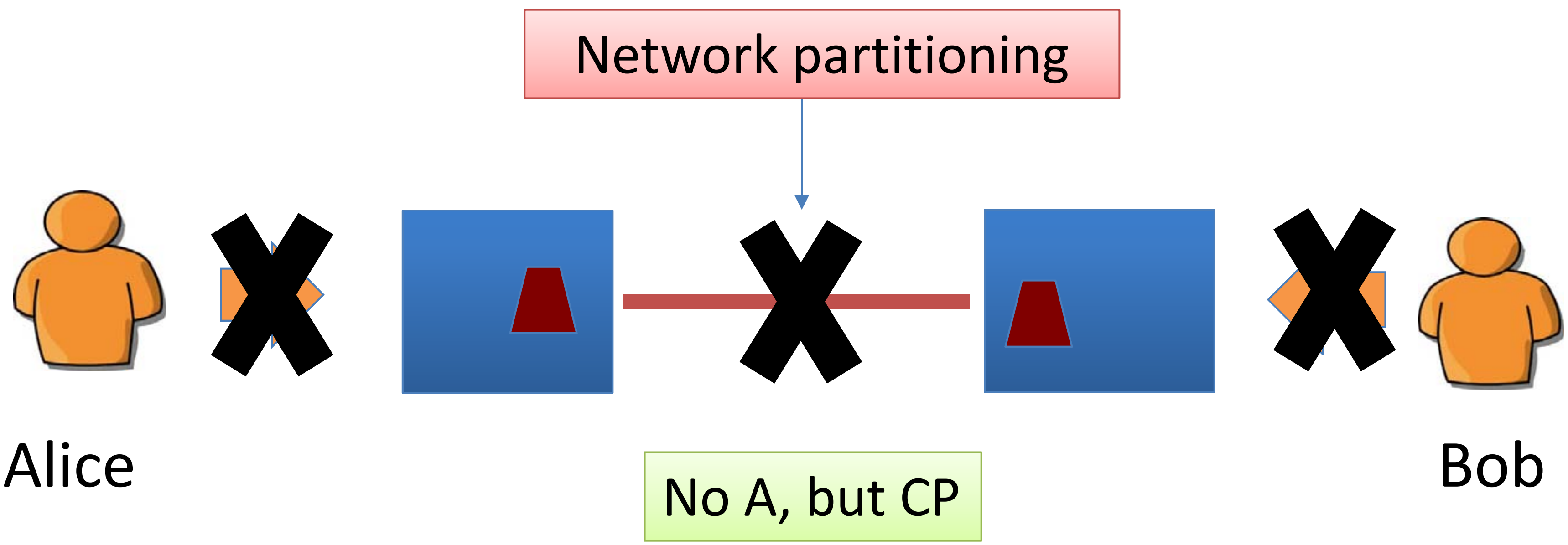

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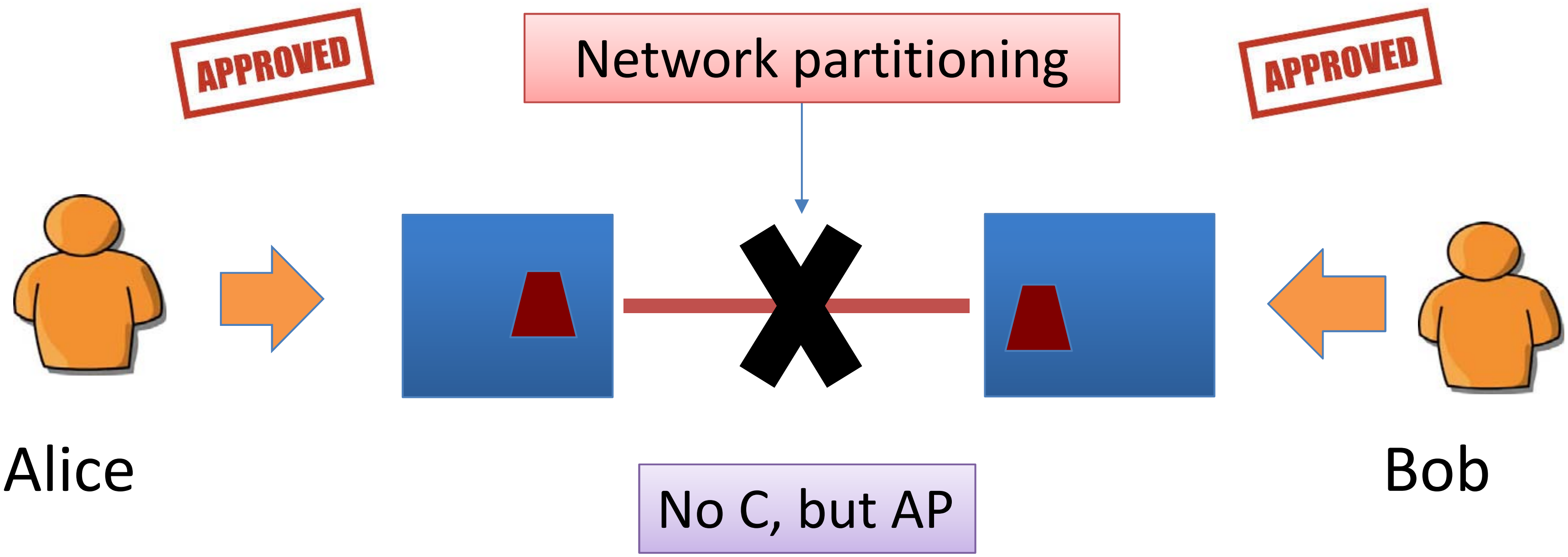
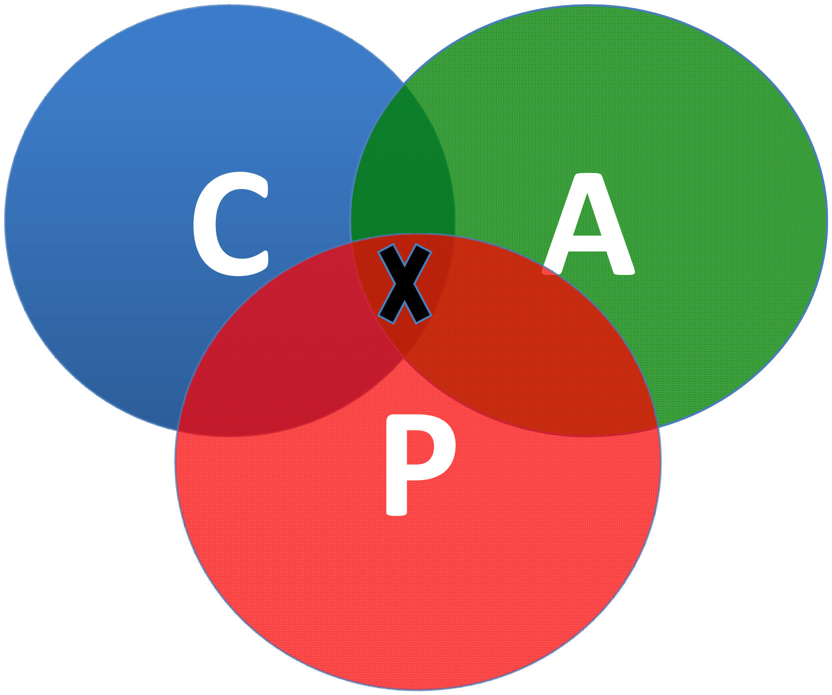
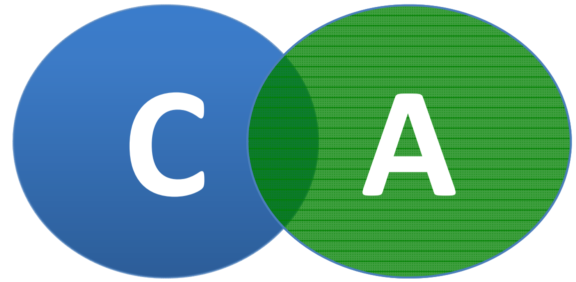


Types of CAP systems

- CAP says *"pick two out of three"*
- The following systems seem possible:
  - CP
  - AP
  - CA
- But it's not so easy…



CA Systems



- A "perfect" system!
- But with strong assumptions:
  - Either the network is reliable (Fallacy of DS…)
  - Or, the network is not used (then it is not a DS!)
- *"Of the CAP theorem's Consistency, Availability, and Partition-Tolerance,* ***Partition Tolerance is mandatory in distributed systems****. You cannot not choose it."*
  - Coda Hale, Yammer software engineer

*Misconception #1: Always choose two

- CA systems cannot be used in practice
- **But,** when there are **no network partitions**, every system can behave like CA!
- In other words, choose two only takes effect **during network partitions**
- So in reality, there are **only two types of systems** ... I.e., if there is a partition, does the system **give up availability or consistency?**
  – Daniel Abadi, co-founder of Hadapt

Misconception #2: C, A are binary

- CAP theorem uses very narrow definitions of C,A:
  - Consistency: linearizability
  - Availability: infinite latency budget, 100% successful
- *"The "2 of 3" formulation was always **misleading** because it tended to oversimplify the tensions among properties. CAP prohibits only a tiny part of the design space: **perfect availability and consistency** in the presence of **partitions**, which are **rare**."*
  - Eric Brewer, CAP theorem

Reality of the CAP Theorem

- *"Many designers incorrectly conclude that the theorem imposes certain restrictions on a DDBS **during normal operation** and therefore implement an **unnecessarily limited system**."*
  - Daniel Abadi, Co-founder of Hadapt
- All systems are, in fact, CAP, but tune how much C and A are provided during P
  - CP → C(a)P, and AP → (c)AP
- Provides **freedom** to design system to **suit** application requirements
  - e.g., by choosing appropriate consistency level

AP: Best Effort Consistency

- Example:
  - Web caching (cf., cache consistency)
  - Network File System (cf., concurrent writes)
- Characteristics:
  - Optimistic replication (i.e., lazy replication)
  - Expiration/Time-to-live
  - Conflict resolution (e.g., CRDTs)
- Cassandra, Dynamo are AP systems:
  - Eventual consistency: stale data can be read
  - Cassandra can be tuned towards CP

CP: Best Effort Availability

- Example:
  - Distributed lock services (Chubby, ZooKeeper)
  - Paxos (safe, not live)
- Characteristics:
  - Eager replication
  - Pessimistic locking
  - Minority partition becomes unavailable
- BigTable / Hbase are CP systems:
  - Provide linearizability
  - Under partitions, cannot access TabletServer/RegionServer

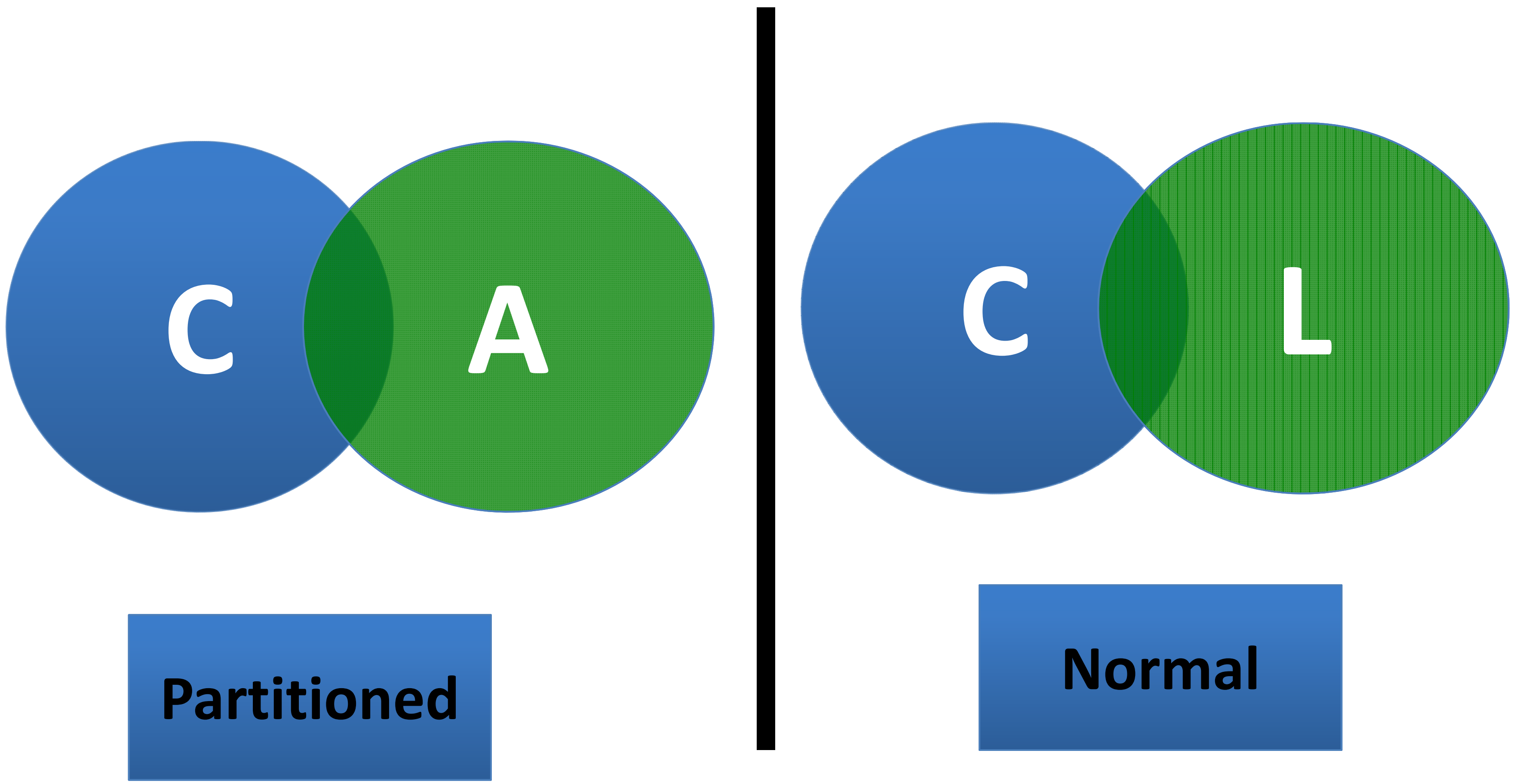
Misconception #3: Static systems

- Systems don’t always behave the same way at run-time
- It is possible to design systems which behave differently depending on the operational situation when **partitioning**
- Example: airline reservation system
  - When most seats available: system **behaves AP**, worries about capacity limit later
  - When plane is close to capacity: system **behaves CP**, ensures no overbooking, or **behaves AP** to maximize profit and handle compensations out-of-band

Extended Model: PACELC

- A more complete description of the space of potential tradeoffs for distributed system:
  - **If** there is a partition (P), how does the system trade off availability and consistency (A and C); **else (E)**, when the system is running normally in the absence of partitions, how does the system trade off **latency (L) and consistency (C)?**
- Original CAP theorem ignores latency, yet important in practice

PAC/ELC



Examples

- PA/EL: Give up consistency at all times for availability and lower latency
  - Dynamo, Cassandra (tuneable), Riak, web caching
- PC/EC: Refuse to give up consistency, pay the cost in availability and latency
  - BigTable, Hbase, VoltDB/H-Store
- PA/EC: Give up consistency when partitions occur, but keep consistency during normal operation
  - MongoDB
- PC/EL: Keep consistency when partitions occur, but give up consistency for latency during normal operations
  - Yahoo! PNUTS

Summary CAP Theorem

- Classically described as *"pick two out of three"*: **c**onsistency, **a**vailability, **p**artition-tolerance
- Really boils down to **choosing C or A**, since P is a **must-have** for practical systems
- During normal operations, systems can all be **CA**
- Only concerns **"perfect" notions** of C and A
- In reality, C and A **are tunable,** systems tend to maintain C and A during P to some degree
- Systems can **adapt** to become AP or CP for different operational situations
- PACELC: extended model which considers **normal operation and latency**