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MIDLAB Middleware Laboratory

The CAP theorem and the design of large scale distributed systems: Part I

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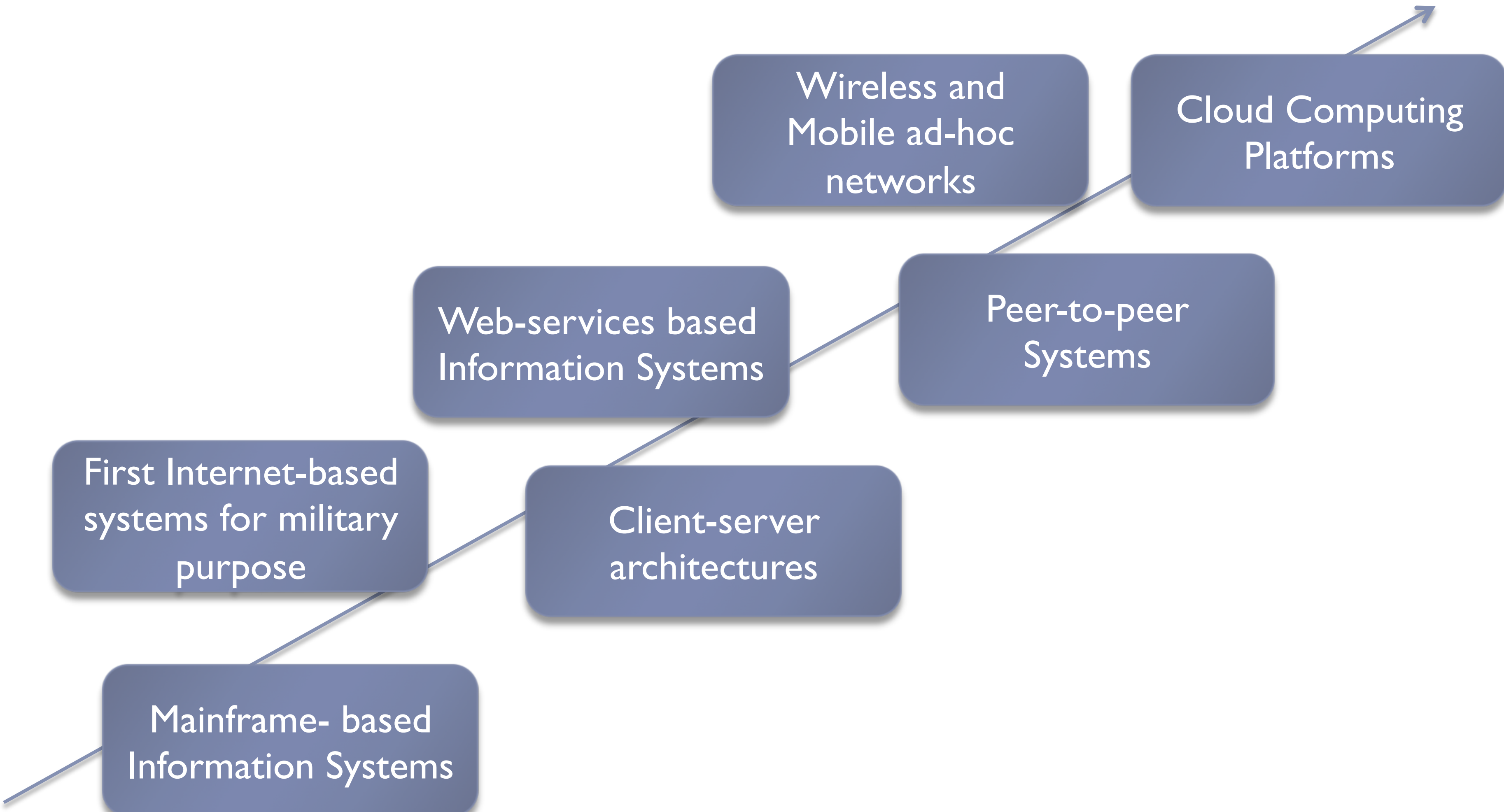
Great Ideas in Computer Science & Engineering
A.A. 2012/2013

A little bit of History



Relational Databases History

- Relational Databases – mainstay of business
- Web-based applications caused spikes
  - Especially true for public-facing e-Commerce sites
- Developers begin to front RDBMS with memcache or integrate other caching mechanisms within the application

Scaling Up

- Issues with scaling up when the dataset is just too big
- RDBMS were not designed to be distributed
- Began to look at multi-node database solutions
- Known as ‘scaling out’ or ‘horizontal scaling’
- Different approaches include:
  - Master-slave
  - Sharding

Scaling RDBMS – Master/Slave

- Master-Slave
  - All writes are written to the master. All reads performed against the replicated slave databases
  - Critical reads may be incorrect as writes may not have been propagated down
  - Large data sets can pose problems as master needs to duplicate data to slaves

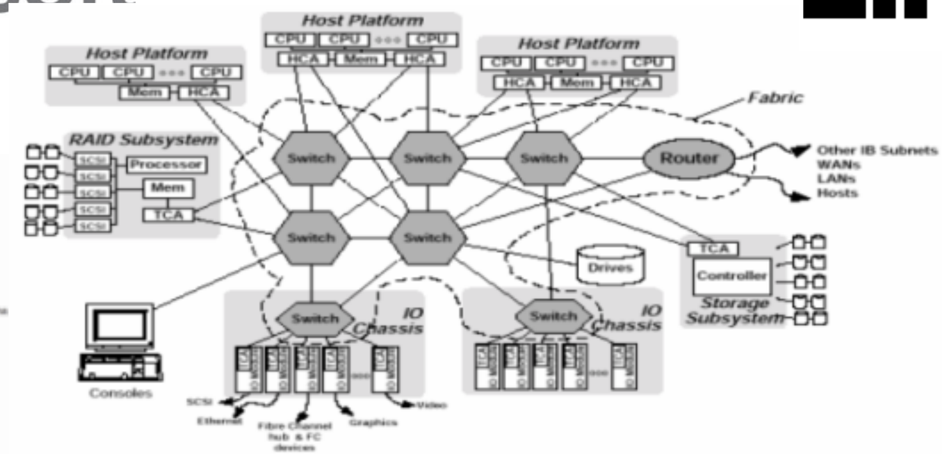
Scaling RDBMS - Sharding

- Partition or sharding
  - Scales well for both reads and writes
  - Not transparent, application needs to be partition-aware
  - Can no longer have relationships/joins across partitions
  - Loss of referential integrity across shards

Other ways to scale RDBMS

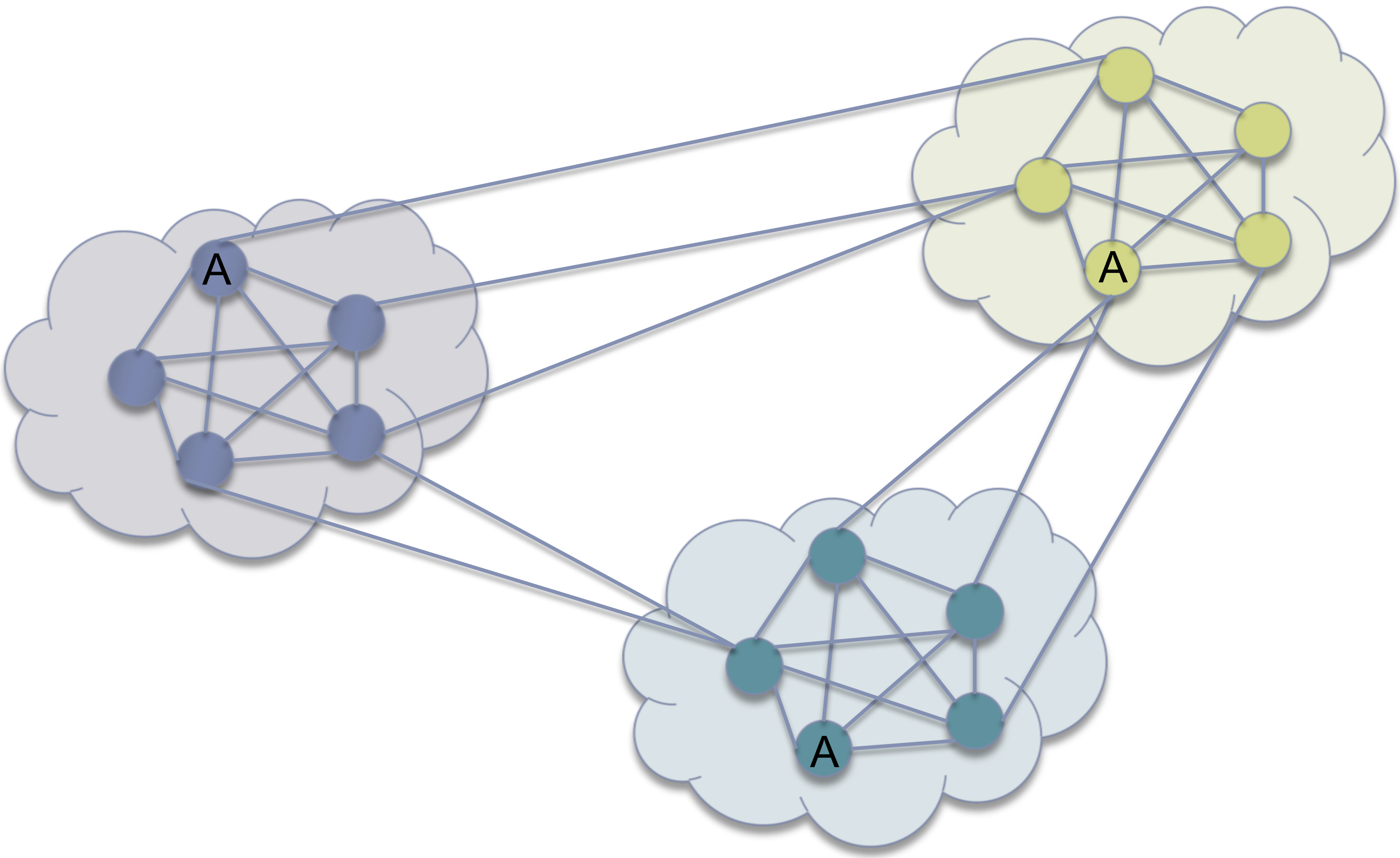
- Multi-Master replication
- INSERT only, not UPDATES/DELETES
- No JOINs, thereby reducing query time
  - This involves de-normalizing data
- In-memory databases

Today…


Host Platform
CPU
HCA
Mem
Fabric
RAID Subsystem
SCSI
Processor
TCA
Switch
Router
Other IB Subnets
WANs
LANs
Hosts
Drives
Controller
Storage Subsystem
IO Chassis
Consoles

Context

- Networked Shared-data Systems



Fundamental Properties

- Consistency
  - (informally) “every request receives the right response”
  - E.g. If I get my shopping list on Amazon I expect it contains all the previously selected items

- Availability
  - (informally) “each request eventually receives a response”
  - E.g. eventually I access my shopping list

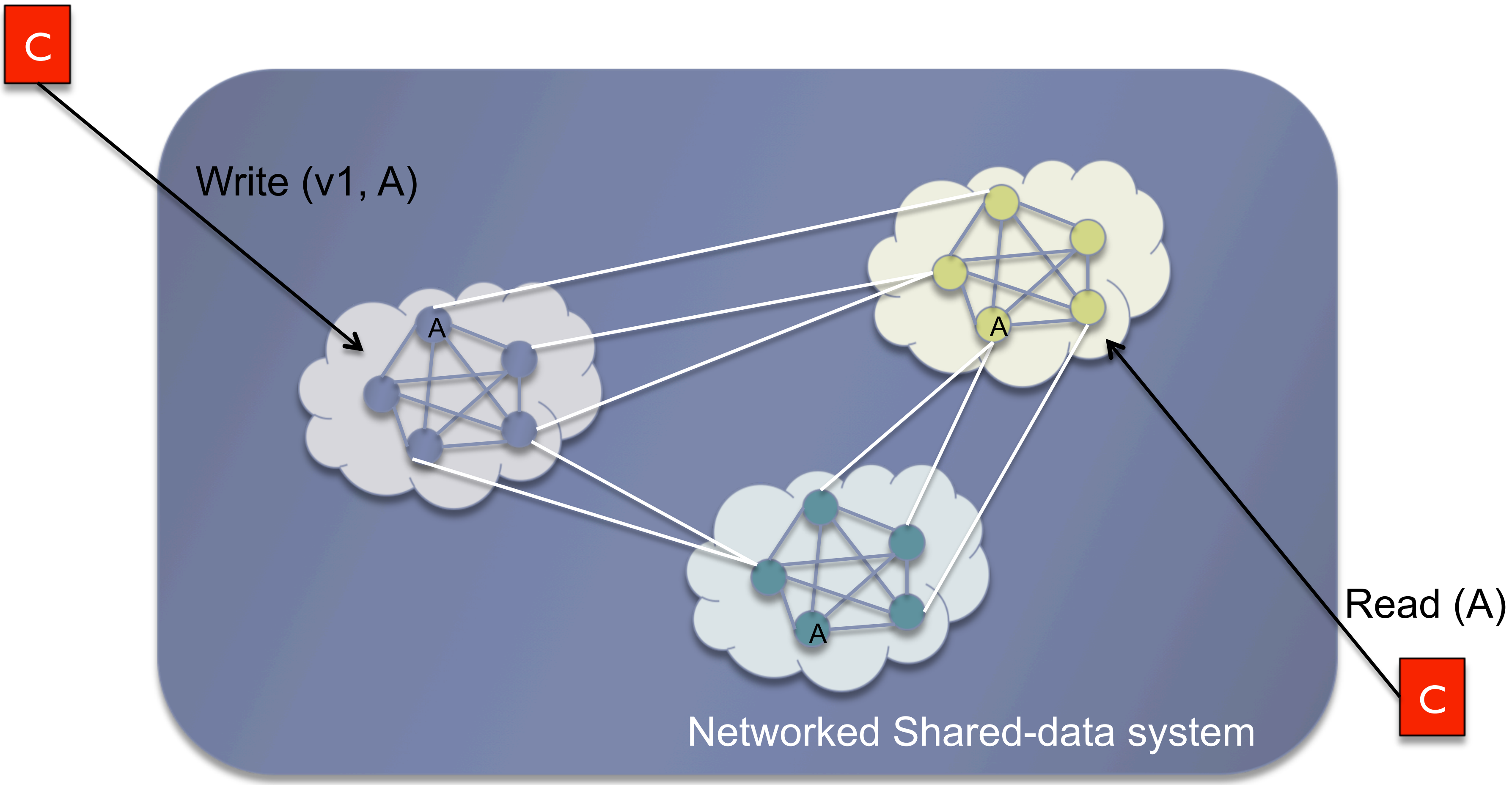
- tolerance to network Partitions
  - (informally) “servers can be partitioned in to multiple groups that cannot communicate with one other”

CAP Theorem

- 2000: Eric Brewer, PODC conference keynote
- 2002: Seth Gilbert and Nancy Lynch, ACM SIGACT News 33(2)

"Of three properties of shared-data systems (Consistency, Availability and tolerance to network Partitions) only two can be achieved at any given moment in time."

Proof Intuition

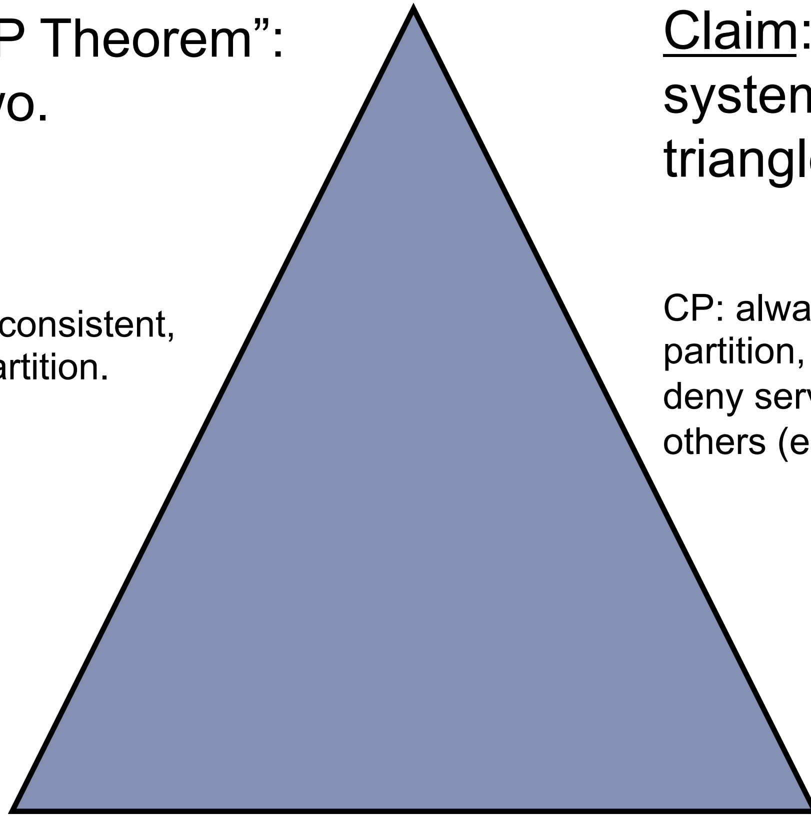


consistency

C

Fox&Brewer “CAP Theorem”:
C-A-P: choose two.

Claim: every distributed system is on one side of the triangle.



CA: available, and consistent, unless there is a partition.

CP: always consistent, even in a partition, but a reachable replica may deny service without agreement of the others (e.g., quorum).

A

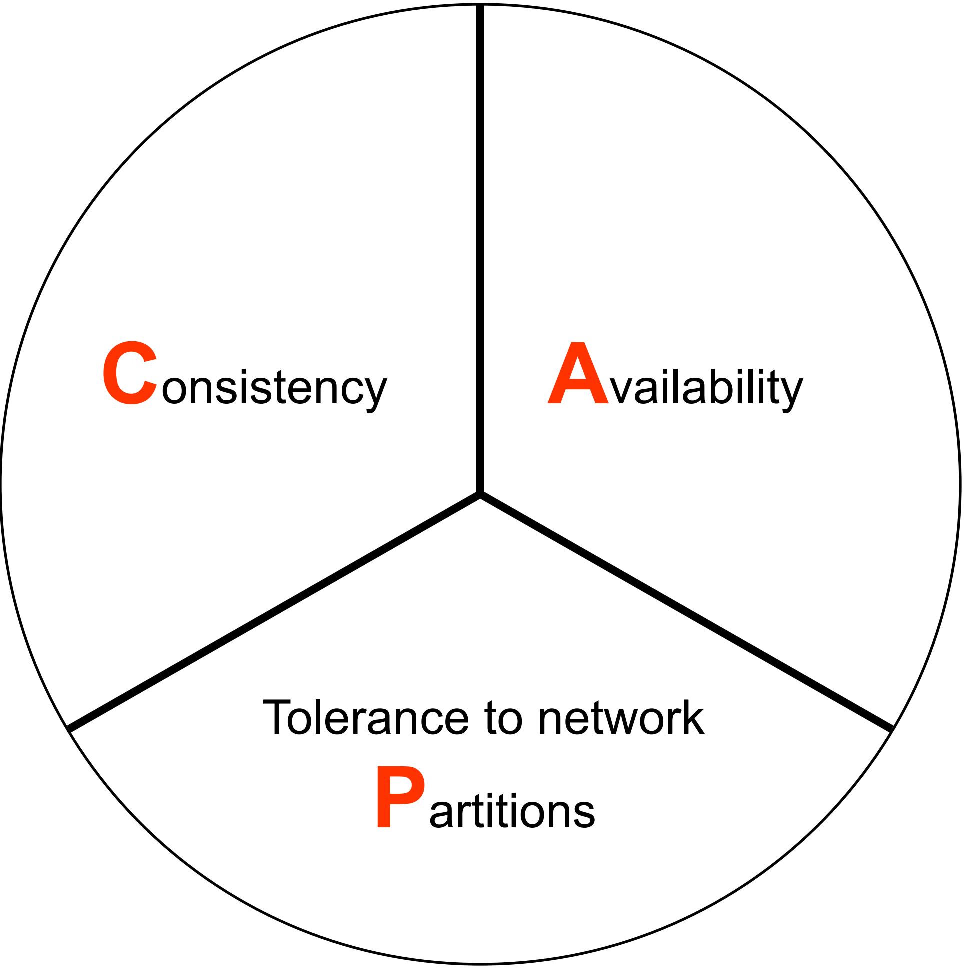
Availability

AP: a reachable replica provides service even in a partition, but may be inconsistent.

P

Partition-resilience

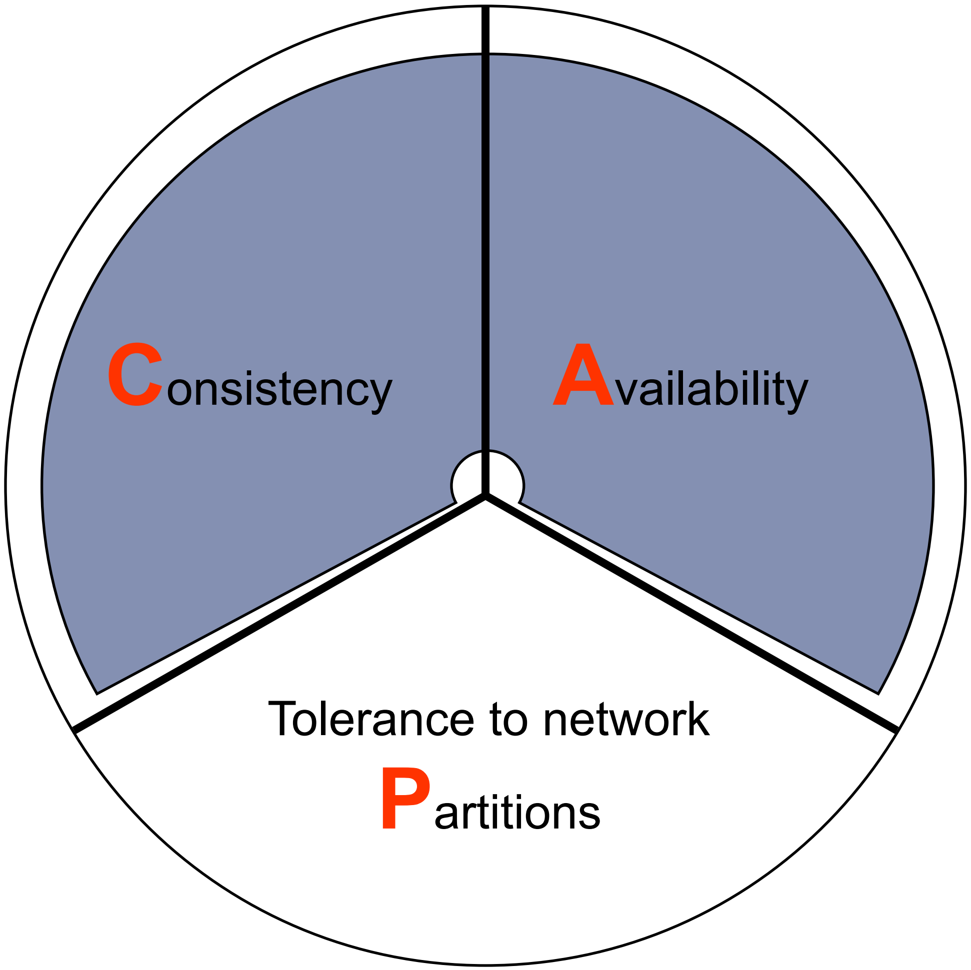
The CAP Theorem



Theorem: You can have **at most two** of these invariants for any shared-data system

Corollary: consistency boundary must choose A or P

Forfeit Partitions



Examples

- Single-site databases
- Cluster databases
- LDAP
- Fiefdoms

Traits

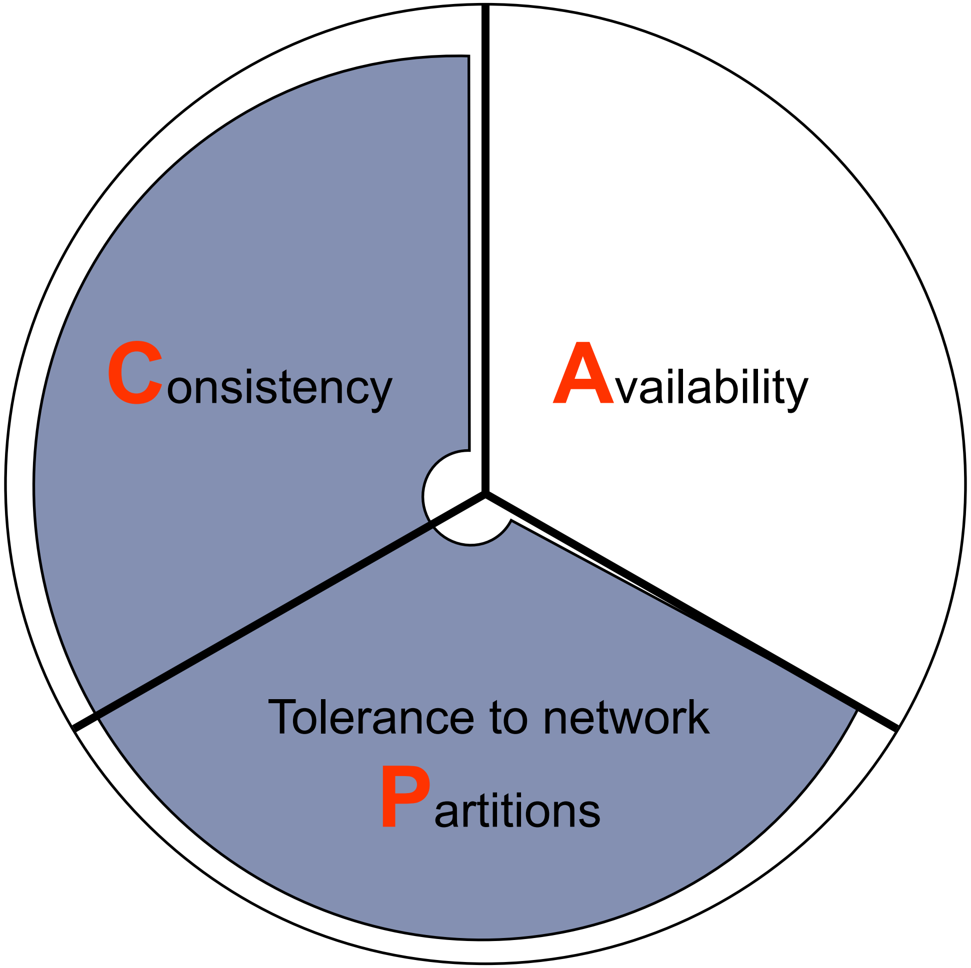
- 2-phase commit
- cache validation protocols
- The "inside"

Observations

- CAP states that in case of failures you can have at most two of these three properties for any shared-data system

- To scale out, you have to distribute resources.
  - P in not really an option but rather a need
  - The real selection is among consistency or availability
  - In almost all cases, you would choose availability over consistency

Forfeit Availability



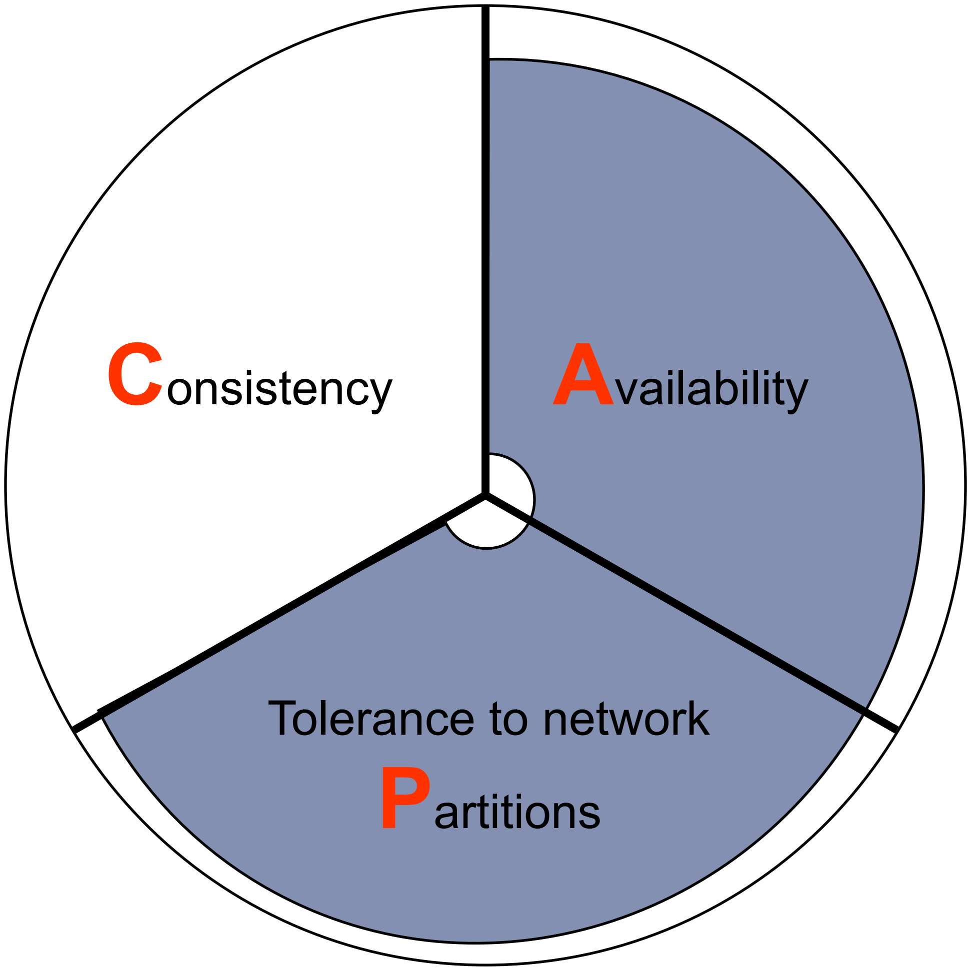
Examples

- Distributed databases
- Distributed locking
- Majority protocols

Traits

- Pessimistic locking
- Make minority partitions unavailable

Forfeit Consistency



Examples

- Coda
- Web caching
- DNS
- Emissaries

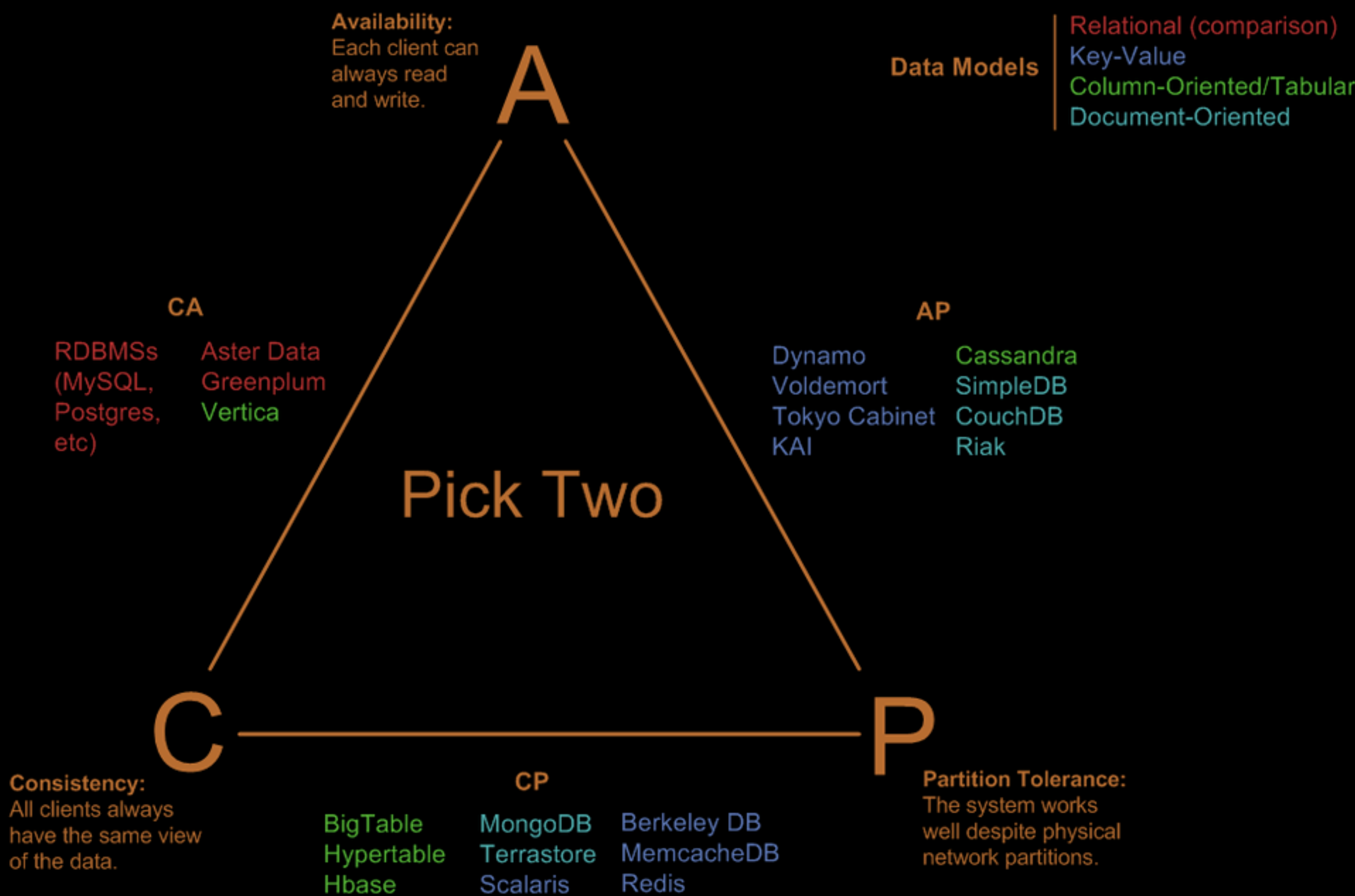
Traits

- expirations/leases
- conflict resolution
- Optimistic
- The "outside"

Consistency Boundary Summary

- We can have consistency & availability within a cluster.
  - No partitions within boundary!
- OS/Networking better at A than C
- Databases better at C than A
- Wide-area databases can't have both
- Disconnected clients can't have both

Visual Guide to NoSQL Systems



CAP, ACID and BASE

- BASE stands for Basically Available Soft State Eventually Consistent system.

- Basically Available: the system available most of the time and there could exists a subsystems temporarily unavailable

- Soft State: data are "volatile" in the sense that their persistence is in the hand of the user that must take care of refresh them

- Eventually Consistent: the system eventually converge to a consistent state

CAP, ACID and BASE

- Relation among ACID and CAP is core complex

- Atomicity: every operation is executed in "all-or-nothing" fashion
- Consistency: every transaction preserves the consistency constraints on data
- Integrity: transaction does not interfere. Every transaction is executed as it is the only one in the system
- Durability: after a commit, the updates made are permanent regardless possible failures

CAP, ACID and BASE

CAP

- C here looks to single-copy consistency
- A here look to the service/ data availability

ACID

- C here looks to constraints on data and data model
- A looks to atomicity of operation and it is always ensured
- I is deeply related to CAP. I can be ensured in at most one partition
- D is independent from CAP

Warning!

- What CAP says:
  - When you have a partition in the network you cannot have both C and A

- During Normal Periods (i.e. period with no partitions) both C and A can be achieved

2 of 3 is misleading

- Partitions are rare events
  - there are little reasons to forfeit by design C or A
- Systems evolve along time
  - Depending on the specific partition, service or data, the decision about the property to be sacrificed can change
- C, A and P are measured according to continuum
  - Several level of Consistency (e.g. ACID vs BASE)
  - Several level of Availability
  - Several degree of partition severity

2 of 3 is misleading

- In principle every system should be designed to ensure both C and A in normal situation
- When a partition occurs the decision among C and A can be taken
- When the partition is resolved the system takes corrective action coming back to work in normal situation

Consistency/Latency Trade Off

- CAP does not force designers to give up A or C but why there exists a lot of systems trading C?

LATENCY !

- CAP does not explicitly talk about latency…
- … however latency is crucial to get the essence of CAP

Consistency/Latency Trade Off

High Availability

- High Availability is a strong requirement of modern shared-data systems

Replication

- To achieve High Availability, data and services must be replicated

Consistency

- Replication impose consistency maintenance

Latency

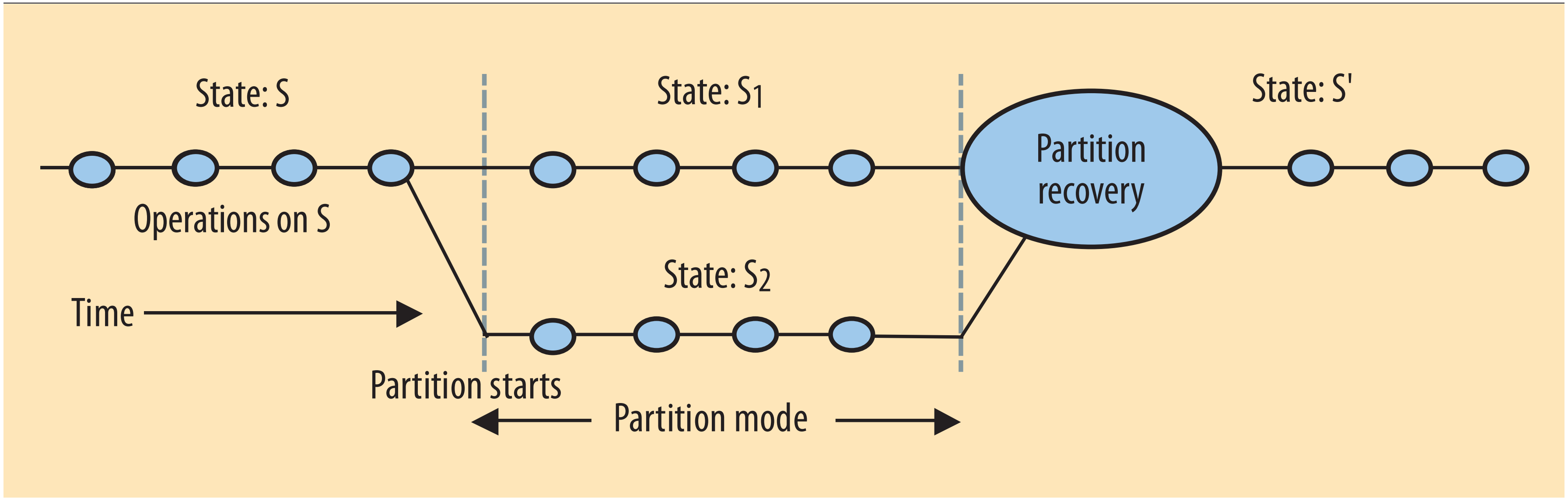
- Every form of consistency requires communication and a stronger consistency requires higher latency

PACELC

- Abadi proposes to revise CAP as follows:

"*PACELC (pronounced pass-elk): 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)?*"

Partitions Management



Partition Detection

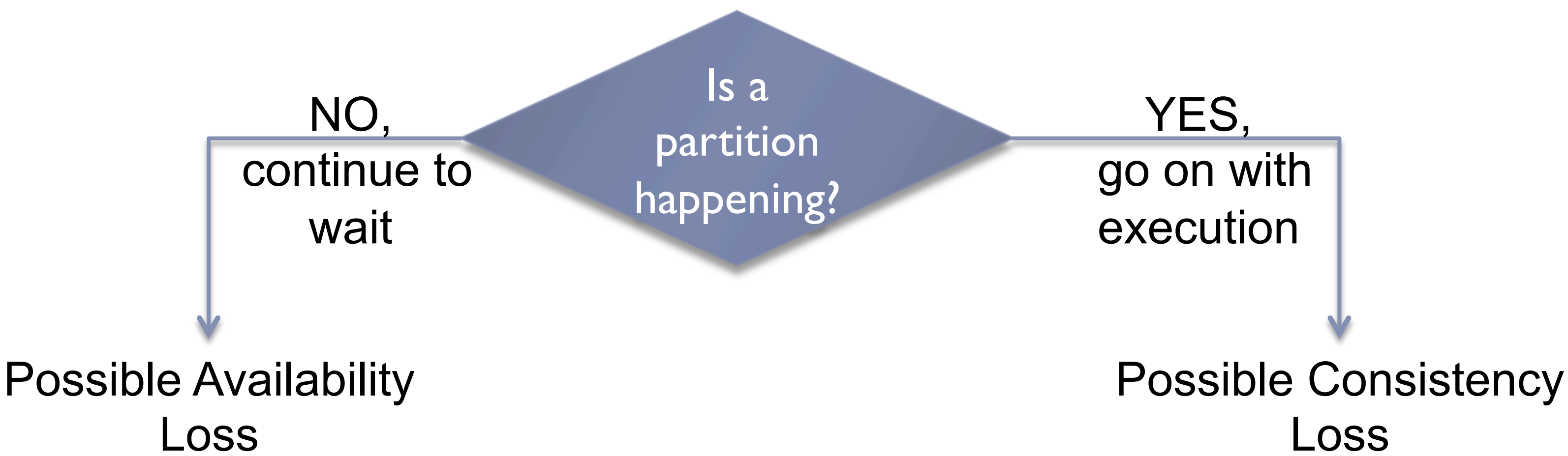
Activating Partition Mode

Partition Recovery

Partition Detection

- CAP does not explicitly talk about latencies

- However…
  - To keep the system live time-outs must be set
  - When a time-out expires the system must take a decision



Partition Detection

- Partition Detection is not global
  - An interacting part may detect the partition, the other not.
  - Different processes may be in different states (partition mode vs normal mode)
- When entering Partition Mode the system may
  - Decide to block risk operations to avoid consistency violations
  - Go on limiting a subset of operations

Which Operations Should Proceed?

- Live operation selection is an hard task
  - Knowledge of the severity of invariant violation
  - Examples
    - every key in a DB must be unique
      - Managing violation of unique keys is simple
      - Merging element with the same key or keys update
    - every passenger of an airplane must have assigned a seat
      - Managing seat reservations violation is harder
      - Compensation done with human intervention
  - Log every operation for a possible future re-processing

Partition Recovery

- When a partition is repaired, partitions' logs may be used to recover consistency
- Strategy 1: roll-back and executed again operations in the proper order (using version vectors)
- Strategy 2: disable a subset of operations (Commutative Replicated Data Type - CRDT)

Basic Techniques: Version Vector

- In the version vector we have an entry for any node updating the state
- Each node has an identifier
- Each operation is stored in the log with attached a pair <nodeId, timeStamp>

- Given two version vector A and B, A is newer than B if
  - For any node in both A and B, ta(B) ≤ ts(A) and
  - There exists at least one entry where ta(B) < ts(A)

Version Vectors: example

$$\begin{array}{cc} \boxed{\begin{array}{c}1\\0\\0\end{array}} & \boxed{\begin{array}{c}1\\1\\0\end{array}} \\ \text{ts(B)} & \text{Ts(A)} \end{array}$$

ts(A) < ts(B) then A → B

$$\begin{array}{cc} \boxed{\begin{array}{c}1\\0\\0\end{array}} & \boxed{\begin{array}{c}0\\0\\1\end{array}} \\ \text{ts(B)} & \text{Ts(A)} \end{array}$$

ts (A) ≠ ts (B) then A || B

POTENTIALLY INCONSISTENT!

Basic Techniques: Version Vector

- Using version vectors it is always possible to determine if two operations are causally related or they are concurrent (and then dangerous)

- Using vector versions stored on both the partitions it is possible to re-order operations and raising conflicts that may be resolved by hand

- Recent works proved that this consistency is the best that can be obtained in systems focussed on latency

Basic Techniques: CRDT

- Commutative Replicated Data Type (CRDT) are data structures that provably converges after a partition (e.g. set).

- Characteristics:
  - All the operations during a partition are commutative (e.g. add(a) and add(b) are commutative) or
  - Values are represented on a lattice and all operations during a partitions are monotonically increasing wrt the lattice (giving an order among them)
    - Approach taken by Amazon with the shopping cart.
  - Allows designers to choose A still ensuring the convergence after a partition recovery

Basic Techniques: Mistake Compensation

- Selecting A and forfaiting C, mistakes may be taken
  - Invariants violation
- To fix mistakes the system can
  - Apply deterministic rule (e.g. "last write win")
  - Operations merge
  - Human escalation
- General Idea:
  - Define specific operation managing the error
    - E.g. re-found credit card

What is NoSQL?

- Stands for **N**ot **O**nly **SQL**
- Class of non-relational data storage systems
- Usually do not require a fixed table schema nor do they use the concept of joins
- All NoSQL offerings relax one or more of the ACID properties (will talk about the CAP theorem)

Why NoSQL?

- For data storage, an RDBMS cannot be the be-all/end-all
- Just as there are different programming languages, need to have other data storage tools in the toolbox
- A NoSQL solution is more acceptable to a client now than even a year ago

How did we get here?

- Explosion of social media sites (Facebook, Twitter) with large data needs
- Rise of cloud-based solutions such as Amazon S3 (simple storage solution)
- Just as moving to dynamically-typed languages (Ruby/Groovy), a shift to dynamically-typed data with frequent schema changes
- Open-source community

Dynamo and BigTable

- Three major papers were the seeds of the NoSQL movement
  - BigTable (Google)
  - Dynamo (Amazon)
    - Gossip protocol (discovery and error detection)
    - Distributed key-value data store
    - Eventual consistency

Thank You!

Questions?!