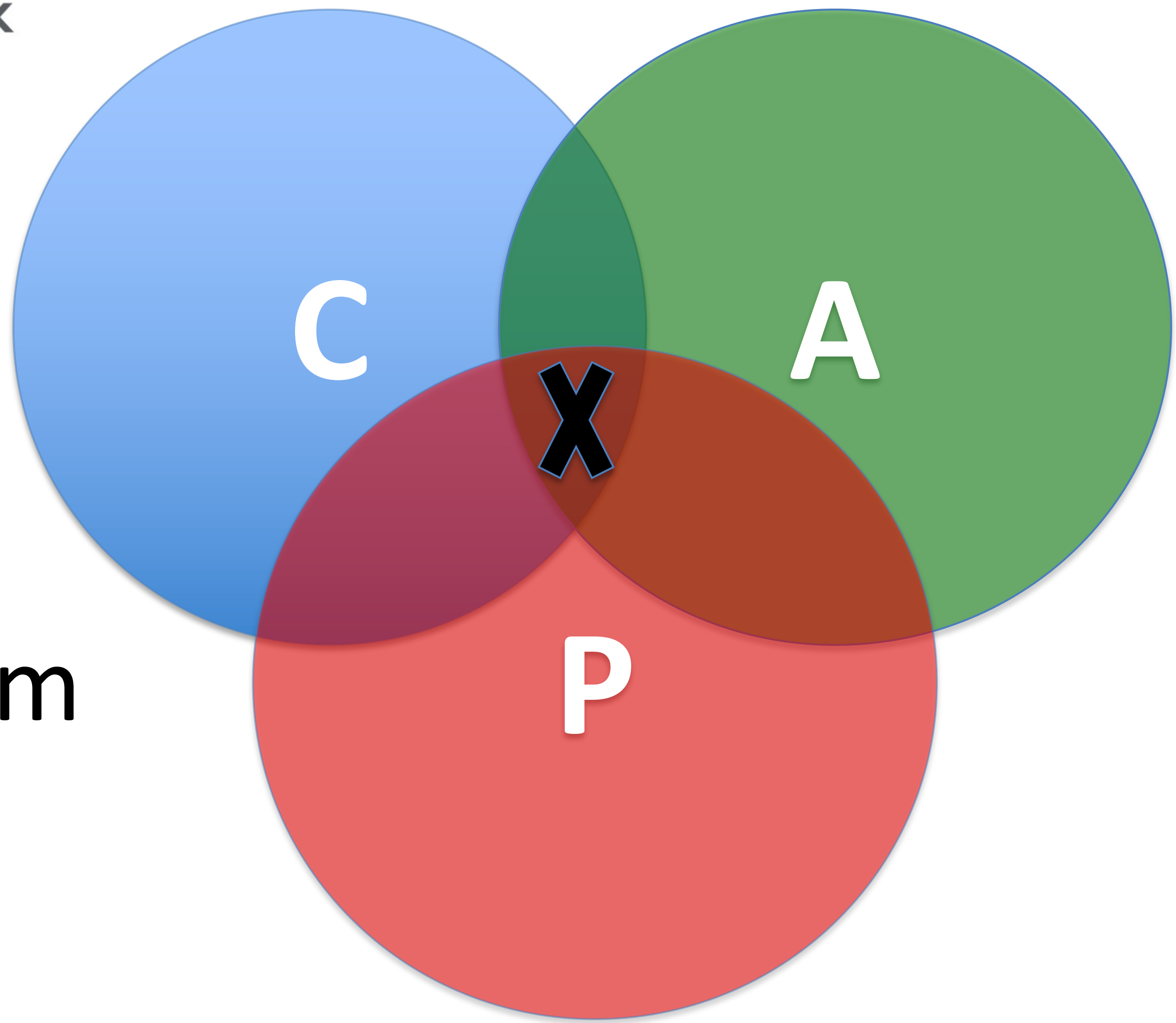
CouchDB relax Redis Neo4j the graph database Cassandra mongoDB membase riak



CAP Theorem

Thanks to Arvind K., Dong W., and Mihir N. for slides.

CAP Theorem

- "It is impossible for a web service to provide these *three guarantees at the same time (pick 2 of 3)*:
  - **(Sequential) Consistency**
  - **Availability**
  - **Partition-tolerance**"
- Conjectured by Eric Brewer in '00
  - Proved by Gilbert and Lynch in '02
  - But with definitions that do not match what you'd assume (or Brewer meant)
- Influenced the NoSQL mania
- Highly controversial: *"the CAP theorem encourages engineers to make awful decisions." – Stonebraker*
  - Many misinterpretations

CAP Theorem

- **<u>C</u>**onsistency:
  - Sequential consistency (a data item behaves as if there is one copy)
- **<u>A</u>**vailability:
  - Node failures do not prevent survivors from continuing to operate
- **<u>P</u>**artition-tolerance:
  - The system continues to operate despite network partitions
- CAP says that *"A distributed system can satisfy any two of these guarantees at the same time **but not all three"***

C in CAP != C in ACID

- They are different!

- CAP's C(onsistency) = sequential consistency
  - Similar to ACID's A(tomicity) = Visibility to all future operations
- ACID's C(onsistency) = Does the data satisfy schema constraints

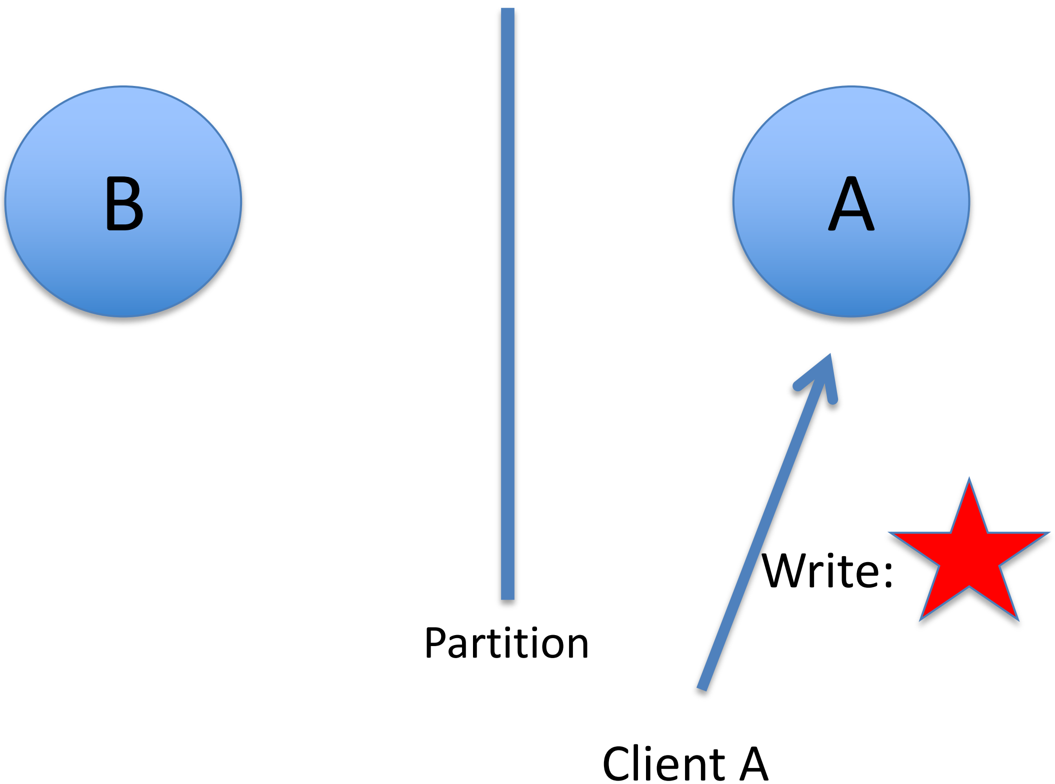
Sequential consistency

- Makes it appear as if there is one copy of the object
- Strict ordering on ops from same client
- A single linear ordering across client ops
  - If client a executes operations {a1, a2, a3, ...}, client b executes operations {b1, b2, b3, ...}
  - Then, globally, clients observe <u>some</u> serialized version of the sequence
    - e.g., {a1, b1, b2, a2, ...} (or whatever)

    Notice how a1 precedes a2, b1 precedes b2, etc

CAP Theorem: Proof

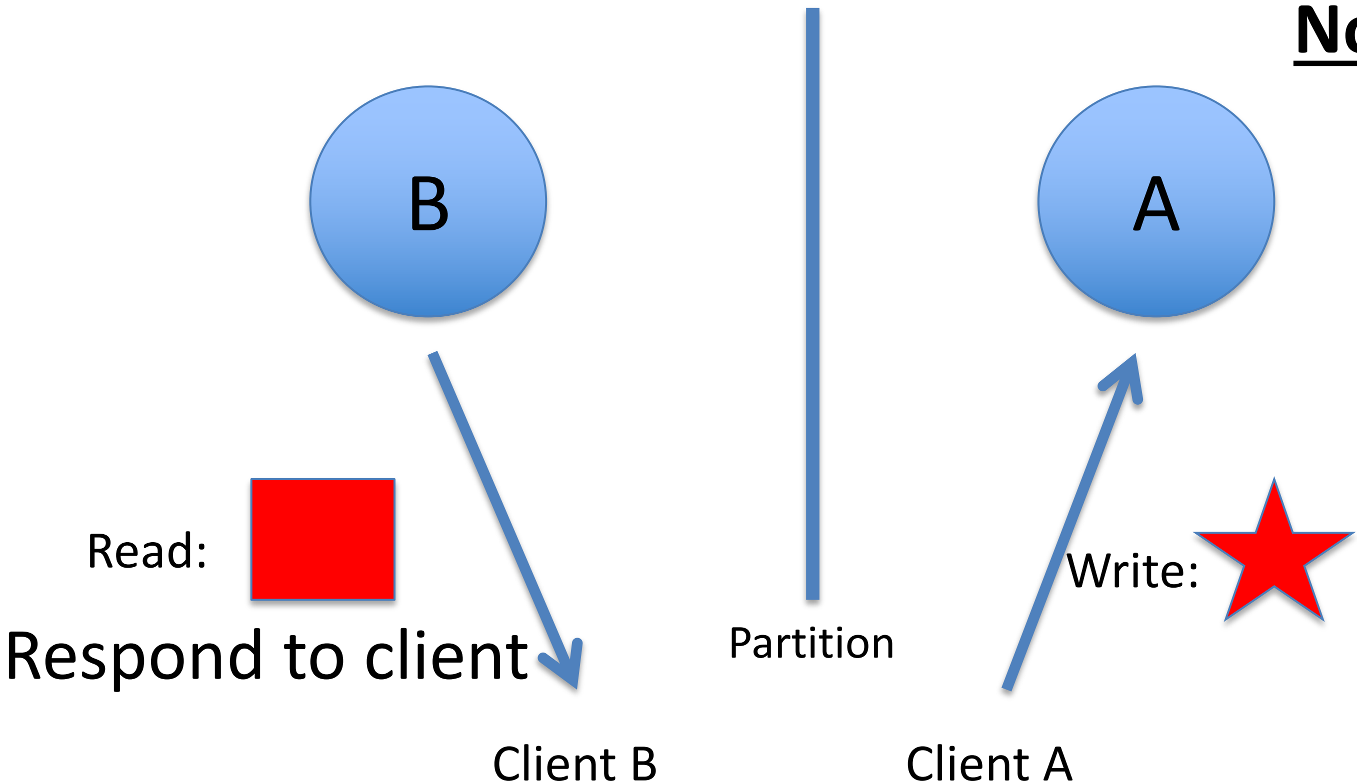
- A simple proof using two nodes:



CAP Theorem: Proof

- A simple proof using two nodes:

Not Consistent!



CAP Theorem: Proof

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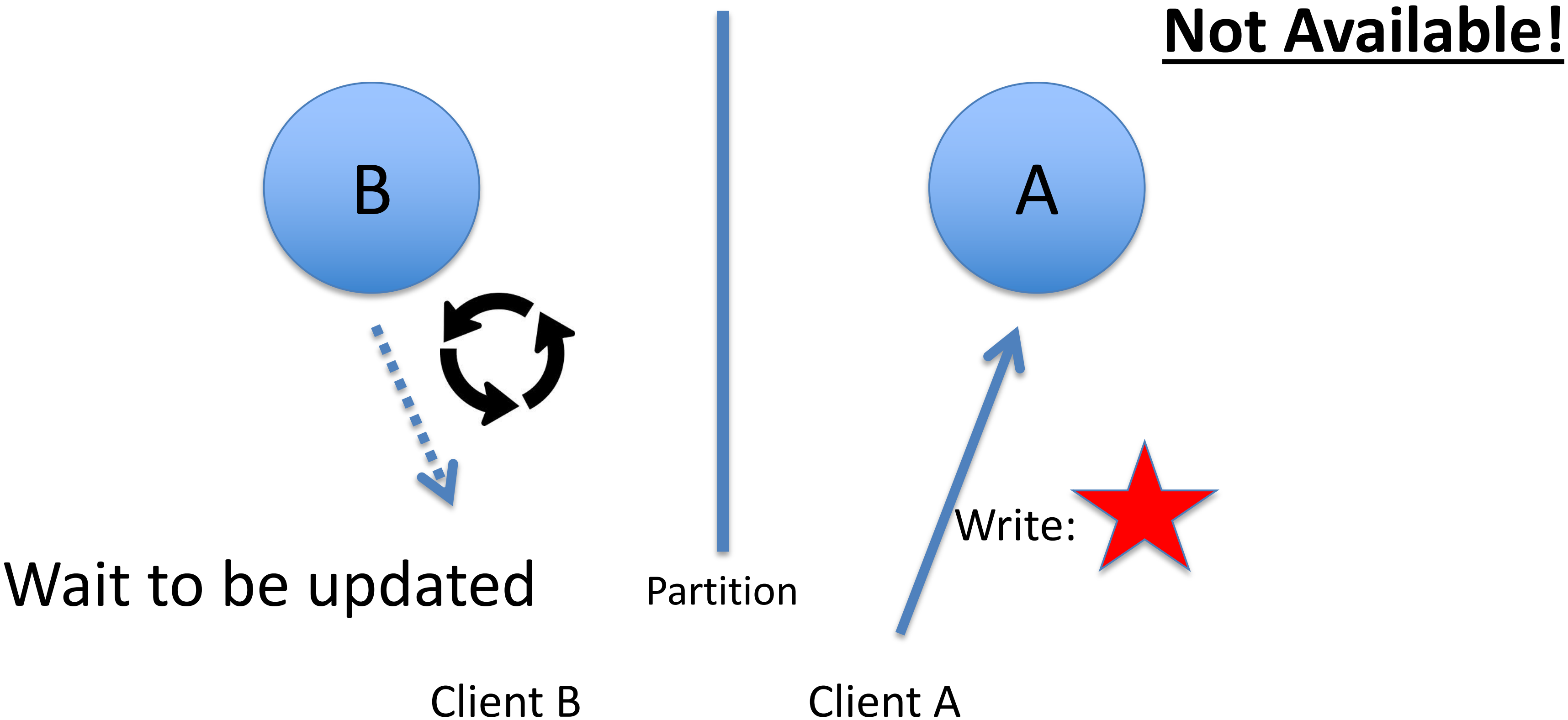

CAP Theorem: Proof

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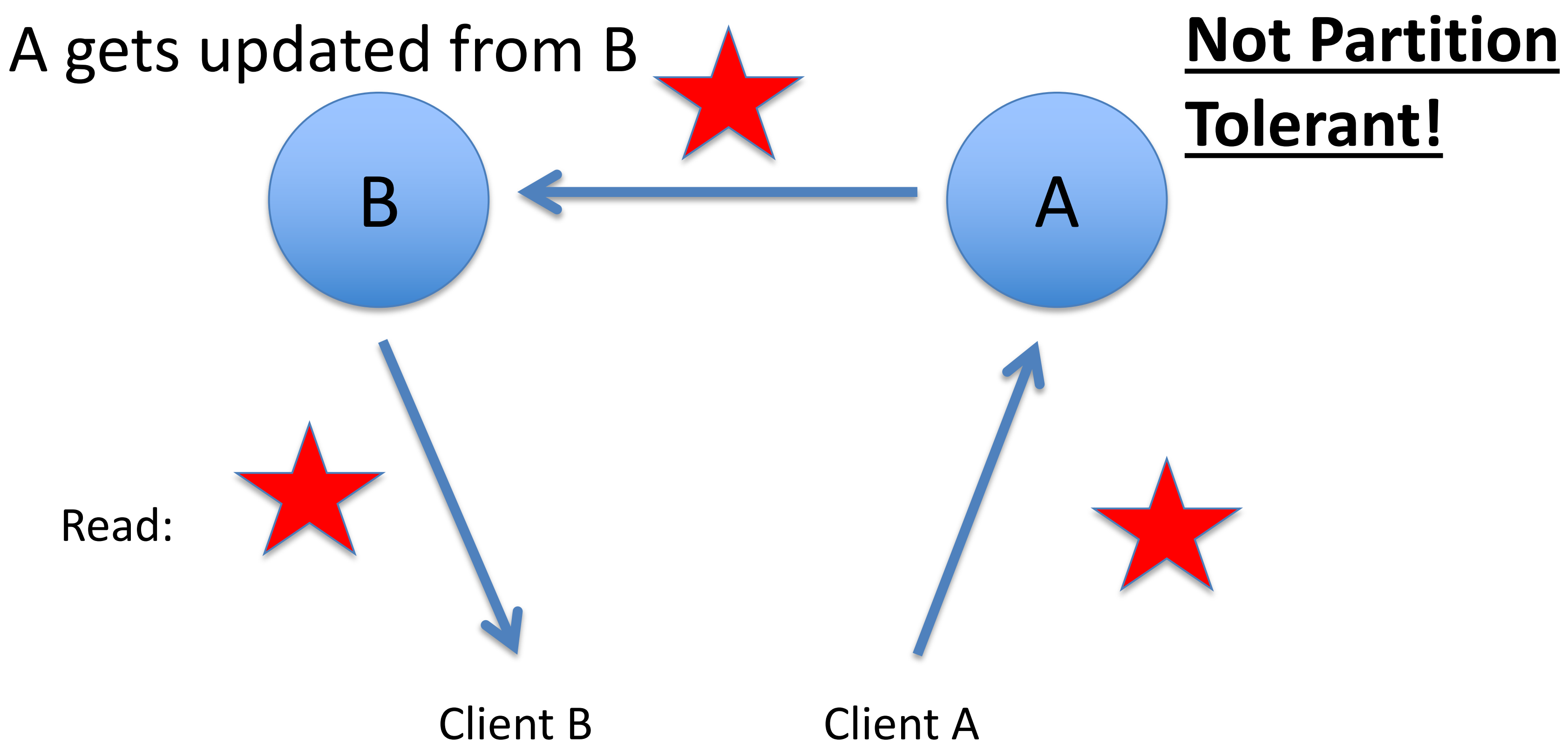
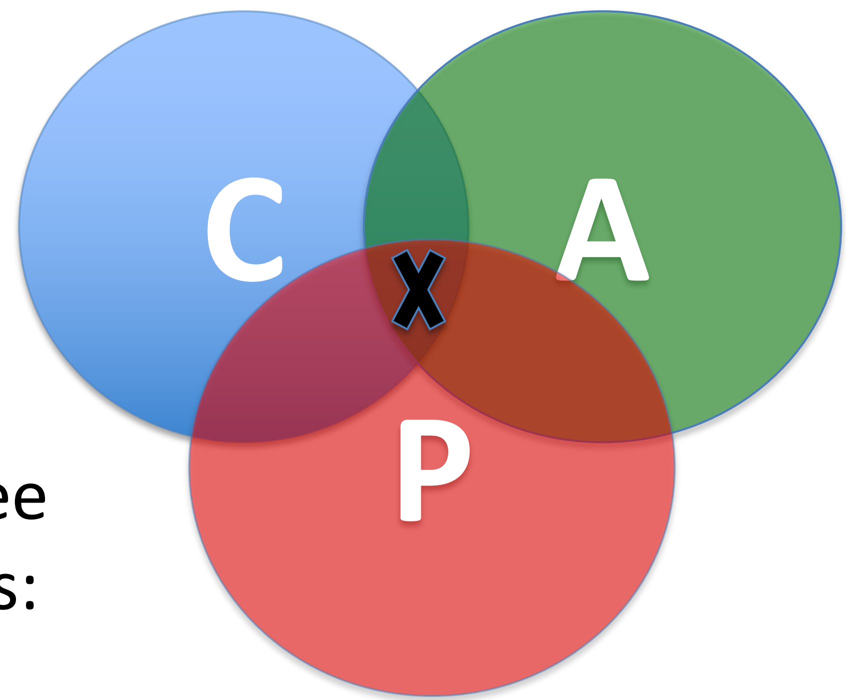


CAP => 3 types of systems

- Of the following three guarantees potentially offered by distributed systems:
  - Consistency
  - Availability
  - Partition tolerance
- Pick two
- This suggests there are three kinds of distributed systems:
  - CP
  - AP
  - CA



Issues with CAP

- What does it mean to choose or not choose partition tolerance?
  - P is a <u>property of the environment</u>, C and A are <u>goals</u>
  - In other words, what's the difference between a "CA" and "CP" system? both give up availability on a partition!
- Better phrasing: *"if the network can have partitions, do we give up on consistency or availability?"*

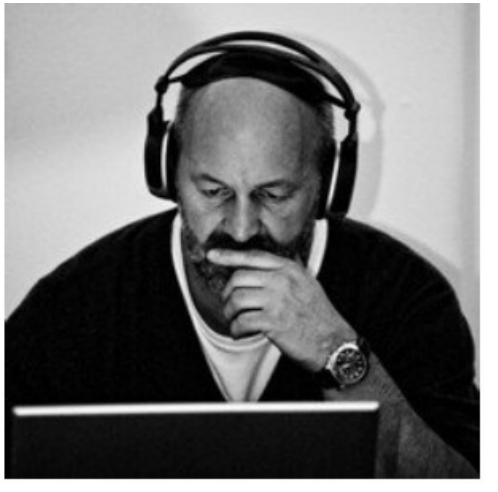
Witnesses: P is unavoidable

- Coda Hale, Yammer (Microsoft?) software engineer:
  - *"Of the CAP theorem's Consistency, Availability, and Partition Tolerance,* ***Partition Tolerance is mandatory in distributed systems****. You cannot not choose it."*

http://codahale.com/you-cant-sacrifice-partition-tolerance/

Witnesses: P is unavoidable

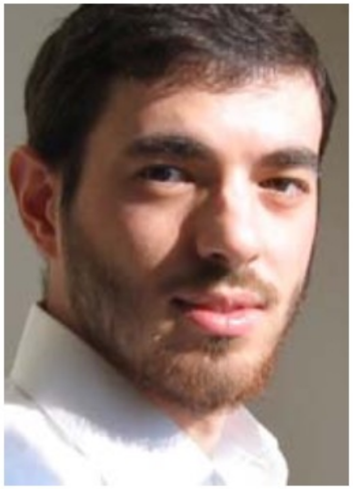
- Werner Vogels, Amazon CTO
  - *"An important observation is that in larger distributed-scale systems, network partitions are a given; therefore,* ***consistency and availability cannot be achieved at the same time****."*



http://www.allthingsdistributed.com/2008/12/eventually_consistent.html

Witnesses: P is unavoidable

- Daneil Abadi (UMD), Co-founder of Hadapt; Vertica, VoltDB contributor
  - *"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?"***



http://dbmsmusings.blogspot.com/2010/04/problems-with-cap-and-yahoos-little.html

Witnesses: P?
Who cares about P!?

- Michael Stonebraker
  - [VoltDB, TuringAward'14]
  - *"In my experience,* ***network partitions do not happen often****. Specifically, they occur less frequently than the sum of bohrbugs [deterministic DB crashes], application errors, human errors and reprovisioning events. So it doesn't much matter what you do when confronted with network partitions.* ***Surviving them will not "move the needle" on availability*** *because higher frequency events will cause global outages.* ***Hence, you are giving up something (consistency) and getting nothing in return****."*

https://www.voltdb.com/blog/2010/10/21/clarifications-cap-theorem-data-related-errors/

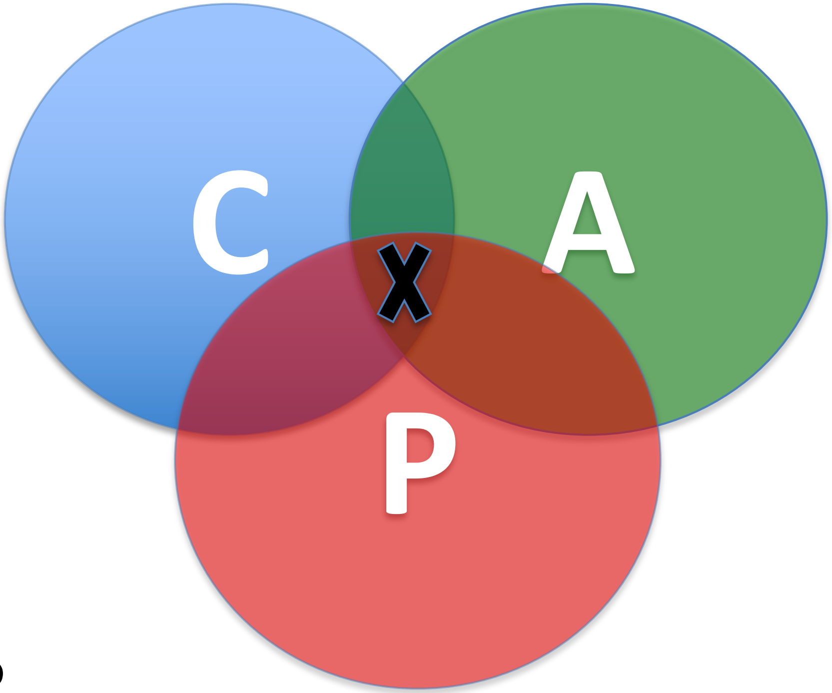
CAP Theorem 12 year later

- Eric Brewer: father of CAP
  - “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.”

http://www.infoq.com/articles/cap-twelve-years-later-how-the-rules-have-changed

Consistency or Availability

- *Consistency and Availability is not a "binary" decision*
- AP systems relax consistency in favor of availability – *but are not inconsistent*
- CP systems sacrifice availability for consistency- *but are not unavailable*
- This suggests both AP and CP systems can offer a degree of consistency, and availability, as well as partition tolerance



AP: Best Effort Consistency

- Examples:
  - CDNs / Web caches
  - DNS
  - BlockChain
  - CRDTs
- Traits:
  - Optimistic concurrency control
  - Expiration/Time-to-live
  - Conflict resolution

CP: Best Effort Availability

- Examples:
  - Majority protocols (Paxos, Raft)
  - Distributed Locking (Google Chubby Lock service)
- Traits:
  - Pessimistic locking
  - Make minority partition unavailable

Types of Consistency

- Strong Consistency
  - After the update completes, **any subsequent access** will return the **same** updated value.
- Weak Consistency
  - It is **not guaranteed** that subsequent accesses will return the updated value.
- **Eventual Consistency**
  - Specific form of weak consistency
  - It is guaranteed that if **no new updates** are made to object, **eventually** all accesses will return the last updated value (e.g., *propagate updates to replicas in a lazy fashion*)

Eventual Consistency Variations

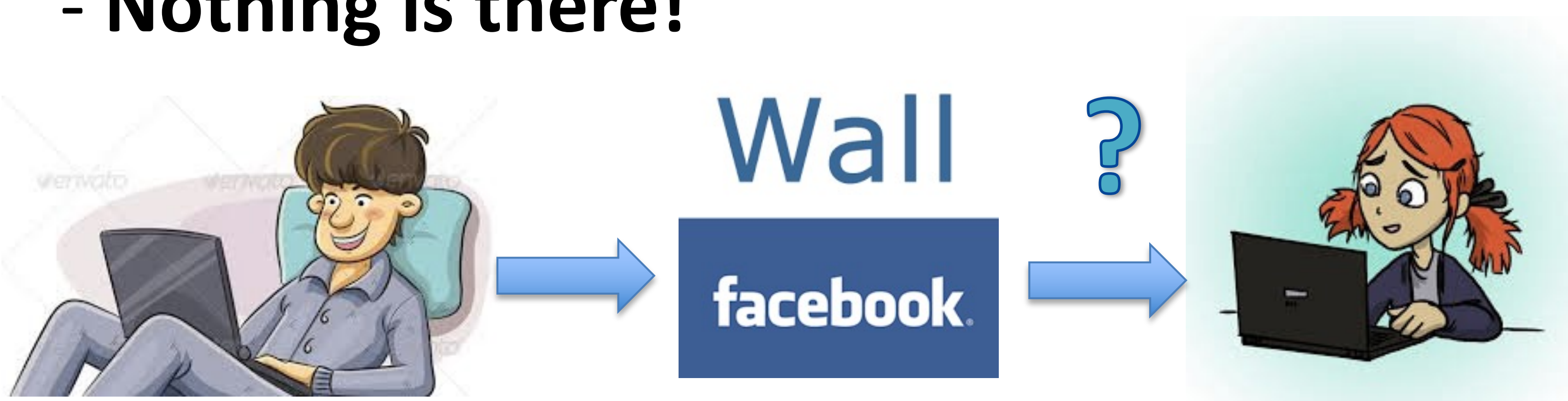
- Causal consistency
  - Processes that have causal relationship will see consistent data
- Read-your-write consistency
  - A process always accesses the data item after it's update operation and never sees an older value
- Session consistency
  - As long as session exists, system guarantees read-your-write consistency
  - Guarantees do not overlap sessions

Eventual Consistency Variations

- Monotonic read consistency
  - If a process has seen a particular value of data item, any subsequent processes will never return any previous values
- Monotonic write consistency
  - The system guarantees to serialize the writes by the *same* process
- In practice
  - A number of these properties can be combined
  - Monotonic reads and read-your-writes are most desirable

Eventual Consistency
- A Facebook Example

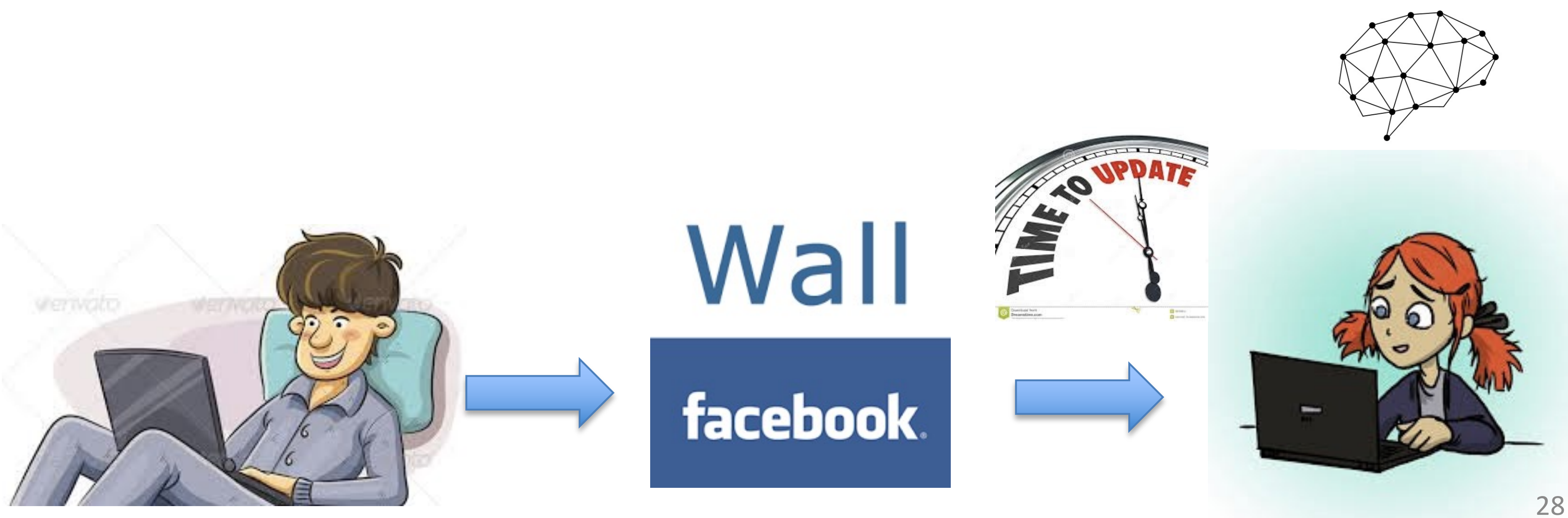
- Bob finds an interesting story and shares with Alice by posting on her Facebook wall
- Bob asks Alice to check it out
- Alice logs in her account, checks her Facebook wall but finds:
  - **Nothing is there!**



Eventual Consistency
- A Facebook Example

- Bob tells Alice to wait a bit and check out later
- Alice waits for a minute or so and checks back:

  - **She finds the Cambridge Analytica story Bob shared with her!**



Eventual Consistency
- A Facebook Example

- Reason: it is possible because Facebook uses an **eventual consistent model**
- Why would Facebook choose an eventual consistent model over the strong consistent one?
  – Facebook has more than 1 billion active users
  – It is non-trivial to efficiently and reliably store the huge amount of data generated at any given time
  – Eventual consistent model offers the option to **reduce the load and improve availability**

Dynamic Tradeoff between **C** and **A**

- An airline reservation system:
  - When most of seats are available: it is ok to rely on somewhat out-of-date data, availability is more critical
  - When the plane is close to be filled: it needs more accurate data to ensure the plane is not overbooked, consistency is more critical
- Neither strong consistency nor guaranteed availability, but it may significantly increase the tolerance of network disruption

Heterogeneity: Segmenting **C** and **A**

- No single uniform requirement
  - Some aspects require strong consistency
  - Others require high availability
- Segment the system into different components
  - Each provides different types of guarantees
- Overall guarantees neither consistency nor availability
  - Each part of the service gets exactly what it needs
- Can be partitioned along different dimensions

Partitioning Strategies

- Data Partitioning
- Operational Partitioning
- Functional Partitioning
- User Partitioning
- Hierarchical Partitioning

- Idea: provide differentiated guarantees depending on X {data/op/func/user/component}

Partitioning Examples

Data Partitioning

- Different data may require different consistency and availability
- Example:
  - Shopping cart: high availability, responsive, can sometimes suffer anomalies
  - Product information need to be available, slight variation in inventory is sufferable
  - Checkout, billing, shipping records must be consistent

Partitioning Examples

Operational Partitioning

- Each operation may require different balance between consistency and availability
- Example:
  - Reads: high availability; e.g.., “query”
  - Writes: high consistency, lock when writing; e.g., “purchase”

Partitioning Examples

Functional Partitioning

- System consists of sub-services (microservices)
- Different sub-services provide different balances
- Example: A comprehensive distributed system
  - Distributed lock service (e.g., Chubby) :
    - Strong consistency
  - DNS service:
    - High availability

Partitioning Examples

User Partitioning

- Try to keep related data close together to assure better performance
- Example: Craigslist
  - Might want to divide its service into several data centers, e.g., east coast and west coast
    - Users get high performance (e.g., high availability and good consistency) if they query servers close to them
    - Poorer performance if a New York user query Craglist in San Francisco

Partitioning Examples

Hierarchical (node) Partitioning

- Large global service with local “extensions”
- Different location in hierarchy may use different consistency
- Example:
  - Local servers (better connected) guarantee more consistency and availability
  - Global servers has more partition and relax one of the requirement

  - Systems that do this: DNS, NTP

Take-aways

- CAP is a tool for thinking about trade-offs in distributed systems
- Misinterpreted + contentious
- The devil (in designing distributed systems) is often in the details: real systems cannot be classified into one of CA/AP/CP
- Many eventual consistency variants, widely adopted by popular systems