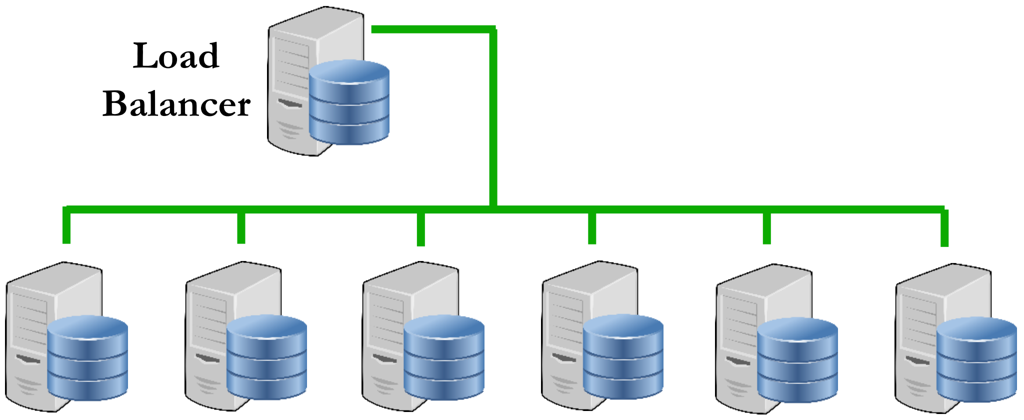
Consistency and CAP

- Types of consistency
- Examples
- CAP theorem

Northwestern University

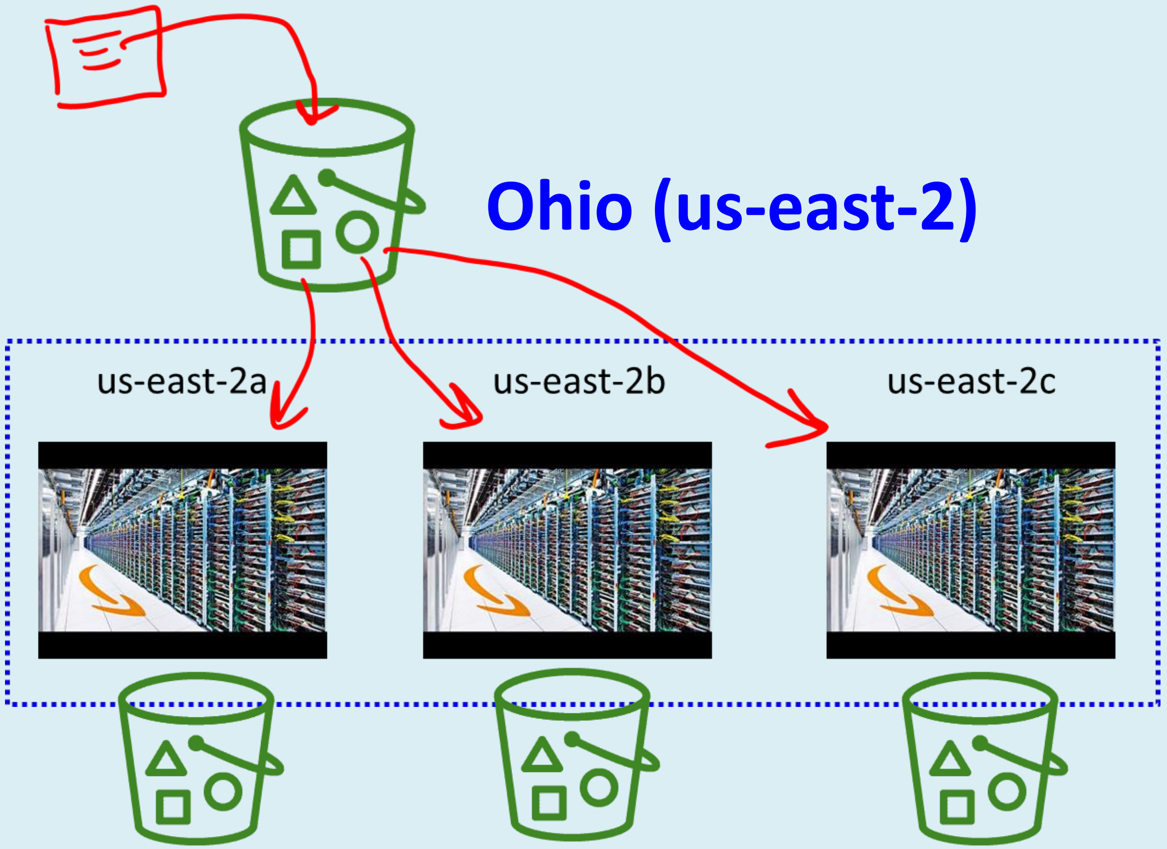
Availability / fault tolerance

- Computers crash, it will happen…
- Only way to keep your system **available** is with multiple computers
- A system that keeps running in presence of failures is **fault tolerant**



Example: S3 is fault tolerant

- Buckets are replicated across all sites in a region in case one of the sites loses power / network connectivity…

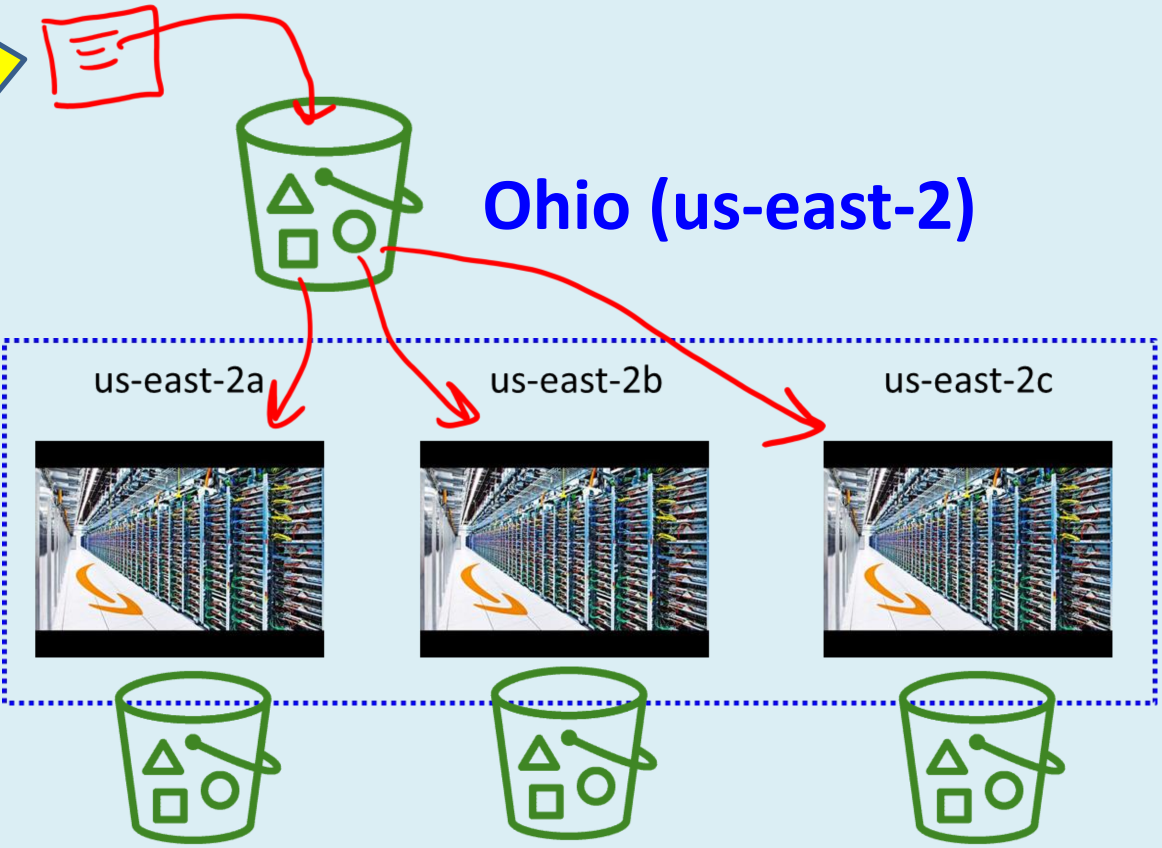


Interesting question…

- **What type of consistency does AWS guarantee?**

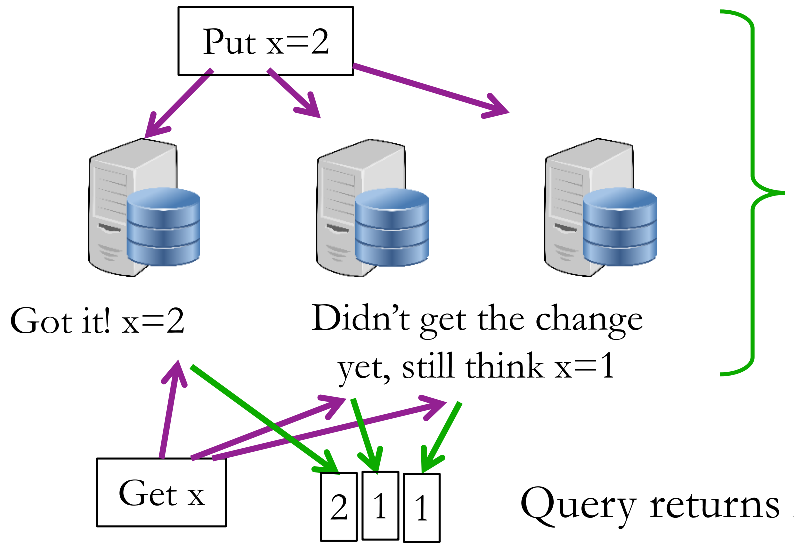
If we upload an image to S3, how soon is it available in all 3 sites?

What if a download request is routed to a site that hasn't finished replicating? What happens? What does AWS guarantee, if anything?



Consistency

- Whenever data is replicated, there is a possibility of **inconsistency**.
  - Example: x =1. An update is then sent to three replicas:



Communication and queueing delays are unpredictable. We can send messages, but we don't know exactly when they'll arrive.

Query returns inconsistent answers!

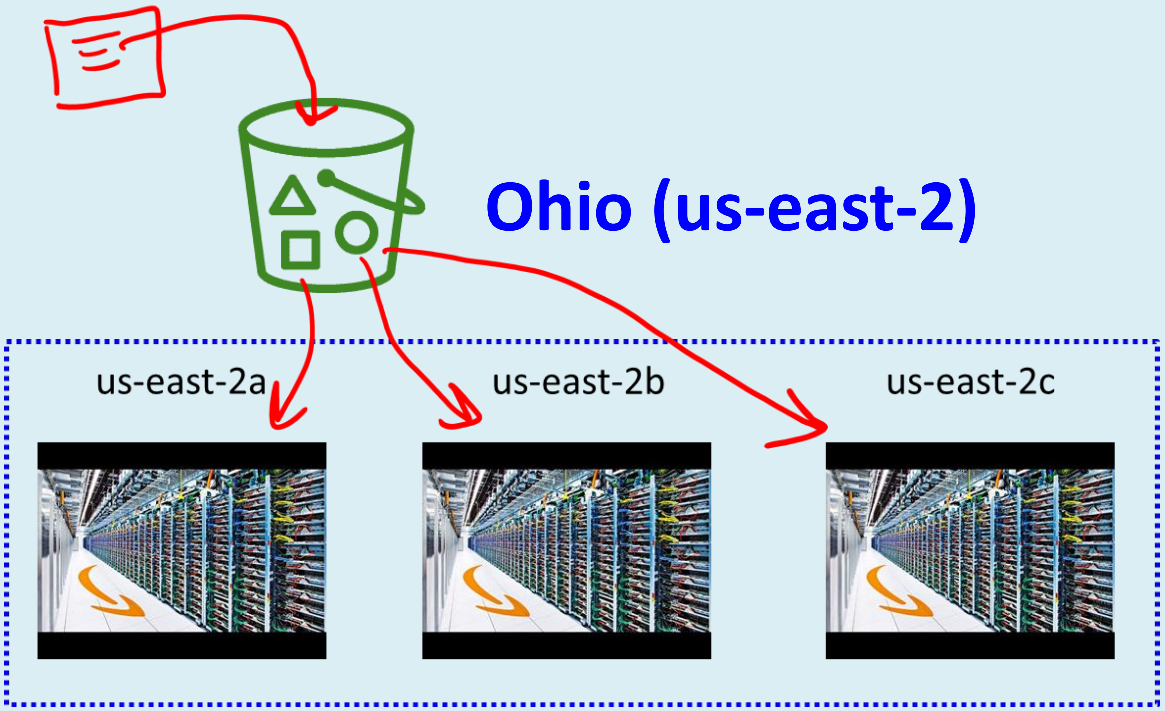
Types of consistency

- **Eventual**
  - *An update to a distributed system will *eventually* yield a consistent view*
  - *BASE:*
    - *Basically-available*
    - *Soft-state*
    - *Eventually-consistent*
- **Strong**
  - *A distributed system provides a single, consistent view at all times*
  - *ACID:*
    - *Atomic*
    - *Consistent*
    - *Isolated*
    - *Durable*

The type of consistency impacts how you call / use a given service. Can you trust the response you get?

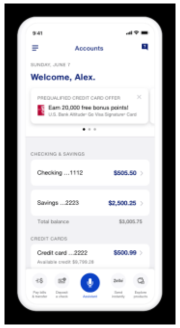
S3? Answer…

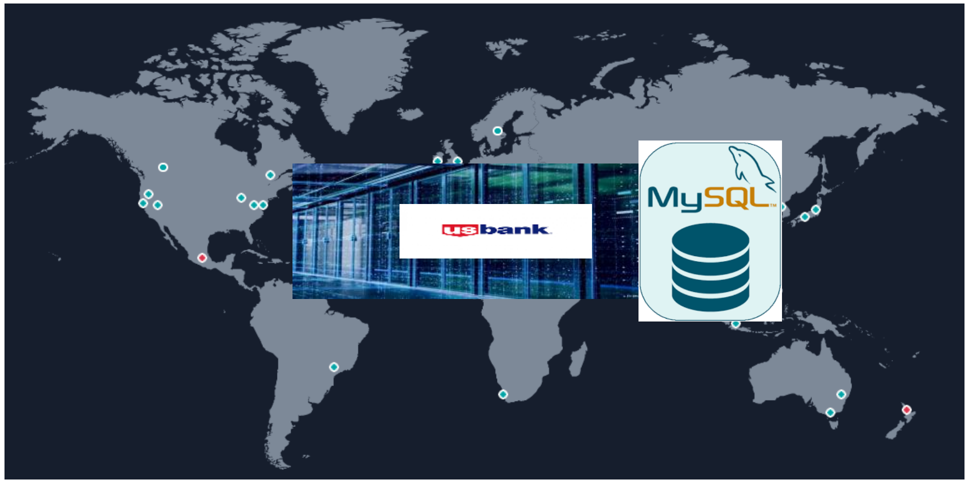
- **The image will be available for download no matter which site is accessed**
  - *AWS S3 guarantees* ***strong consistency***
  - *The client's view of S3 is THE SAME across all sites*

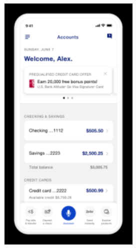


Banks require strongly consistency

- Suppose a bank account has exactly $1,000
- How does the bank prevent two different people from withdrawing $1,000 from that account at the same time?







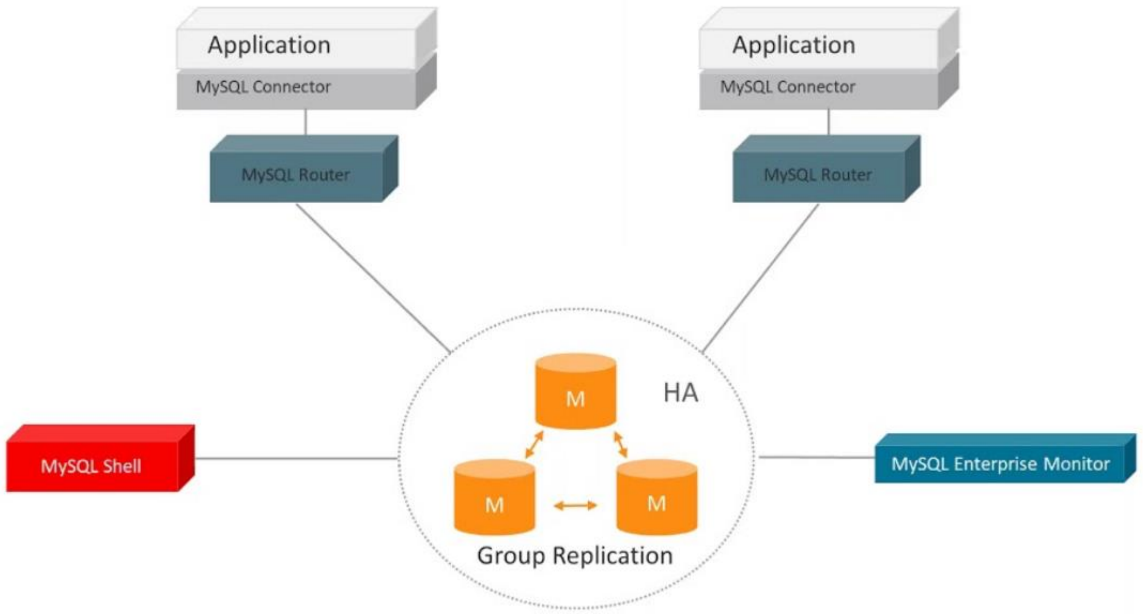
Databases are strongly consistent

- **Most DB systems offer strong consistency**

- **This is HARD to implement:**
  - *Must replicate data so it's accessible at all times anywhere*
  - *Must ensure a strongly consistent view of all data!*

MySQL Cluster

- **MySQL Cluster is a <u>distributed</u> database system**
  - *Replicates the data across multiple servers for fault tolerance*
  - *Still guarantees strong consistency*



MySQL High Availability Cluster

Example

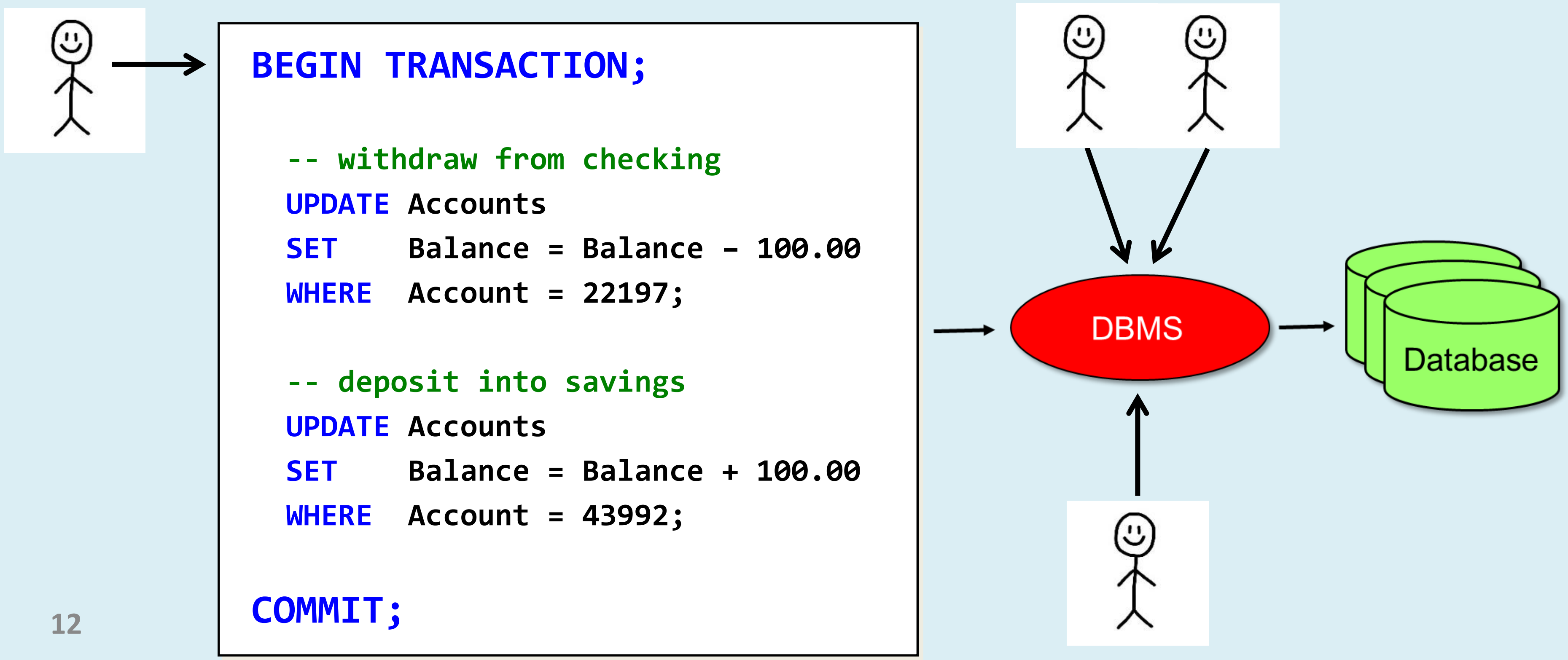
- Banks cannot risk losing track of customer $
- Banks use a DB to keep track…
- Transferring $ requires two SQL queries:

```
-- withdraw from checking
UPDATE Accounts
SET    Balance = Balance – 100.00
WHERE  Account = 22197;

-- deposit into savings
UPDATE Accounts
SET    Balance = Balance + 100.00
WHERE  Account = 43992;
```

What if the computer crashes right here? The money would be lost… What must be done to ensure strong consistency?

Answer

- You must wrap the SQL within a **transaction**
- Databases are strongly consistent only in the presence of properly-written transactions…



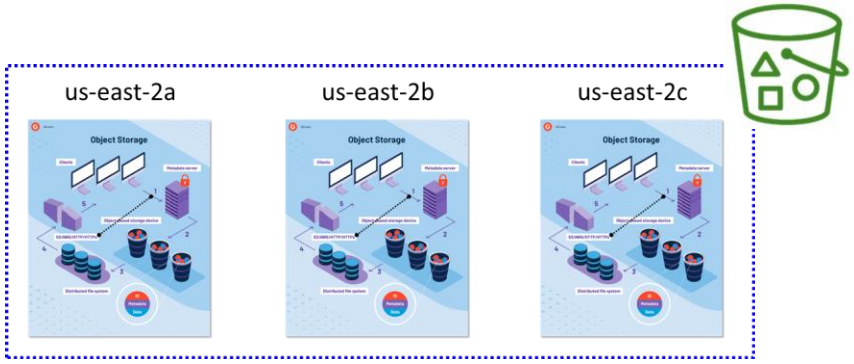
```
BEGIN TRANSACTION;

  -- withdraw from checking
  UPDATE Accounts
  SET    Balance = Balance – 100.00
  WHERE  Account = 22197;

  -- deposit into savings
  UPDATE Accounts
  SET    Balance = Balance + 100.00
  WHERE  Account = 43992;

COMMIT;
```

CAP Theorem

One of the most important results in distributed systems theory

Theorem: a distributed system cannot achieve ***all three*** of the following:

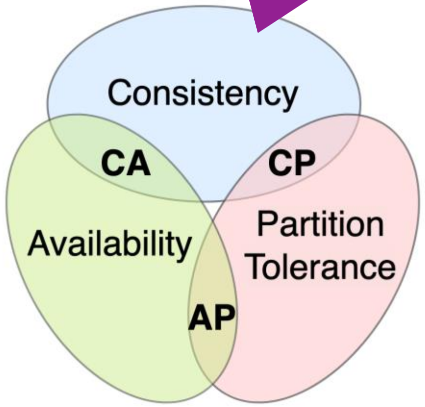
- **Consistency**: reads always return the most recent write (or an error)
- **Availability:** every request receives a timely, non-error response
- **Partition tolerance:** the system continues to operate even in the presence of failures (software, hardware, network, power, etc.)



You have to pick two…

CAP Theorem implications

Pick Two: CA, CP, AP



- **Consistency**: reads always return the most recent write (or error)
- **Availability:** every request receives a timely, non-error response
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Implications?

Redundancy is the only way to achieve partition tolerance, i.e. fault-tolerant, highly-available systems. **So you always choose P.**

This implies architects have to choose between

- **Availability (AP)**: returning an answer to the client that may be inconsistent (old)

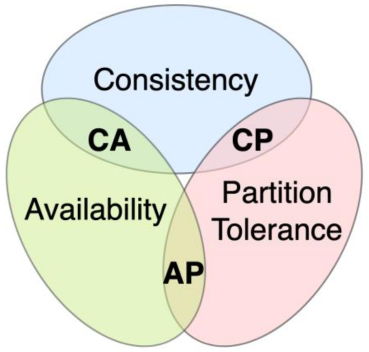
or

- **Consistency (CP)**: making the client wait until consistent answer is available (in the worst-case, request could error/timeout & client will have to try again)

Client-centric consistency models

- The CAP theorem gives us a tradeoff between **consistency** & **delay**
- Inconsistency is bothersome --- makes client-side programming harder
  - *Example: imagine if the database gave different answers to the same query?!*
- Delay is usually something client-side apps can handle…

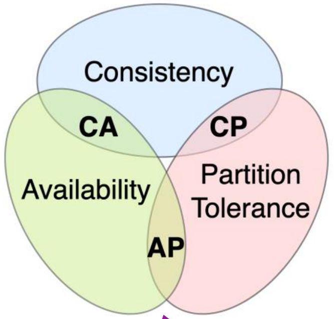
Most architects agree that CP is the right choice



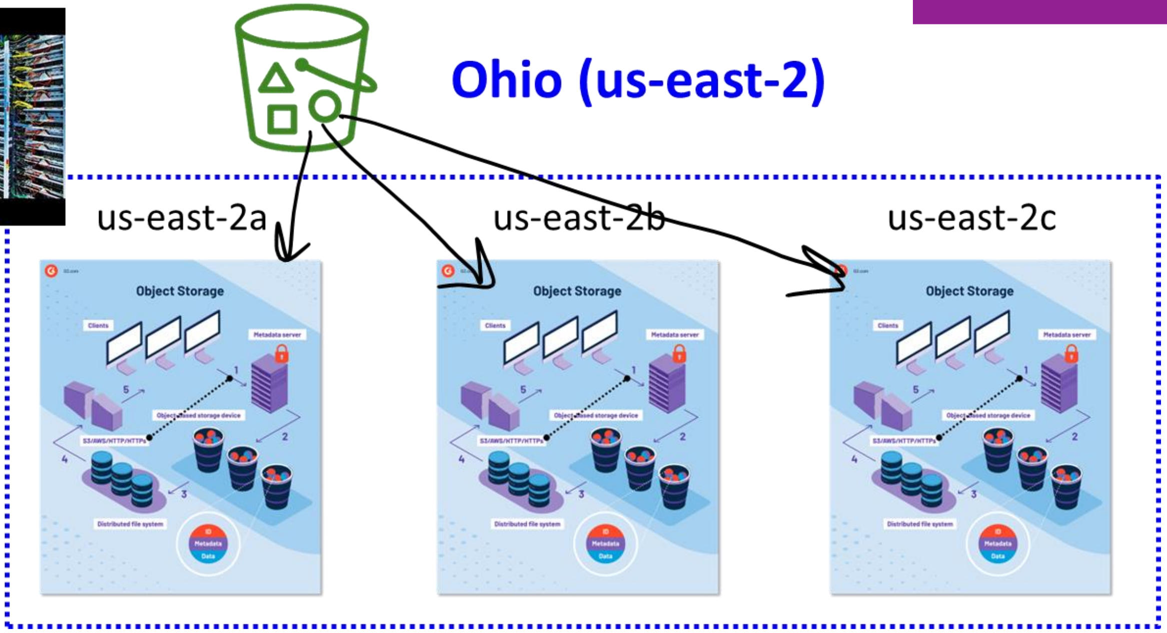
- Client-side code is less complex
- In almost all systems, you want correct responses over fast (but wrong) responses
- Good summary from a Google architect

S3: eventual to strongly consistent

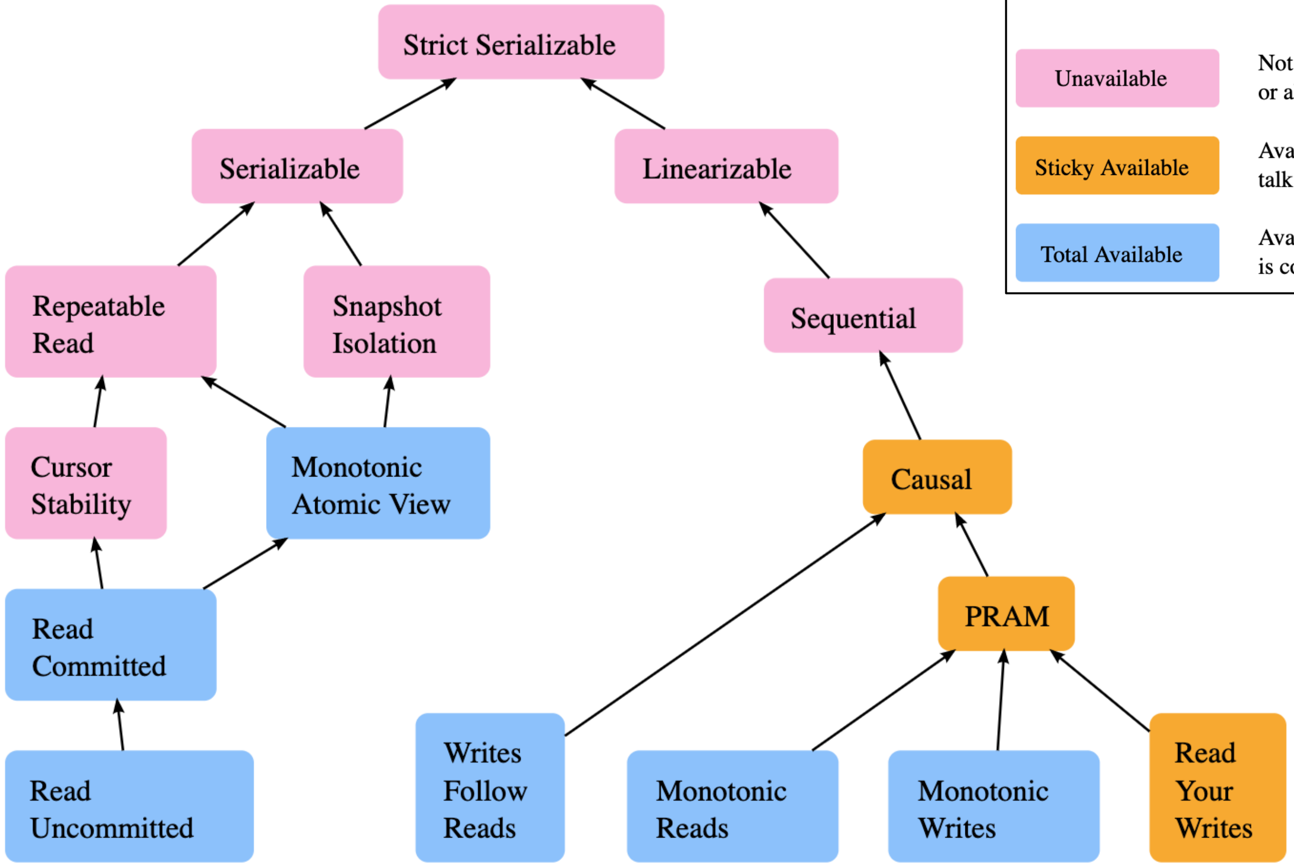
- **In 2020, S3 was redesigned to be strongly consistent**
  - *https://www.allthingsdistributed.com/2021/04/s3-strong-consistency.html*



What did they give up?



Consistency is a subtle topic, with many models.



Legend

🟪 Unavailable	Not available during some types of network failures. Some or all nodes must pause operations in order to ensure safety.
🟧 Sticky Available	Available on every non-faulty node, so long as clients only talk to the same servers, instead of switching to new ones.
🟦 Total Available	Available on every non-faulty node, even when the network is completely down.

Core Challenges Distributed Systems

01 **Complexity**
Multiple components requiring seamless integration and coordination

02 **Consistency**
Difficult to maintain across different nodes, especially in stateful apps.

03 **Fault Tolerance**
Crucial to design for failure recovery with minimal downtime.

04 **Scalability**
Must scale efficiently under varying loads without performance loss.

05 **Concurrency**
Managing simultaneous operations and conflict resolution in components.

06 **Security**
Ensuring confidentiality, integrity, and availability in a distributed network.

07 **Network Issues**
Susceptible to latency and partitioning in network communication.

08 **Deployment and Management:**
Resource-intensive, often needs specialized infrastructure and tools.

09 **Debugging and Monitoring**
More challenging due to distributed systems' dispersed nature.

10 **Decoupling**
Improves flexibility but complicates coherence and system coordination.

That's it, thank you!