# Tying It All Together

COS 418/518: Distributed Systems

Lecture 22

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# Back in Lecture 1…

# Distributed Systems, Why?

- Or, why not 1 computer to rule them all?
- Failure => Fault Tolerance
- Limited computation/storage => Scalability
- Physical location => Availability, Low Latency

# Distributed Systems Goal

- Service with higher-level abstractions/interface
  - e.g., database, programming model, …
- Hide complexity - Do “heavy lifting” so app developer doesn’t need to
  - Reliable (fault-tolerant)
  - Scalable (scale-out)
  - Strong guarantees (consistency and transactions)
- Efficiently
  - Lower latency (faster interactions, e.g., page load)
  - Higher throughput (fewer machines)

# What We Learned

(Much of it at least, at a *very* high level)

# Network communication

- How can multiple computers communicate?
- Networking stack solves this for us!
- We use it to build distributed systems, relying on the guarantees it provides.

# Remote Procedure Calls

- Additional layer on top of networking stack
- At least once – dealing with failures!
- At most once – ensuring correctness despite concurrency and failures

# Time, logical clocks

- Concurrency!
- Real time often inadequate for distributed systems?
- Lamport clocks: $A \rightarrow B \Rightarrow LC(A) < LC(B)$
- Vector clocks: $A \rightarrow B \Leftrightarrow VC(A) < VC(B)$

# Eventual Consistency, Bayou

- Favor availability above all else
  - e.g., disconnected dropbox operation
- Eventual consistency
- Bayou system design
  - Operation log (logical, not physical, replication)
  - Causal consistency from log propagation and lamport timestamps

# Consistent Hashing & DHTs

- Goal: scale lookup state, lookup computation, storage; fault tolerant
- Scale lookup state, lookup computation w/ Chord
- Scale storage with sharding
- Fault tolerance through replication, robust protocols

# Dynamo

- Favor availability above all + scalable storage
- Eventual consistency (really eventual)
- Zero-hop DHT on top of data sharded with consistent hashing
  - Virtual nodes enable better load balancing (improves throughput), but design to still ensure fault tolerance

# So far…

- Can build systems that are fault tolerant, scalable, provide low latency, highly available

- But…

- Weak guarantees

| | Fault Tolerant | Scalable | Highly Available & Low Latency | Guarantees |
|---|---|---|---|---|
| Bayou | yes | no | yes | causal |
| Dynamo | yes | yes | yes | eventual |
| | | | | |
| | | | | |
| | | | | |

# Strong Guarantees + Fault Tolerance

- Linearizability: acts just like 1 machine processing requests 1 at a time!
- Replicated state machines:
  - Log of operations, execute in order
  - Primary-backup (and VM-FT)
    - Special mechanism for failure detection
    - React to failure
  - Paxos, RAFT
    - Built in failure detection using quorums (f+1 out of 2f+1)
    - Mask non-leader failure

| | Fault Tolerant | Scalable | Highly Available & Low Latency | Guarantees |
|---|---|---|---|---|
| Bayou | yes | no | yes | causal |
| Dynamo | yes | yes | yes | eventual |
| Paxos/RAFT | yes | no | no | linearizability |
| | | | | |
| | | | | |

# Impossibility Results Guide Us

- CAP: Must choose either availability of all replicas or consistency between replicas

- PRAM: Must choose either low latency of operations or consistency between replicas

# Availability + Low Latency + Scalability + Strong*er* Guarantees

- COPS provides causal consistency
  - Stronger guarantees impossible w/ low latency
  - Like a scalable Bayou

- Sharding to scale storage within a datacenter
- Geo-replicate data across datacenters
  - Replication and sharding!

- New protocols for replicating writes between replicas and reading data
  - Distributed protocols w/ work on only some machines in each replica for scalability
  - Consistently reading data across shards required transactions

| | Fault Tolerant | Scalable | Highly Available & Low Latency | Guarantees |
|---|---|---|---|---|
| Bayou | yes | no | yes | causal |
| Dynamo | yes | yes | yes | eventual |
| Paxos/RAFT | yes | no | no | linearizability |
| COPS | yes | yes | yes | Causal & read-only txns |
| | | | | |

# Strong Guarantees + Scalability

- Strict Serializability: acts just like 1 machine processing requests 1 at a time with transactions across shards
- Atomic Commit w/ 2PC
- Concurrency control
  - 1 Big Lock: No concurrency ☹
  - 2PL: Growing phase then shrinking phase
  - OCC: Assume you will succeed, only acquire locks during 2PC

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| Bayou | yes | no | yes | causal |
| Dynamo | yes | yes | yes | eventual |
| Paxos/RAFT | yes | no | no | linearizability |
| COPS | yes | yes | yes | causal & read-only txns |
| 2PL | no | yes | - | strict serializability |

# Strong Guarantees + Scalability + Fault Tolerance

- Google's Spanner
  - Sharding to scale storage
  - Paxos for fault tolerance
  - 2PL + 2PC for read-write transactions
    - Strict serializability
    - Scalable processing … mostly

- So many reads, make read-only txns efficient!
  1. Strictly serializable read-only transactions that block, but do not acquire any locks
  2. Stale read-only transactions that do not even block

- Enabled by TrueTime
  - TrueTime gives bounded wall-clock time interval
  - Commit wait ensures a transaction completes after its wall-clock commit time

| | Fault Tolerant | Scalable | Highly Available & Low Latency | Guarantees |
|---|---|---|---|---|
| Bayou | yes | no | yes | causal |
| Dynamo | yes | yes | yes | eventual |
| Paxos/RAFT | yes | no | no | linearizability |
| COPS | yes | yes | yes | causal & read-only txns |
| 2PL | no | yes | - | strict serializability |
| Spanner (stale-read) | yes | yes | no (yes) | strict serializability (stale) |

# Strong Guarantees + Scalability + Low Latency?

- SNOW is impossible for read-only transactions
- Must choose either the strongest guarantees (Strict Serializability & Write transactions) or the lowest latency (Non-blocking & One Round)
- PRAM / CAP are for replication SNOW / NOCS is for sharding

# Now You Can!

- Build systems that are fault tolerant, scalable, provide low latency, highly available
  - + strong*er* guarantees, but not the strongest

- OR

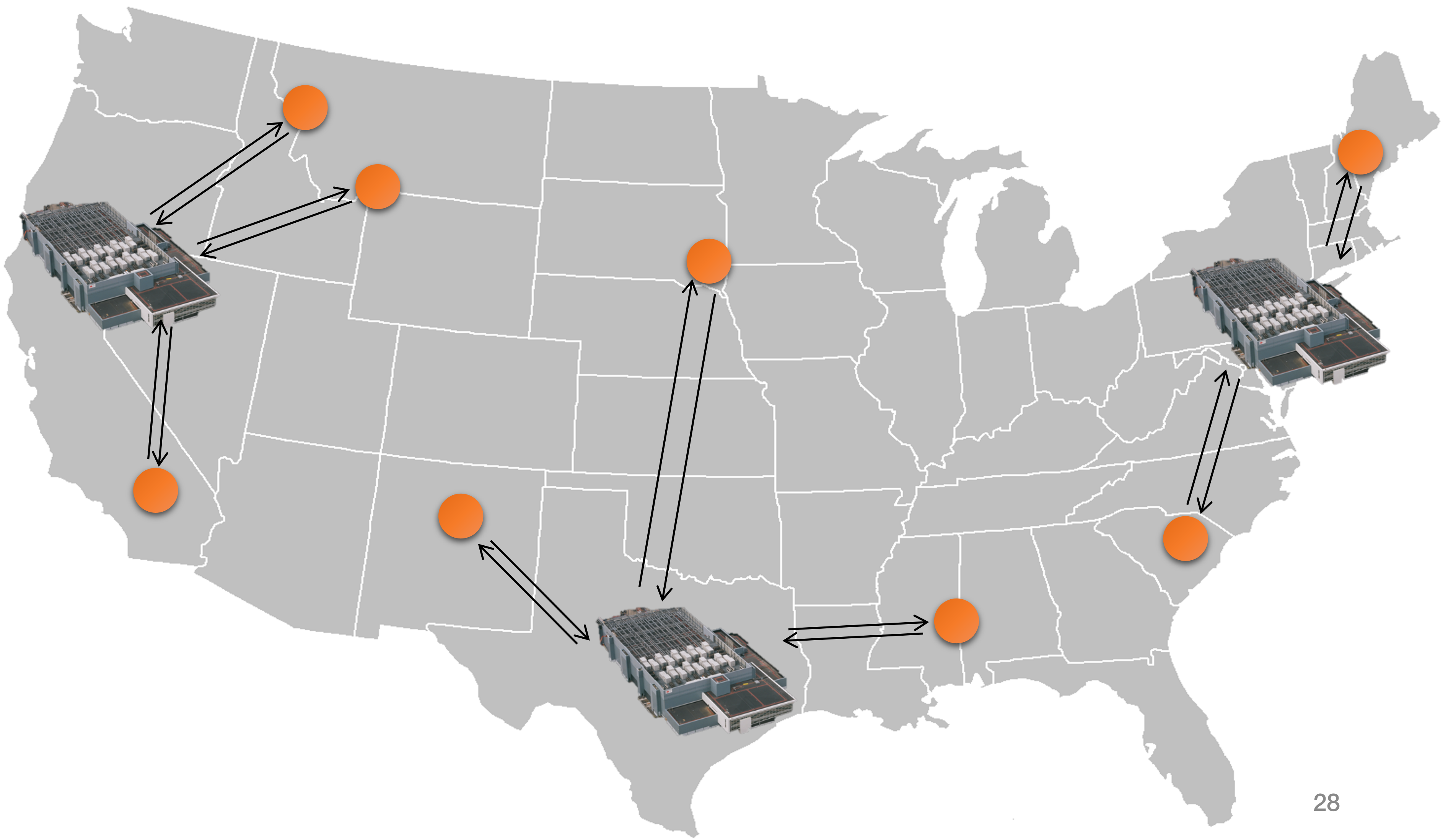
- Build systems that are fault tolerant, scalable, and provide the strongest guarantees

# Making Systems Faster

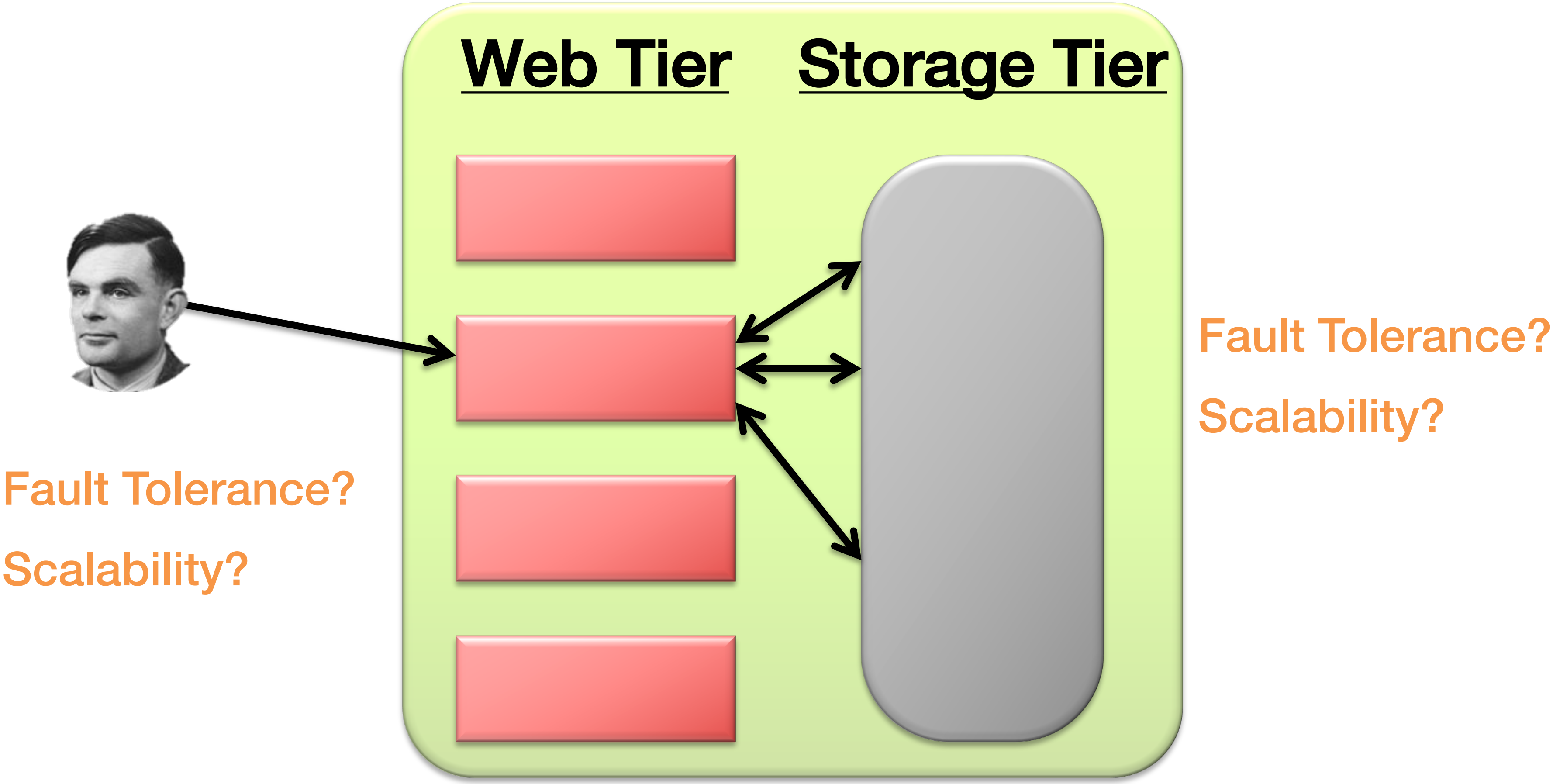
- Reasoning about the performance of distributed systems using a mental model

# Let’s See It In Action

# Client → Frontend Server



# Inside the Datacenter

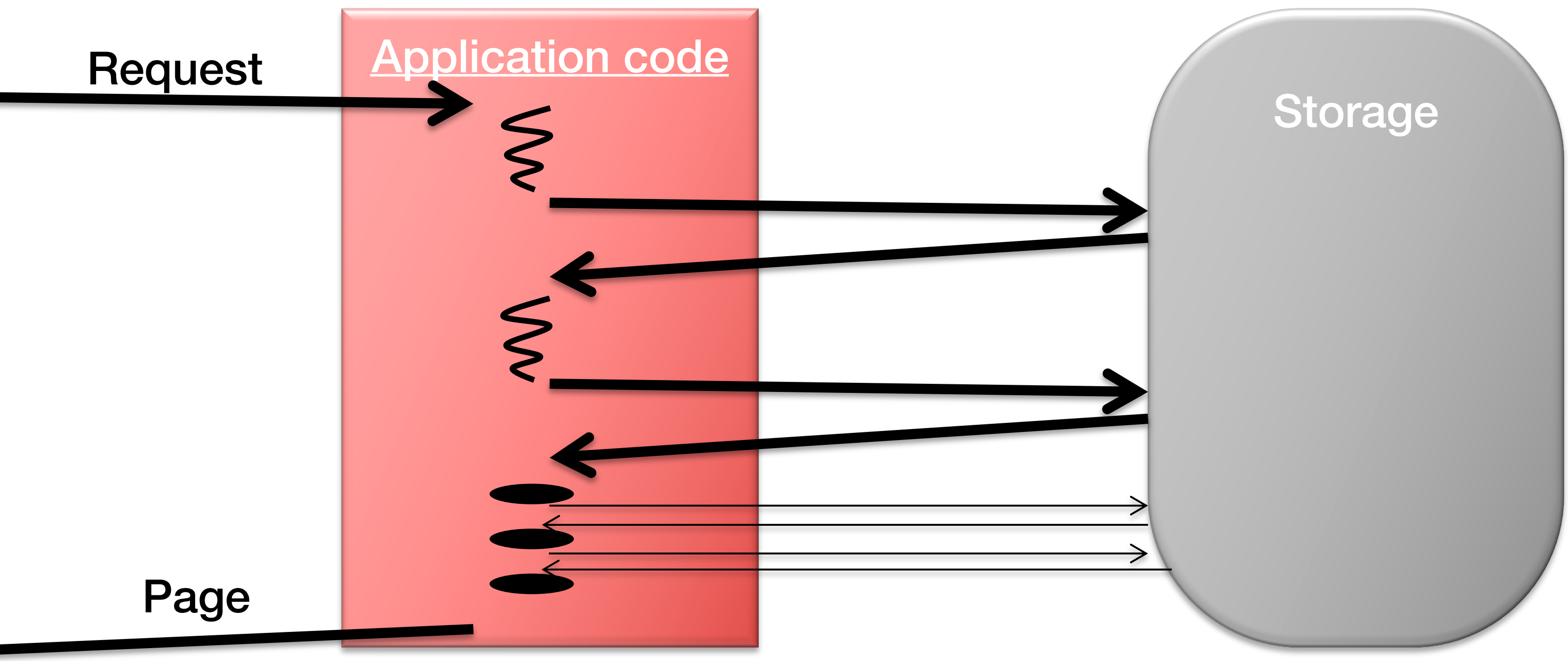



Executes frontend, application code

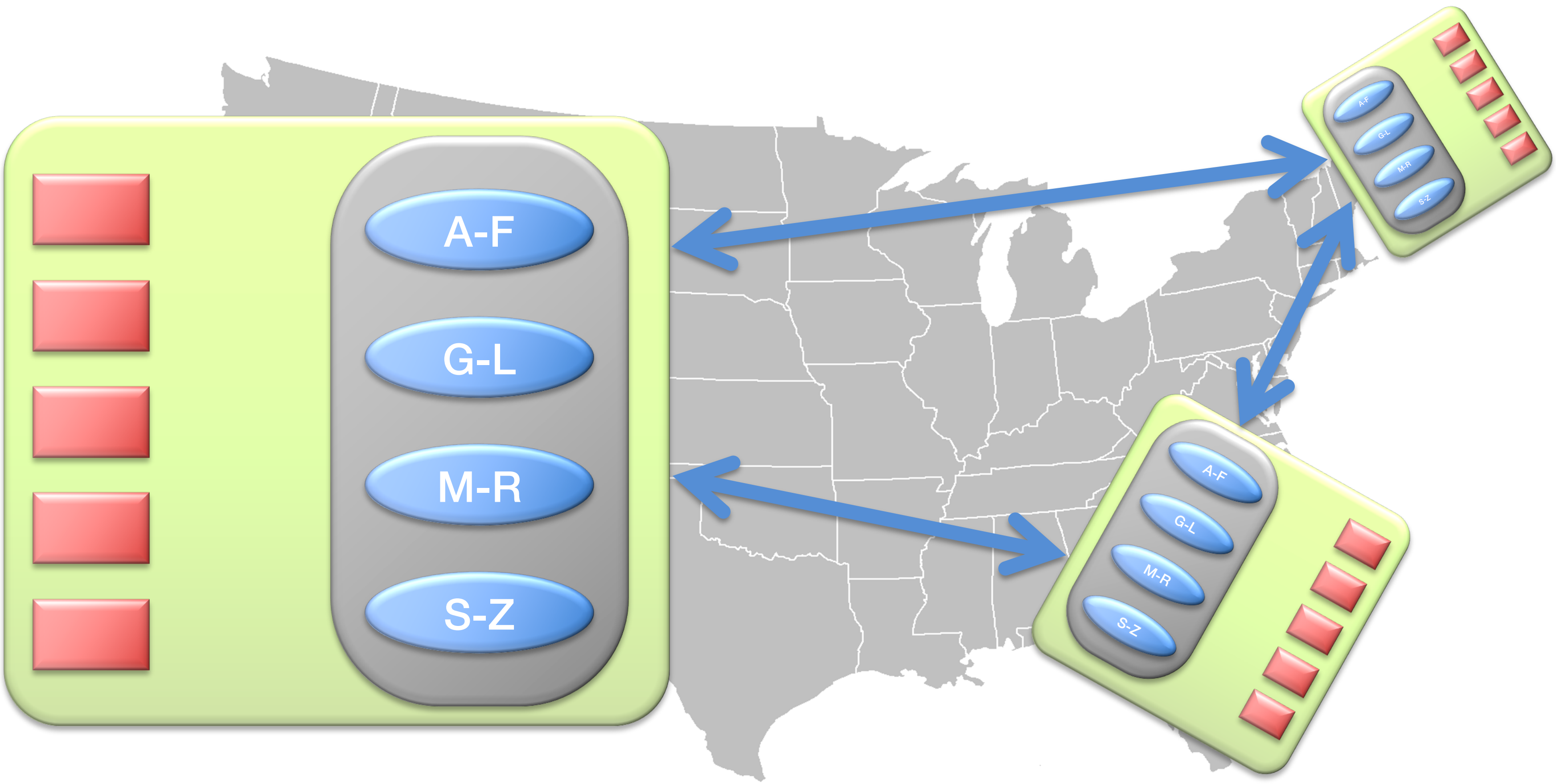
Stores state, provides …

# Application Code Reads/Writes to the Storage Tier

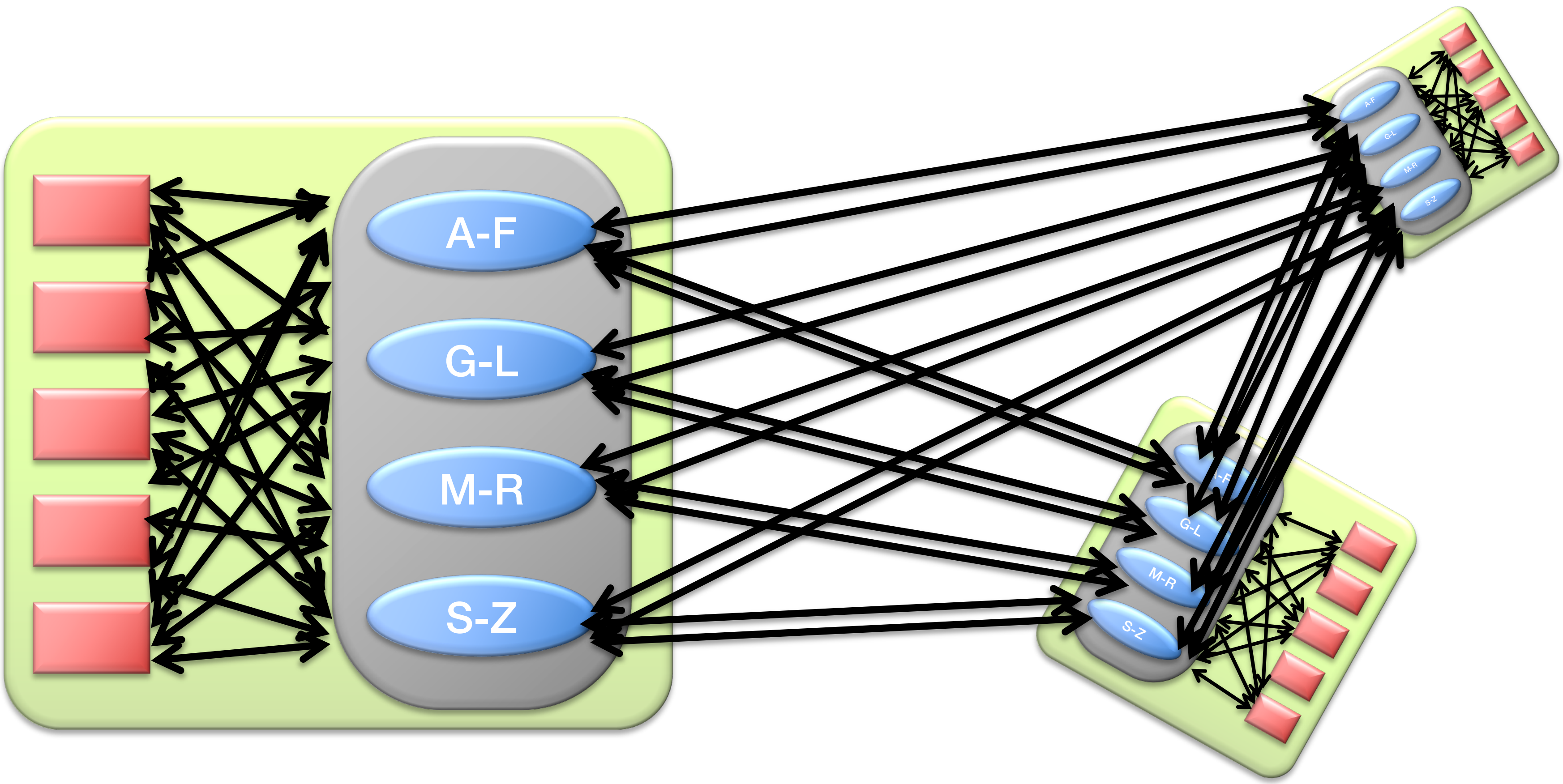
Facebook page load has 1000s of reads,
chains of sequential reads dozens long [HotOS '15]



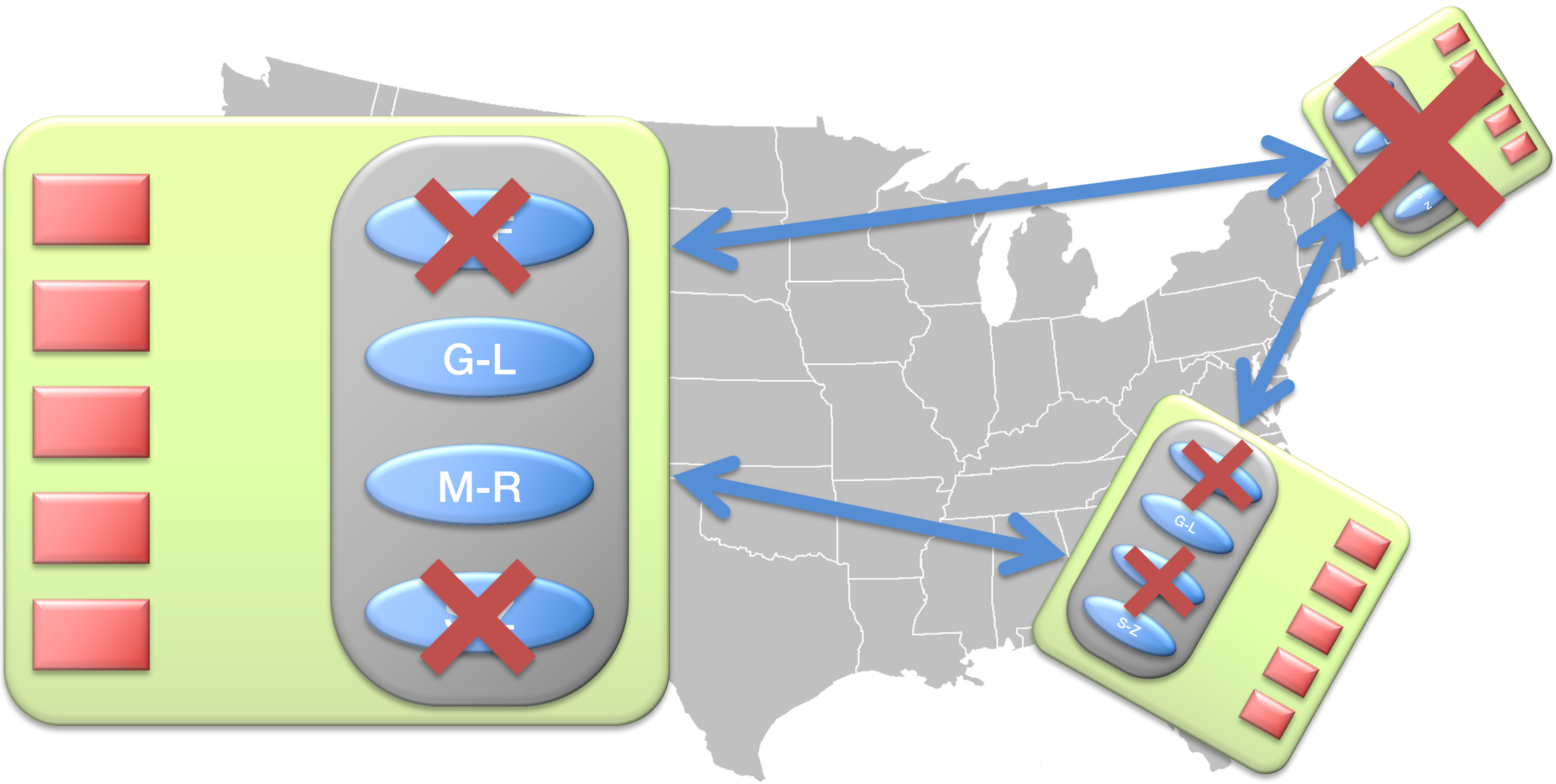
# Scalable Storage is Sharded and Geo-Replicated



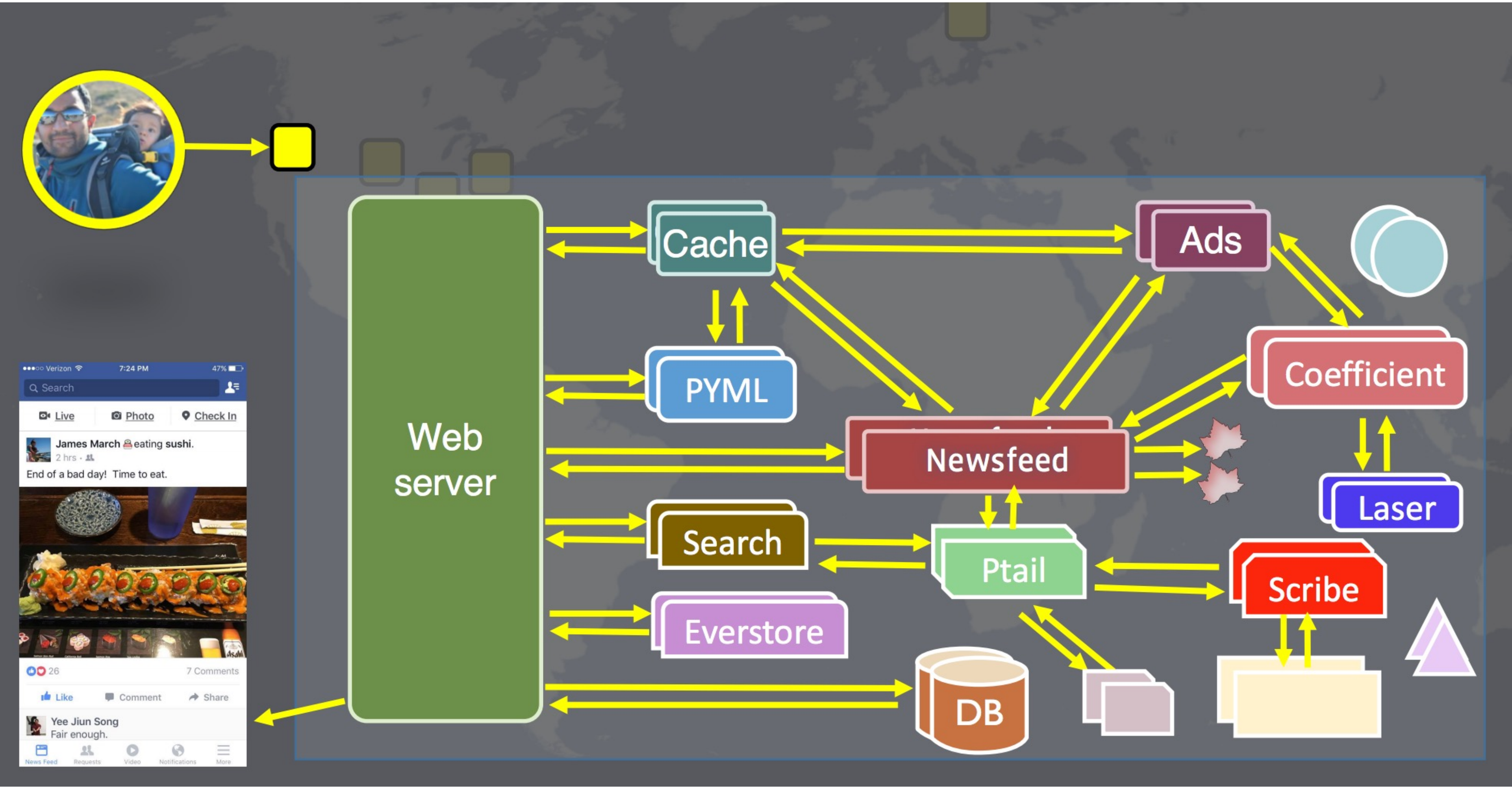
# So Much Concurrency!



# So Many Failures!



# Not Just One Backend System




[Diagram from Kaushik Veeraraghavan's OSDI '16 Talk]

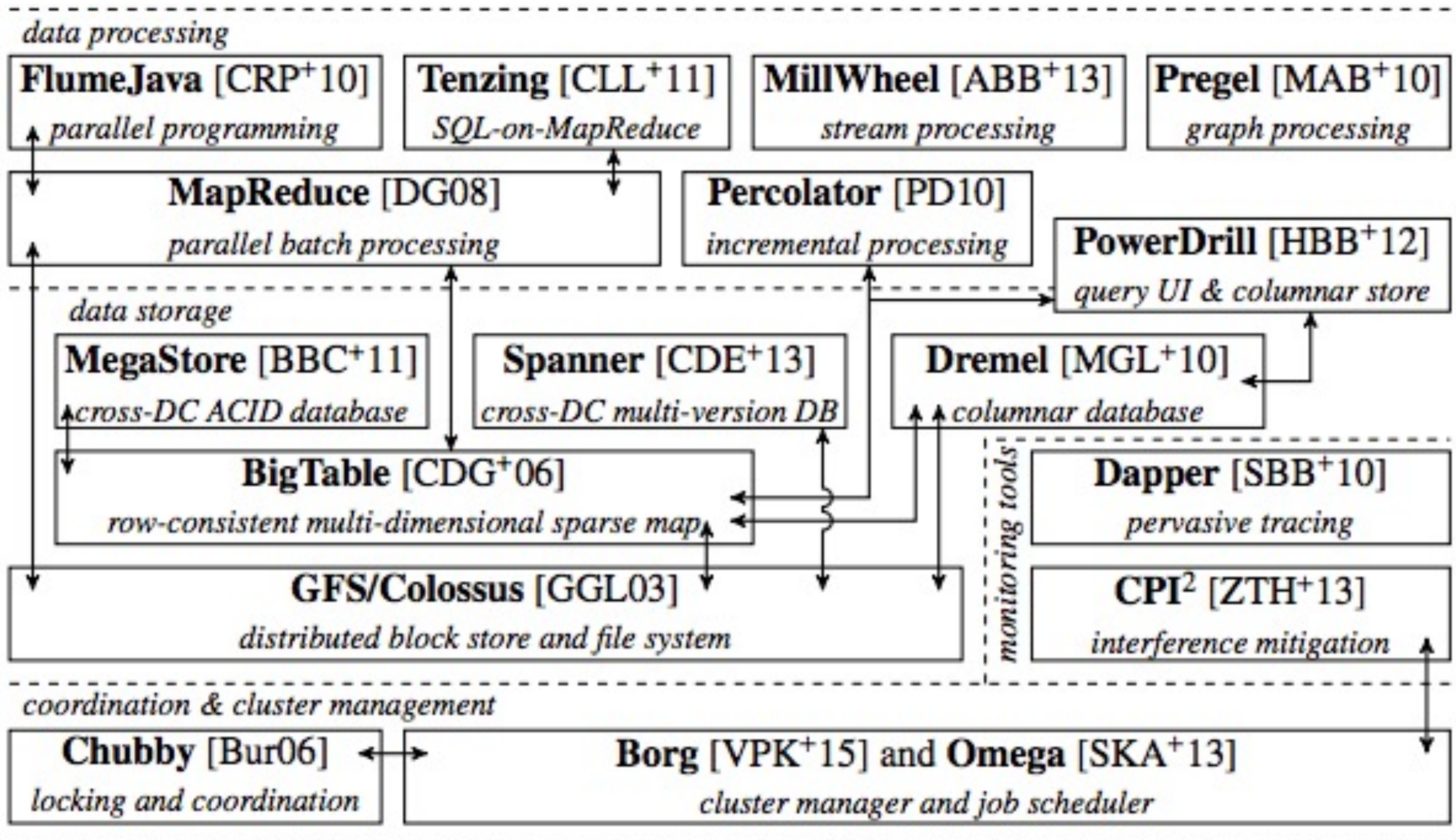
# Each Backend System is a Distributed System

- But with different tradeoffs and designs depending on use

- LIKE count?
  - Eventually consistent storage system

- User Password?
  - Strongly consistent storage system

# Distributed Systems on Distributed Systems on …




[Diagram from Malte Schwarzkopf PhD Thesis 2015]

# More Systems next Year?!?!!

- COS 316 – Principles of Computer System Design
  - Fall
  - Wyatt Lloyd
- COS 461 – Computer Networks
  - Spring
  - Kyle Jamieson
- COS 318 – Operating Systems
  - Spring
  - Mae Milano & Amit Levy

# Thanks!