# Distributed Systems Intro

COS 418/518: Distributed Systems
Lecture 1
Fall 2025

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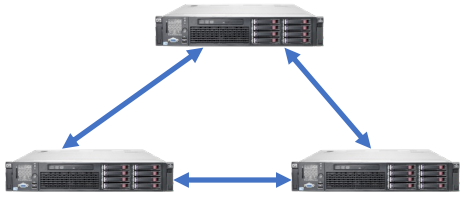
## Distributed Systems, What?



1) Multiple computers
2) Connected by a network
3) Doing something together

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## Distributed Systems, Why?

- Or, why not 1 computer to rule them all?
  - Failure
  - Limited computation/storage/…
  - Physical location

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## Distributed Systems, Where?

- Web Search (e.g., Google, Bing)
- Shopping (e.g., Amazon, Walmart)
- File Sync (e.g., Dropbox, iCloud)
- Social Networks (e.g., Facebook, Twitter)
- Music (e.g., Spotify, Apple Music)
- Ride Sharing (e.g., Uber, Lyft)
- Video (e.g., Youtube, Netflix)
- Online gaming (e.g., Minecraft, Roblox)
- AI Models (OpenAI, Anthropic)

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“The Cloud” is not amorphous

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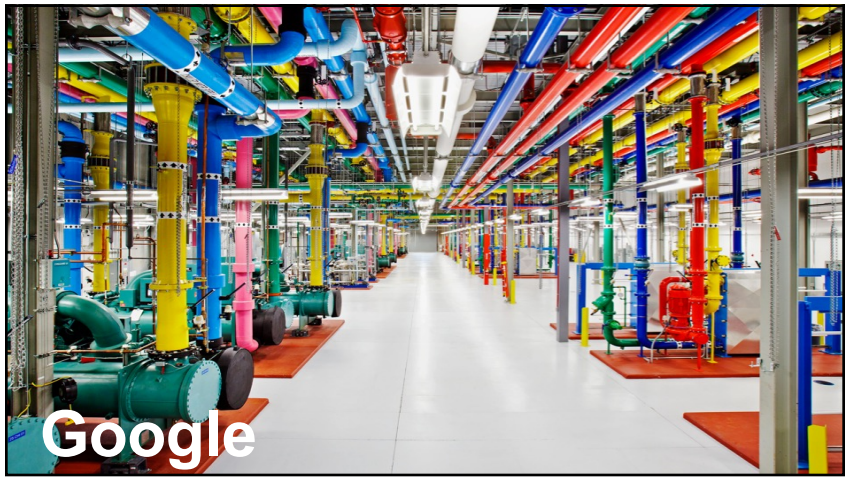
Google

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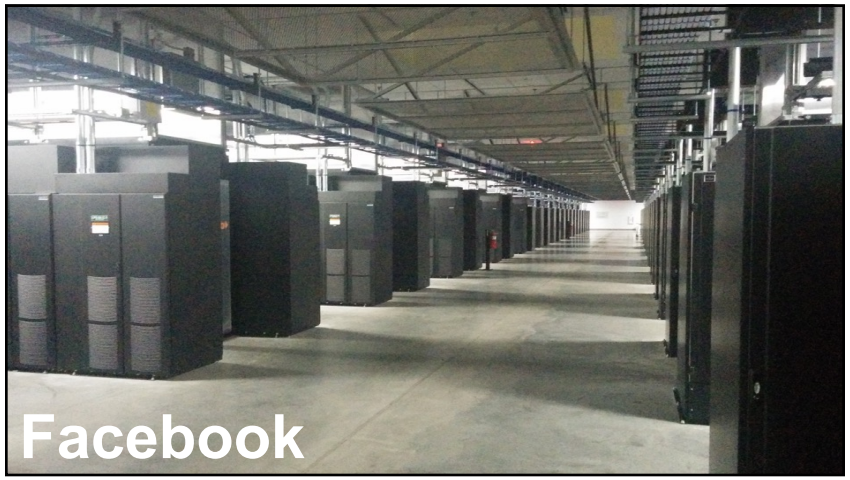
Facebook

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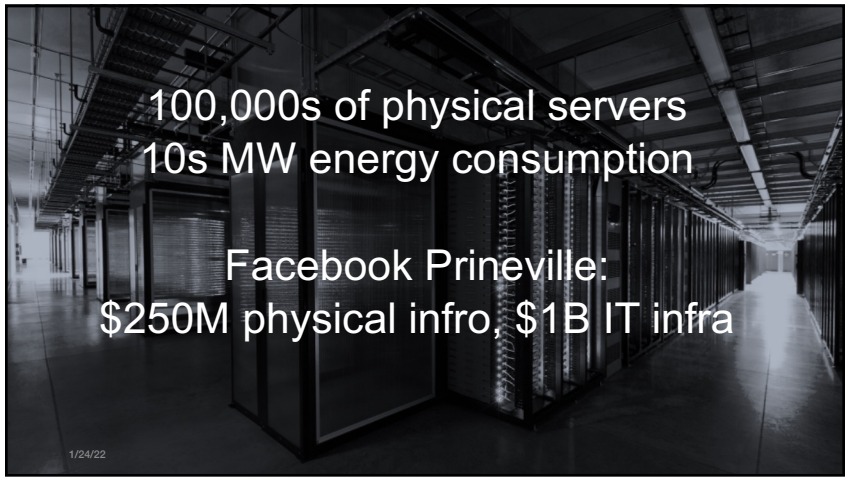
100,000s of physical servers
10s MW energy consumption
Facebook Prineville:
$250M physical infro, $1B IT infra
1/24/22

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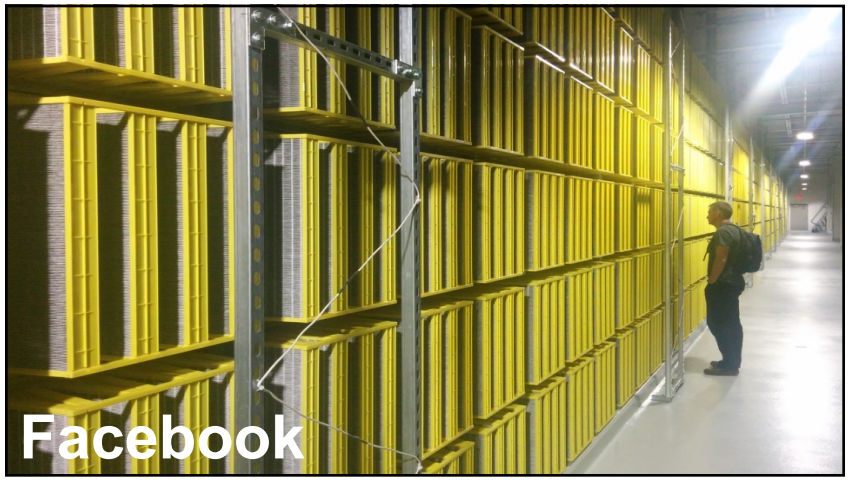
Facebook

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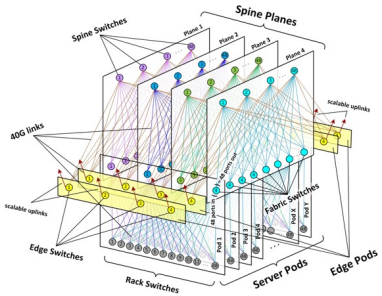
## Everything changes at scale




"Pods provide 7.68Tbps to backplane"

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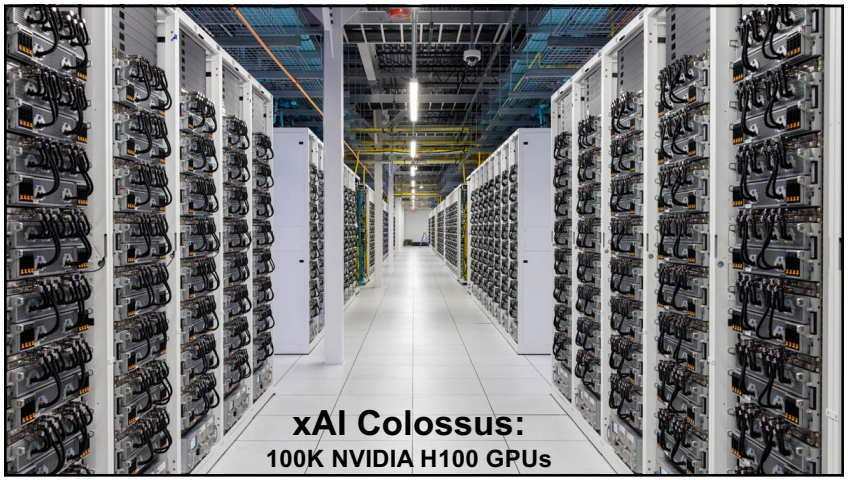


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## Distributed Systems Goal

- Service with higher-level abstractions/interface
  - e.g., file system, database, key-value store, programming model, …
- Hide complexity
- Scalable (scale-out)
- Reliable (fault-tolerant)
- Well-defined semantics (consistent)
- Do "heavy lifting" so app developer doesn't need to

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## Scalable Systems in this Class

- Scale computation across many machines
  - MapReduce
- Scale storage across many machines
  - Dynamo, COPS, Spanner

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## Fault Tolerant Systems in this Class

- Retry on another machine
  - MapReduce, Distributed Snapshots
- Maintain replicas on multiple machines
  - Primary-backup replication
  - Paxos
  - RAFT
  - Bayou
  - Dynamo, COPS, Spanner

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## Range of Abstractions and Guarantees

- Eventual Consistency
  - Dynamo
- Causal Consistency
  - Bayou, COPS
- Linearizability
  - Paxos, RAFT, Primary-backup replication
- Strict Serializability
  - 2PL, Spanner

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## Advanced Topics

- Blockchain as a distributed system
- AI inference in distributed systems

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## Learning Objectives

- Reasoning about concurrency
- Reasoning about failure
- Reasoning about performance

- Building systems that correctly handle concurrency and failure

- Knowing specific system designs and design components

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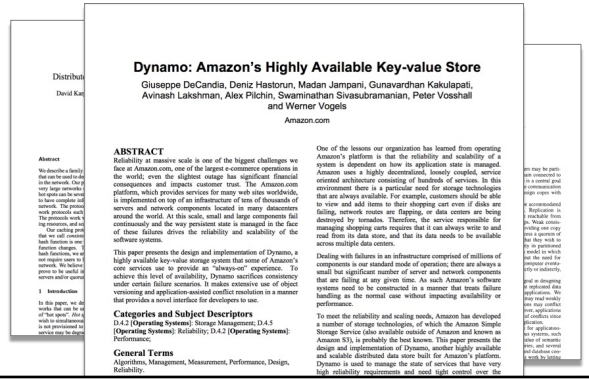
## Research results matter: NoSQL



**Dynamo: Amazon's Highly Available Key-value Store**

Giuseppe DeCandia, Deniz Hastorun, Madan Jampani, Gunavardhan Kakulapati, Avinash Lakshman, Alex Pilchin, Swaminathan Sivasubramanian, Peter Vosshall and Werner Vogels

Amazon.com

**ABSTRACT**

Reliability at massive scale is one of the biggest challenges we face at Amazon.com, one of the largest e-commerce operations in the world; even the slightest outage has significant financial consequences and impacts customer trust. The Amazon.com platform, which provides services for many web sites worldwide, is implemented on top of an infrastructure of tens of thousands of servers and network components located in many datacenters around the world. At this scale, small and large components fail continuously and the way persistent state is managed in the face of these failures drives the reliability and scalability of the software systems.

This paper presents the design and implementation of Dynamo, a highly available key-value storage system that some of Amazon's core services use to provide an "always-on" experience. To achieve this level of availability, Dynamo sacrifices consistency under certain failure scenarios. It makes extensive use of object versioning and application-assisted conflict resolution in a manner that provides a novel interface for developers to use.

**Categories and Subject Descriptors**

D.4.2 [**Operating Systems**]: Storage Management; D.4.5 [**Operating Systems**]: Reliability; D.4.2 [**Operating Systems**]: Performance;

**General Terms**

Algorithms, Management, Measurement, Performance, Design, Reliability.

One of the lessons our organization has learned from operating Amazon's platform is that the reliability and scalability of a system is dependent on how its application state is managed. Amazon uses a highly decentralized, loosely coupled, service oriented architecture consisting of hundreds of services. In this environment there is a particular need for storage technologies that are always available. For example, customers should be able to view and add items to their shopping cart even if disks are failing, network routes are flapping, or data centers are being destroyed by tornados. Therefore, the service responsible for managing shopping carts requires that it can always write to and read from its data store, and that its data needs to be available across multiple data centers.

Dealing with failures in an infrastructure comprised of millions of components is our standard mode of operation; there are always a small but significant number of server and network components that are failing at any given time. As such Amazon's software systems need to be constructed in a manner that treats failure handling as the normal case without impacting availability or performance.

To meet the reliability and scaling needs, Amazon has developed a number of storage technologies, of which the Amazon Simple Storage Service (also available outside of Amazon and known as Amazon S3), is probably the best known. This paper presents the design and implementation of Dynamo, another highly available and scalable distributed data store built for Amazon's platform. Dynamo is used to manage the state of services that have very high reliability requirements and need tight control over the

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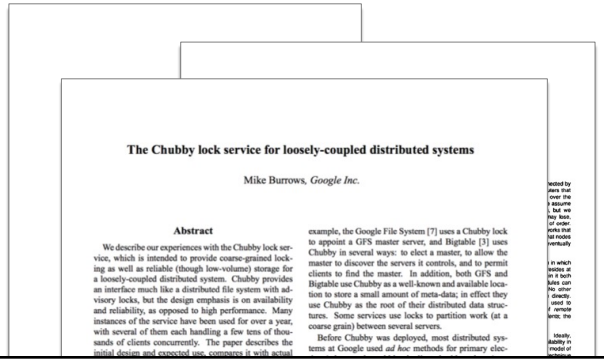
## Research results matter: Paxos



**The Chubby lock service for loosely-coupled distributed systems**

Mike Burrows, *Google Inc.*

**Abstract**

We describe our experiences with the Chubby lock service, which is intended to provide coarse-grained locking as well as reliable (though low-volume) storage for a loosely-coupled distributed system. Chubby provides an interface much like a distributed file system with advisory locks, but the design emphasis is on availability and reliability, as opposed to high performance. Many instances of the service have been used for over a year, with several of them each handling a few tens of thousands of clients concurrently. The paper describes the initial design and expected use, compares it with actual

example, the Google File System [7] uses a Chubby lock to appoint a GFS master server, and Bigtable [3] uses Chubby in several ways: to elect a master, to allow the master to discover the servers it controls, and to permit clients to find the master. In addition, both GFS and Bigtable use Chubby as a well-known and available location to store a small amount of meta-data; in effect they use Chubby as the root of their distributed data structures. Some services use locks to partition work (at a coarse grain) between several servers.

Before Chubby was deployed, most distributed systems at Google used *ad hoc* methods for primary elec-

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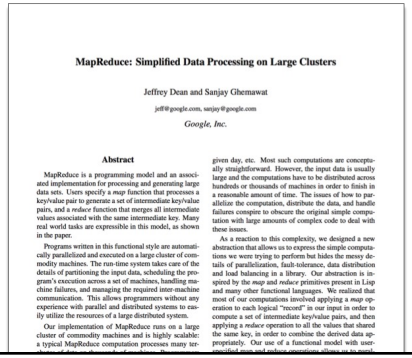
## Research results matter: MapReduce



**MapReduce: Simplified Data Processing on Large Clusters**

Jeffrey Dean and Sanjay Ghemawat

jeff@google.com, sanjay@google.com

*Google, Inc.*

**Abstract**

MapReduce is a programming model and an associated implementation for processing and generating large data sets. Users specify a *map* function that processes a key/value pair to generate a set of intermediate key/value pairs, and a *reduce* function that merges all intermediate values associated with the same intermediate key. Many real world tasks are expressible in this model, as shown in the paper.

Programs written in this functional style are automatically parallelized and executed on a large cluster of commodity machines. The run-time system takes care of the details of partitioning the input data, scheduling the program's execution across a set of machines, handling machine failures, and managing the required inter-machine communication. This allows programmers without any experience with parallel and distributed systems to easily utilize the resources of a large distributed system.

Our implementation of MapReduce runs on a large cluster of commodity machines and is highly scalable: a typical MapReduce computation processes many terabytes of data on thousands of machines. Programmers find the system easy to use: hundreds of MapReduce programs have been implemented and upwards of one thousand MapReduce jobs are executed on Google's clusters every

given day, etc. Most such computations are conceptually straightforward. However, the input data is usually large and the computations have to be distributed across hundreds or thousands of machines in order to finish in a reasonable amount of time. The issues of how to parallelize the computation, distribute the data, and handle failures conspire to obscure the original simple computation with large amounts of complex code to deal with these issues.

As a reaction to this complexity, we designed a new abstraction that allows us to express the simple computations we were trying to perform but hides the messy details of parallelization, fault-tolerance, data distribution and load balancing in a library. Our abstraction is inspired by the *map* and *reduce* primitives present in Lisp and many other functional languages. We realized that most of our computations involved applying a *map* operation to each logical "record" in our input in order to compute a set of intermediate key/value pairs, and then applying a *reduce* operation to all the values that shared the same key, in order to combine the derived data appropriately. Our use of a functional model with user-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# Research results matter: Chain Replication








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# Conclusion

- Distributed Systems
  - Multiple machines doing something together
  - Pretty much everywhere and everything computing now
- "Systems"
  - Hide complexity and do the heavy lifting (i.e., **interesting**!)
  - Scalability, fault tolerance, guarantees

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