

CS 425 / ECE 428

Distributed Systems

Fall 2026

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(Thanks to Indranil Gupta)

Lecture 2: Introduction to Cloud Computing

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What was the world's first bug in a
program?

World's First Bug (1947)

9/9

0800 Antan started
 1000 " stopped - antan ✓
 1300 (032) MP-MC 1.2700 9.037 847 025
 (033) PRO 2 2.130476415 9.037 846 995 correct
 correct 2.130476415 4.615925059(-2)
 Relays 6-2 in 033 failed special speed test
 in relay 10,000 test.
 Relays changed

1100 Started Cosine Tape (Sine check)
 1525 Started Multi Adder Test.

1545  Relay #70 Panel F
 (moth) in relay.

First actual case of bug being found.

1630 Antan started.
 1700 closed down.

Relay 3145
 Relay 3371

- <https://education.nationalgeographic.org/resource/worlds-first-computer-bug/>

Quiz: Where is the World's Largest Datacenter?

Quiz: Where is the World's Largest Datacenter?

- (2018-2025) China Telecom. 10.7 Million sq. ft.
- (2017) “The Citadel” Nevada. 7.2 Million sq. ft.
- (2015) In Chicago!
 - 350 East Cermak, Chicago, 1.1 MILLION sq. ft.
 - Shared by many different “carriers”
 - Critical to Chicago Mercantile Exchange
- See:
 - <http://ict-price.com/top-10-biggest-data-centres-from-around-the-world/>
 - <https://www.gigabitmagazine.com/top10/top-10-biggest-data-centres-world>
 - <https://www.racksolutions.com/news/data-center-news/top-10-largest-data-centers-world/>



(There was and is) The Hype!

- Forrester in 2010 – Cloud computing will go from **\$40.7 billion** in 2010 to **\$241 billion** in 2020.
- Today: Cloud Market is **\$676B** (expected to reach **\$2.3T** by 2032)
- Companies and even Federal/state governments using cloud computing now: **fbo.gov**

Many Cloud Providers

- AWS: Amazon Web Services
 - EC2: Elastic Compute Cloud
 - S3: Simple Storage Service
 - EBS: Elastic Block Storage
- Microsoft Azure
- Google Cloud/Compute Engine/AppEngine
- Rightscale, Salesforce, EMC, Gigaspaces, 10gen, Datastax, Oracle, VMWare, Yahoo, Cloudera
- And many many more!

Two Categories of Clouds

- Can be either a (i) public cloud, or (ii) private cloud
- Private clouds are accessible only to company employees
- Public clouds provide service to any paying customer:
 - Amazon S3 (Simple Storage Service): store arbitrary datasets, pay per GB-month stored
 - Recently: ~fractions of cent to a few cents, per GB month
 - Amazon EC2 (Elastic Compute Cloud): upload and run arbitrary OS images, pay per CPU hour used
 - Recently: few cents per CPU hr (depending on strength), only CPUs not GPUs
 - Google cloud: similar pricing ranges as above
 - Google AppEngine/Compute Engine: develop applications within their appengine framework, upload data that will be imported into their format, and run

Customers Save Time and \$\$\$

- (Stories from mid-2010s)
- Dave Power, Associate Information Consultant at Eli Lilly and Company: “With AWS, Powers said, a new server can be up and running in **three minutes** (it used to take Eli Lilly **seven and a half weeks** to deploy a server internally) and a **64-node Linux cluster** can be online in five minutes (compared with three months internally). ... It's just shy of instantaneous.”
- Ingo Elfering, Vice President of Information Technology Strategy, GlaxoSmithKline: “With Online Services, we are able to reduce our IT **operational costs** by roughly **30%** of what we’re spending”
- Jim Swartz, CIO, Sybase: “At Sybase, a private cloud of virtual servers inside its datacenter has saved nearly **\$US2 million annually** since 2006, Swartz says, because the company can share computing power and storage resources across servers.”
- 100s of startups in Silicon Valley can harness large computing resources without buying their own machines.

But what exactly IS a cloud?

What is a Cloud?

- It's a cluster!
- It's a supercomputer!
- It's a datastore!
- It's superman!



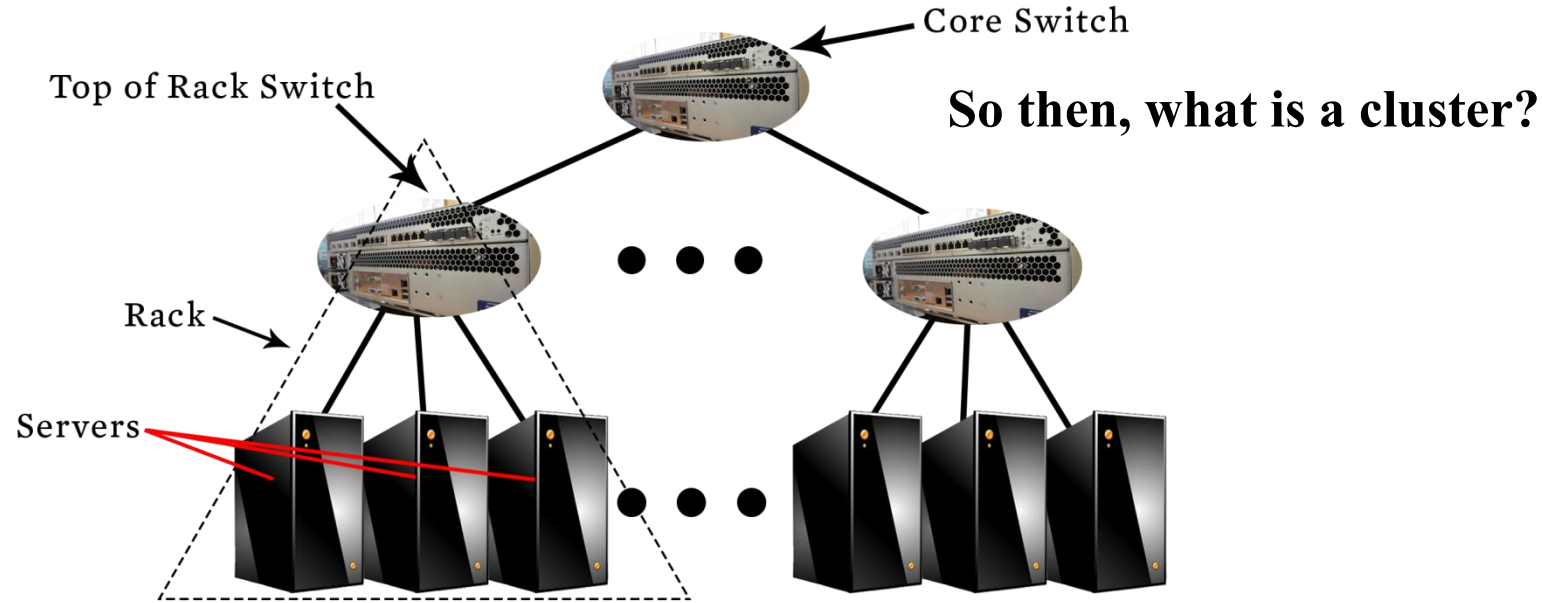
- None of the above
- All of the above

- Cloud = Lots of storage + compute cycles nearby

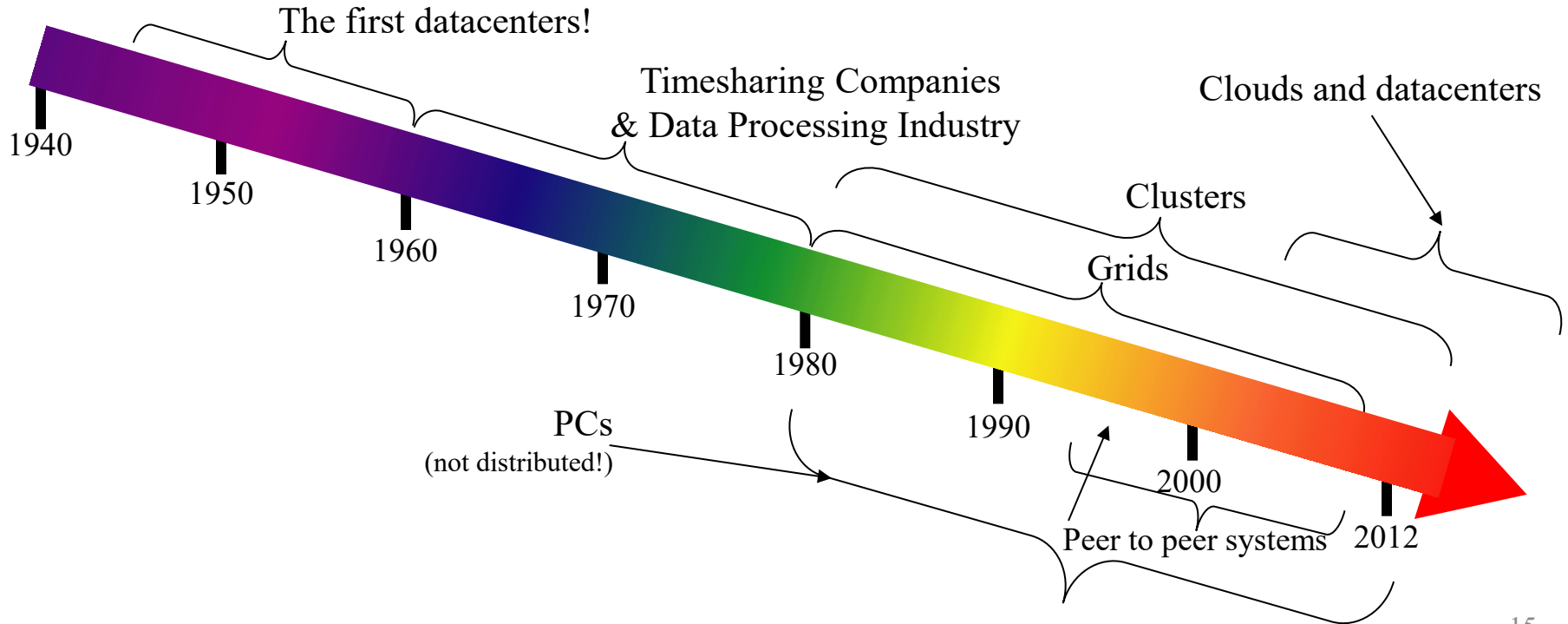
What is a Cloud?

- A single-site cloud (aka “Datacenter”) consists of
 - Compute nodes (grouped into racks) (2)
 - Switches, connecting the racks
 - A network topology, e.g., hierarchical
 - Storage (backend) nodes connected to the network (3)
 - Front-end for submitting jobs and receiving client requests (1)
 - (1,2,3: Often called “three-tier architecture”)
 - Software Services
- A geographically distributed cloud consists of
 - Multiple such sites
 - Each site perhaps with a different structure and services

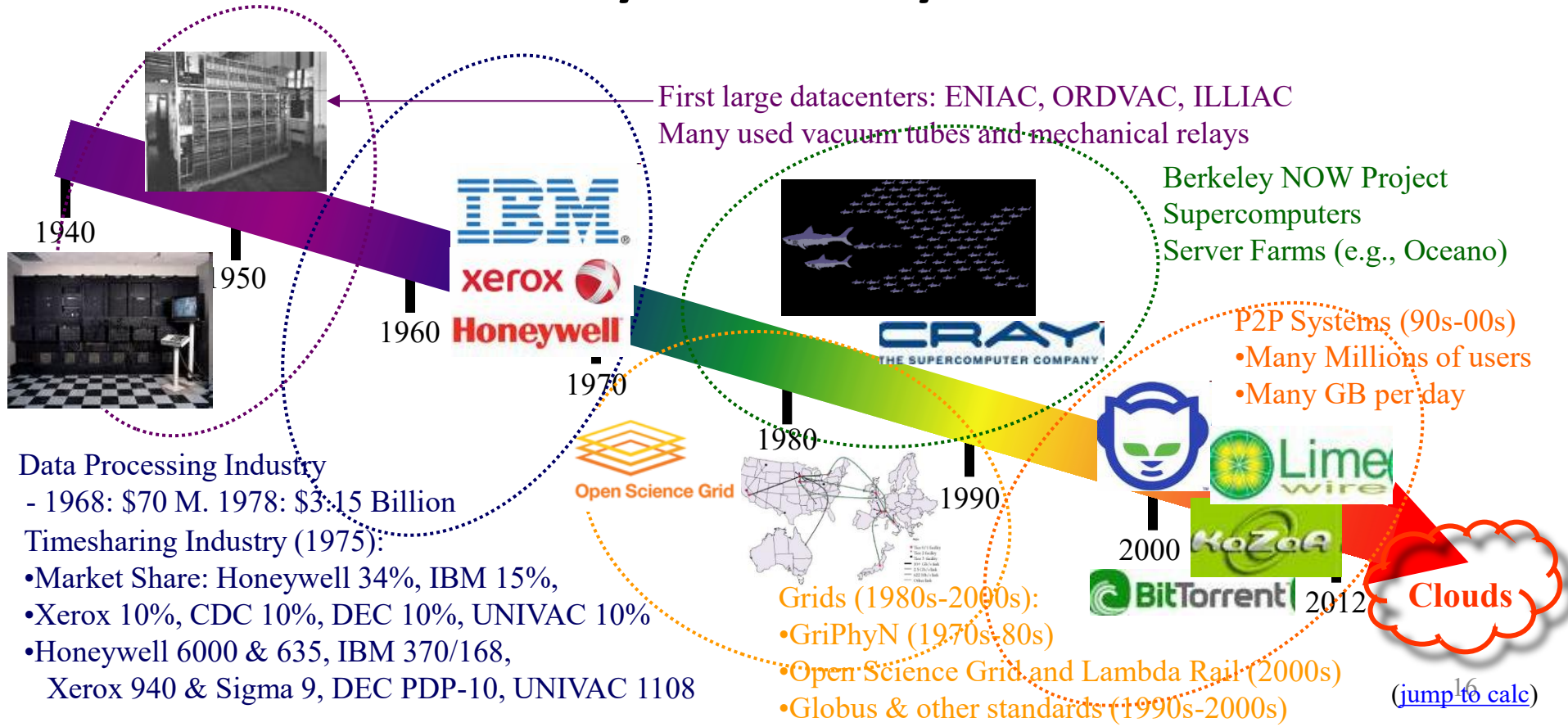
A Sample Cloud Topology



“A Cloudy History of Time”



“A Cloudy History of Time”



Trends: Technology

- Doubling Periods – storage: 12 mos, bandwidth: 9 mos, and (what law is this?) cpu compute capacity: 18 mos
- Then and Now
 - Bandwidth
 - 1985: mostly 56Kbps links nationwide
 - Today: Tbps links widespread
 - Disk capacity
 - Today's PCs have TBs, far more than a 1990 supercomputer

Trends: Users

- Then and Now

- Biologists:

- 1990: were running small single-molecule simulations
 - Today: CERN's Large Hadron Collider producing many PB/year

Prophecies

- In 1965, MIT's Fernando Corbató and the other designers of the Multics operating system envisioned a computer facility operating “like a power company or water company”.
- **Plug** your thin client into the computing Utility **and Play** your favorite Intensive Compute & Communicate Application
 - Have today’s clouds brought us closer to this reality? Think about it.

Four Features New in Today's Clouds

I. Massive scale.

II. On-demand access: Pay-as-you-go, no upfront commitment.

- And anyone can access it

III. Data-intensive Nature: What was MBs has now become TBs, PBs and XBs.

- Daily logs, forensics, Web data, etc.
- Humans have data numbness: Wikipedia (large) compressed is only about 10 GB!

IV. New Cloud Programming Paradigms: MapReduce/Hadoop, NoSQL/Cassandra/MongoDB and many others.

- High in accessibility and ease of programmability
- Lots of open-source

Combination of one or more of these gives rise to novel and unsolved distributed computing problems in cloud computing.

Announcements

- **4 cr only: MP Groups Form DUE this week Mon Sep 1st @ 5 pm** (see course webpage).
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I. Massive Scale

- Facebook [GigaOm, 2012]
 - 30K in 2009 -> 60K in 2010 -> 180K in 2012
- Microsoft [NYTimes, 2008]
 - 150K machines
 - Growth rate of 10K per month
 - 80K total running Bing
 - In 2013, Microsoft Cosmos had 110K machines (4 sites)
- Yahoo! [2009]:
 - 100K
 - Split into clusters of 4000
- AWS EC2 [Randy Bias, 2009]
 - 40K machines
 - 8 cores/machine
- eBay [2012]: 50K machines
- HP [2012]: 380K in 180 DCs
- Google [2011, Data Center Knowledge] : 900K (reputed in 2016: 2.5M)

What does a datacenter look like from inside?

- A virtual walk through a datacenter (Facebook Prineville Datacenter, Mid 2010s)
- References:
 - https://www.youtube.com/watch?v=4A_A-CmrqpQ
 - <http://gigaom.com/cleantech/a-rare-look-inside-facebooks-oregon-data-center-photos-video/>

Servers



Front



Back



In



Some highly secure (e.g., financial info)²⁵

Cooling



Air sucked in from top (also, Bugzappers)



Water purified



Water sprayed into air



15 motors per server bank

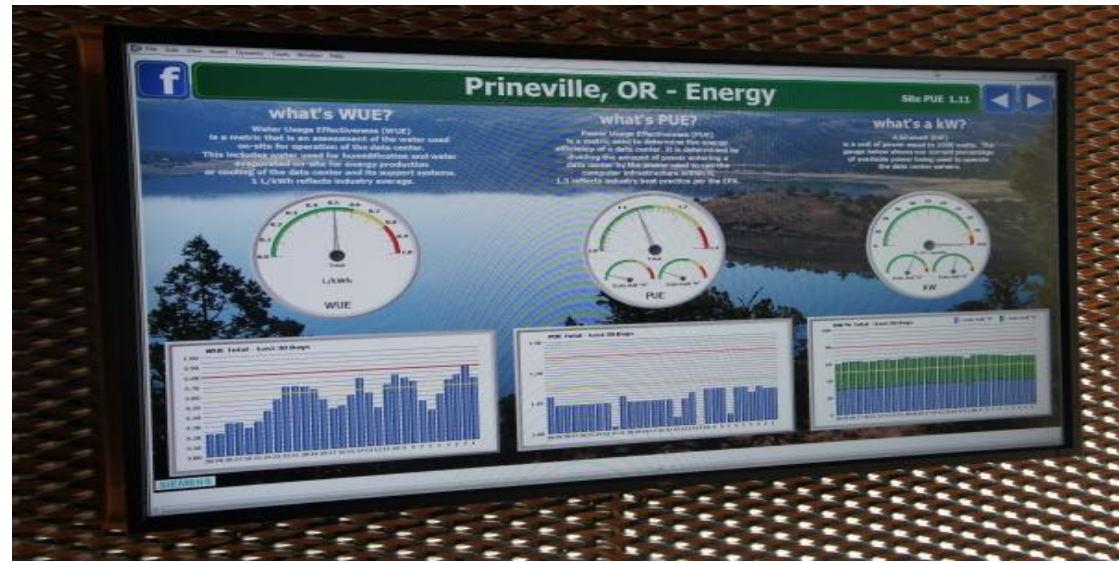
Power



Off-site

On-site

- $WUE = \text{Annual Water Usage} / \text{IT Equipment Energy (L/kWh)}$ – low is good
- $PUE = \text{Total facility Power} / \text{IT Equipment Power}$ – low is good (e.g., Google~1.1)



Extra - Fun Videos to Watch

- Microsoft GFS Datacenter Tour (Youtube)
 - <http://www.youtube.com/watch?v=hOxA111pQIw>
- Timelapse of a Datacenter Construction on the Inside (Fortune 500 company)
 - <http://www.youtube.com/watch?v=ujO-xNvXj3g>

II. On-demand access: *aaS

Classification

On-demand: renting a cab vs. (previously) renting a car, or buying one. E.g.:

- AWS Elastic Compute Cloud (EC2): a few cents to a few \$ per CPU hour
- AWS Simple Storage Service (S3): a few cents per GB-month
- HaaS: Hardware as a Service
 - You get access to barebones hardware machines, do whatever you want with them, Ex: Your own cluster
 - Not always a good idea because of security risks
- IaaS: Infrastructure as a Service
 - You get access to flexible computing and storage infrastructure. Virtualization or containerization is one way of achieving this (cgroups, Kubernetes, Dockers, VMs,...). Often said to subsume HaaS.
 - Ex: Amazon Web Services (AWS: EC2 and S3), OpenStack, Eucalyptus, Rightscale, Microsoft Azure, Google Cloud.

II. On-demand access: *aaS

Classification

- PaaS: Platform as a Service
 - You get access to flexible computing and storage infrastructure, coupled with a software platform (often tightly coupled)
 - Ex: Google's AppEngine (Python, Java, Go)
- SaaS: Software as a Service
 - You get access to software services, when you need them. Often said to subsume SOA (Service Oriented Architectures).
 - Ex: Google docs, MS Office 365 Online
- And new recently: FaaS = Function as a Service
 - e.g., AWS Lambda, Azure Functions, etc.

III. Data-intensive Computing

- Computation-Intensive Computing
 - Example areas: MPI-based, High-performance computing, Grids
 - Typically run on supercomputers (e.g., NCSA Blue Waters)
- Data-Intensive
 - Typically store data at datacenters
 - Use compute nodes nearby
 - Compute nodes run computation services
- In data-intensive computing, the **focus shifts from computation to the data**: CPU utilization no longer the most important resource metric, instead I/O is (disk and/or network)

IV. New Cloud Programming Paradigms

- Easy to write and run highly parallel programs in new cloud programming paradigms:
 - Google: MapReduce and Sawzall
 - Amazon: Elastic MapReduce service (pay-as-you-go)
 - Google (MapReduce)
 - Indexing: a chain of 24 MapReduce jobs
 - ~200K jobs processing 50PB/month (in 2006)
 - Yahoo! (Hadoop + Pig)
 - WebMap: a chain of several MapReduce jobs
 - 300 TB of data, 10K cores, many tens of hours (~2008)
 - Facebook (Hadoop + Hive)
 - ~300TB total, adding 2TB/day (in 2008)
 - 3K jobs processing 55TB/day
 - Similar numbers from other companies, e.g., Yildex, eharmony.com, etc.
 - NoSQL: MySQL is an industry standard, but Cassandra is 2400 times faster!

Two Categories of Clouds

- Can be either a (i) public cloud, or (ii) private cloud
- Private clouds are accessible only to company employees
- Public clouds provide service to any paying customer
- You're starting a new service/company: should you use a public cloud or purchase your own private cloud?

Single site Cloud: to Outsource or Own?

- Medium-sized organization: wishes to run a service for M months
 - Service requires 128 servers (1024 cores) and 524 TB
 - Same as UIUC CCT (Cloud Computing Testbed) cloud site (bought in 2009, now decommissioned)
- **Outsource** (e.g., via AWS): *monthly* cost
 - S3 costs: \$0.12 per GB month. EC2 costs: \$0.10 per CPU hour (costs from 2009)
 - Storage = \$ 0.12 X 524 X 1000 ~ \$62 K
 - Total = Storage + CPUs = \$62 K + \$0.10 X 1024 X 24 X 30 ~ \$136 K
- **Own**: monthly cost
 - Storage ~ \$349 K / M
 - Total ~ \$ 1555 K / M + 7.5 K (includes 1 sysadmin / 100 nodes)
 - using 0.45:0.4:0.15 split for hardware:power:network and 3 year lifetime of hardware

Single site Cloud: to Outsource or Own?

- Breakeven analysis: **more preferable to own if:**
 - $\$349 \text{ K} / M < \62 K (storage)
 - $\$1555 \text{ K} / M + 7.5 \text{ K} < \136 K (overall)
- Breakeven points*
 - $M > 5.55$ months (storage)
 - $M > 12$ months (overall)
- As a result
 - **Startups use clouds a lot**
 - **Cloud providers benefit monetarily most from storage**



Academic Clouds: Emulab/CloudLab

- A community resource open to researchers in academia and industry. Very widely used by researchers everywhere today.
- <https://www.emulab.net/>
- A cluster, with currently ~500 servers
- Founded and owned by University of Utah (led by Late Prof. Jay Lepreau)
- As a user, you can:
 - Grab a set of machines for your experiment
 - You get root-level (sudo) access to these machines
 - You can specify a network topology for your cluster
 - You can emulate any topology

All images © Emulab

Public Research Clouds

- Accessible to researchers with a qualifying grant
- Chameleon Cloud: <https://www.chameleoncloud.org/>
 - HaaS
 - OpenStack (~AWS)
- CloudLab: <https://www.cloudlab.us/>
 - Build your own cloud on their hardware

Summary

- Clouds build on many previous generations of distributed systems
- Especially the timesharing and data processing industry of the 1960-70s.
- Need to identify unique aspects of a problem to classify it as a new cloud computing problem
 - Scale, On-demand access, data-intensive, new programming
- Otherwise, the solutions to your problem may already exist!
- Next: Mapreduce!

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