*“I think there is a world market for maybe five computers”*

Thomas Watson, President of IBM, 1943

# Lecture A.3:
# Practical Aspects of Cloud Computing

**CS205: Computing Foundations for Computational Science**
**Dr. David Sondak**
**Spring Term 2021**


HARVARD
School of Engineering
and Applied Sciences


INSTITUTE FOR APPLIED
COMPUTATIONAL SCIENCE
AT HARVARD UNIVERSITY

**Lectures developed by Dr. Ignacio M. Illorente**

# Before We Start

## Where We Are

Computing Foundations for Computational and Data Science

How to use modern computing platforms in solving scientific problems

Intro: Large-Scale Computational and Data Science

A. Parallel Processing Fundamentals

- A.1. Parallel Processing Architectures
- A.2. Large-scale Processing on the Cloud
- A.3. Practical Aspects of Cloud Computing
- A.4. Application Parallelism
- A.5. Designing Parallel Programs

B. Parallel Computing

C. Parallel Data Processing

Wrap-Up: Advanced Topics

# CS205: Contents

APPLICATION SOFTWARE

APPLICATION PARALLELISM

PARALLEL PROGRAM DESIGN

PROGRAMMING MODEL

Optimization

OpenACC

OpenMP

MPI

Spark

Map-Reduce

PLATFORM

B. BIG COMPUTE

C. BIG DATA

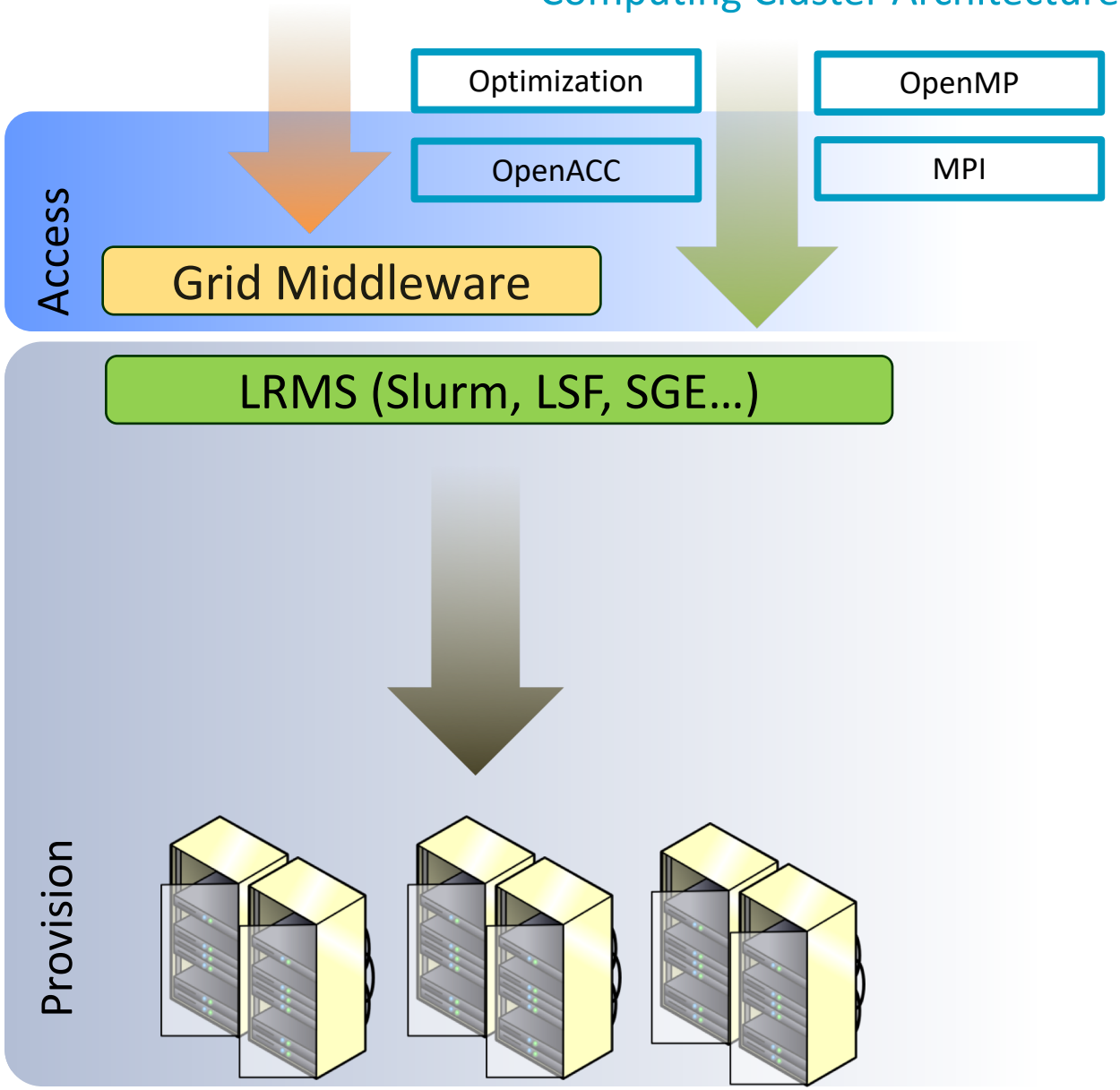



CLOUD COMPUTING

PARALLEL ARCHITECTURES

# Context

## Computing Cluster Architecture




# HPC

Programming Model

+

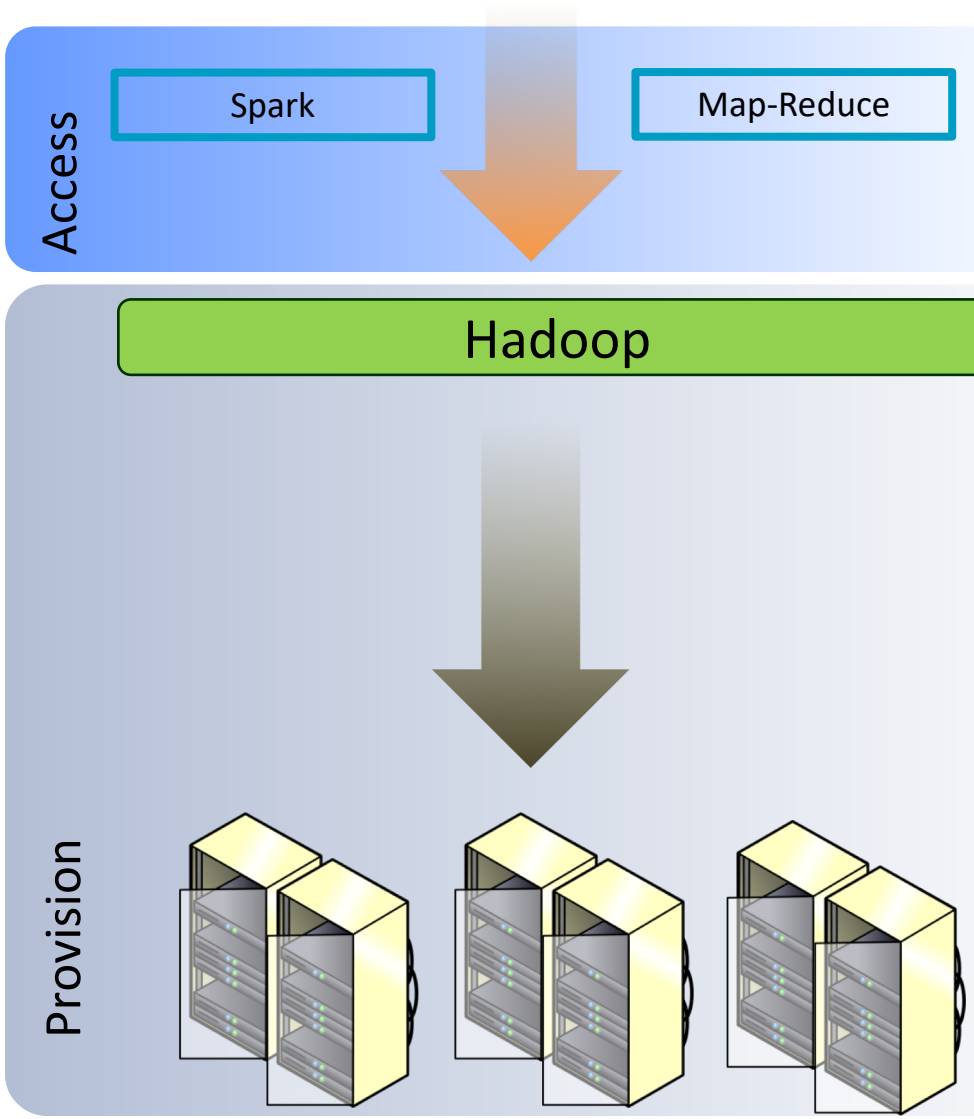
Platform

+

Architecture

# Context

## Computing Cluster Architecture




BIG DATA

Programming Model

+

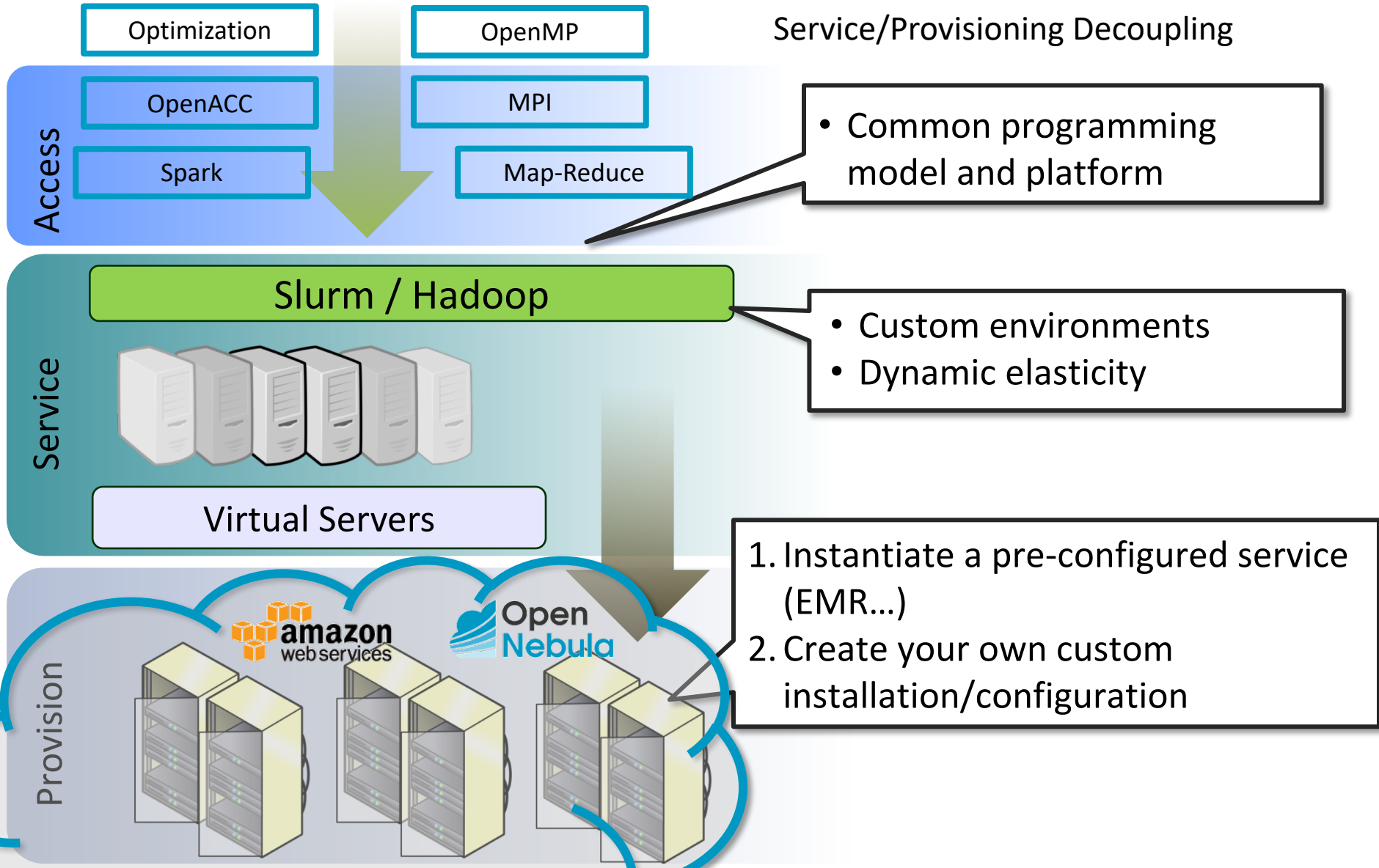
Platform

+

Architecture

# Context

## Cloud as Infrastructure Tool



# Roadmap

## Practical Aspects of Cloud Computing

Numerical Reproducibility and Replicability

Economic Aspects

The State of Public Cloud

The Need for Private Clouds

The Anatomy of the Cloud

# Numerical Reproducibility and Replicability

## The Four Rs

Who has ever written a paper/report including numerical experiments (computational physics, bioinformatics, applied mathematics, statistics….)?

Would I be able to reuse your software/data?

Would I be able to rewrite your software/data?

Would I be able to reproduce your experiment (software/data + execution environment) in a different computing infrastructure and get the same numerical result?

Would I be able to replicate (repeat) your experiment (software/data + execution environment + computing infrastructure) and get the same computing result?

# Numerical Reproducibility and Replicability

## The Four Rs

**Reusability**

- Reusability refers to the possibility to reuse the software or parts of it for different purposes, in different environments, and by researchers other than the original authors.

**Rewriteability**

- Rewriteability refers to the possibility to modify and extend the software or parts of it.

**Reproducibility**

- Reproducibility of a computational experiment means that it can be repeated by a different researcher in a different computing infrastructure but with the same execution environment and to come to the same numerical results.

**Replicability**

- The attribute Replicability describes the ability to repeat a computational experiment on the same computing infrastructure and to come to the same numerical results and computing performance.

# Numerical Reproducibility and Replicability

## The Four Rs

AERODYNAMICS

NAVIER-STOKES

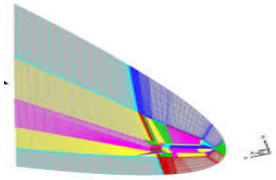
$$\frac{\partial u}{\partial t}+\frac{1}{r^\tau}\frac{\partial(r^\tau uu)}{\partial r}+\frac{\partial(vu)}{\partial z}=-\frac{\partial p}{\partial r}+\frac{1}{Re}\frac{\partial}{\partial z}\left(\frac{\partial u}{\partial z}-\frac{\partial v}{\partial r}\right)+\frac{1}{Fr^2}g_r,$$

$$\frac{\partial v}{\partial t}+\frac{1}{r^\tau}\frac{\partial(r^\tau uv)}{\partial r}+\frac{\partial(vv)}{\partial z}=-\frac{\partial p}{\partial z}+\frac{1}{Re\,r^\tau}\frac{\partial}{\partial r}\left(r^\tau\left(\frac{\partial u}{\partial z}-\frac{\partial v}{\partial r}\right)\right)+\frac{1}{Fr^2}g_z,$$

$$\frac{1}{r^\tau}\frac{\partial(r^\tau u)}{\partial r}+\frac{\partial v}{\partial z}=0,$$

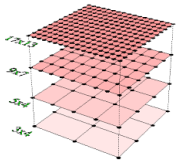
PHYSICS

FINITE DIFFERENCE



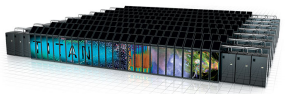
ACCURACY

MULTIGRID



COMPLEXITY

PARALLEL



SPEED-UP

**EXECUTION ENVIRONMENT**

- Algorithm, application version and dependencies
- VIRTUAL MACHINES
- SOFTWARE CONTAINERS

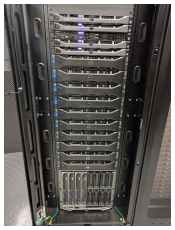
**SYSTEM CAPACITY**

- Execution time, performance…
- CLOUD PROVIDERS

# Economic Aspects

## Private vs. Public

ON-PREMISES

Open Nebula

FASRC


CLOUD (VIRTUALIZATION)

VARIABLE COSTS

FIXED COSTS
SECURITY ASPECTS
PERFORMANCE
(DATA/ACCESS LATENCY)
INTEGRATE WITH LOCAL
PROCESSES/SERVICES

FLEXIBILITY/ELASTICITY

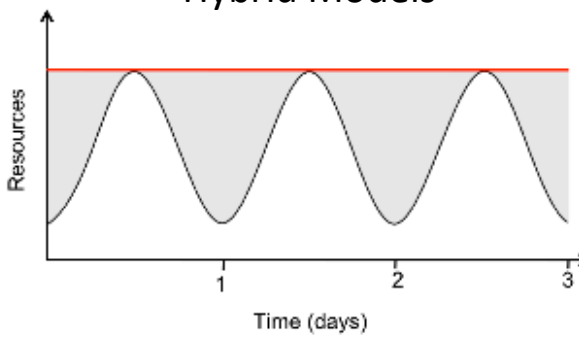
PERFORMANCE (HPC)

# Economic Aspects

## Private vs. Public

5 Servers: 15,000 $ – 2x Quad-Core Servers
Rack and switch: 1,500 $
Total Hardware: 16,500 $
Cost Equipment Annual: 5,500 $ (depreciation 3 years)
Power: 3,500 $ (0.4kW per server)
Admin: 2,000 $ (420 server)
Cooling/install: 5,500 $
Cost Maintenance Annual: 11,000 $
Total Annual: 16,500 $
Hours Year: 8,760
Cost per Hour and Server: 0.37 $
Cost Instance Extra Large: 0.68 $
Instance Usage: 54%

Hybrid Models



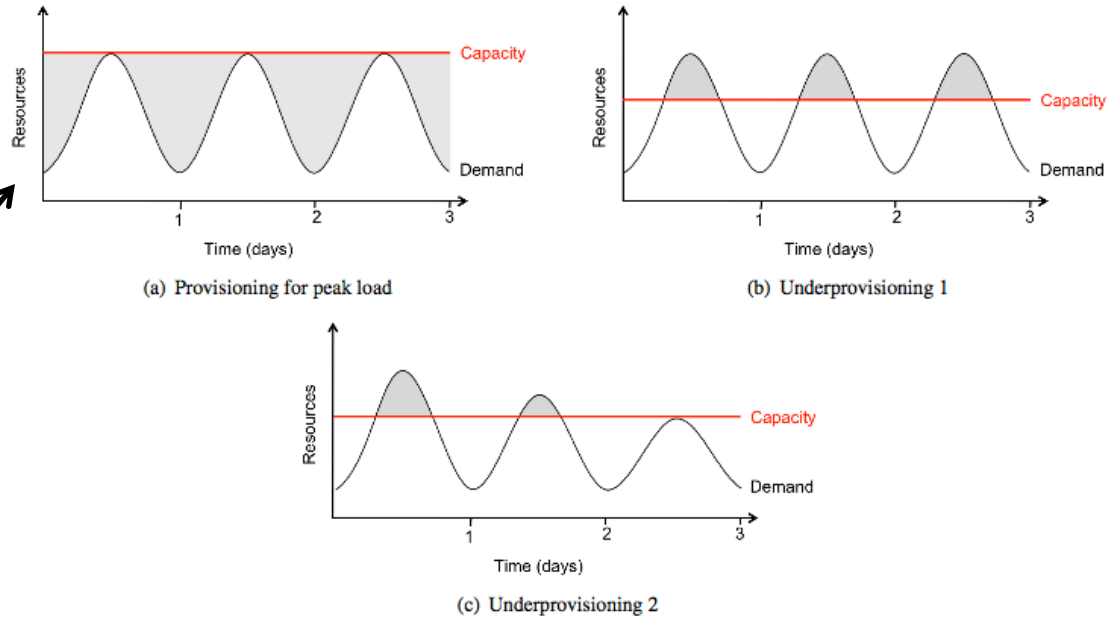
# Economic Aspects

## Sources of Variability

### Variability of the Demand

- Data centers work on average at 5-20% of capacity
- Systems are sized to meet peak of demand
- Example with daily patterns

Max: 500 servers
Min: 100 servers
Average: 300 servers
Utilization: 7,200 s-h
Provision: 12,000 s-h
Ratio: 1.7

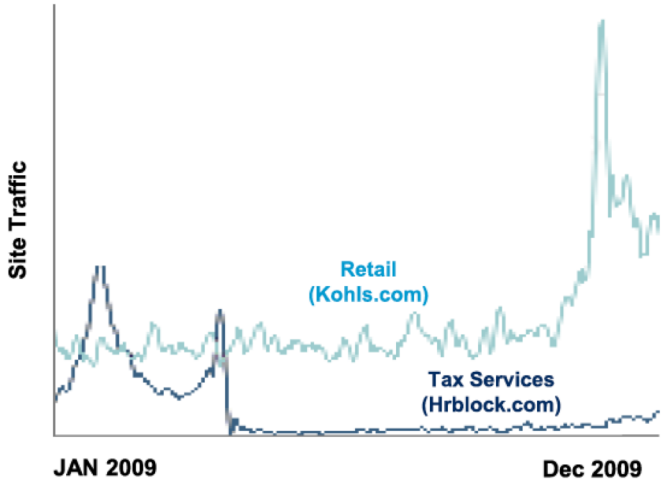



*Source: Above the Clouds: A Berkeley View of Cloud Computing, Berkeley*

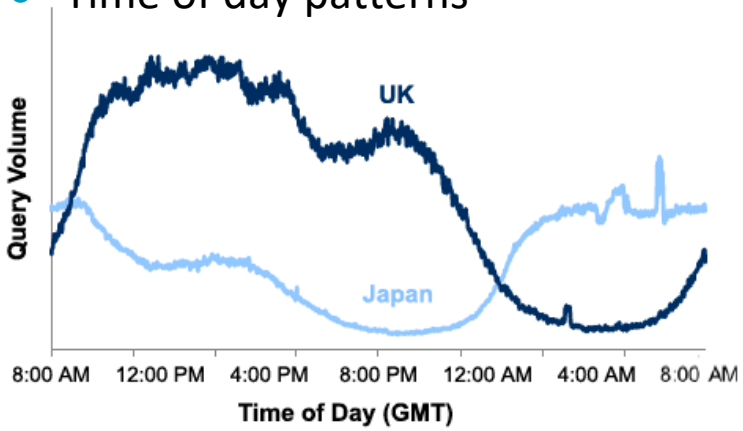
# Economic Aspects

## Sources of Variability

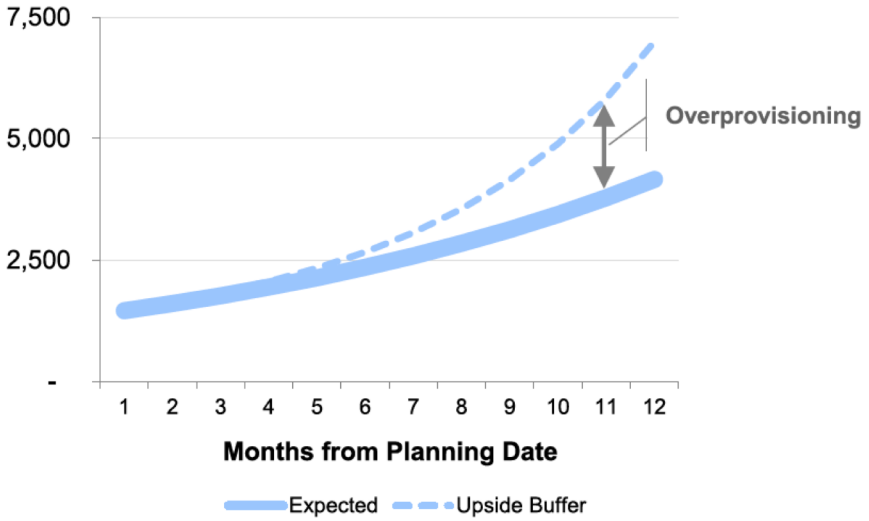
- Industry-specific variability




- Time of day patterns




- Uncertain growth patterns




*Source: The Economics of the Cloud, Microsoft*

# Economic Aspects

## Hidden Costs and Overheads

### Consider All Hidden Costs and Overheads

Data Set: 500 GB
Local Infrastructure: 10 servers, each needs 1 hour to process 1 GB → Local Time: 50 hours
Amazon EC2: If we now go to AWS, how much time is needed?
(assume virtual servers with same capacity as the local infrastructure and no upload overhead)

Poll: How much time would it take to do the calculation on AWS?

- 50 hours
- 1 hour
- 25 hours

*Source: Above the Clouds: A Berkeley View of Cloud Computing, Berkeley*

# Economic Aspects

## Hidden Costs and Overheads

### Consider All Hidden Costs and Overheads

- Cost and overhead to upload data

Upload Data to S3: 20 Mbits/sec => 55 hours
(Hint: 8 bits / Byte)
Best Remote Time: 56 hours
Additional Cost for Data Upload?

### Breakout Room Questions:

- Why 55 hour upload time?
- Why is the *best* remote time 56 hours?
- Should this group move to the cloud?

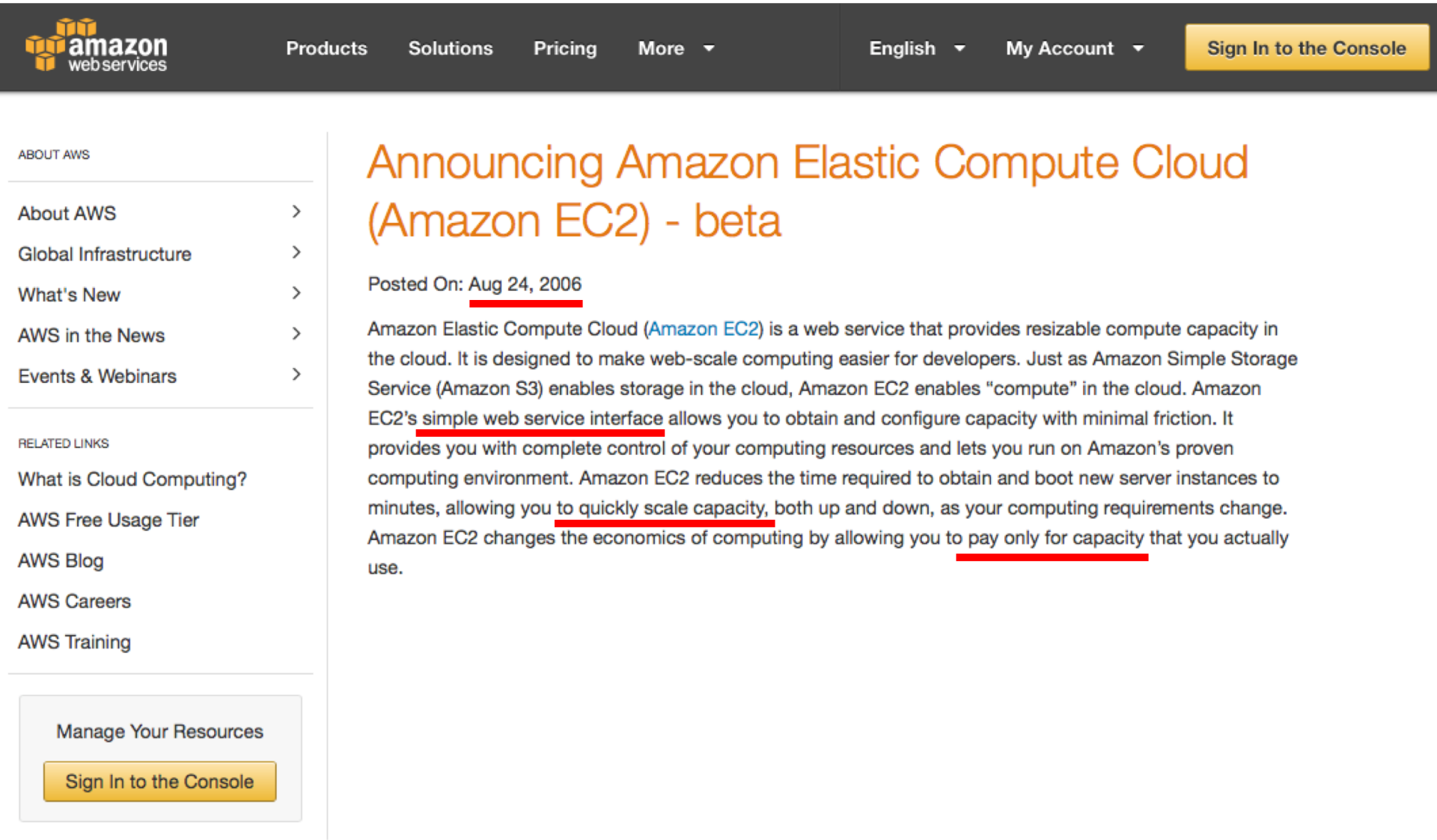
### Considerations about elasticity

- 100 servers 1 hour = 1 server 100 hours
- Massive parallelism is usually cheaper

*Source: Above the Clouds: A Berkeley View of Cloud Computing, Berkeley*

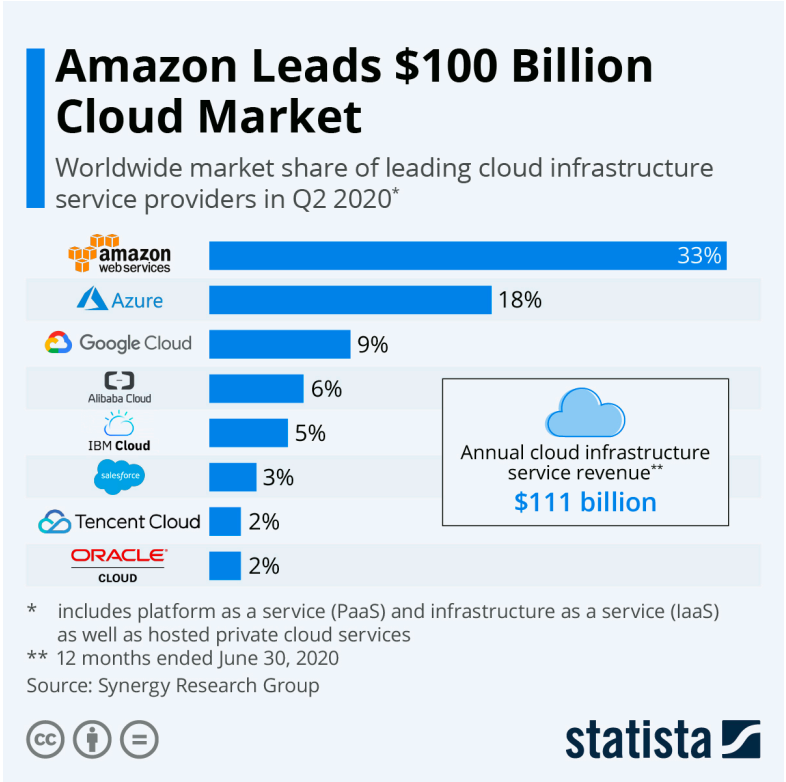
# The State of Public Cloud

## August 2006 – Fourteen Years Ago



# The State of Public Cloud

## Public Cloud Market Becoming an Oligopoly




Growing market
Cloud services grew by 32% annually in Q4

Highly concentrated market
The 5 big players aggregate 71% and the next 3 players 7%

Increasing concentration
Big players gaining market share

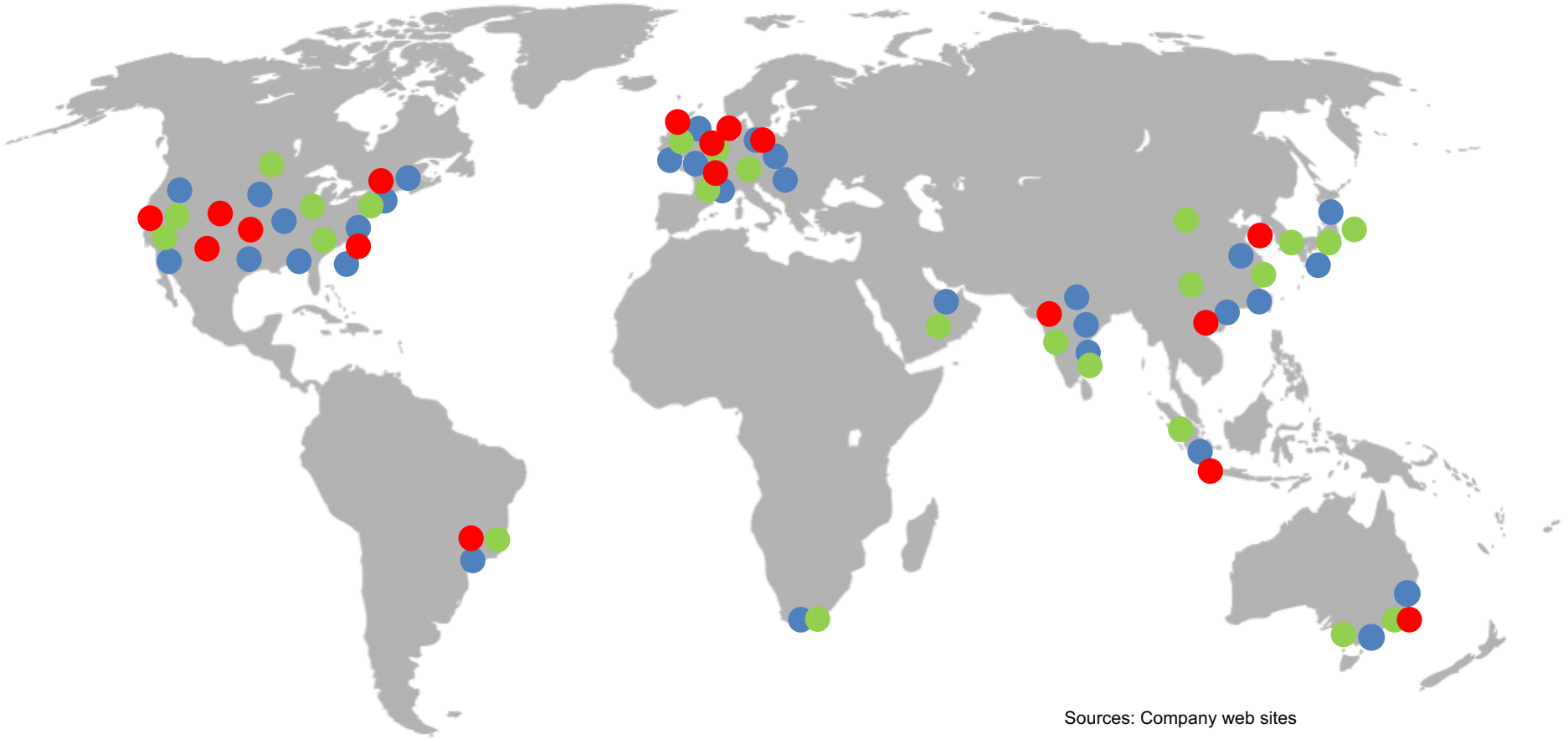
# The State of Public Cloud

## A Global Infrastructure

amazon web services 24 in 2021

Microsoft Azure 54 in 2021

24 in 2021

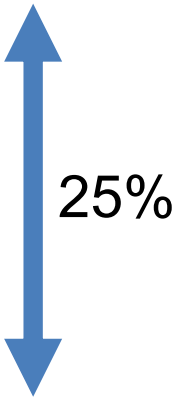


Sources: Company web sites

# The State of Public Cloud

## Focus on Deploying Massive, Centralized Datacenters

| | Zones (2016=>2017) | Servers (Millions) | New Zones in 2018 |
|---|---|---|---|
| amazon web services | 38=>50 | 2-4 | 12 |
| Microsoft Azure | 30=>36 | 1-3 | 8 |
| | 31=>44 | 1-3 | 12 |
| IBM | 39 | 1-3 | 8 |




Each zone can have 1 or more datacenters
Most datacenters house between 50K and 80K servers

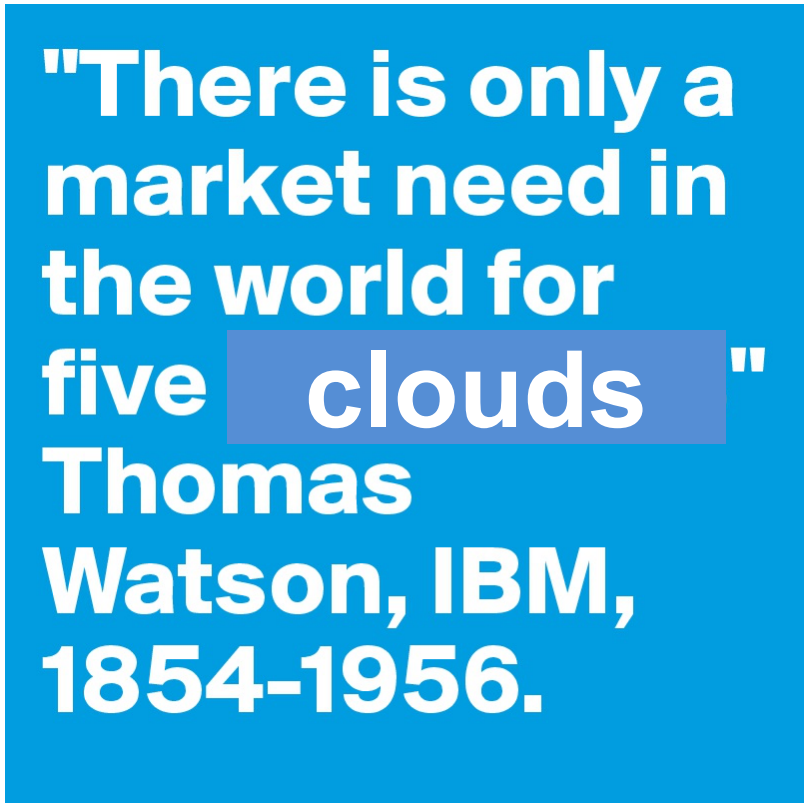
The 4 big players house approx. 10 million servers

This number is estimated to grow 25% annually (probably much higher if we consider their 50% annual growth in revenues)

Sources:
- Company web sites
- http://datacenterfrontier.com/inside-amazon-cloud-computing-infrastructure
- http://www.datacenterknowledge.com/archives/2013/07/15/ballmer-microsoft-has-1-million-servers/

# The State of Public Cloud

## Centralization…After All, Was Thomas Watson Right?



# The Need for Private Clouds

## Centralized Public Cloud Does Not Fit All

Not so fast?

Main barriers to adoption

1. Cost
2. Performance
3. Security

# The Need for Private Clouds

## You Can Do It Cheaper

Cost

1. You may have sufficient scale to be able to do it cheaper
2. Public cloud is becoming more expensive
3. Cost benefit strongly depends on variability

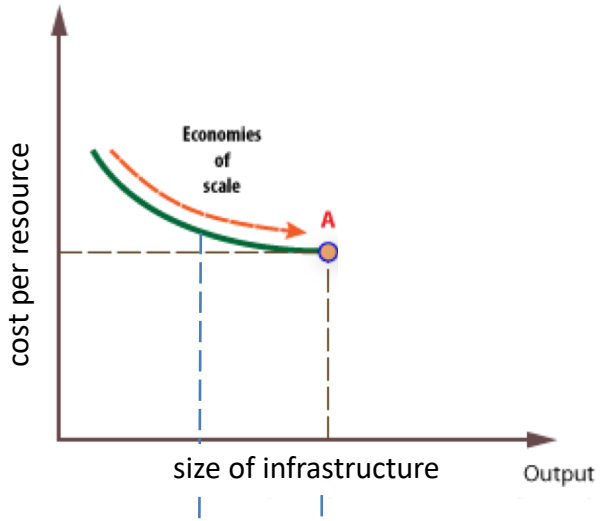
# The Need for Private Clouds

## Many Datacenters Do Cheaper Themselves

Public cloud is a high-volume business
Larger data centers can in principle deploy computational resources at significantly lower cost than smaller ones

Economies of Scale

- Infrastructure innovation
- Technical economies
- Purchasing economies
- Savings
- …




Diseconomies of Scale

- Communication overheads
- Coordination
- Complex management
- Complex operation
- …

Huge data centers are only marginally less expensive than medium sized data centers

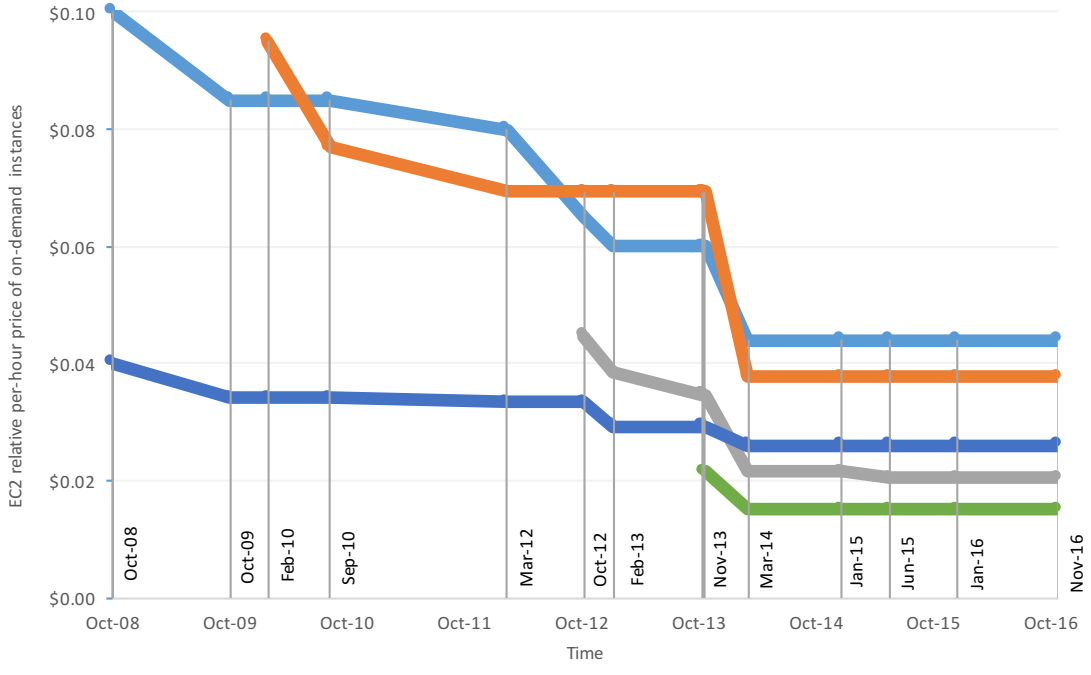
Point where economies of scale advantages go down (50K servers)

Many datacenters have sufficient scale to be able to do it cheaper themselves

Sources:
- http://datacenterfrontier.com/inside-amazon-cloud-computing-infrastructure/
- http://economicsonline.co.uk/Business_economics/Economies_of_scale.html

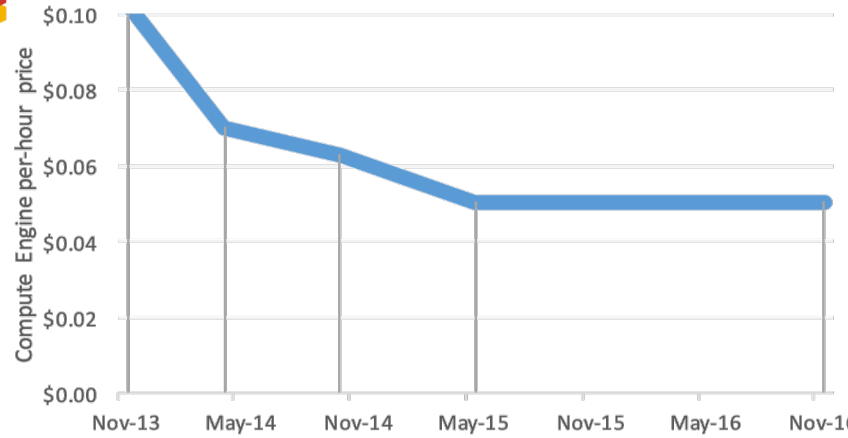
# The Need for Private Clouds

## Public Cloud is Becoming more Expensive




10% annual drop

Public Cloud pricing is not tracking Moore's Law with hardware cost dropping 30% annually




21% annual drop

DOE centers have historically delivered average improvements in computing capability of 40%-80% per year with relatively flat budgets

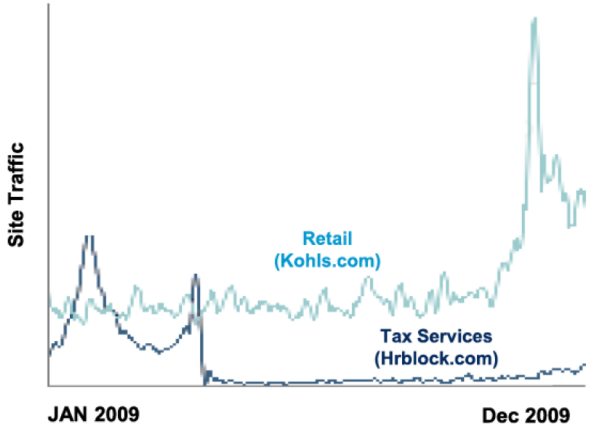
Sources:

- Companies web sites
- http://science.energy.gov/~/media/ascr/pdf/program-documents/docs/Magellan_Final_Report.pd

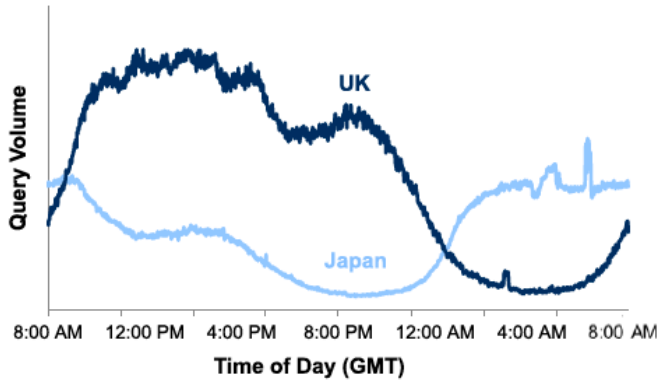
# The Need for Private Clouds

## Cost Benefit Strongly Depends on Variability

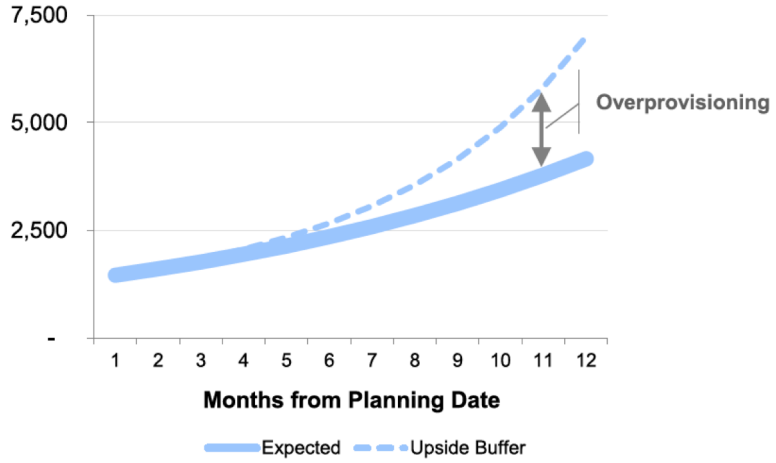
- Industry-specific patterns




- Time of day patterns




- Uncertain grown patterns



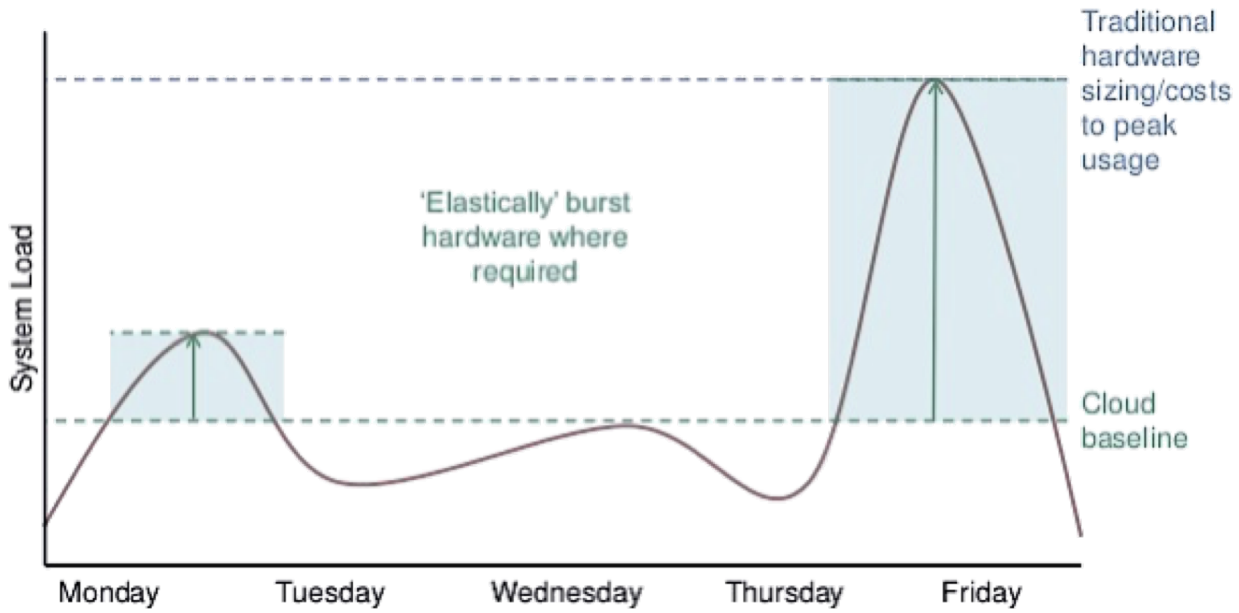

*Source: The Economics of the Cloud, Microsoft*

# The Need for Private Clouds

## Cost Benefit Strongly Depends on Variability

### Hybrid cloud offers the optimal cost solution

- Workloads that are highly variable over time or with uncertain growth pattern
- Public cloud can be as much as four times more expensive than traditional data center, mostly for traditional legacy apps running 24/7 at peak on redundant architecture
- There is always a level of utilization at which private cloud becomes more cost-effective than public cloud




Sources: http://www.rightscale.com/blog/cloud-industry-insights/cloud-computing-trends-2015-state-cloud-survey

# The Need for Private Clouds

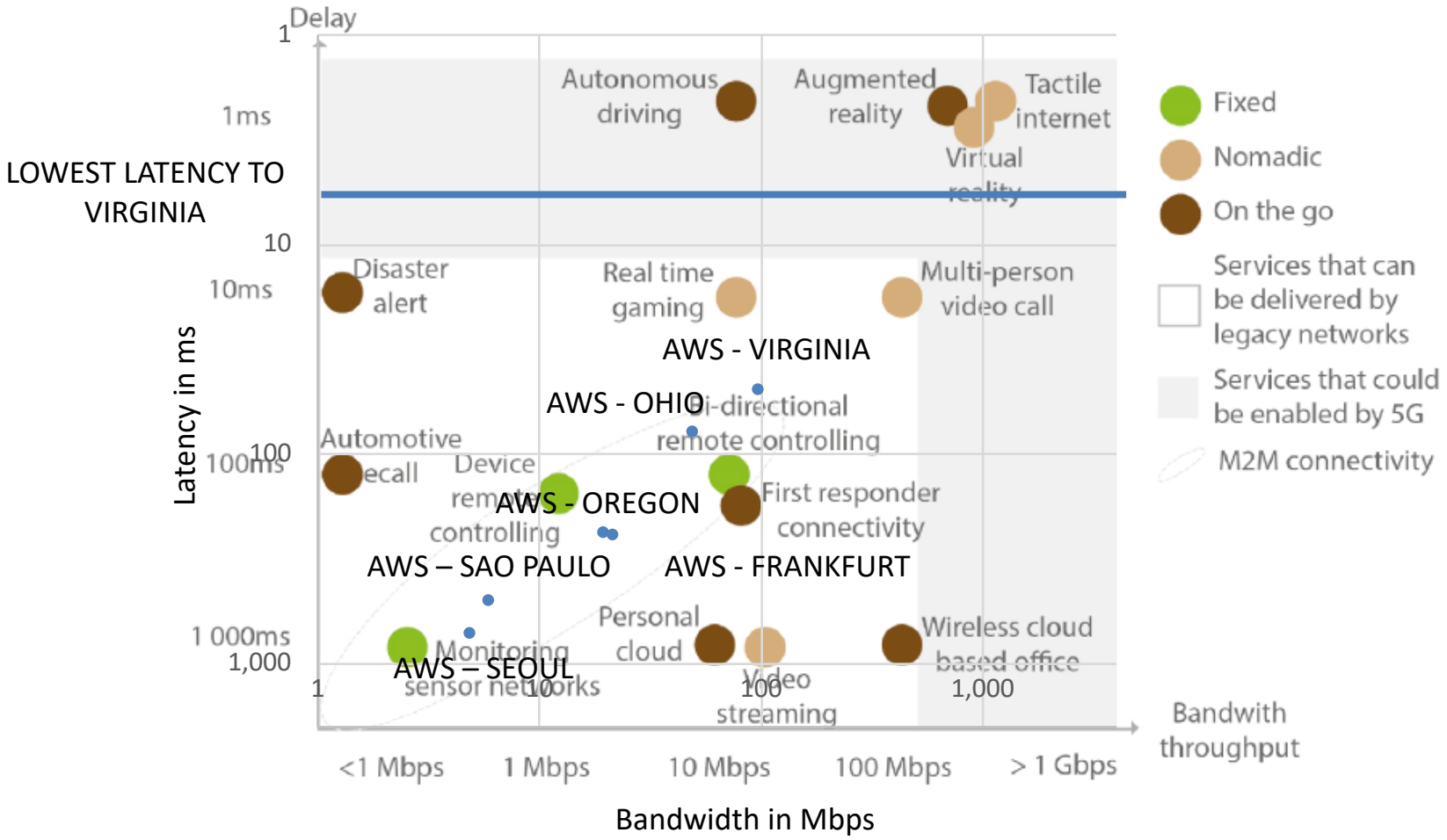
## Not All Applications are Public Cloud-friendly

**Performance needs?**

1. **Proximity to users or on-premises DC**
2. **Special high performance infrastructure**

# The Need for Private Clouds

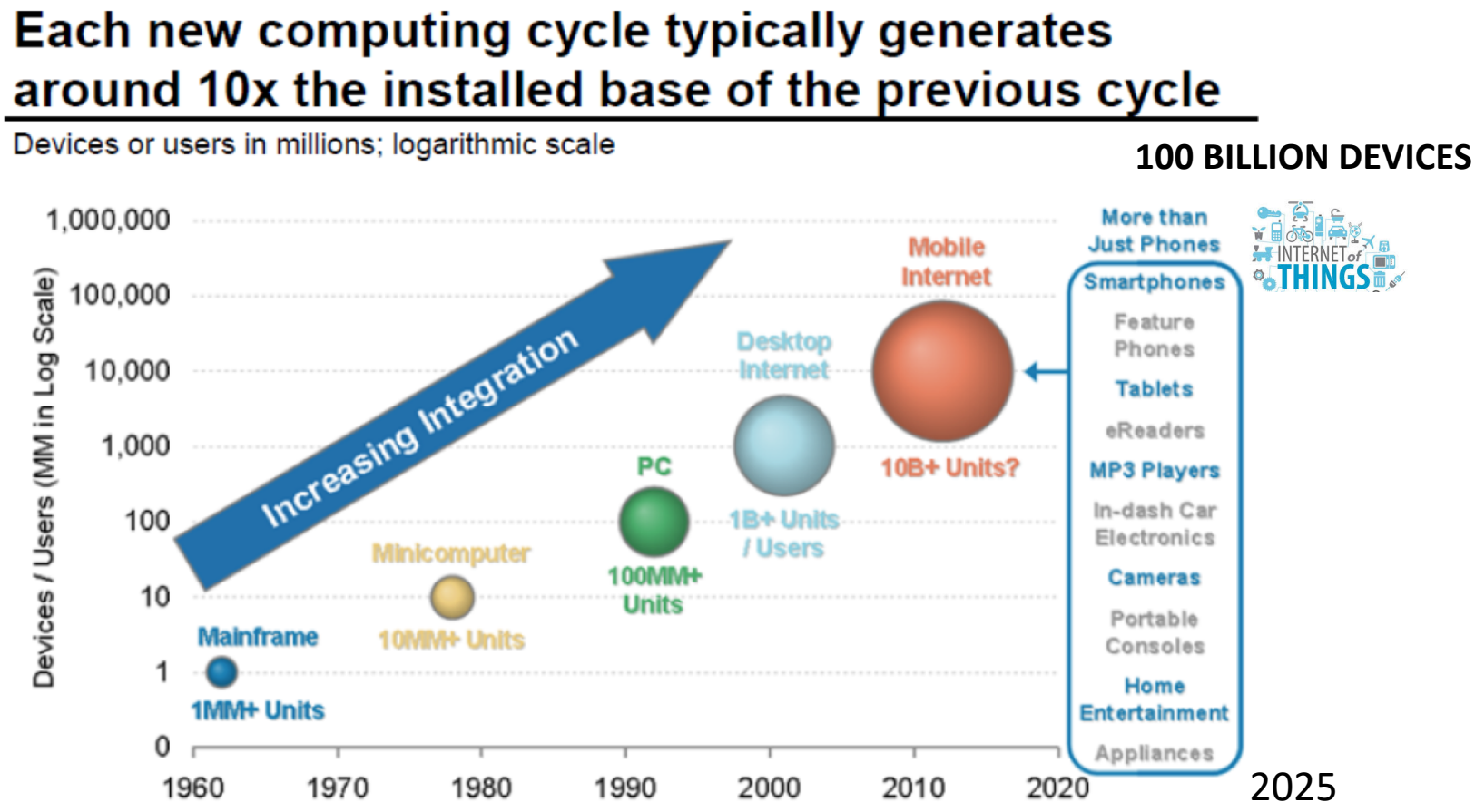
## When Proximity Matters



# The Need for Private Clouds

## When Proximity Matters

Example: Distributed Big Data Processing



# The Need for Private Clouds

## Performance

Example: High Performance Computing

| Rank | System | Cores | Rmax (TFlop/s) | Rpeak (TFlop/s) | Power (kW) |
|---|---|---|---|---|---|
| 1 | **Supercomputer Fugaku** - Supercomputer Fugaku, A64FX 48C 2.2GHz, Tofu interconnect D, Fujitsu<br>RIKEN Center for Computational Science<br>Japan | 7,630,848 | 442,010.0 | 537,212.0 | 29,899 |

442 PFlops with 7.6M cores and 158K servers

One AWS datacenter has in the range of 40K-80K servers

But with different networking, CPU and I/O trade-offs more oriented to the efficient execution of tightly coupled application

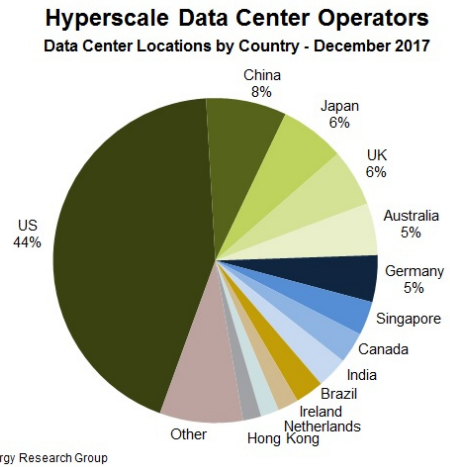
# The Need for Private Clouds

## Public Cloud Is a Fraction of IT Infrastructure Market

Public Cloud represents 20% of Internet computing power
10 million blade servers shipped annually
50 million servers in operation in 2017 (not including private cloud)

Public Cloud represents a tiny fraction of existing data centers
3 million data centers only in the U.S. in 2013
Number datacenters growing, peaking at 8.6 M worldwide in 2017

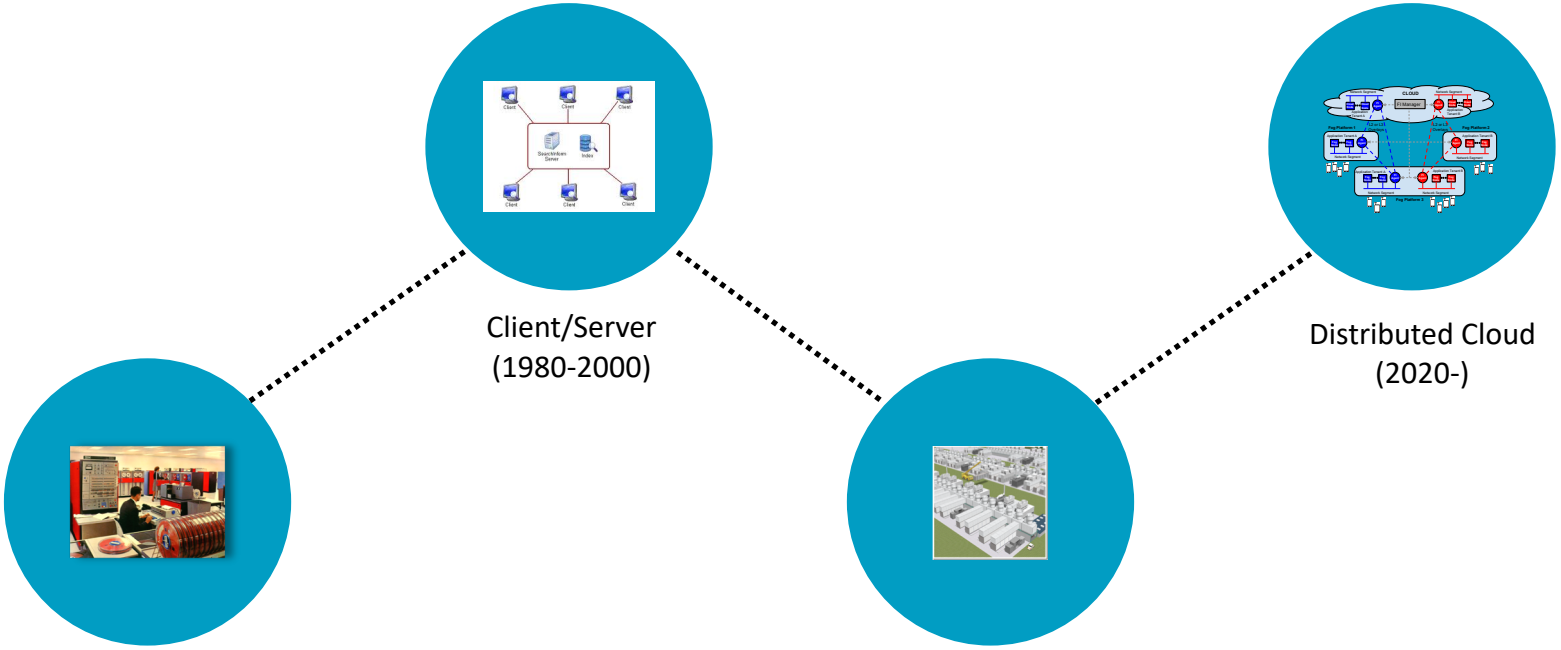
Public Cloud represents 50% of existing hyperscale DCs
There are now close to 400 Hyper-Scale Data Centers in the world




Sources:
- http://www.gartner.com/newsroom/id/3530117
- http://energy.gov/eere/articles/10-facts-know-about-data-centers
- http://worldstopdatacenters.com/idc-number-of-data-centers-will-peak-at-8-6-million-in-2017-then-begin-to-decline/
- http://www.datacenterknowledge.com/cloud/research-there-are-now-close-400-hyper-scale-data-centers-world

# Evolution Toward a Distributed Cloud

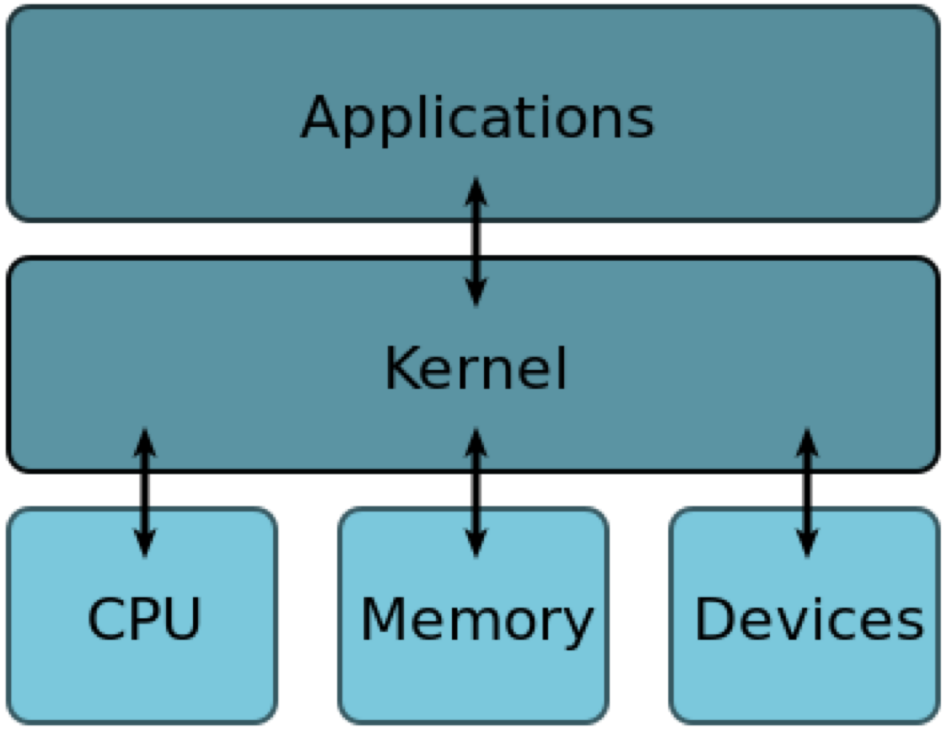
## Back to the Future



# The Anatomy of the Cloud

## What is an Operating System?

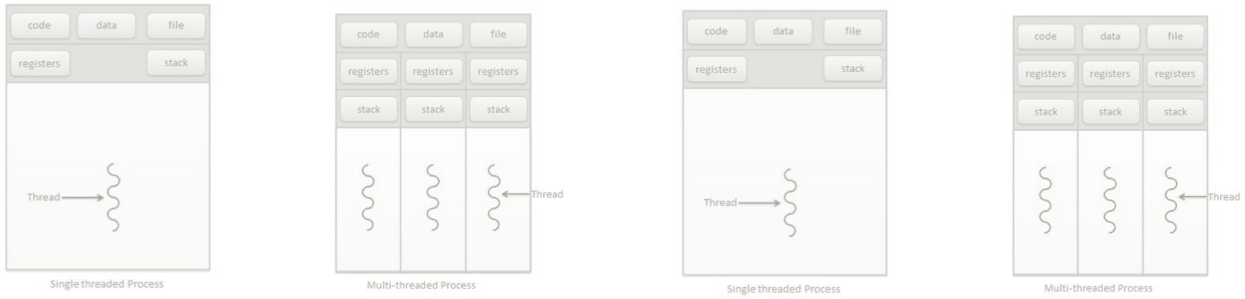
"An operating system (OS) is system software that manages computer hardware and software resources and provides common services for computer programs" (source: Wikipedia)



# The Anatomy of the Cloud

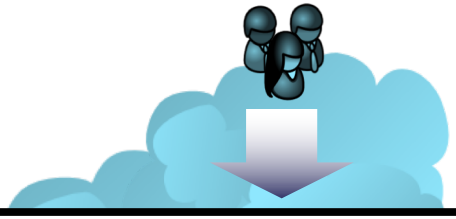
## What is an Operating System?

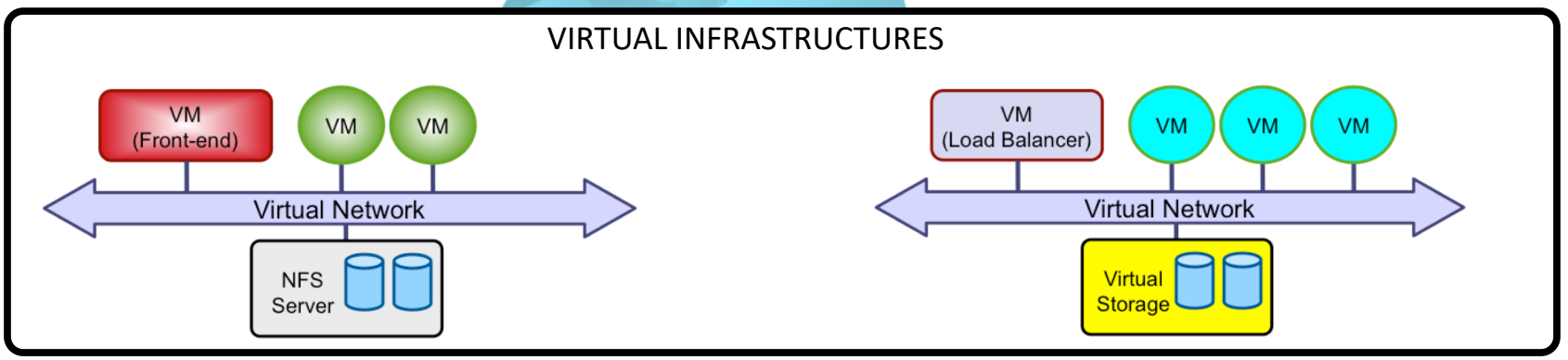
PROCESSES

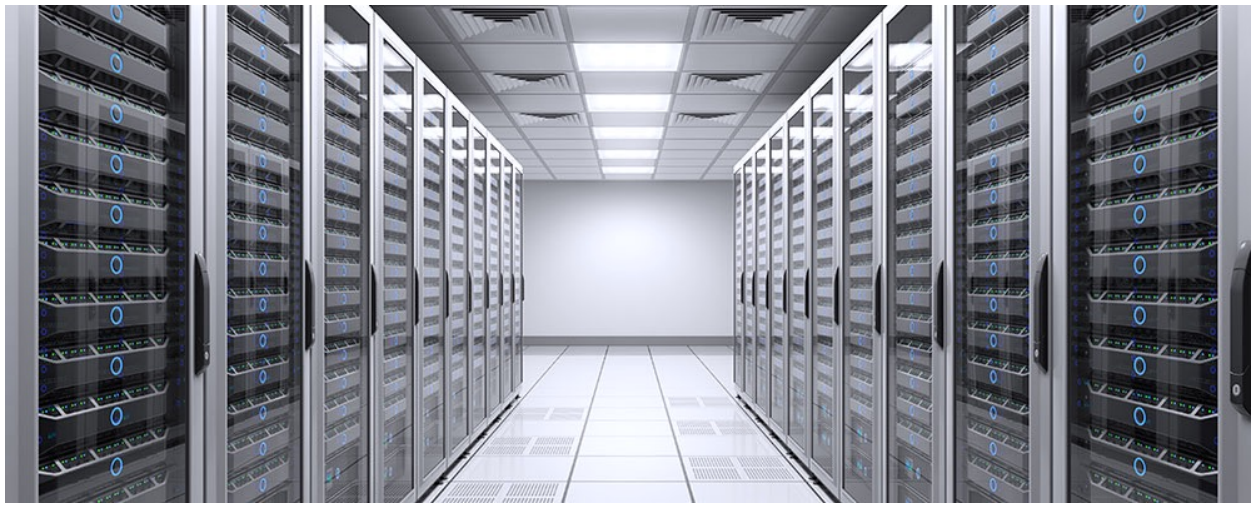



# The Anatomy of the Cloud

## What is a Cloud Management Platform?

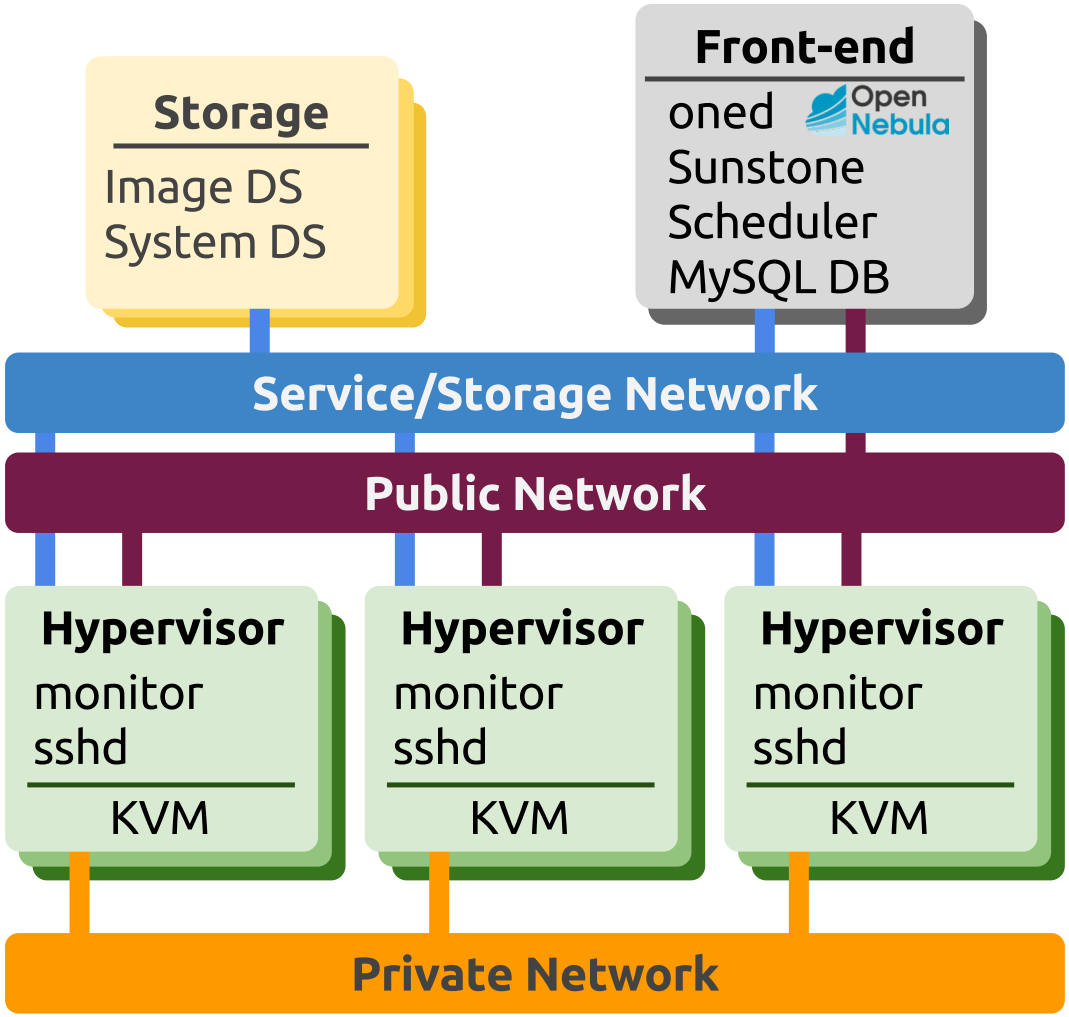




# The Anatomy of the Cloud

## The Internals of a Cloud Instance



# Reading Assignments / Open Discussion

## Potential of Cloud for Scientific Applications

J. Riley, J. Noss, W. Dillingham, J. Cuff, I. M. Llorente, *"A High-Availability Cloud for Research Computing"*,
IEEE Computer, Volume: 50, Issue: 6, 2017.

What are the basic components of the architecture?

Why a private cloud?

What is data centric cloud computing?

# Next Steps

- Get ready for **next lecture**:

  A.4. Application parallelism

# Questions

## Practical Aspects of Cloud Computing