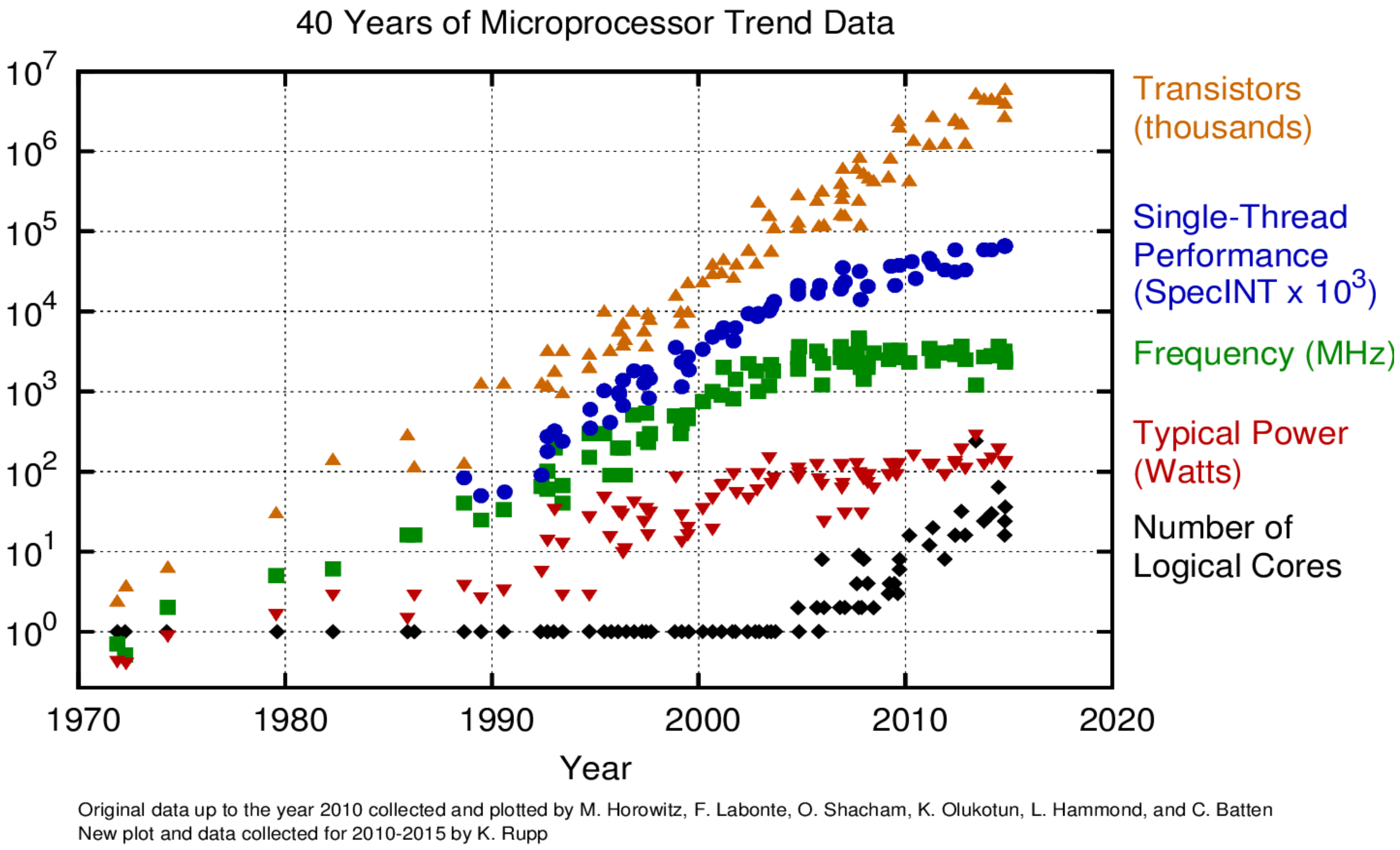
Energy-efficient Computing and Data Centers

Lecture 12

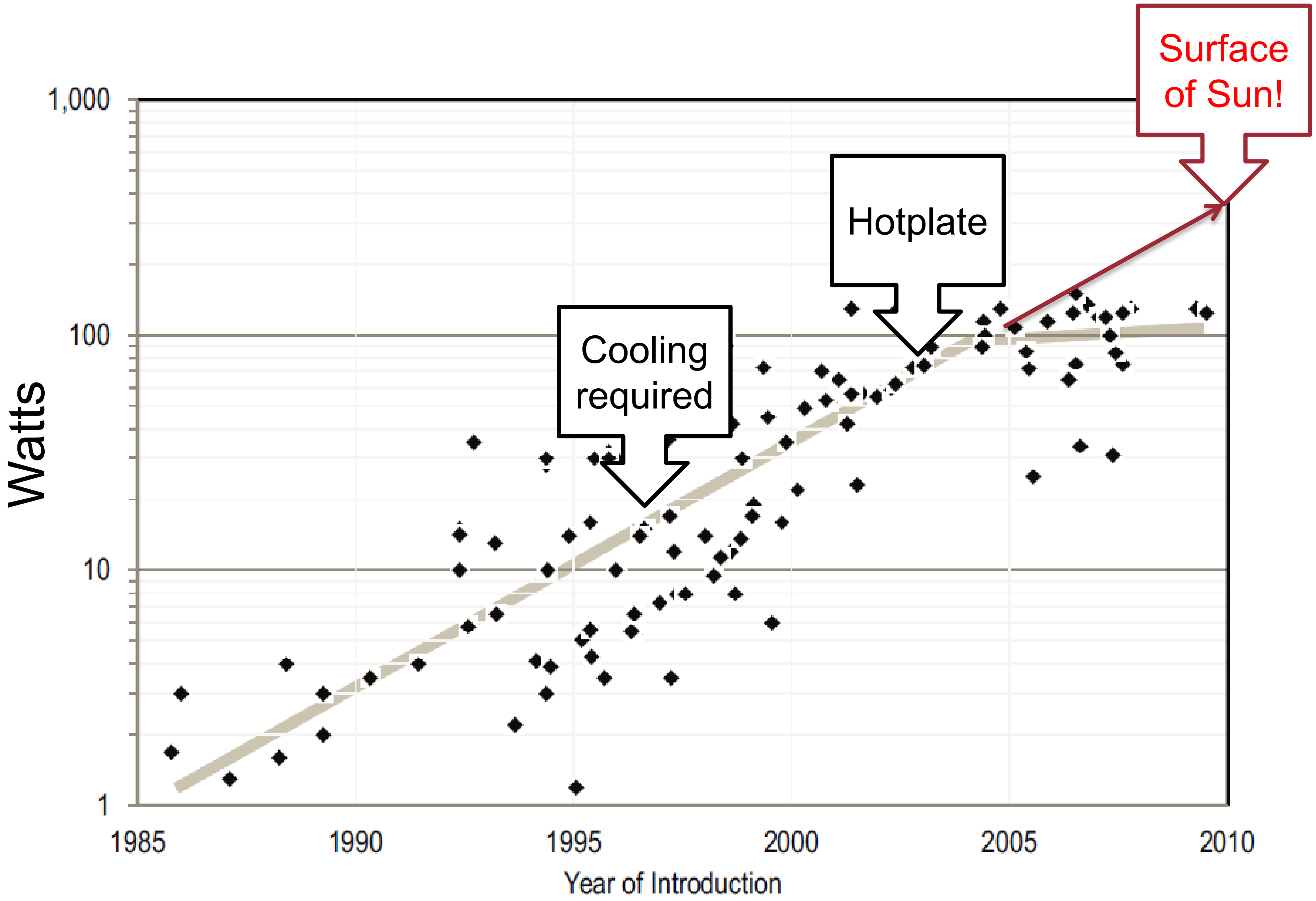
Outline

- Energy-efficient Computing
  - Mobile computing
    - How ARM does it
    - Heterogeneous computing
  - Enterprise computing
    - Energy-efficient data center
      - How Google does it
    - Cloud computing
      - How Amazon does it

Microprocessor Clock Frequency over time (1970-2020)



Microprocessor Power Dissipation over time (1985-2010)



Where Does this Matter the Most?

Mobile Computing

Enterprise Computing

Trends in Mobile Computing

- Energy-efficiency
  - Decrease power consumption in the hardware components
  - Increase performance
- Increase capacity of the battery
- ARM processing systems
  - ARM Cortex-A53 found in phones & tablets
  - (Arguably) Designed for power-efficiency
  - Closing in x64 systems in terms of performance
  - Highly customizable architecture

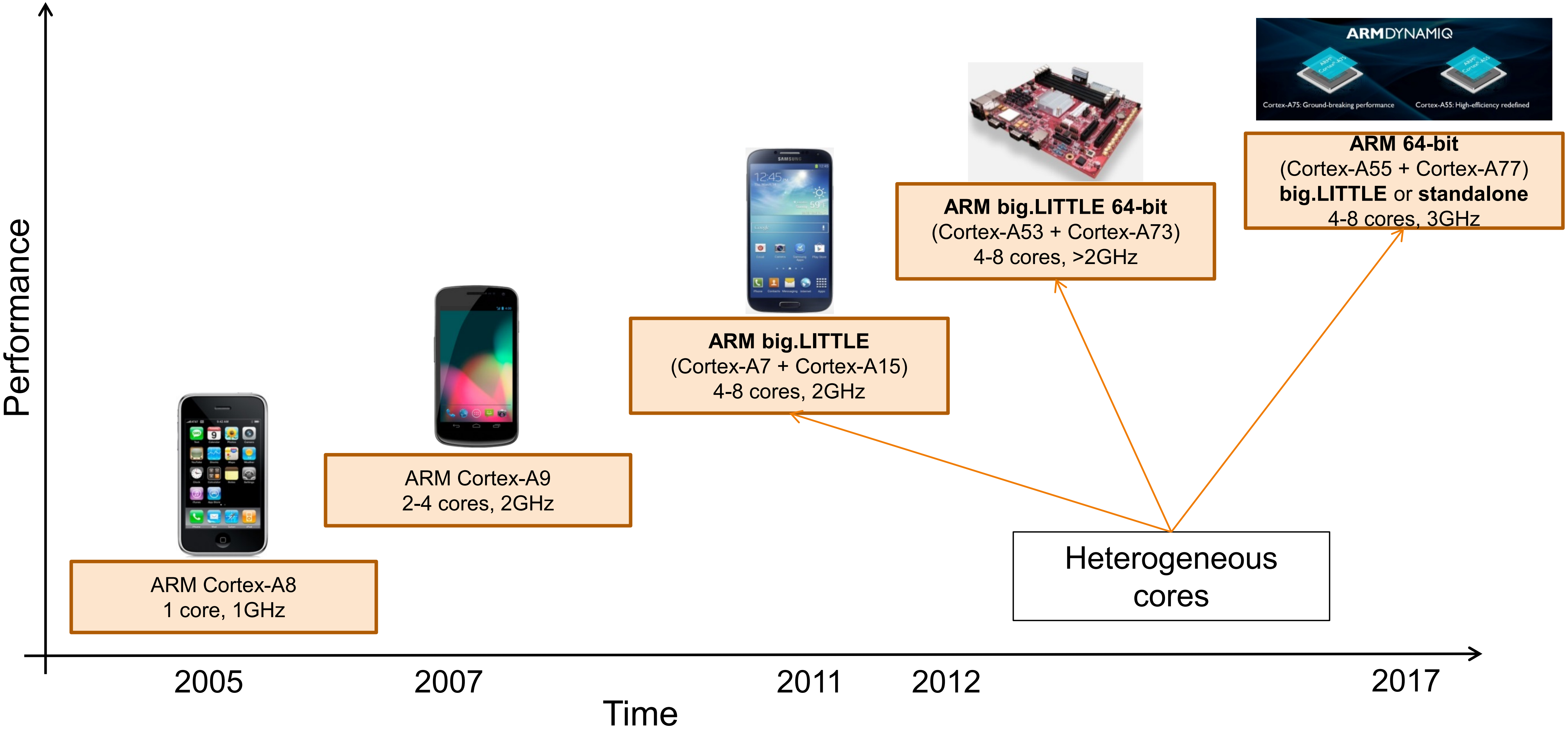
Background on Processing using ARM

- ARM = Advanced RISC Machines (1990)
  - Survived Intel/AMD's domination years
  - Major target: embedded processors

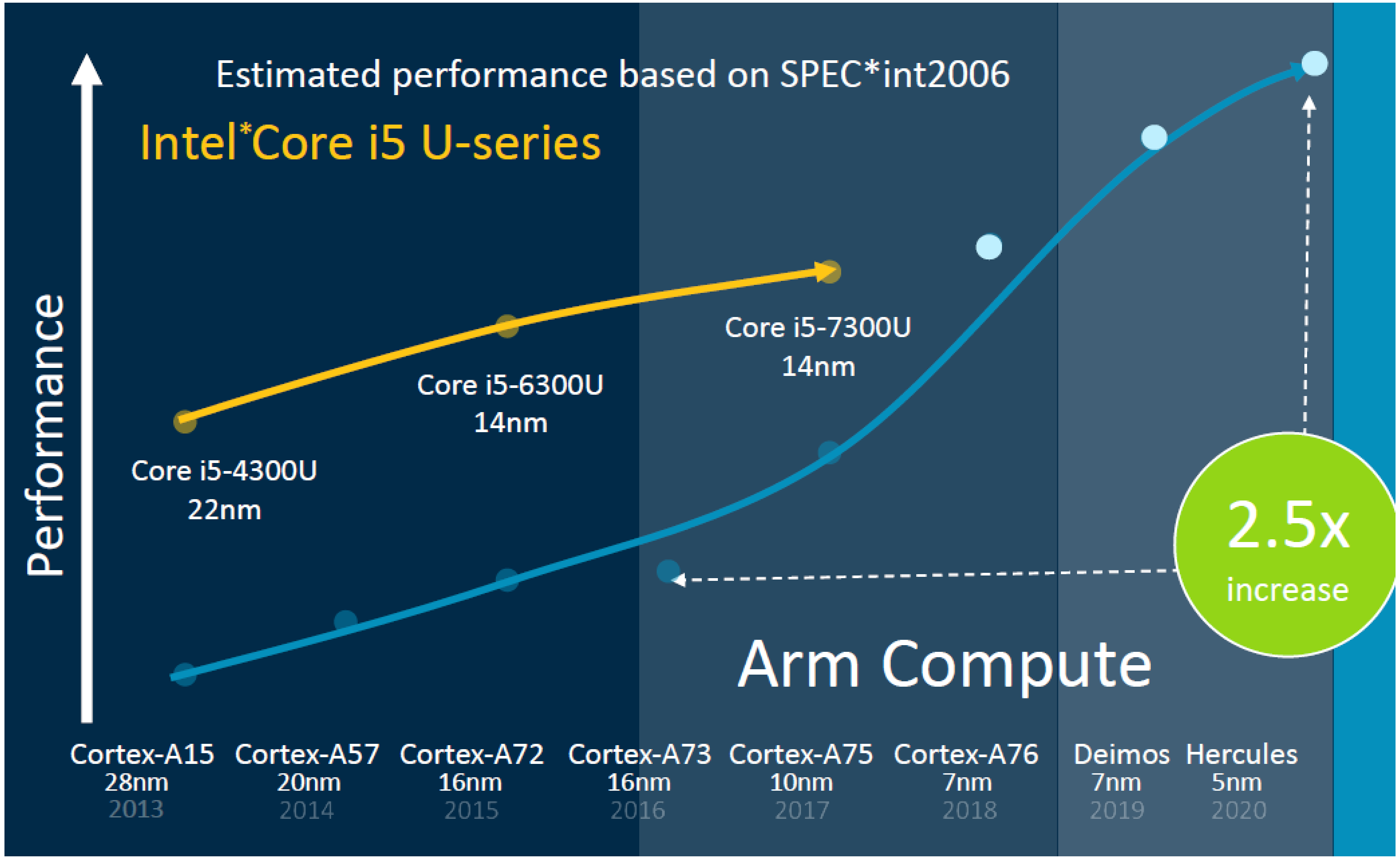
- Only produces IP, does not manufacture
  - Apple, Qualcomm, Samsung, TI, ST-Ericsson, AMD, Intel, …

- Designs many types of processors
  - ARM Cortex-A is the flagship family for mobile devices

ARM Cortex-A Evolution

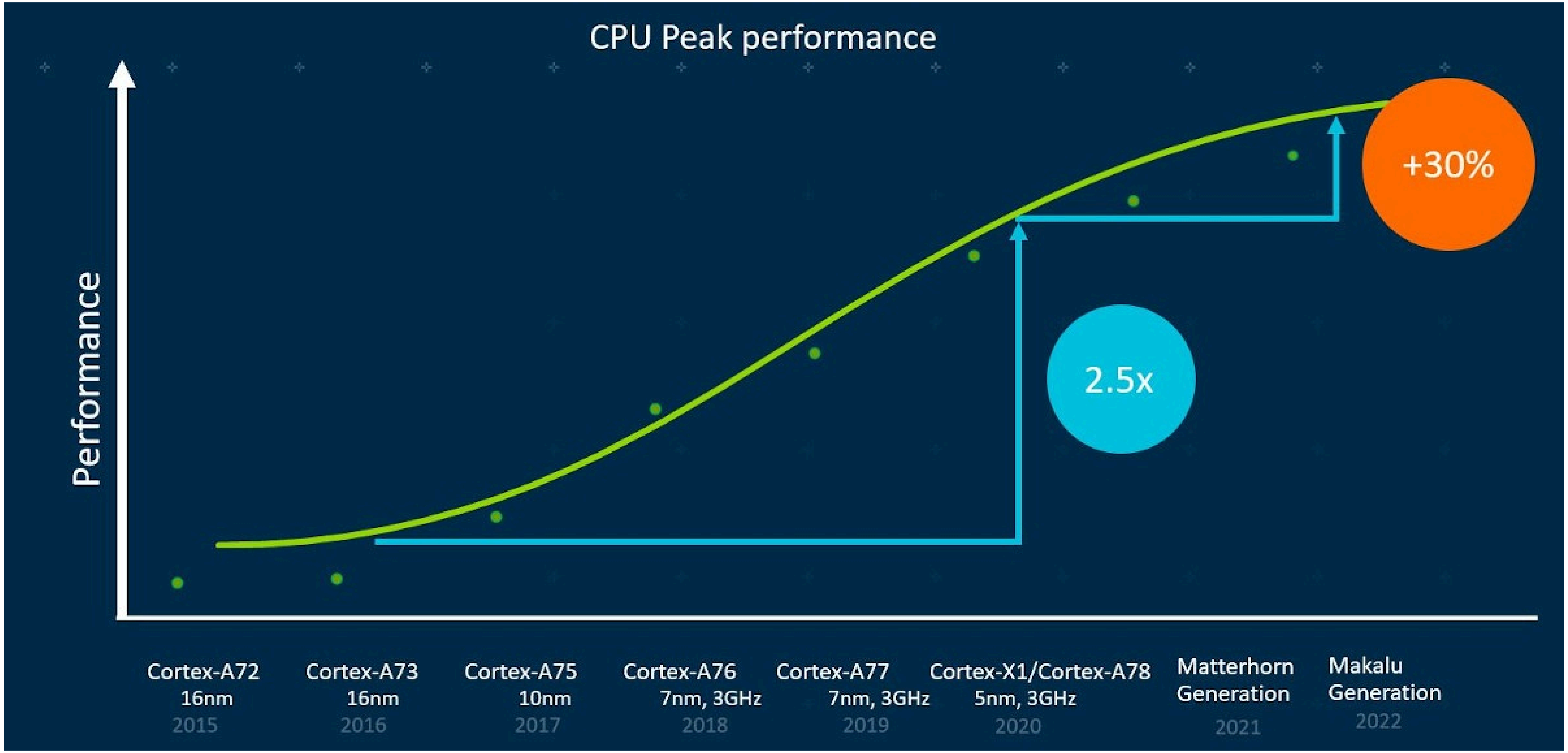


Performance Roadmap - 2018



Measured estimates on SPECint*_base2006 (SPECspeed* Integer component of SPEC CPU* 2006) on Intel Core i5-7300U, Core i5-6300U, Corei5-4300U, Arm single-c
estimates using specific computer systems, software, components, operations, and functions and changes to any of these factors will cause the results to vary.

Performance Roadmap - 2020



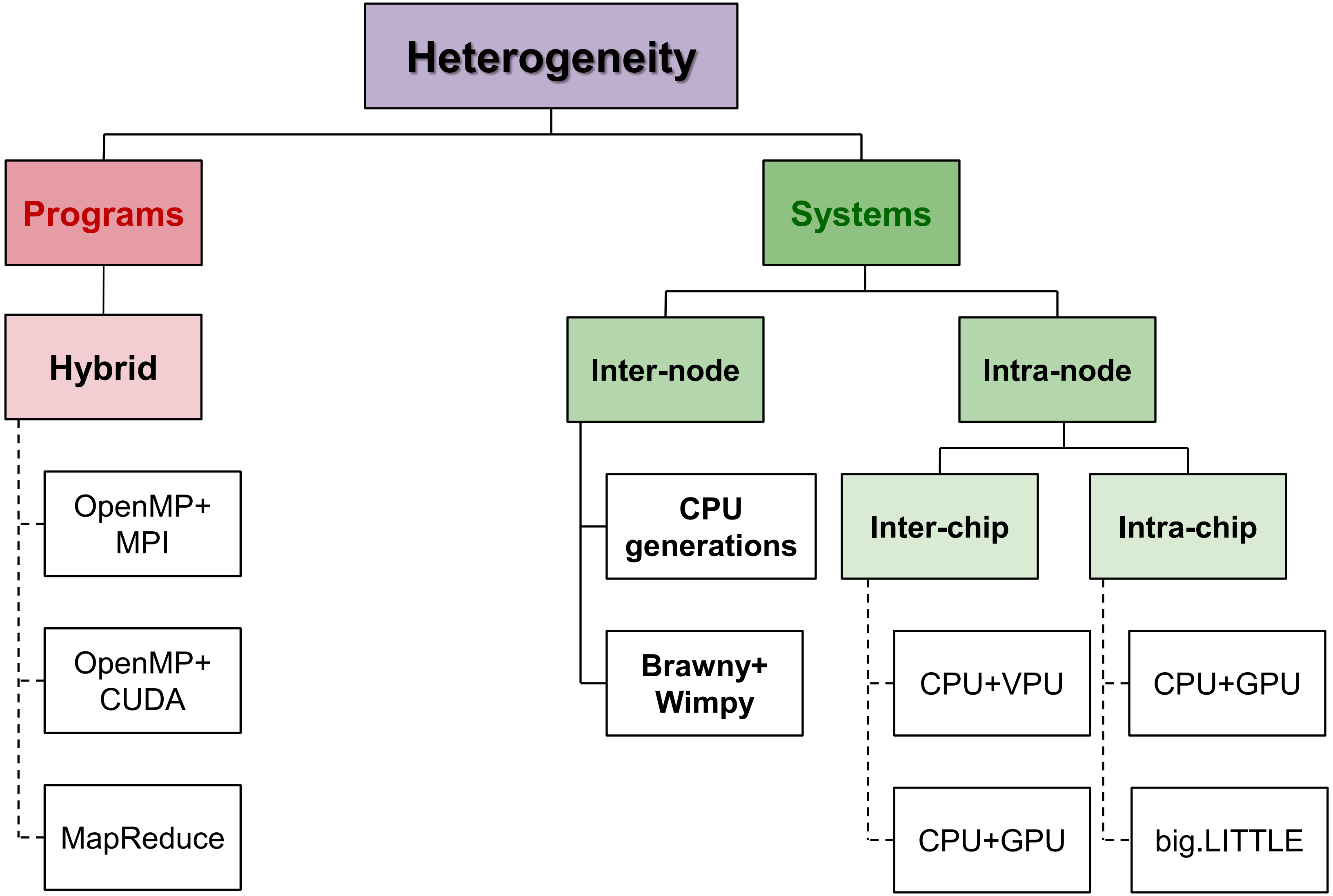
ARM Cortex-A Family

- Similarities to general purpose Intel/AMD servers
  - Processors cores + RAM + I/O interfaces + misc. peripherals
  - Cores use similar execution model (pipelines)
  - Memory hierarchy (L1 + L2 + RAM)
  - Uses Virtual Memory
  - Uses commodity Linux
    - Supports all programming models available on Linux (C/C++ POSIX, Java, etc.)
    - Most server software is available (Apache, MySQL, PHP, Java SDK, MPI etc.)
    - Porting is trivial
  - Hardware virtualization, hardware-level security

ARM Cortex-A Family

- Differences from general purpose Intel/AMD servers
  - RISC Instruction-Set Architecture
  - Heterogeneous cores (big.LITTLE)
    - Fast cores / slow cores
  - Lower instruction-level parallelism exploitation
  - Smaller L1/L2 caches
  - Less RAM (0.5 GB – 4GB), and typically non-upgradable
    - Depends on configuration
  - Lower main-memory bandwidth
  - Simpler I/O interfaces (USB2.0/USB 3.0/SATA2)
    - Next generations: PCI-Express, SATA 3

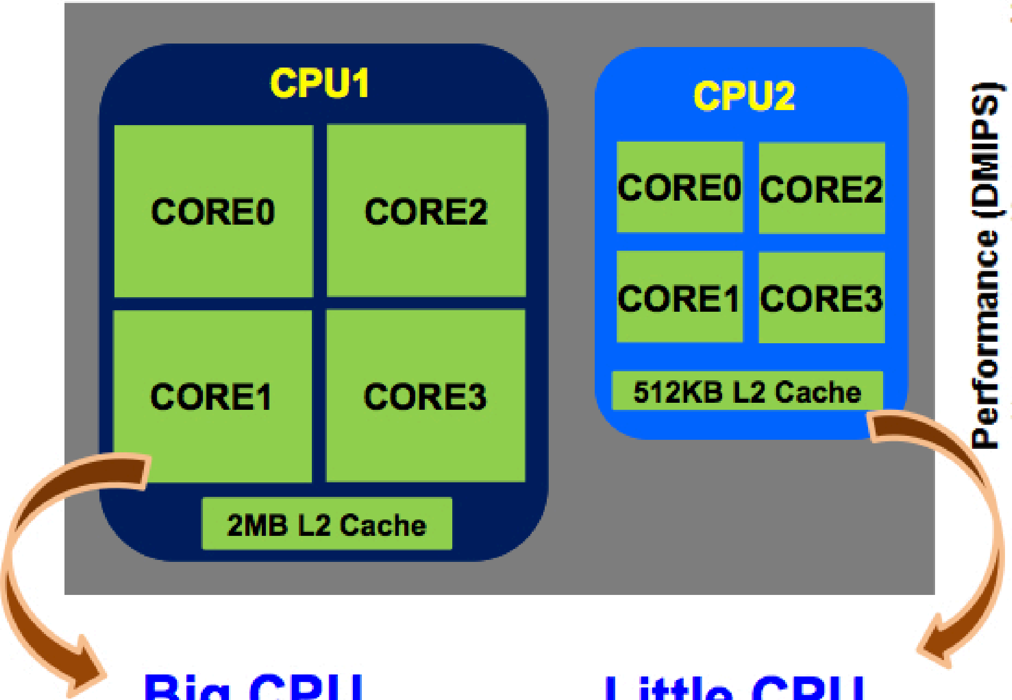
Heterogeneous Computing

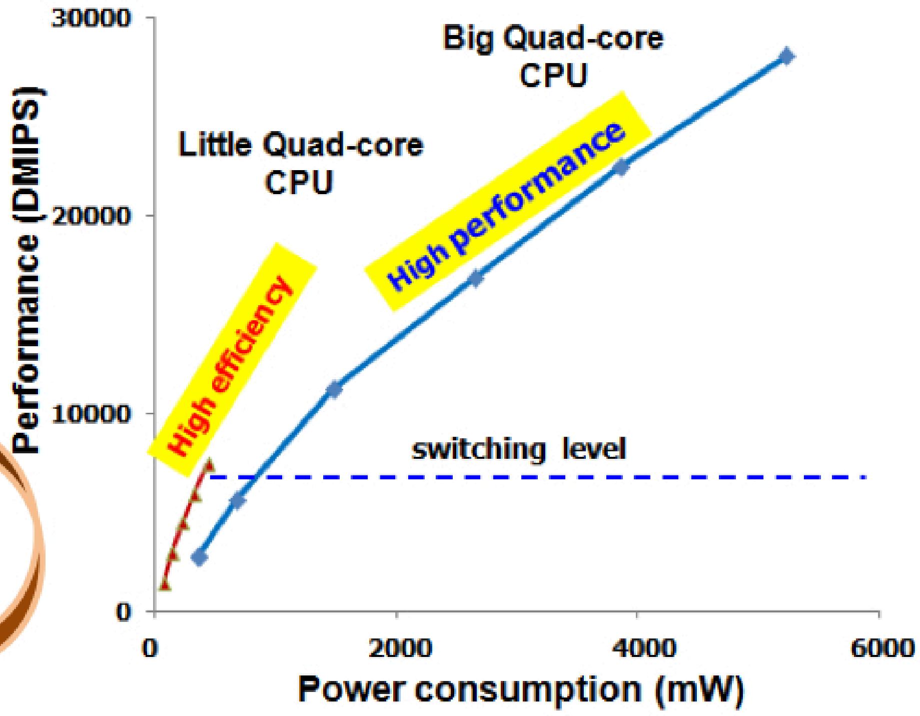


Heterogeneous Computing Platforms

- Processors: brawny vs wimpy, big-little, accelerators, …
- Supercomputer: accelerators
- Data centers: different server generations
- Cloud computing: heterogeneous resources with different price-performance

ARM big.LITTLE – a Low-power Approach



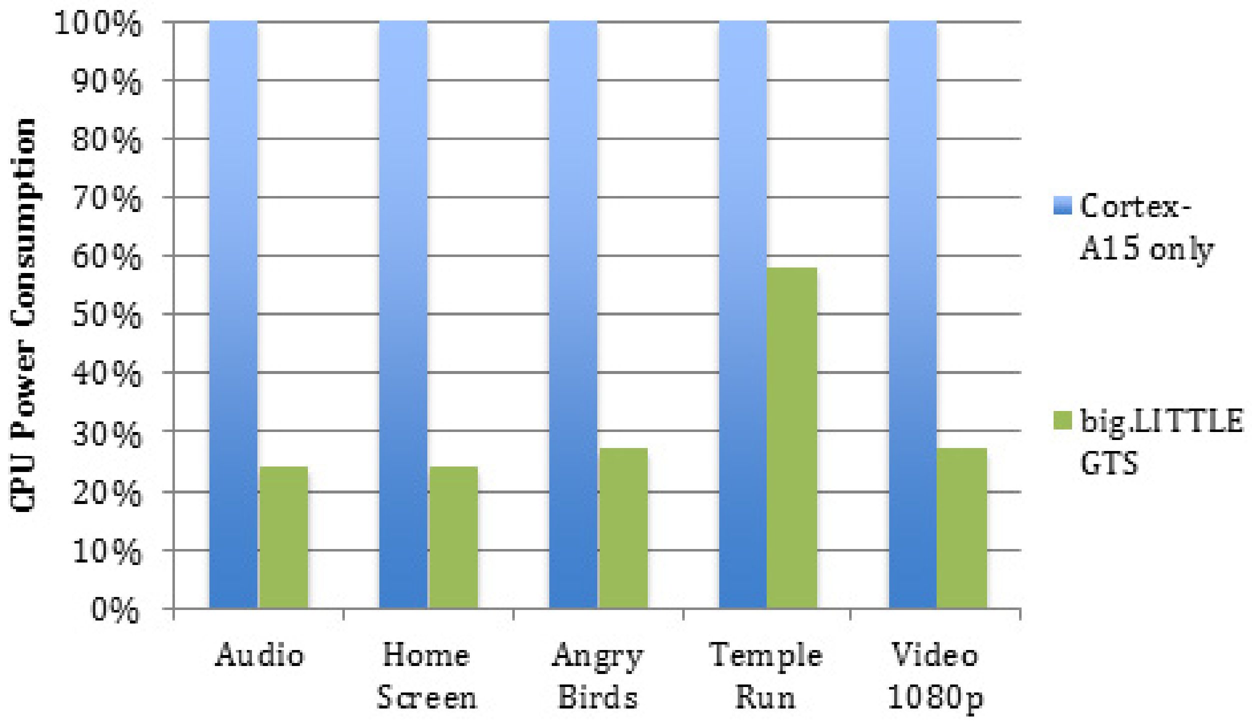


Big CPU
High performance for compute intensive applications

Little CPU
Low power execution of majority workloads

Source: ARM presentation at ISSCC 2013

Power-performance of big.LITTLE



Source: http://hexus.net

Observation: Heterogeneity is more power-efficient.

Reduce Energy Consumption

- Move less data
  - Reduce data transfers to/from memory
  - Exploit locality
  - Use compression
- Use specialized processing
  - Compute less – avoid parallelization if it leads to more work
  - CPU-like cores + throughput optimized cores (GPU-like)
  - FPGAs – programmable hardware

Challenges

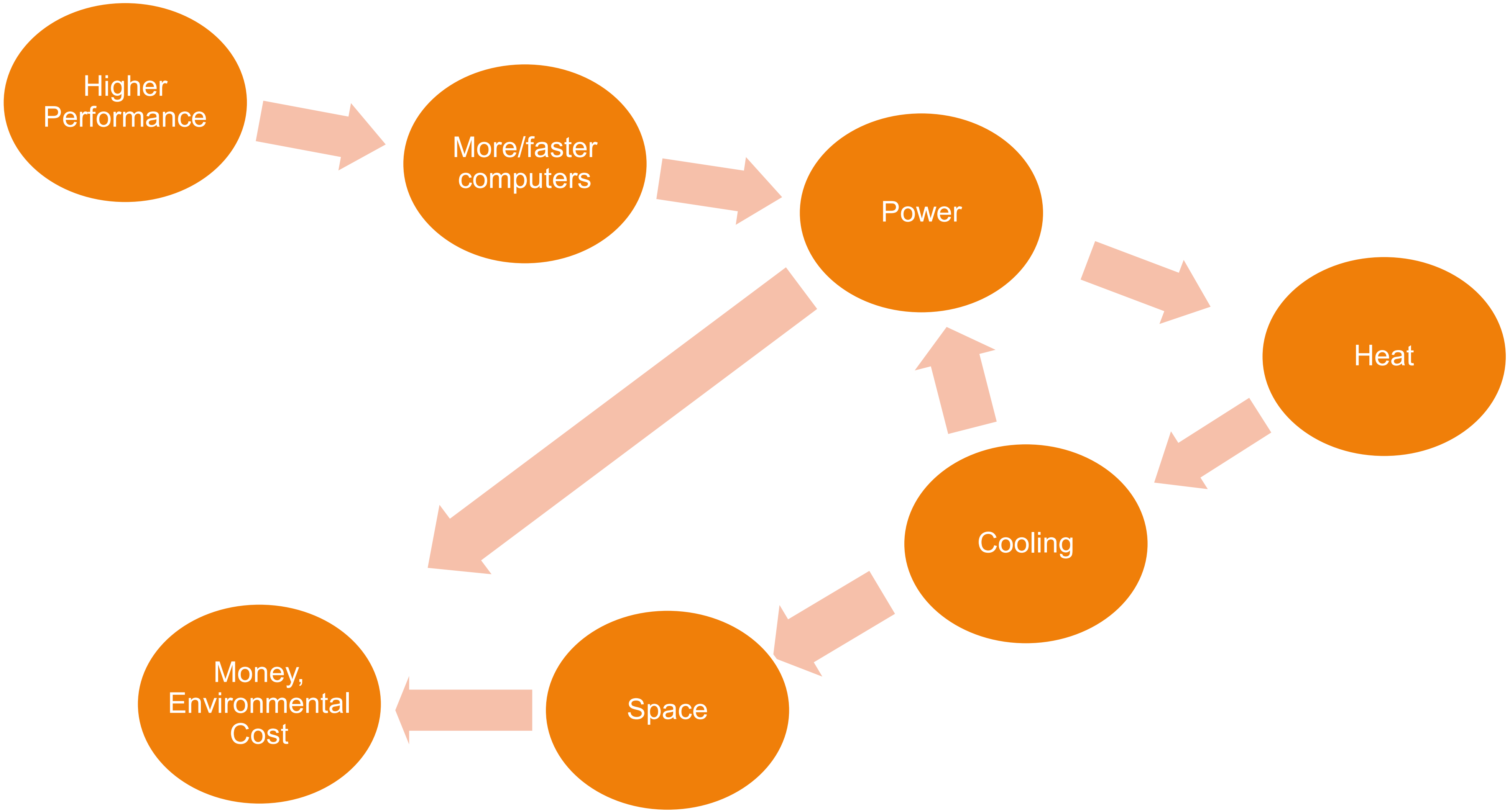
- Usage of heterogeneity to improve energy-efficiency
  - How do we use heterogeneity to reduce power consumption while maintaining good performance?
    - Different ISAs, different performance levels
- Usage of low-power (energy-efficient) nodes
  - Can we replace traditional servers with low-power nodes?
  - What is an energy-efficient configuration for executing a parallel application?
  - Scheduling problem is complex on heterogeneous systems
- Using the resources effectively is pushed to programmer
  - Write efficient, portable code for heterogeneous architectures.

Energy-efficiency: Where Does this Matter the Most?

Mobile Computing

Enterprise Computing

Costs of Computing



Trends in Enterprise Computing

- IT infrastructure is transferred to data centers (cloud)
  - Easy access from any location/machine
  - Increase security

- Design energy-efficient servers/data centers
  - Some Top500 supercomputers use more power than Clementi!

Power Consumption Trends in TOP500

- Power consumption
  - Summit, US ~120PFLOPS @ 10MW
    - Comparable to the consumption of 17000 HDB units
  - Sunway TaihuLight, Wuxi, China ~100PFLOPS @ 15MW
- If power consumption grows linearly with the performance
  - Hit a “Power Wall”

GREEN500 – 2019

Rank	TOP500 Rank	System	Cores	Rmax (TFlop/s)	Power (kW)	Power Efficiency (GFlops/watts)
1	469	**DGX SaturnV Volta** - NVIDIA DGX-1 Volta36, Xeon E5-2698v4 20C 2.2GHz, Infiniband EDR, NVIDIA Tesla V100 , Nvidia NVIDIA Corporation United States	22,440	1,070.0	97	15.113
2	1	**Summit** - IBM Power System AC922, IBM POWER9 22C 3.07GHz, NVIDIA Volta GV100, Dual-rail Mellanox EDR Infiniband , IBM DOE/SC/Oak Ridge National Laboratory United States	2,414,592	148,600.0	10,096	14.719
3	8	**AI Bridging Cloud Infrastructure (ABCI)** - PRIMERGY CX2570 M4, Xeon Gold 6148 20C 2.4GHz, NVIDIA Tesla V100 SXM2, Infiniband EDR , Fujitsu National Institute of Advanced Industrial Science and Technology (AIST) Japan	391,680	19,880.0	1,649	14.423
4	393	**MareNostrum P9 CTE** - IBM Power System AC922, IBM POWER9 22C 3.1GHz, Dual-rail Mellanox EDR Infiniband, NVIDIA Tesla V100 , IBM Barcelona Supercomputing Center Spain	18,360	1,145.0	81	14.131
5	25	**TSUBAME3.0** - SGI ICE XA, IP139-SXM2, Xeon E5-2680v4 14C 2.4GHz, Intel Omni-Path, NVIDIA Tesla P100 SXM2 , HPE GSIC Center, Tokyo Institute of Technology Japan	135,828	8,125.0	792	13.704

GREEN500 - 2020

Rank	TOP500 Rank	System	Cores	Rmax (TFlop/s)	Power (kW)	Power Efficiency (GFlops/watts)
1	393	**MN-3** - MN-Core Server, Xeon 8260M 24C 2.4GHz, MN-Core, RoCEv2/MN-Core DirectConnect, Preferred Networks Preferred Networks Japan	2,080	1,621.1	77	21.108
2	7	**Selene** - DGX A100 SuperPOD, AMD EPYC 7742 64C 2.25GHz, NVIDIA A100, Mellanox HDR Infiniband, Nvidia NVIDIA Corporation United States	272,800	27,580.0	1,344	20.518
3	468	**NA-1** - ZettaScaler-2.2, Xeon D-1571 16C 1.3GHz, Infiniband EDR, PEZY-SC2 700Mhz, PEZY Computing / Exascaler Inc. PEZY Computing K.K. Japan	1,271,040	1,303.2	80	18.433
4	204	**A64FX prototype** - Fujitsu A64FX, Fujitsu A64FX 48C 2GHz, Tofu interconnect D, Fujitsu Fujitsu Numazu Plant Japan	36,864	1,999.5	118	16.876
5	26	**AiMOS** - IBM Power System AC922, IBM POWER9 20C 3.45GHz, NVIDIA Volta GV100, Dual-rail Mellanox EDR Infiniband, IBM Rensselaer Polytechnic Institute Center for Computational Innovations (CCI) United States	130,000	8,339.0	512	16.285

Data Centers - Factories of the digital age [1]

- Construction costs around \$20 billion a year worldwide [2]
- Eat up more than 2 percent of the world's electricity
- Emit roughly as much CO2 as the airline industry [3]
- Exact locations are many times unknown
- You are unaware in which data center your data is processed

[1] https://e360.yale.edu/features/energy-hogs-can-huge-data-centers-be-made-more-efficient

[2] https://datacenterfrontier.com/customer-focus-on-energy-efficiency-driving-green-data-center-market/

[3] https://data-economy.com/data-centers-going-green-to-reduce-a-carbon-footprint-larger-than-the-airline-industry/

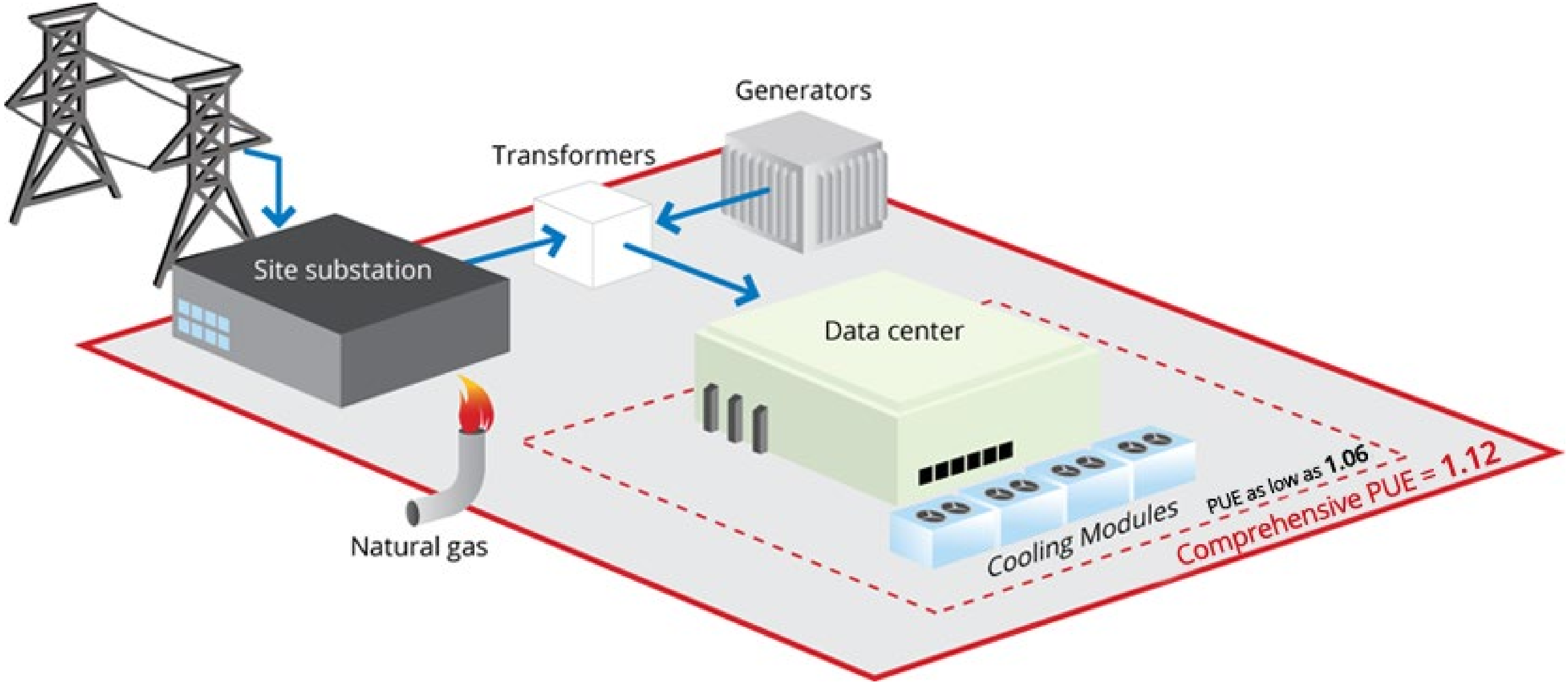
Data Center Efficiency

- Storing, moving, processing, and analyzing data require energy
- Double the energy consumption to keep the building from overheating
- A typical Google search
  - as much energy as illuminating a 60-watt light bulb for 17 seconds
  - is responsible for emitting 0.2 grams of CO2

Efforts Worldwide

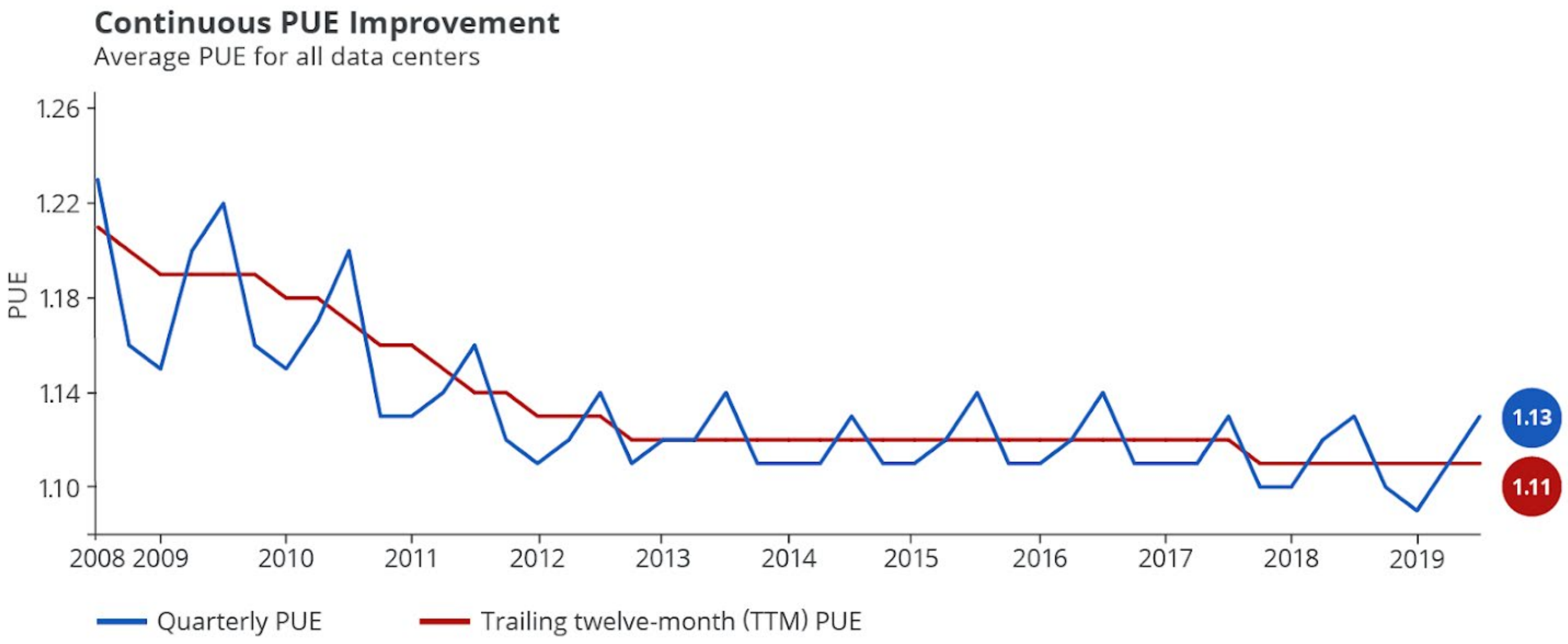
- Use renewable energy
  - Build hubs in Finland, Denmark, Sweden
- Ramping up energy efficiency
  - Measure the energy used for computation and cooling
- Power Use Effectiveness (PUE) - measure of energy efficiency in data centers
  - Index divides the total amount of energy used in the center by the amount needed to run the processors themselves
  - 2008: PUE in US was estimated to be 2.5
  - 2017: PUE in EU is estimated to be 1.8
  - Google: PUE of 1.10 (Singapore PUE is 1.14)

Data center at Google



Energy Efficiency at Google [1]

1. Continuously measure efficiency
   - Computation (IT) energy
   - Overhead: cooling and conversions



[1] https://www.google.com/about/datacenters/efficiency/internal/

Energy Efficiency at Google

2. Building custom, highly-efficient servers
   - High-performance computers that run all the time
   - Minimize power loss in AC/DC conversions
     - Back-up batteries directly on the server racks
   - Remove unnecessary parts
     - Remove peripheral connectors and video cards
   - Strategic positioning on racks
   - Decrease fan speed to optimize cooling
3. Extending the equipment lifecycle
   - Reuse components, resell components

Energy Efficiency at Google

4. Controlling the temperature of the equipment
   - Raise temperature to 26 C in data center
   - Use thermal modeling
     - Avoid hot spots
     - Hot/cold aisles
     - Manage airflow
       - Plastic curtains, blanking panels
5. Cooling with water instead of chillers
   - Evaporative cooling, sea water, recycle water

Another type of data center

CLOUD COMPUTING

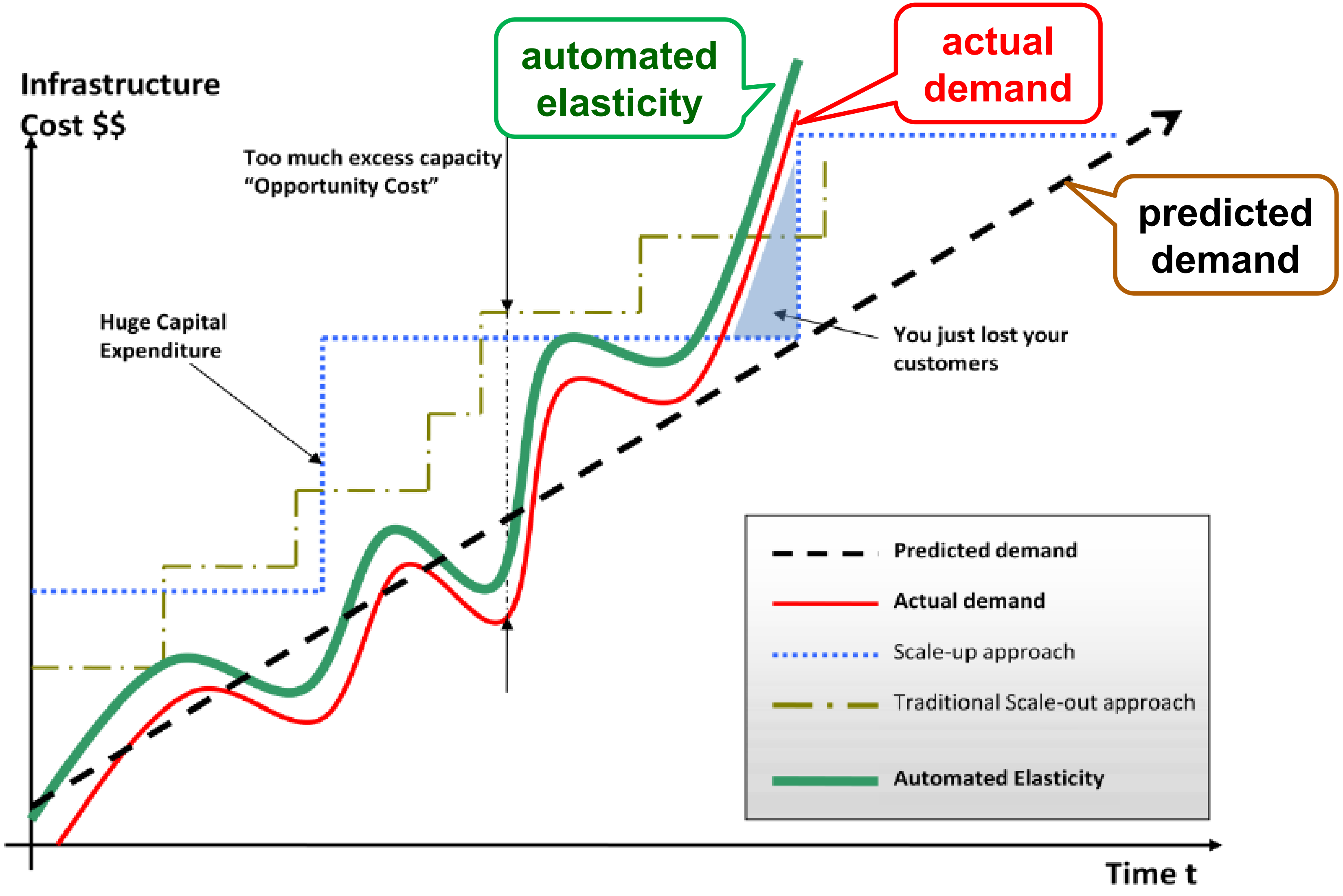
What is Cloud Computing?

"… a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of **configurable computing resources** that can be **rapidly provisioned** and released **with minimal management effort or service provider interaction**."

US National Institute of Standards & Technology (NIST2011)

- Abstraction of underlying applications, information, content and resources
  - ➔ allows resources to be provided and consumed in a more elastic manner and on demand

Why Cloud Computing?



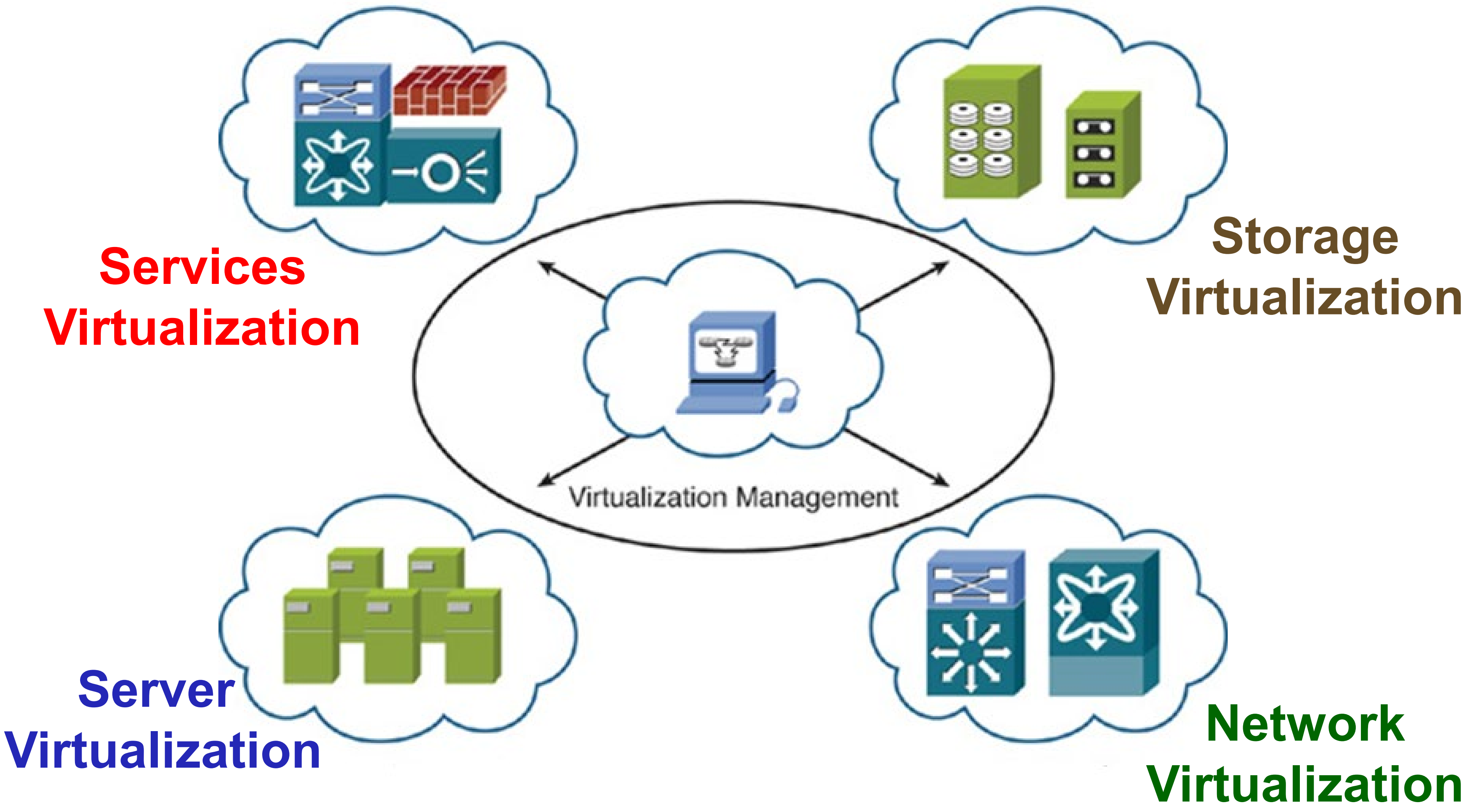
adapted from http://aws.amazon.com/economics

Virtualization

- Creation of a **virtual version** of something, such as an operating system, computing devices (server), storage devices or network devices

- Access resource without being concerned with **where** or **how** the resource is physically located or managed

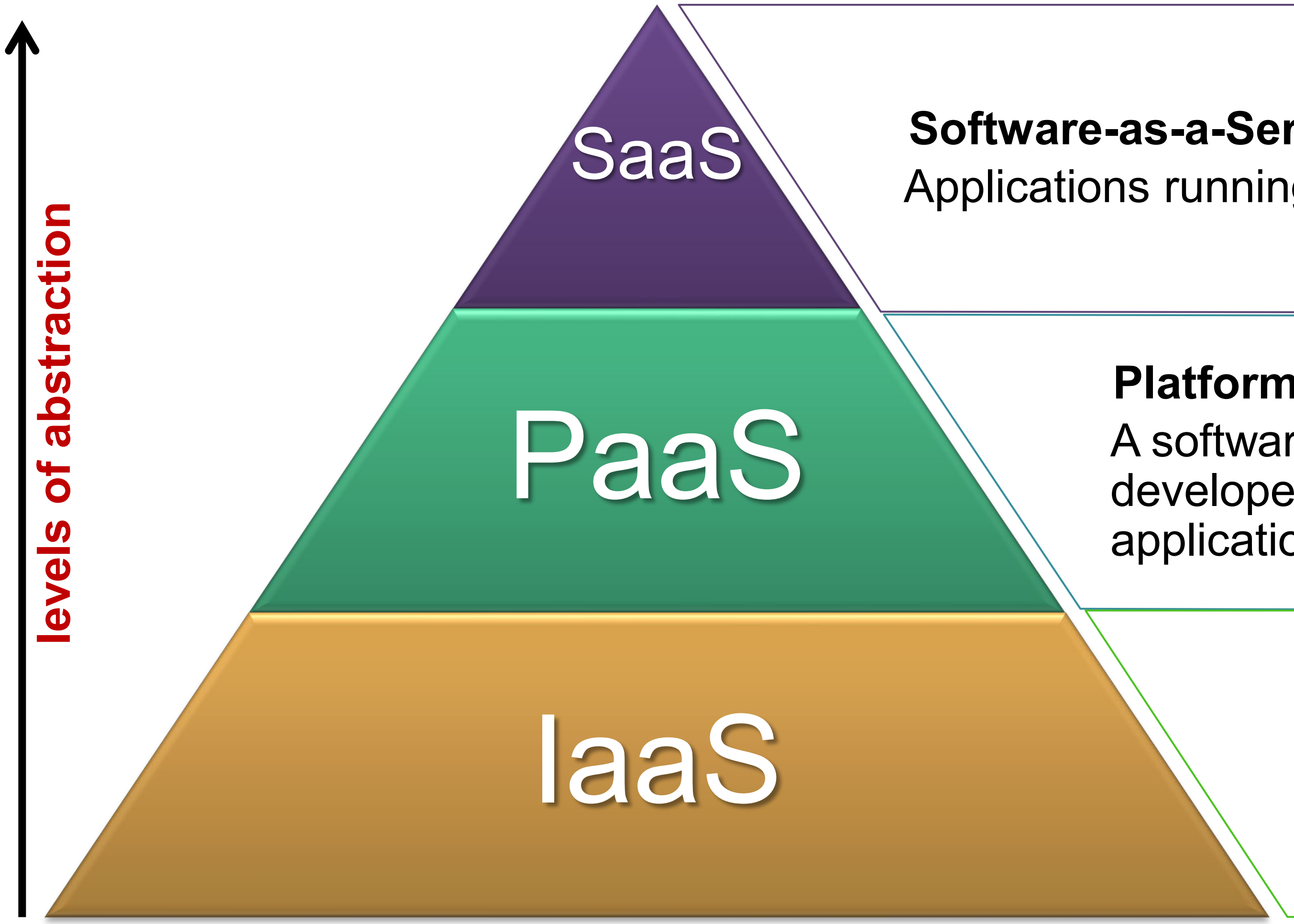
Types of Virtualization



Cloud Services Models

Service Description	Characteristic	Example
Software as a Service (**SaaS**)	Customer accesses the provider's application running on the provider's servers	*Google apps, Amazon AWS*
Platform as a Service (**PaaS**)	Customer runs its applications on the provider's server using the provider's operating systems and tools	*Google's app engine, Salesforce.com, Oracle Cloud Platform, Cloud Foundry*
Infrastructure as a Service (**IaaS**)	Customer users, administers, and controls its operating system and applications running on provider's servers.	*Amazon EC2, Cloud.com, Eucalyptus, IBM Cloud, Nimbus, OpenNebula*

Cloud Service (Delivery) Models

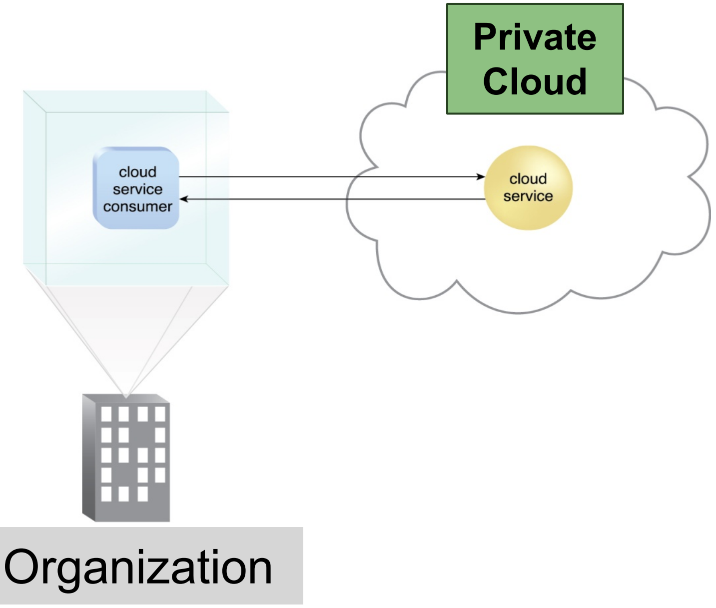


Software-as-a-Service
Applications running on browsers

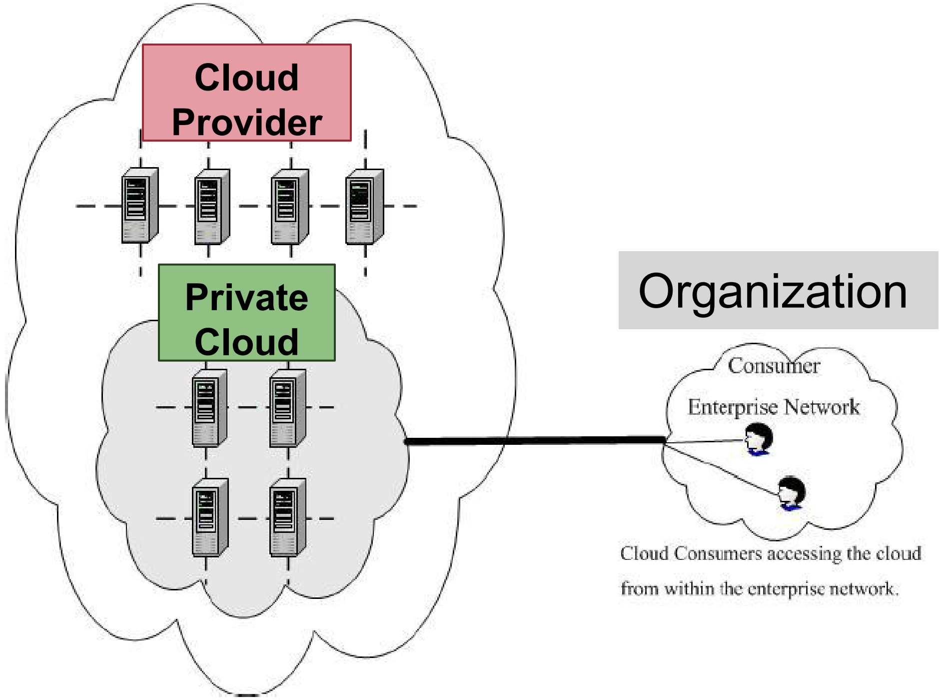
Platform-as-a-Service
A software platform for developers to build cloud applications

Infrastructure-as-a-Service
Computing resources (CPU, memory, disk) made available to users as Virtual Machine Instances

Private Clouds - Examples

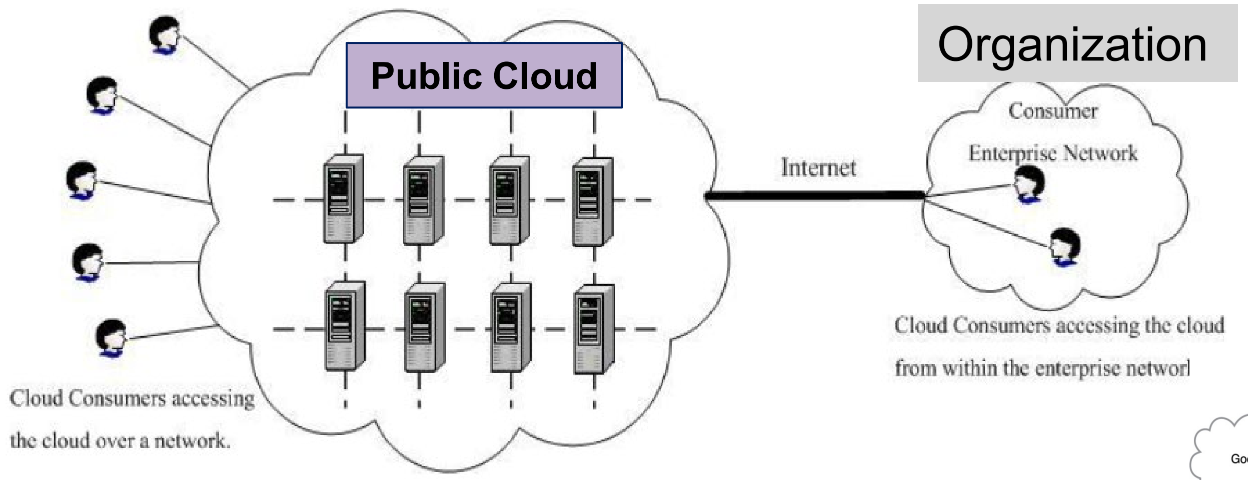


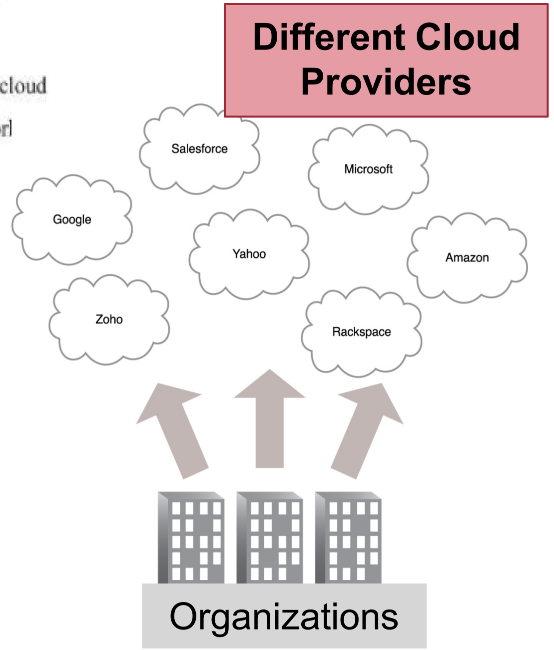
On-site Private Cloud: A cloud service consumer in the organization's on-premise environment accesses a cloud service hosted on the same organization's private cloud via a virtual private network.



Out-sourced Private Cloud

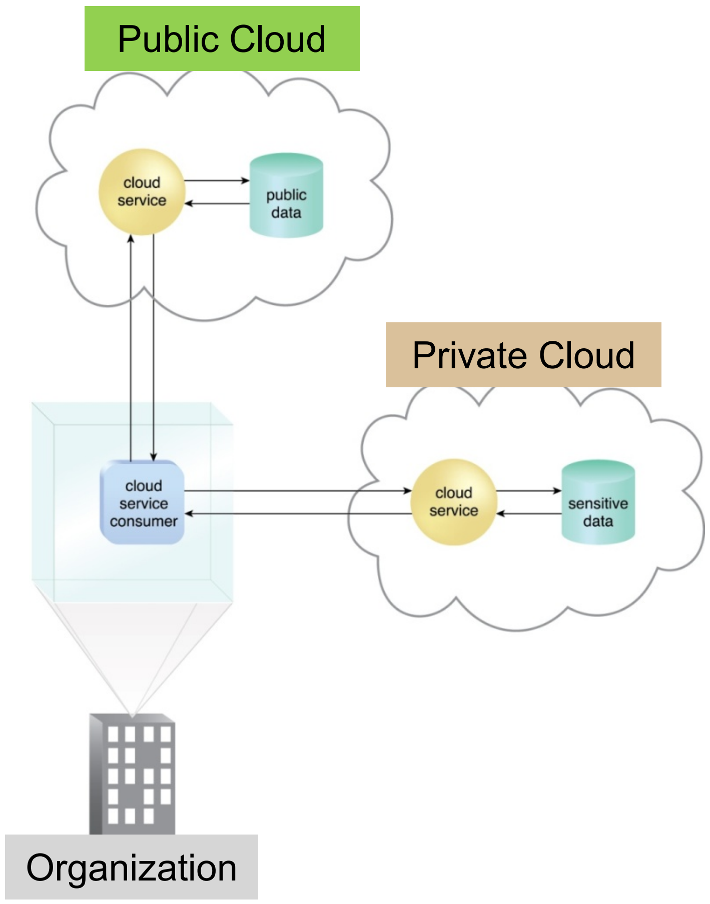
Public Clouds



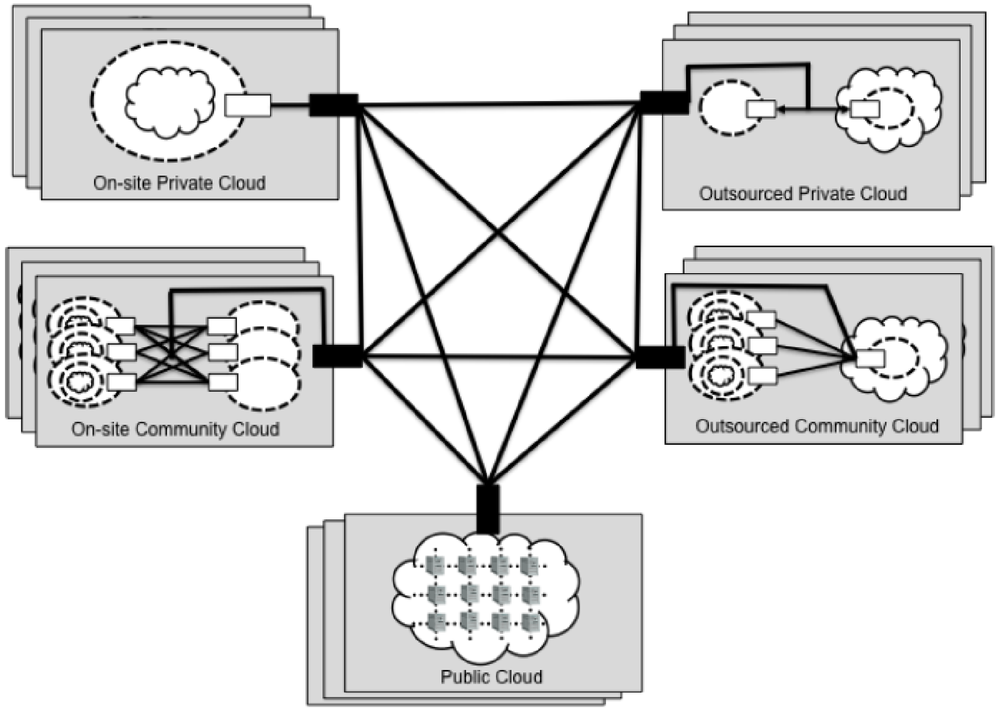


Example: Organizations act as cloud consumers when accessing cloud services and IT resources made available by different cloud providers.

Hybrid Clouds



An organization using a hybrid cloud architecture that utilizes both a private and public cloud.



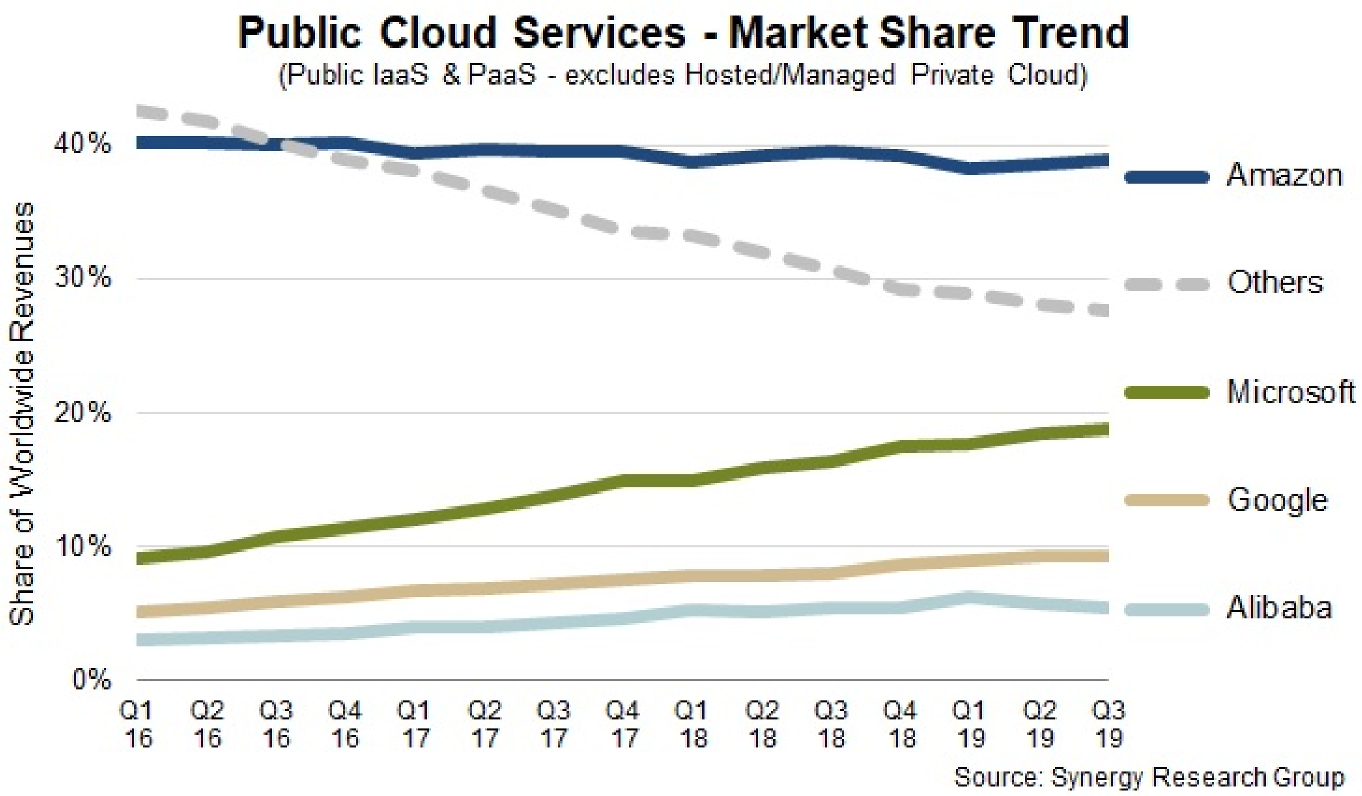
Technical Challenges

- Programming is tricky but improving
- Tools are continuously evolving
- Moving large data is still expensive
- Security
- Quality of Service
- Green computing
- Internet dependence

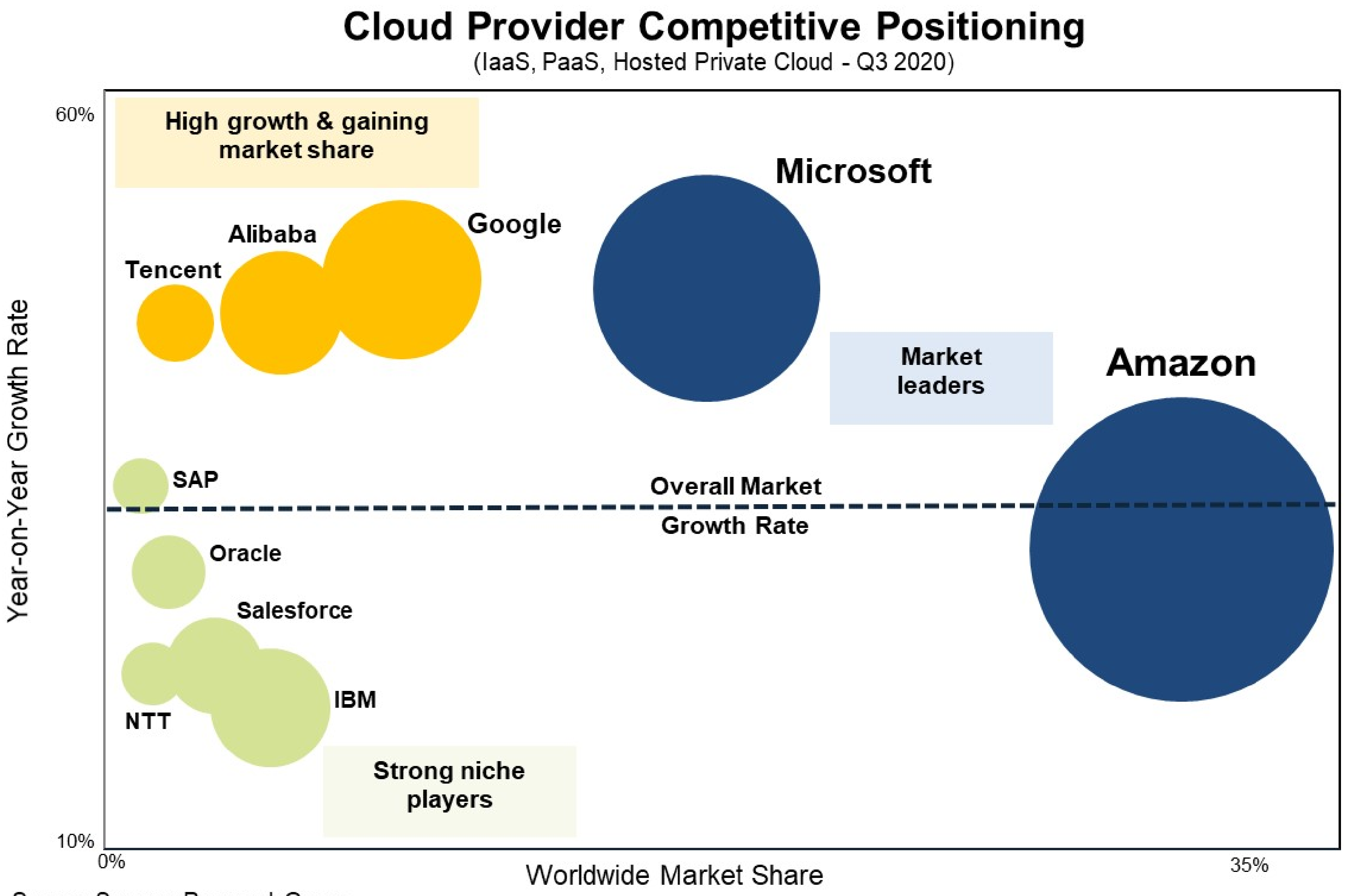
Non-Technical Challenges

- Vendor lock-In
- Non-standardized
- Security risks
- Privacy
- Legal
- Service Level Agreements

Cloud Infrastructure: Providers (2019)



Cloud Infrastructure: Open Source



Source: Synergy Research Group

Amazon Web Services (AWS)

- A collection of >30 remote computing services that together make up a cloud computing platform

- Some AWS services:
  - Compute: EC2 (Amazon Elastic Computing Cloud)
  - Storage: S3 (Amazon Simple Storage Service)
  - Database: RDS (Amazon Relational Database Service)
  - Network: VPC (Amazon Virtual Private Cloud)

Amazon Web Services (AWS)

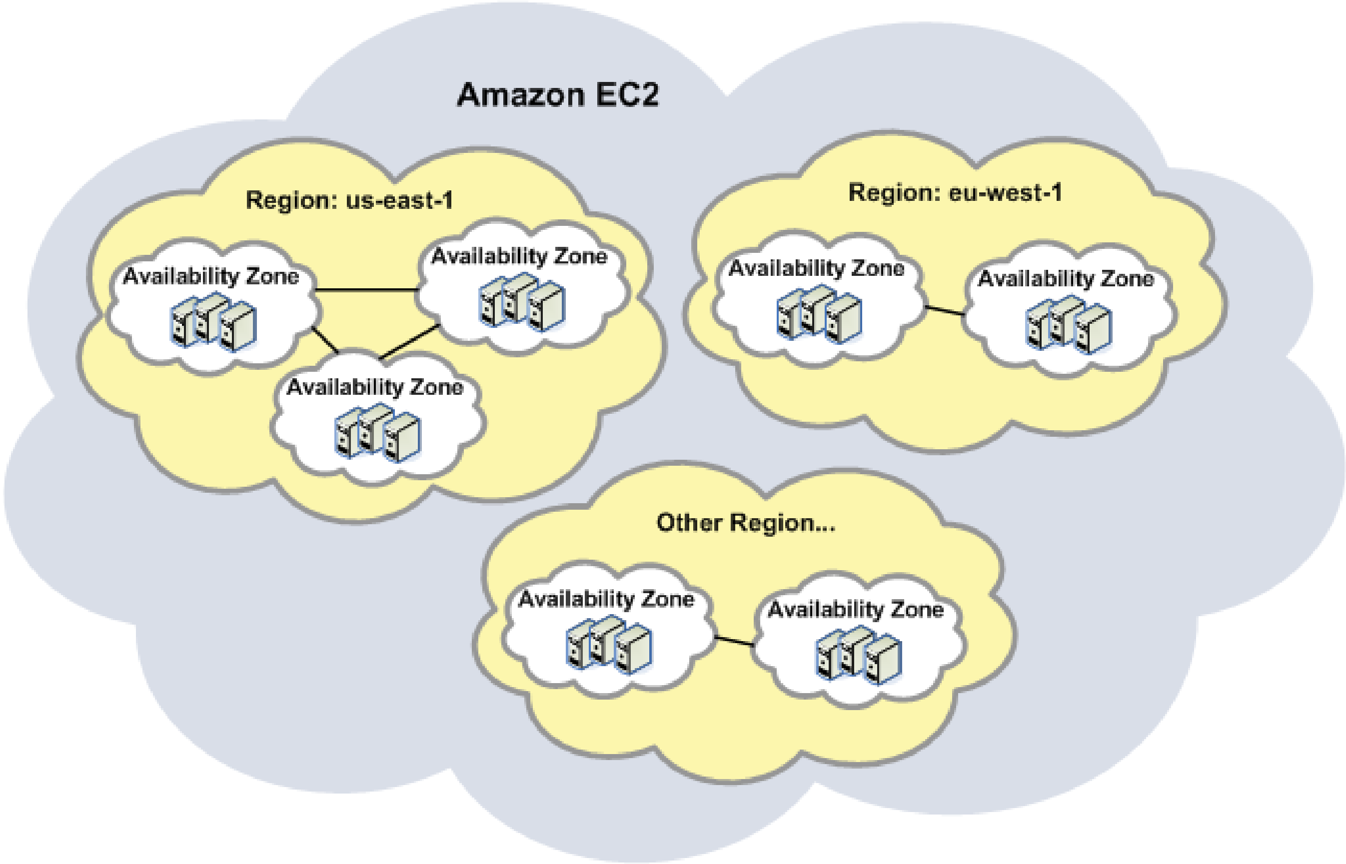
- $10 billion in sales in 2020
  - Netflix, Twitch, Linkedin, Facebook, etc.

- Consists of compute and storage servers interconnected by high-speed networks and supports a set of services

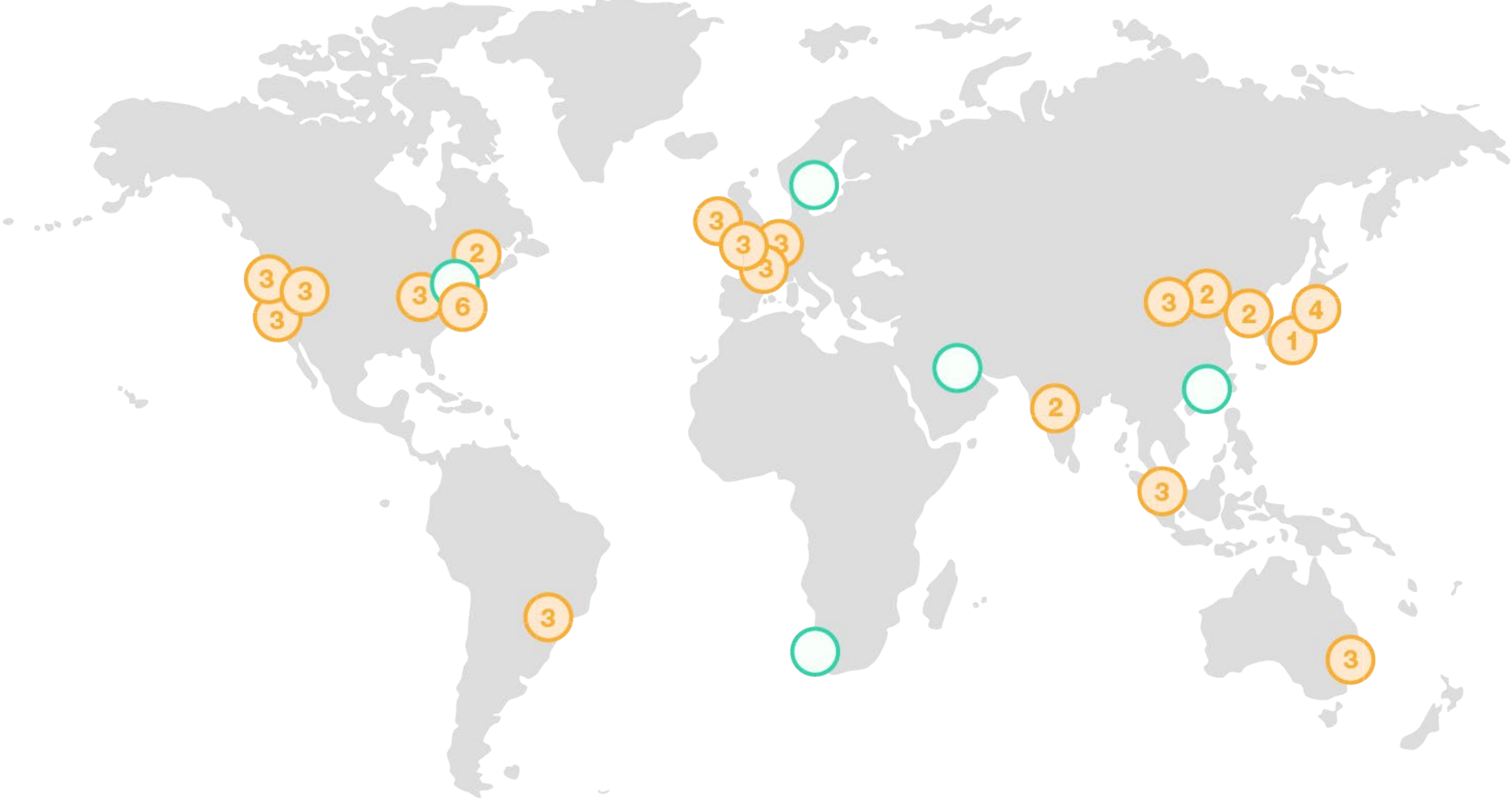
- For an application developer using AWS:
  - Installs applications on a platform of his/her choice
  - Manages resources allocated by Amazon

AWS Regions and Availability Zones

- Offers cloud services through a network of datacenters on several continents



22 Regions and Zones (as of 2019)



Region & Number of Availability Zones

US East (9)
US West (6)
Asia Pacific:
- Mumbai (2)
- Seoul (2)
- Singapore (3)
- Sydney (3)
- Tokyo (4)
- Osaka-Local (1)

Canada (2)
China (5)
Europe (12)
South America (3)
GovCloud (US-West) (3)

Summary

- Overview of energy-efficient computing
- Focus on mobile computing, data centers, cloud computing
- Case studies: ARM, Google, AWS