# Green Data Center

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# Learning Objectives

**Throughout this lecture, it is aimed for the students to be able to**

- **Learn the basic concepts and architecture of data centers**
- **Learn about energy consumption and energy efficiency metrics for data centers**
- **Understand different techniques to reduce energy consumption in data centers with a vision to realize green data centers**

# Industry Invited Talk Today

- **Speaker**: **Ole Sten Volland,** ***CTO (Chief Technology Officer), Green Mountain***

- **Title**: **Green Mountain:**
  **Industry perspective in designing and operating green datacenter**

- **Green Mountain**: **one of the largest operators in the data center sector in Norway with clients in Finance, IT, Government, Health, etc**

# Outline

Data Center Overview

Green Data Center

# DATA CENTER BASICS

# Daily services supported by data centers

- **Search**
- **Gmail**
- **Google map**
- **Youtube**
- **Driving & Navigation**
- **Facebook, Whatsapp, Messenger**
- **Q: more?**

**Google Data Centre at Mayes County, Oklahoma**

**Data center inside**

# Google data centers worldwide

# Norway is very active in the data center business.

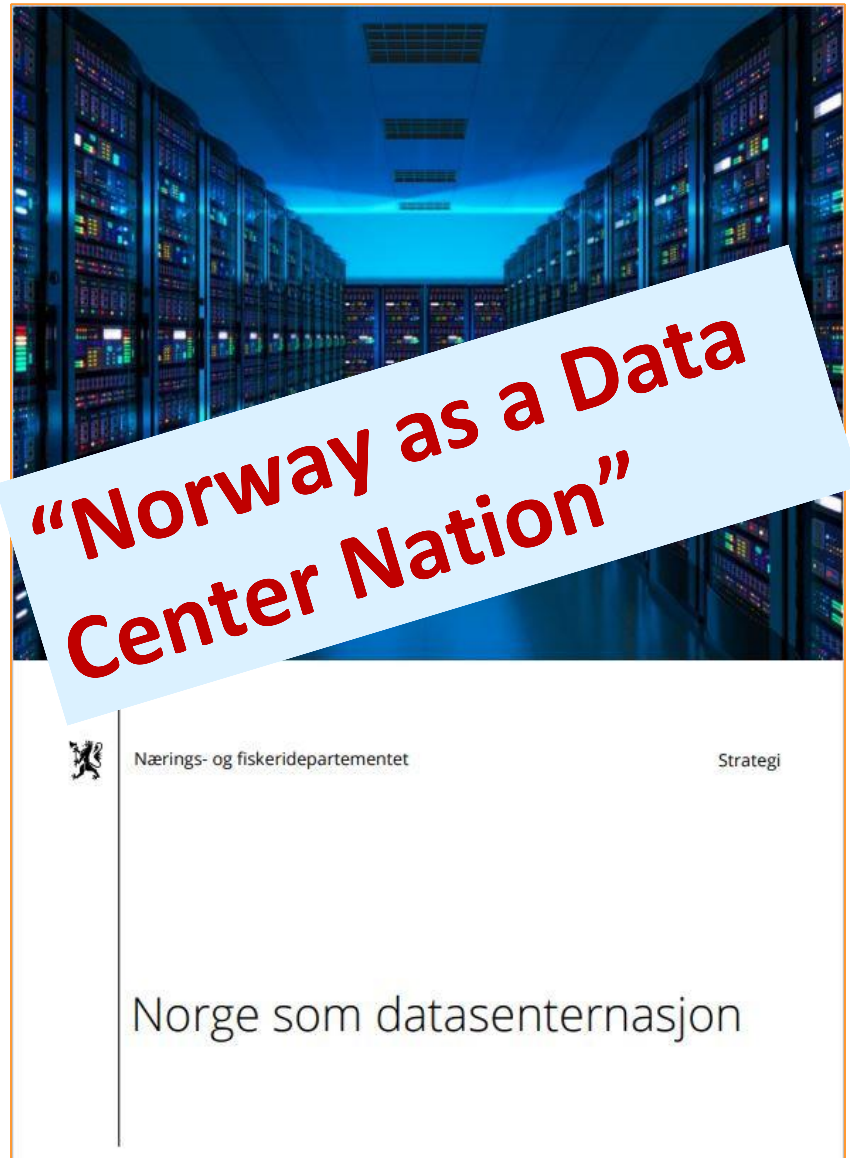
- **In 2018, the Norwegian government has published a plan to boost Norway's data center industry and make the country a world-class player in the sector**

**Many data center players now:**

Green Mountain

DigiPlex

LEFDAL MINE DATACENTER



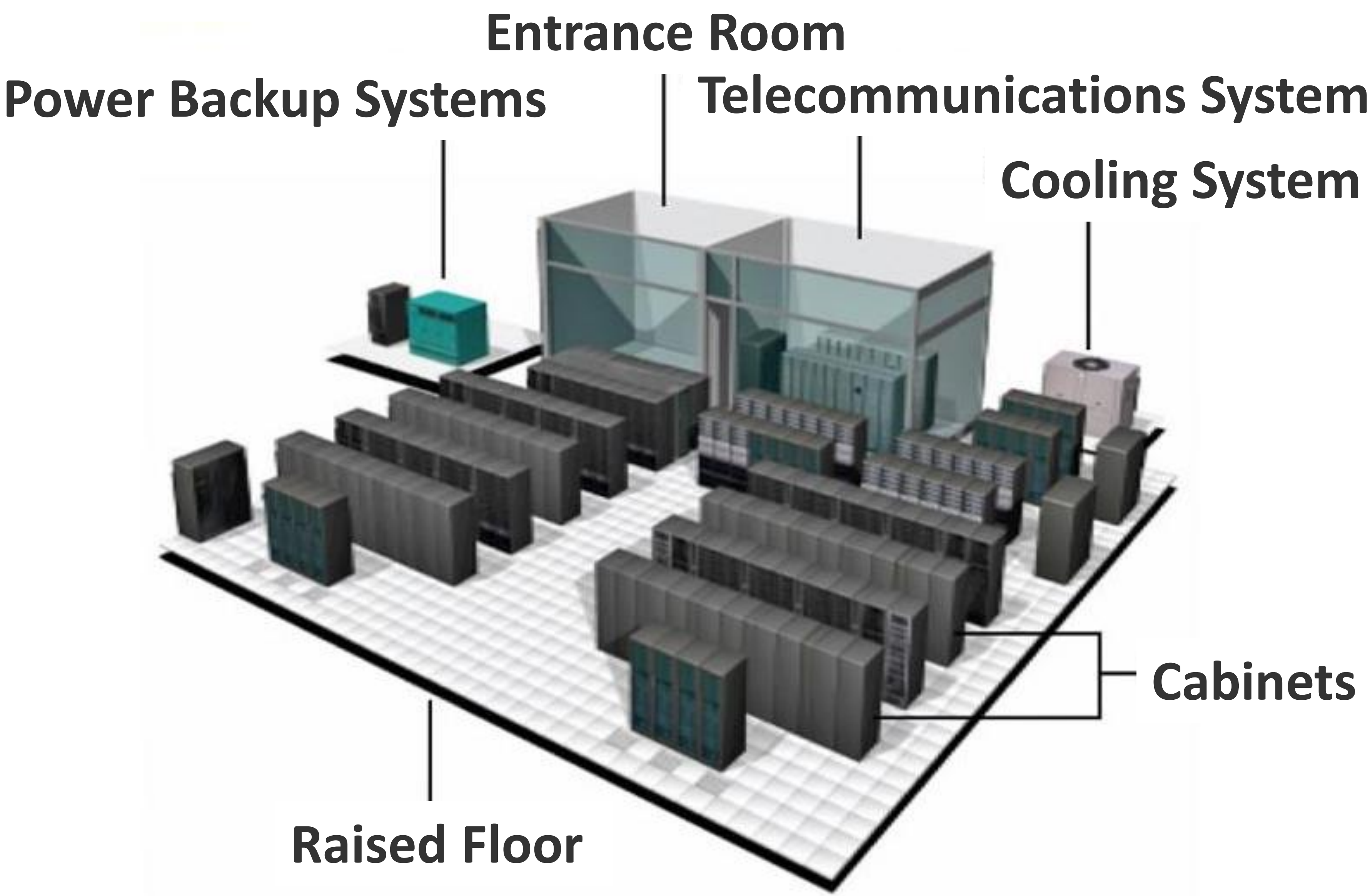
# Data Center Definition

- **A data center is a building/container used to house computing equipment such as servers, along with associated components such as networking devices, storage systems, power distribution units, and cooling systems.**

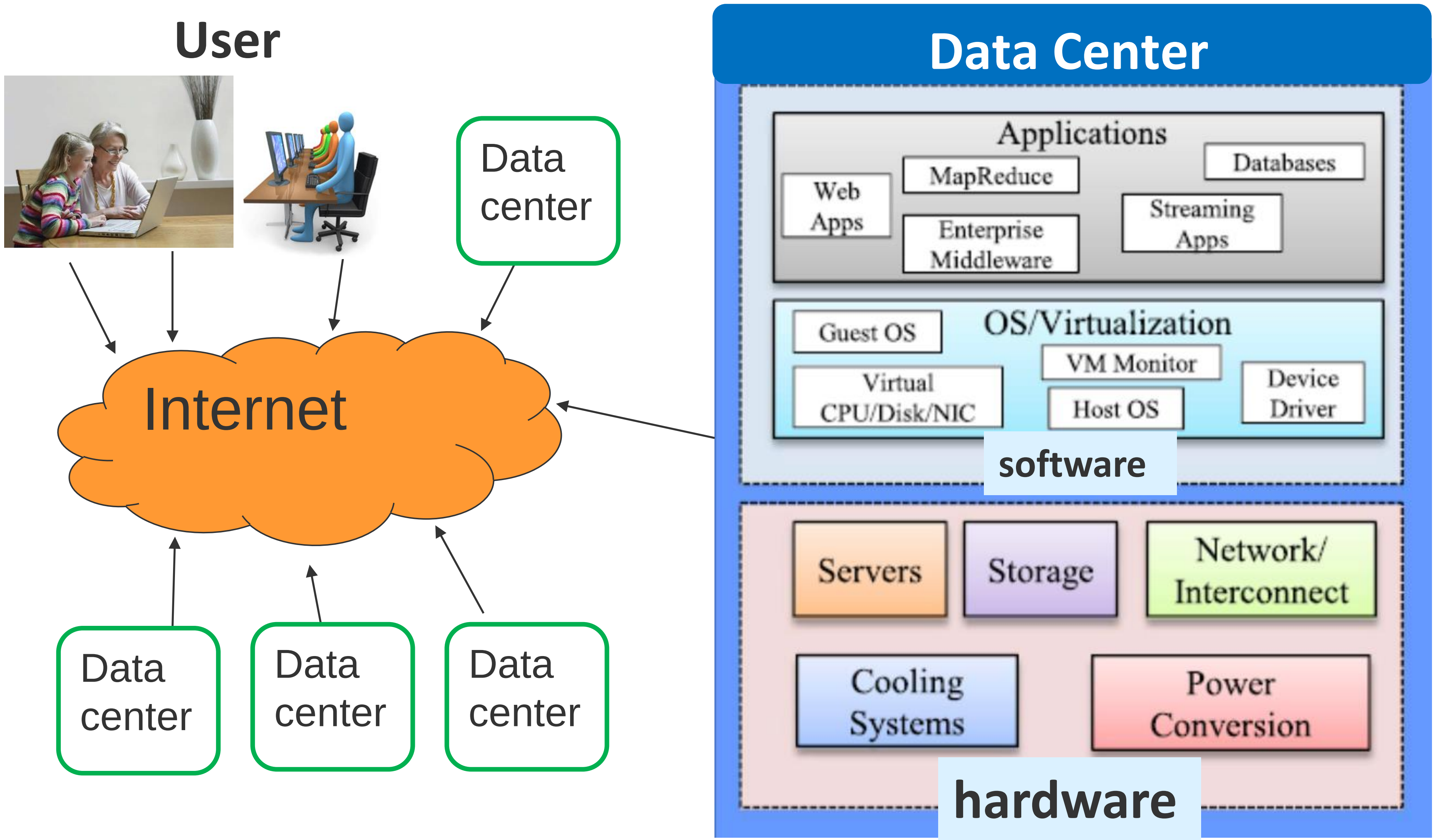
**Common features:**

- **Power: equipped with a guaranteed power supply**
- **Communications: equipped with high bandwidth connectivity**
- **Reliability: duplication of networks, power and IT infrastructure**
- **Environment: maintain a specified temperature and humidity**
- **Security: ensure that the facility and its data remain secure**

# Data Center Physical Layout



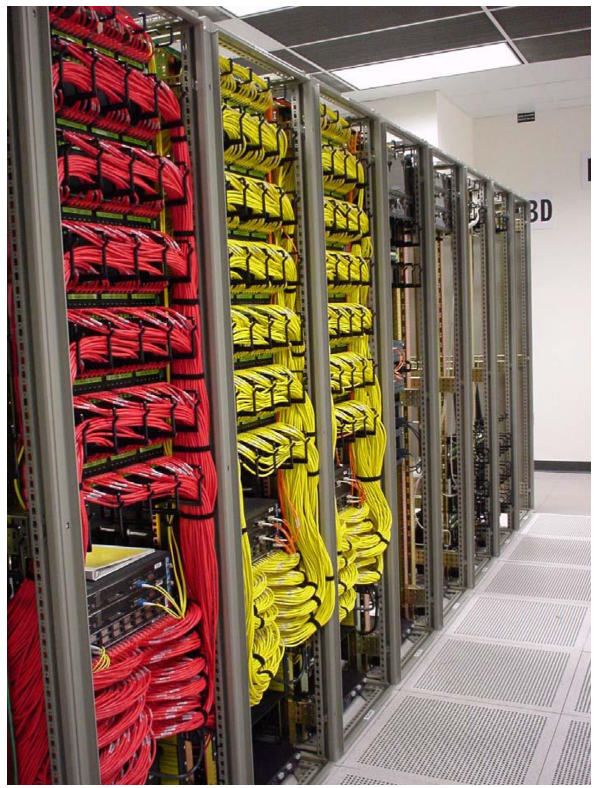
# Data Centers – Hardware/Software Components



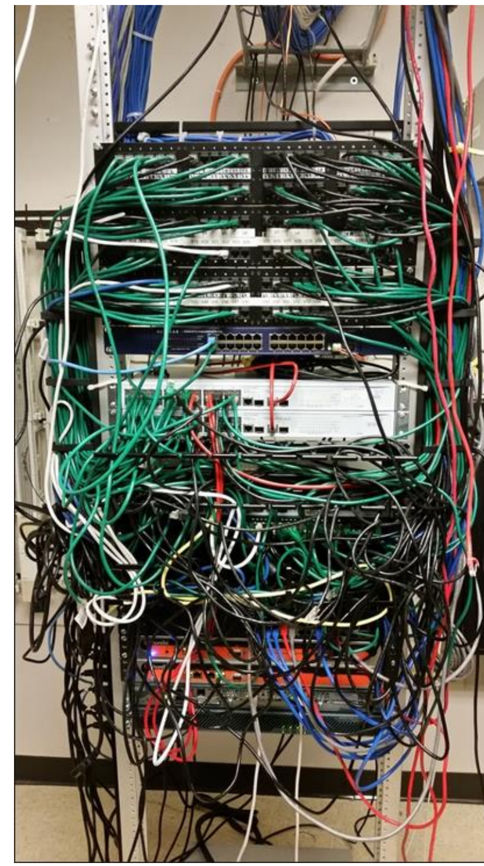
# Data Center Equipment Cables – cable management

**Three Layers: Bottom: Signal; Middle: Power; Top: Fiber**

**Perforated tiles at front of cabinets**

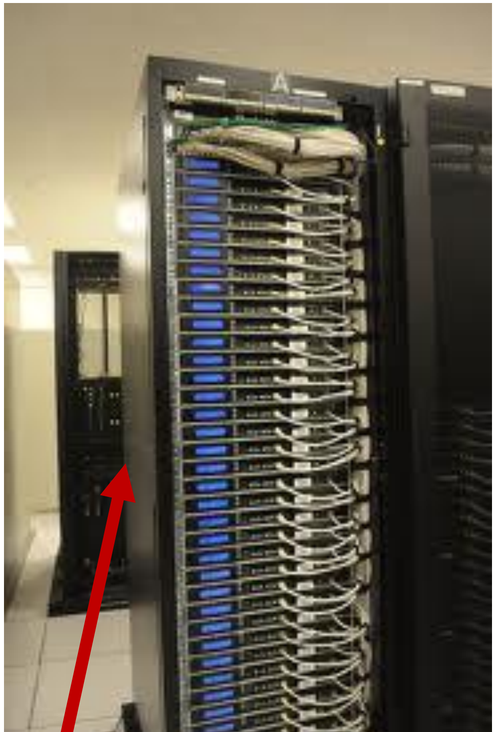


**Q: what may happen in this case?**

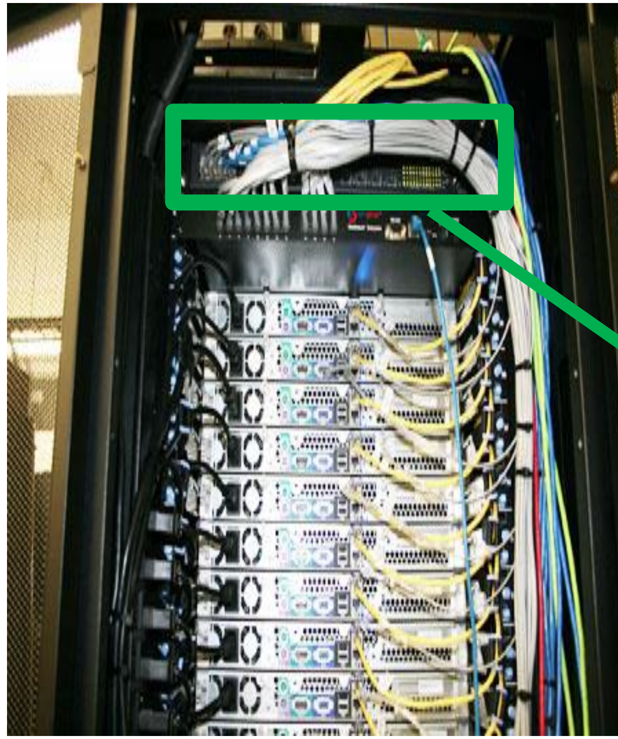


http://www.ieee802.org/3/hssg/public/nov06/diminico_01_1106.pdf

# Servers organized as racks



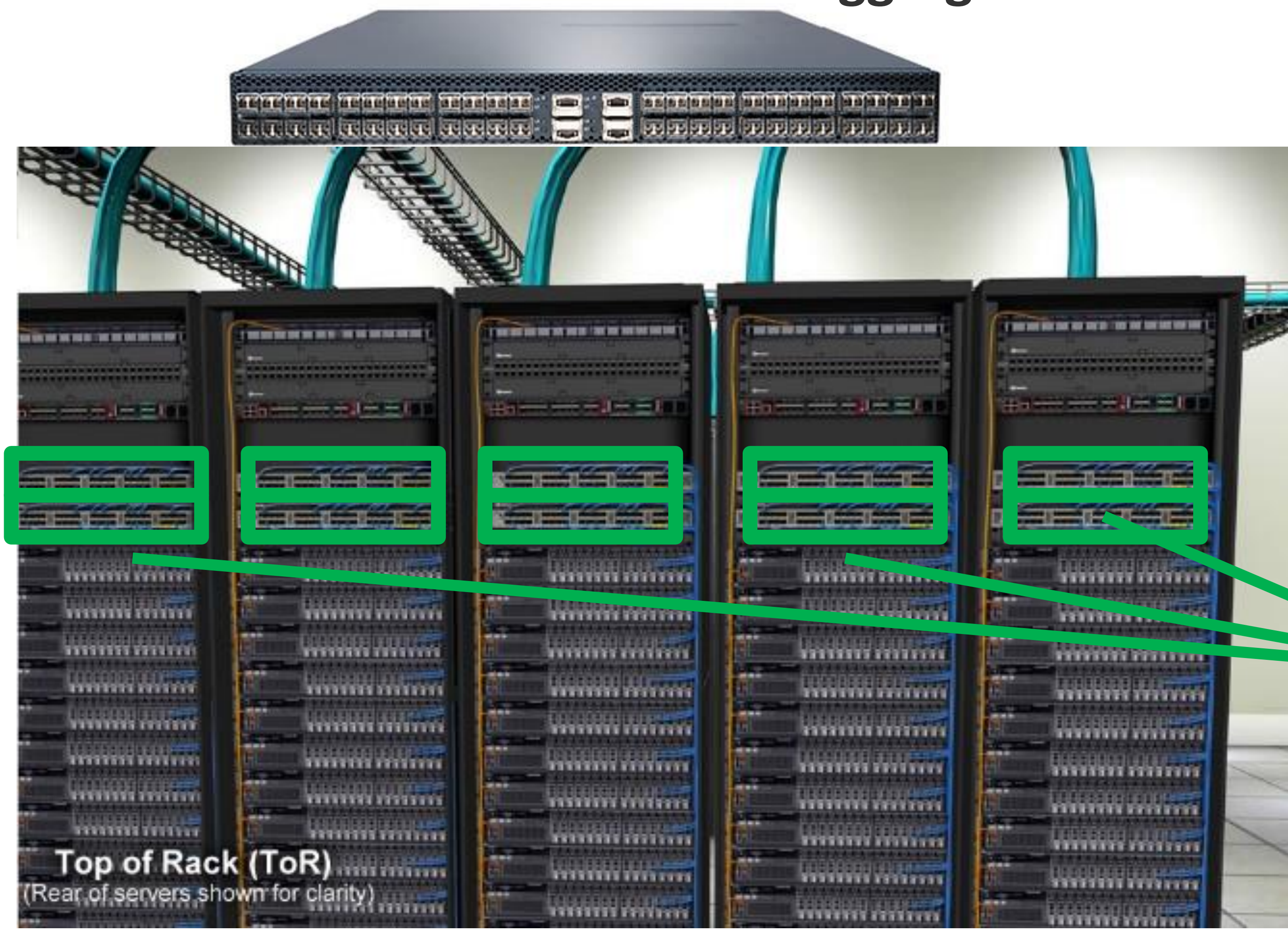
A rack



each rack has a "Top of Rack" (ToR) switch

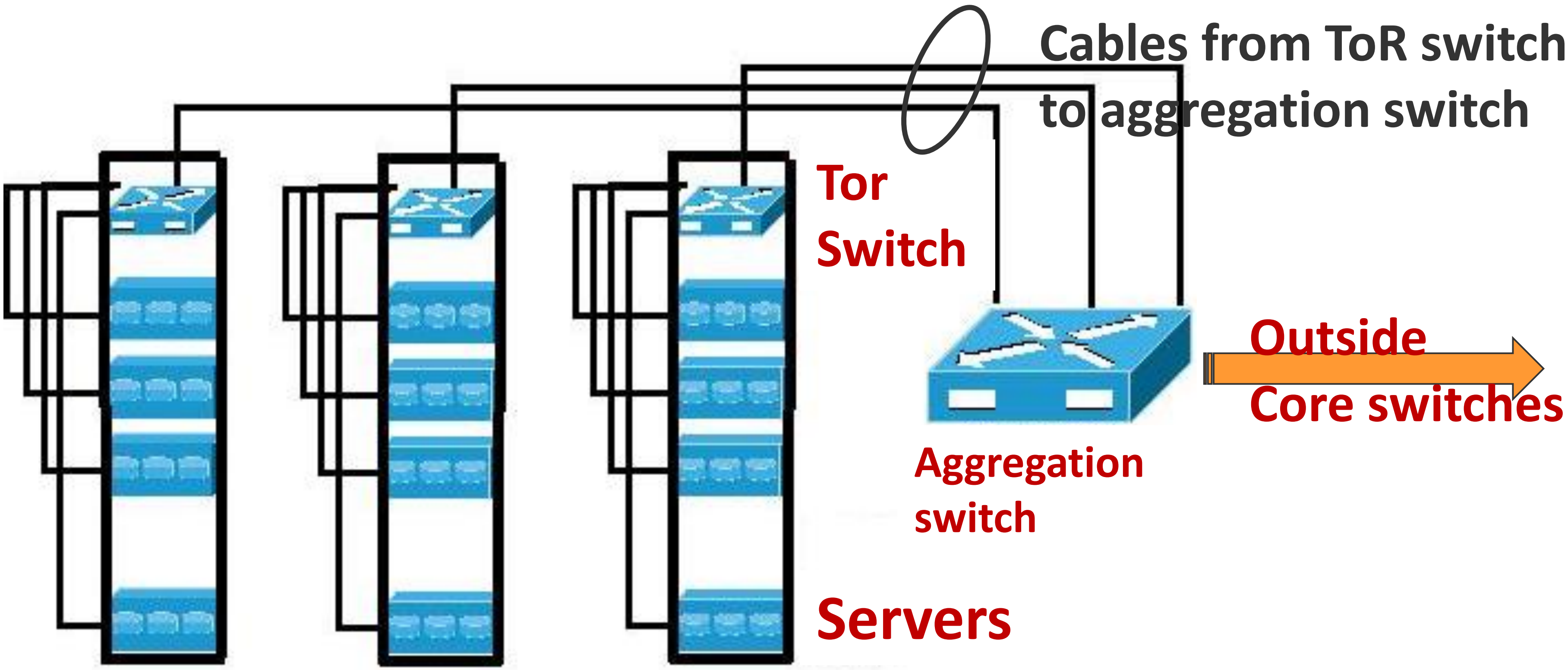
- **Q: in practice, we have many racks, not just one rack in this example. How to connect many racks?**

# “Top of Rack” (ToR) architecture connects many racks




- **Servers are connected to switches within the server racks**
- **Two high-speed and individual switches connect to the aggregation switch.**

# "Top of Rack" (ToR) architecture – abstract model




Source: http://www.excitingip.com/2802/data-center-network-top-of-rack-tor-vs-end-of-row-eor-design/

- **ToR architecture refers to the physical placement of the switch in the top of a server rack. Servers are directly linked to the switch. Each rack usually has two switches. (Q: why two switches?)**
- **All the ToR switches are connected with the aggregation switch. Only a small amount of cables are needed to run from server rack to aggregation switch. Aggregation switch will be further connected to the outside core switches.**

# ToR advantages and disadvantages

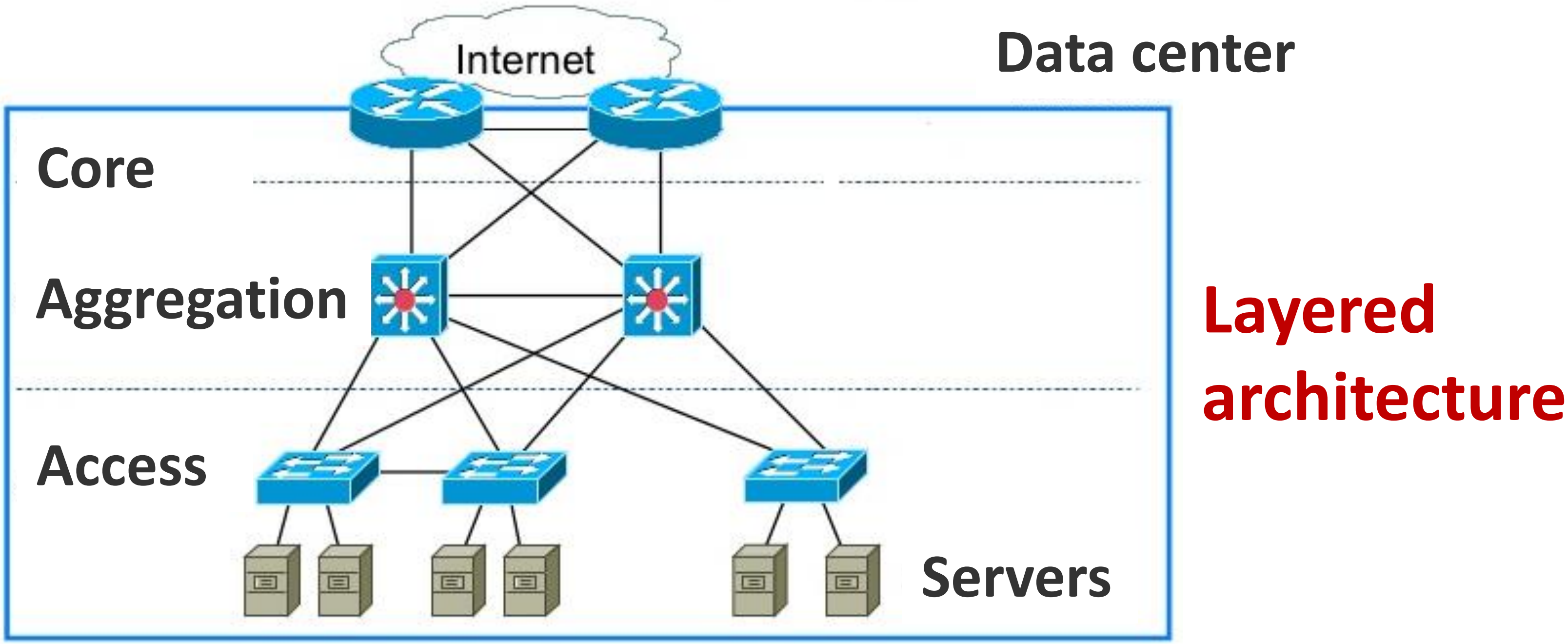
**Advantages:**

- **Cable management is easy with less cables involved: no need large cabling infrastructure. Low cabling costs since all server connections are terminated to its own rack**
- **Flexible "per rack" architecture. Easy "per rack" changes.**

**Disadvantages**

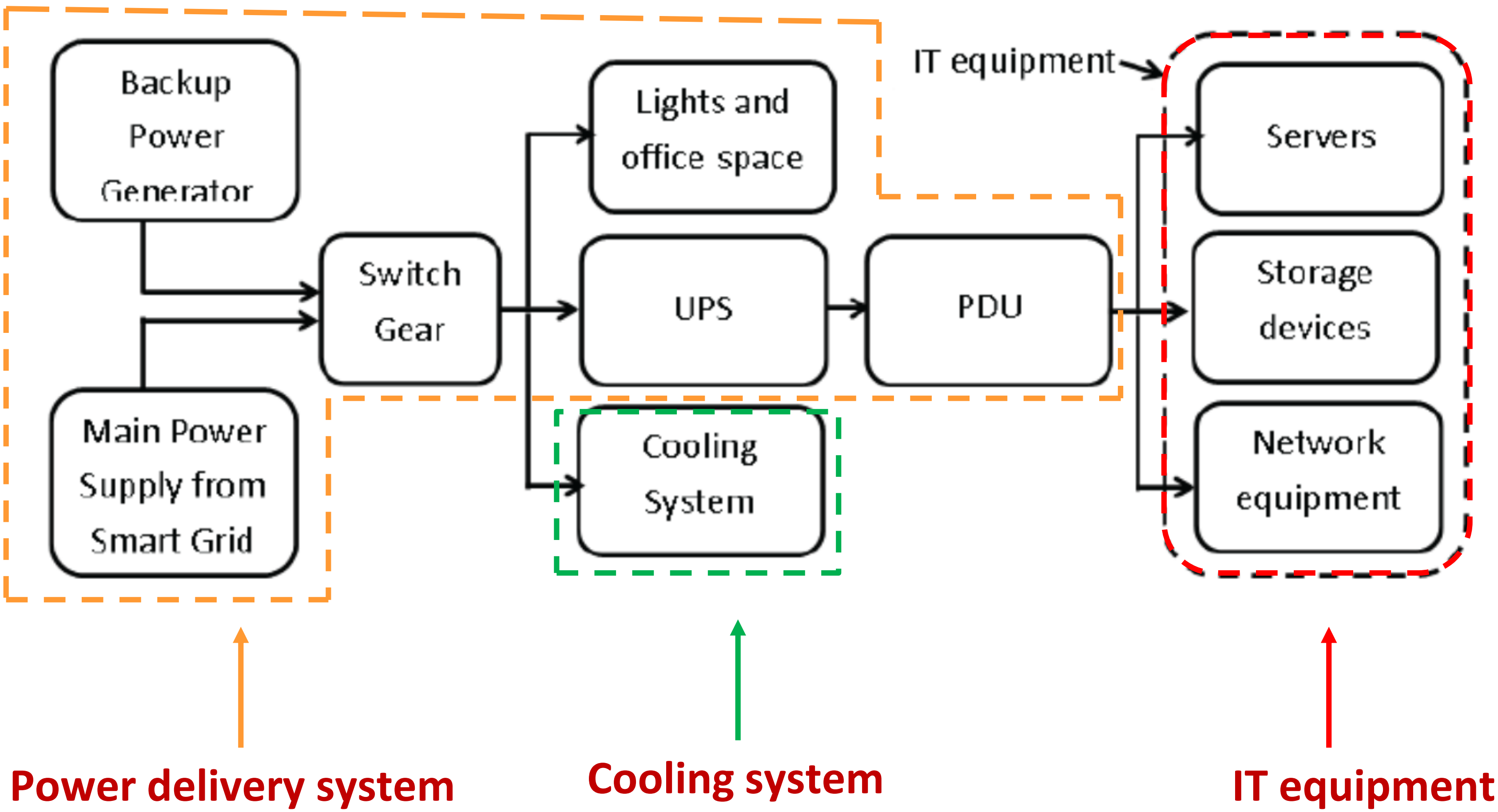
- **High management burden: Each rack switch is individually managed, management burden will increase significantly by adding many new switches to the data center. For example, in a data center with 50 racks, where each rack contained 2 ToR switches, the result would be 100 switches totally. There are 100 copies of switch software that need to be updated, 100 configuration files that need to be created and archived.**
- **Potential scalability concerns: ToR design typically requires higher port densities in the aggregation switches.**

# A 3-Layer Data Center Architecture




- Servers: Racks of equipment that require network access .
- Access Layer: Equipment directly connected to servers
- Aggregation Layer: Equipment that aggregates access layer devices to provide connectivity among Access Layer domains
- Core: Equipment that interconnects aggregation layer devices either within a data center or across geographic locations with outside world

# Major Components in a Data Center




- PDU: power distribution unit
- UPS: Uninterruptible power supply

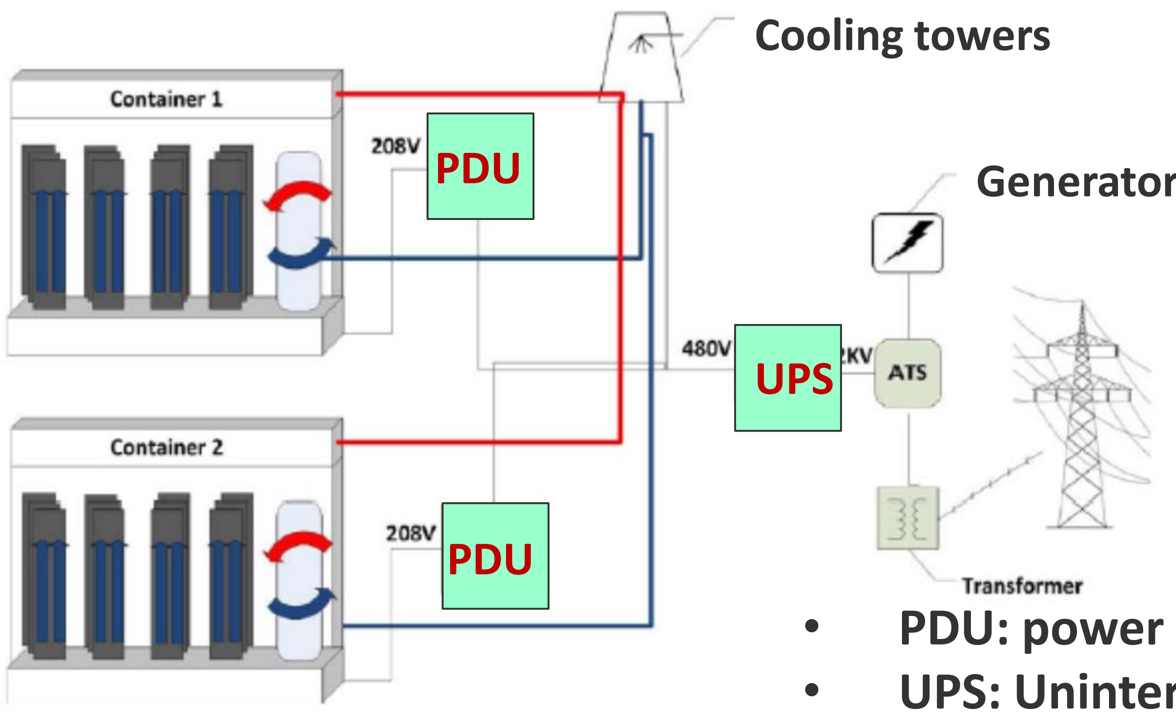
# Data Center Major Components– IT equipments

- **There are three kinds of IT equipments hosted in a typical data center**
  - **servers for data processing**
  - **storage equipment for data storage**
  - **network equipment for data communications**

- **These three types of equipments are collectively known as "information technology" (IT) equipments.**

# Data Center Major Components - power delivery system

- **The power delivery system mostly contains power conversion units, voltage regulators and backup equipment.**
- **Power backup is often provided by Uninterruptible Power Supply (UPS) unit which prevents the IT equipment from experiencing power disruptions and possible serious business disruption or data loss.**

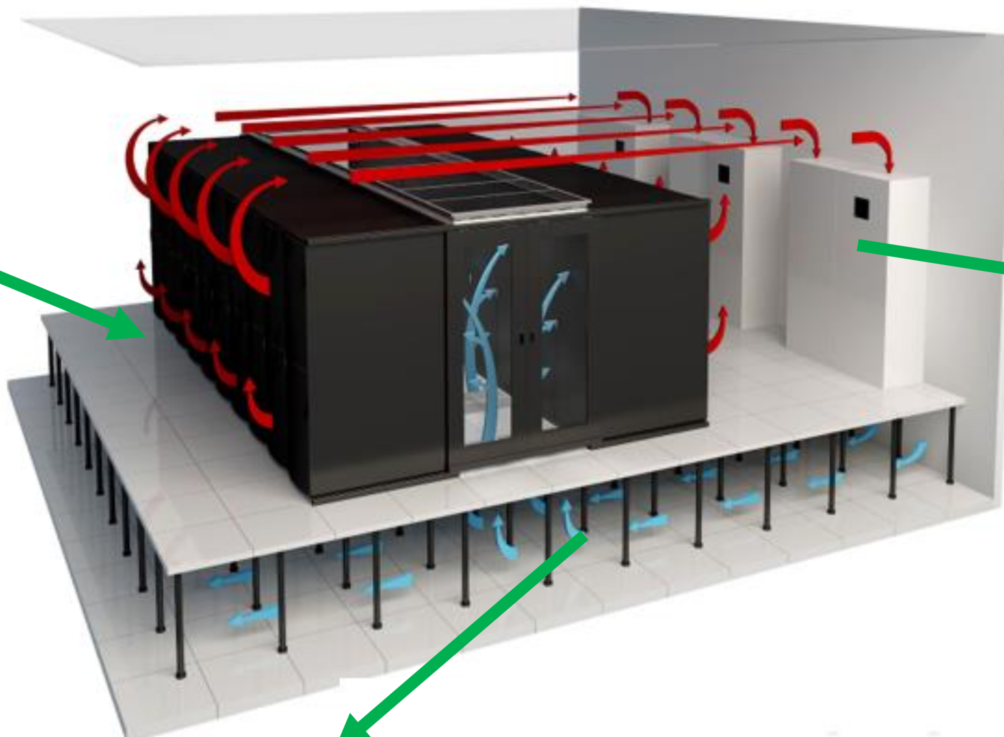



- **PDU: power distribution unit**
- **UPS: Uninterruptible power supply**

# Data Center Major Components – cooling systems

- **Cooling in data centers is often provided by *Computer Room Air Conditioning (CRAC) units*.**

**Perforated floor tiles**

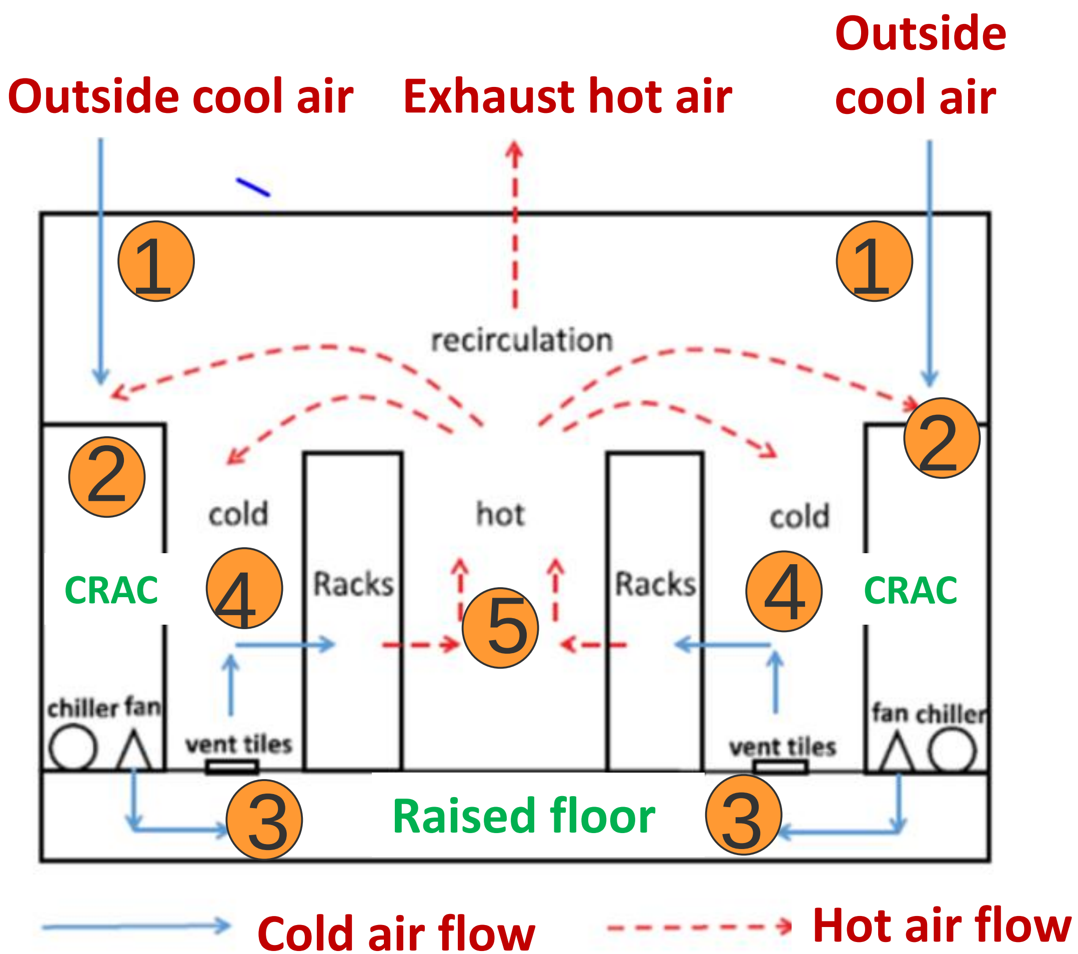


**CRAC: Containing chilled water**

**Raised floor**

# Air Flow in Data Center

1. **Outside cool air enters the top of CRAC units**
2. **Air is conditioned by passing chilled water pumped from a chiller located outside the building.**
3. **The chilled air goes through a raised floor**
4. **The chilled air is then supplied to the servers**
5. **The cold air, while passing through perforated floor tiles, is pulled by the fans located inside the servers.**



# Still, data centers use much energy

- Q: Why place data centers in Finland or undersea?
- Data centers are huge energy consumers, in particular cooling systems, and
  - pay a lot for electricity bill
  - make power grid instable during peak hours
- Cooling system uses sea  water from the Bay of Finland and reduces energy use


# Data Center Energy Consumption

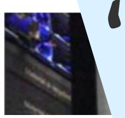
INDEPENDENT News Voices Culture Lifestyle Tech Sport Daily Edition Charity Appeal

Environment

## Global warming: Data centres to consume three times as much energy in next decade, experts warn

416.2 terawatt hours of electricity world's data centres us
consumption

Tom Bawden Environment Editor | @BawdenT



**"US data centers consumed about 70 billion kWh electricity in 2014"**

**- US Department of Energy**

## ...uch Energy All US ...enters Consume

BY YEVGENIY SVERDLIK ON JUNE 27, 2016 1 COMMENT

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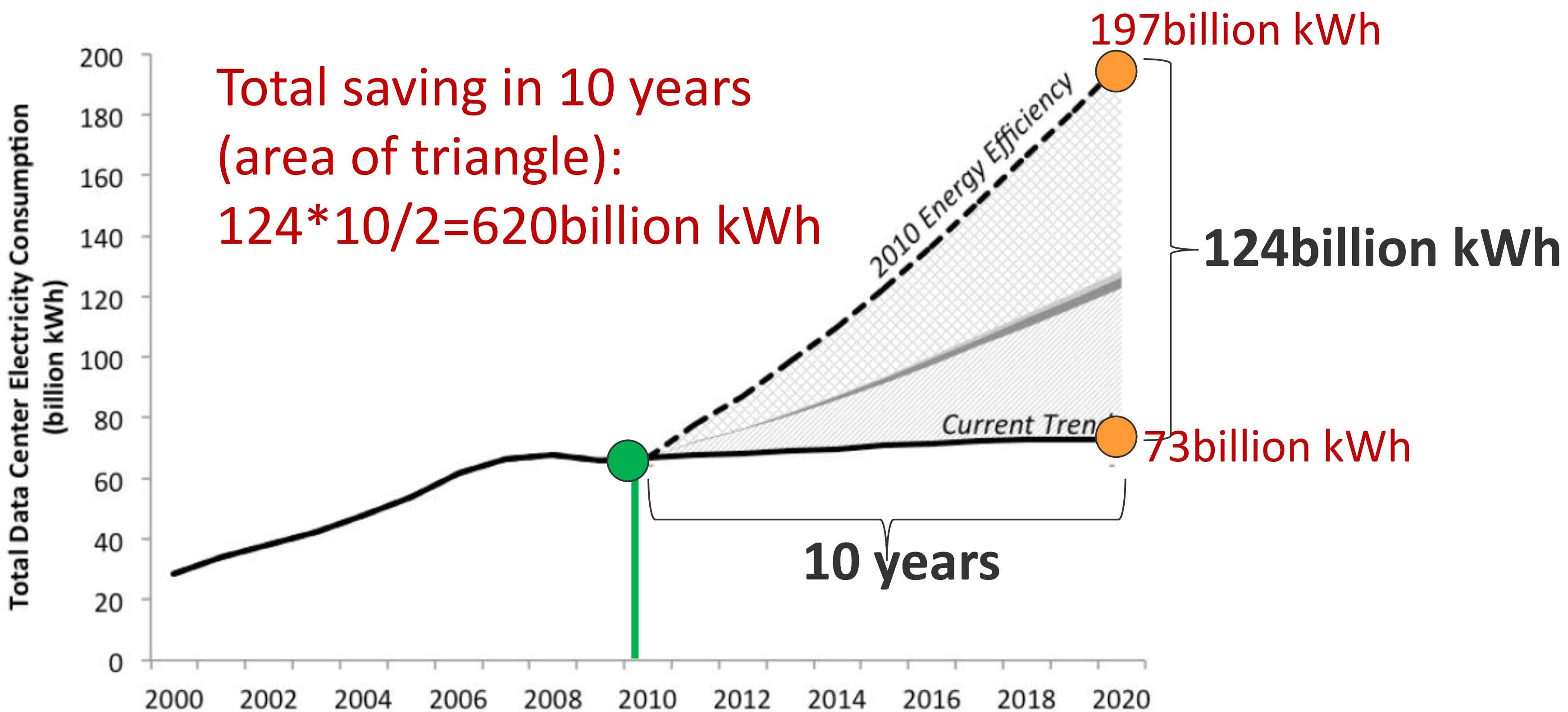
It's no secret that data centers, the massive but bland, unremarkable-looking buildings housing the powerful engines that pump blood through the arteries of global economy, consume a huge amount of energy. But while our reliance on this infrastructure and its ability to scale capacity grows at

# Growth rate of total US data center energy use from 2000 until 2020.




- **Industry has considered efficiency since 2010. The illustration shows how much faster data center energy use would grow if the industry, hypothetically, did not make any further efficiency improvements after 2010. (Source:** US Department of Energy, Lawrence Berkeley National Laboratory**)**

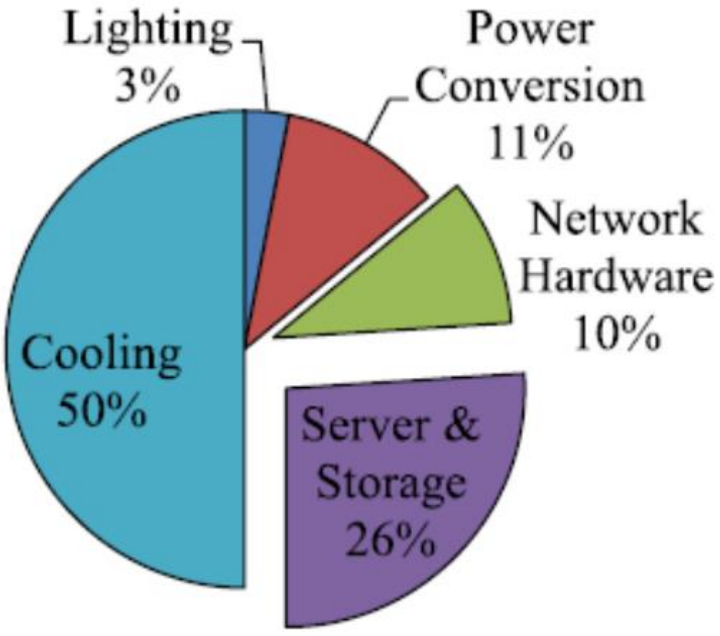
- **Energy consumption in 2020 will reach about 73billion kWh**

# ENERGY CONSUMPTION IN DATA CENTER

# Energy Consumption in Data Center

- **The largest energy consumer in a typical data center is the cooling infrastructure (50%), while servers and storage devices (26%) rank second in the energy consumption hierarchy. -- according to the statistics published by the Infotech group. (Note: that these values might differ from data center to data center)**

- **A breakdown of energy consumption by different components shows: the cooling infrastructure consumes a major portion of the data center energy followed by servers and storage, and other infrastructure elements.**




http://static.infotech.com/downloads/samples/070411_premium_oo_greendc_top_10.pdf

# Energy Efficiency Metrics for Data Centers

- **In order to quantify the energy efficiency of data centers, several energy efficiency metrics have been proposed to help data center operators to improve the energy efficiency and reduce operation costs of data centers.**

- **Two important energy efficiency metrics are**
  - **Power Usage Effectiveness (PUE)**
  - **Data Center energy Productivity (DCeP)**

# Power Usage Effectiveness (PUE)

- **PUE: the most commonly used metric to indicate the energy efficiency of a data center. PUE definition:**

$$PUE = \frac{Total\ Power\ Consumption\ of\ a\ Data\ Center}{Total\ Power\ Consumption\ of\ IT\ Equipment}$$

$$= \frac{Total\ Power\ Consumption\ of\ IT\ Equipment + Total\ Power\ Consumption\ of\ nonIT\ Equipment}{Total\ Power\ Consumption\ of\ IT\ Equipment}$$

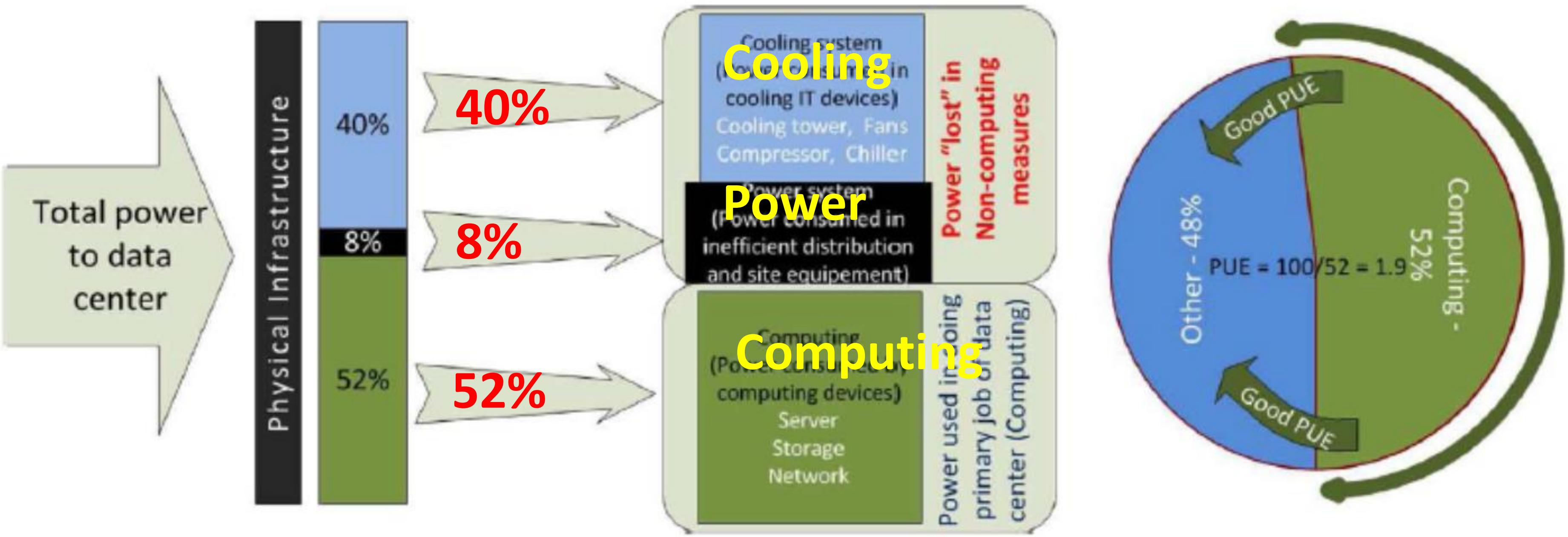
$$= 1 + \frac{Total\ Power\ Consumption\ of\ nonIT\ Equipment}{Total\ Power\ Consumption\ of\ IT\ Equipment} > 1$$

- **Total power consumption of a data center: the sum of power used by all components, including cooling, lightening, and IT equipment.**

- **Total power consumption of IT equipment: the sum of power used by IT equipment (servers, storage, and network).**

- **PUE value greater than 1 since data centers draw considerable amount of power as non-IT power.**

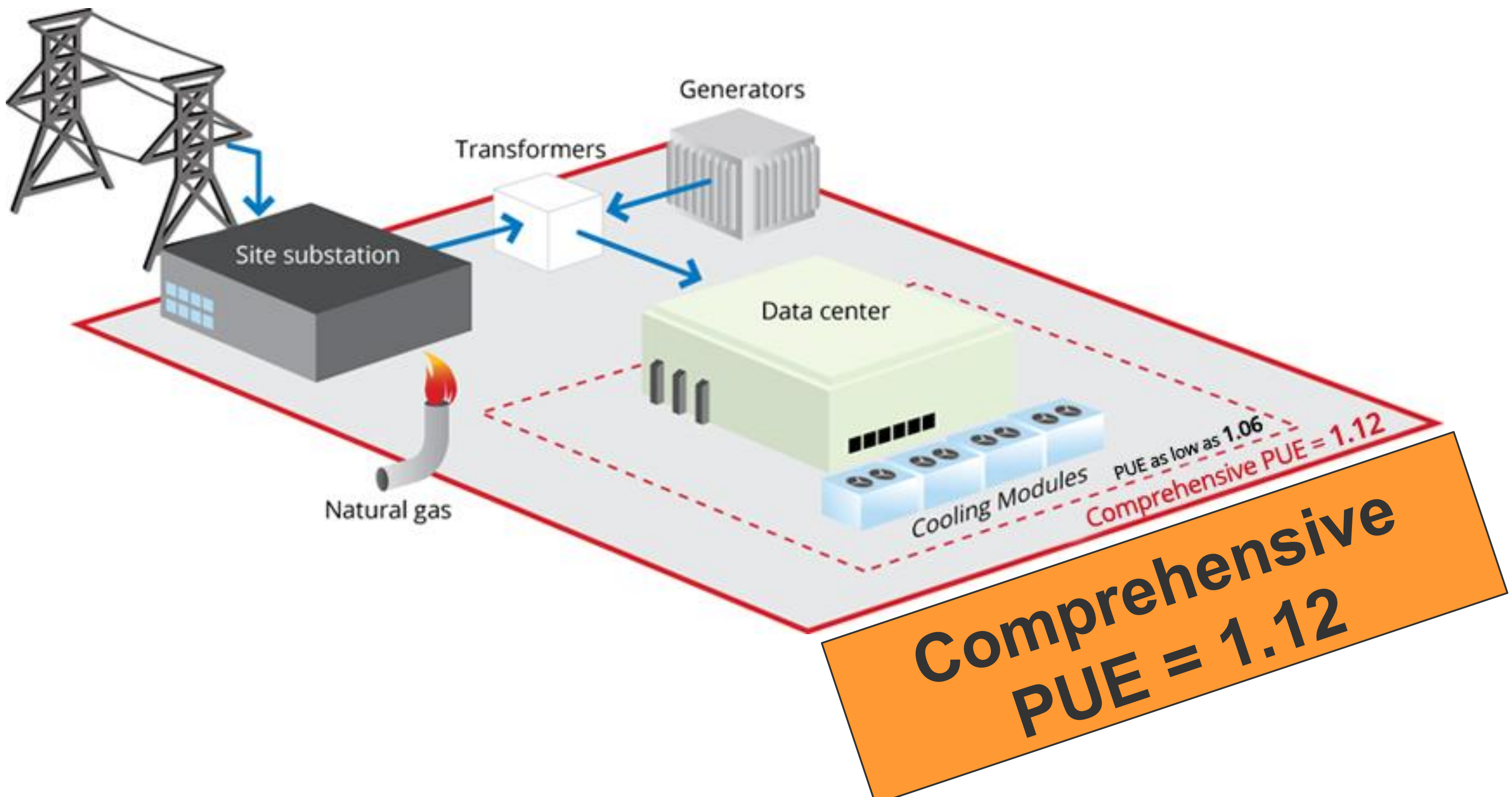
# Power Usage Effectiveness (PUE): an example




Source: J. Shuja, et al.,"Survey of Techniques and Architectures for Designing Energy-Efficient Data Centers," IEEE Systems Journal, vol. 10, no. 2, pp. 507-519, 2016

- **Distribution of data center power among cooling, power distribution, and computing units**
- **In this example, 52% power goes to computing while 48% power goes to non-computing. Then, PUE = 100/52=1.9**

# Google's PUE




- **A PUE closer to 1.0 means nearly all of the energy is used for computing.**
- **Google reports: the average PUE for all Google data centers is 1.12. Best sites can be less than 1.06.**

More information: https://www.google.com/about/datacenters/efficiency/internal/

# PUE Features

- **PUE measures the total power consumption overhead caused by the data center support equipment, including the cooling systems, power delivery, and other facility infrastructure like lighting.**
- **PUE=1.0 implies: there is no power overhead and all power consumption of the data center goes to the IT equipment.**
- **A higher PUE: a greater portion of the electricity coming to the data center spent on cooling and the rest of the infrastructure**
- **Q: can a good PUE value guarantee the global efficiency of a data center?**
- **A good PUE value may not be enough to guarantee the global efficiency of the data center. PUE metric does not consider the actual utilization (applications and workloads) of computational resources, some computation may not be necessary.**

# Data Center energy Productivity (DCeP)

- **Energy efficiency and energy productivity are closely related to each other.**
  - **Energy efficiency focuses on reducing unnecessary power consumption to produce a work output.**
  - **Energy productivity measures the quantity of useful work done relative to the amount of power consumption of a data center in producing this work.**

- **DCeP measures the useful work performed by a data center relative to the energy consumed by the data center in performing the work**

$$DCeP = \frac{Useful\,Work\,Produced}{Total\,Data\,Center\,Power\,Consumed\,Producing\,this\,Work}$$

# DCeP

- **DCeP metric allows the user to define the computational tasks, transactions, or jobs that are of interest, and then assign a measure of importance of economic value to each specific unit of work completed**
- **DCeP allows the continuous monitoring of the productivity of a data center as a function of power consumed by a data center.**
- **DCeP metric tracks the overall work product of a data center per unit of power consumption expended to produce this work.**

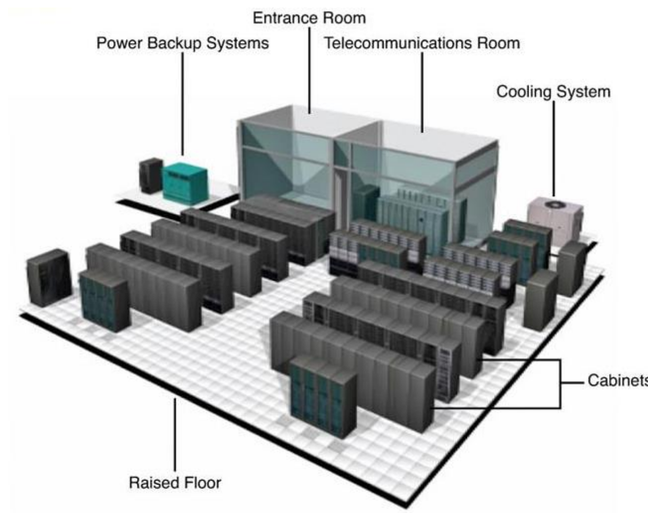
- **Q: Easy to use this metric?**

  **– subjective and may not be easy to define *"Useful Work"***

# GREEN DATA CENTER

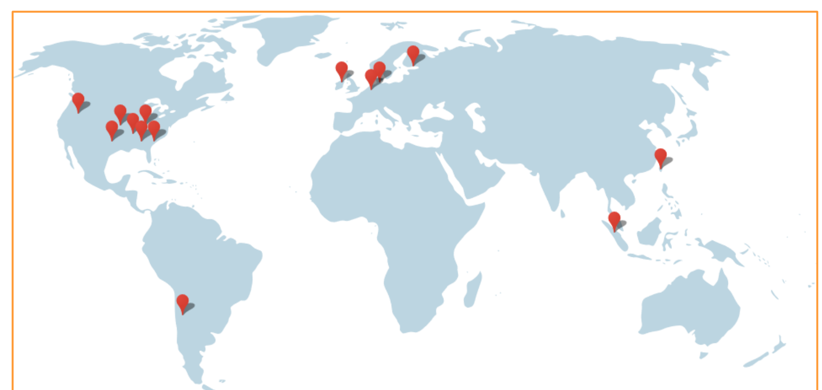
# Green Data Center

- **"Green Data Centers": energy-aware, energy-efficient and CO2 emission minimization designs, protocols, devices, infrastructures and algorithms for data centers**



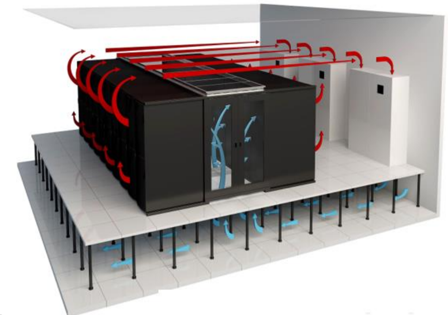

- **Reduce energy consumption in an individual data center**

- **Reduce energy consumption across globally located data center**



# Techniques to Improve Energy Efficiency of Data Centers

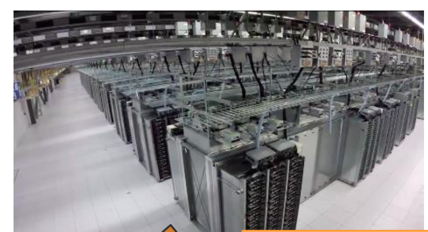
- **Smart Cooling and Thermal Management**



- **Power Management - Chip Level**


- **Power Management – Server Level**

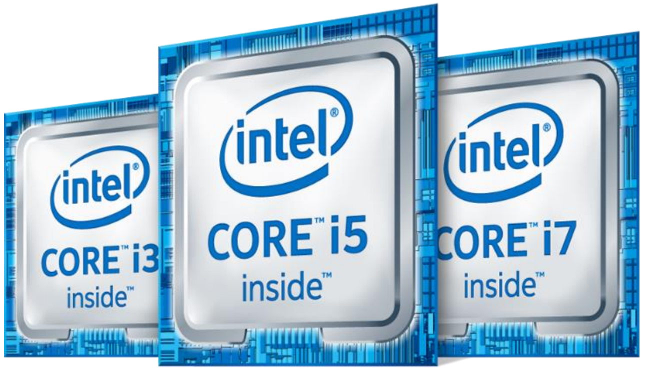
- **Power Management – Data Center Level**



- **Power Management – Inter Data Center Level**

# Chip Level Management

- **Dynamic voltage and frequency scaling (DVFS) is a commonly-used technique to save power at chip level power management**



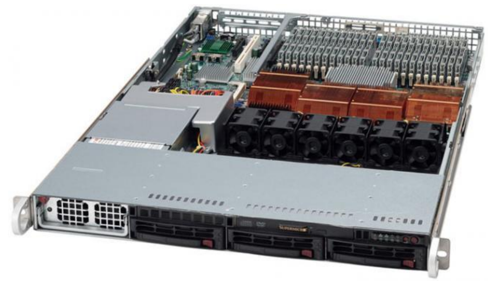

- **Main principle: DVFS is able to reduce the power consumption of CPU by reducing the operating frequency or the supply voltage, as shown by**

$$P = CfV^2 + P_{static}$$

- **where $C$ is the physical capacitance, $V$ is the supply voltage, and $f$ is the operating frequency. The voltage can be reduced as the frequency is reduced . This can yield a significant reduction in power consumption because of the $V^2$ relationship.**

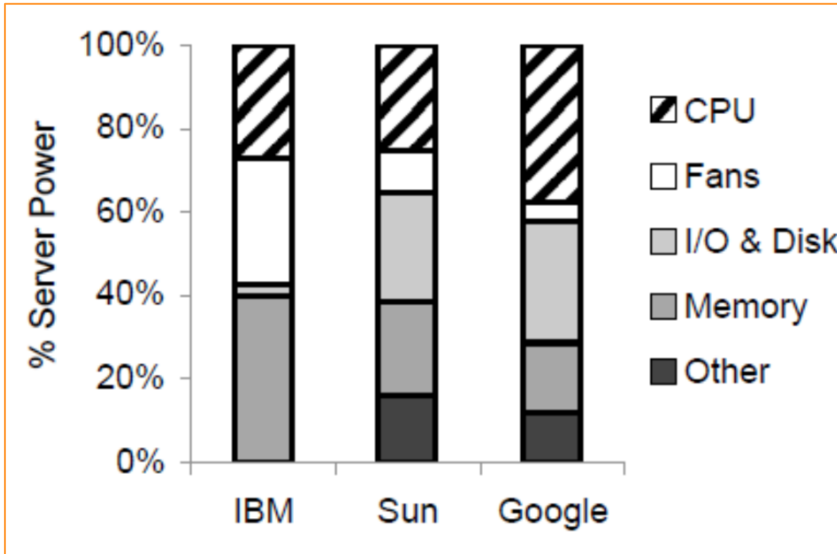
- **Q: what disadvantage after reducing frequency? Delay!**

# Server Level Management



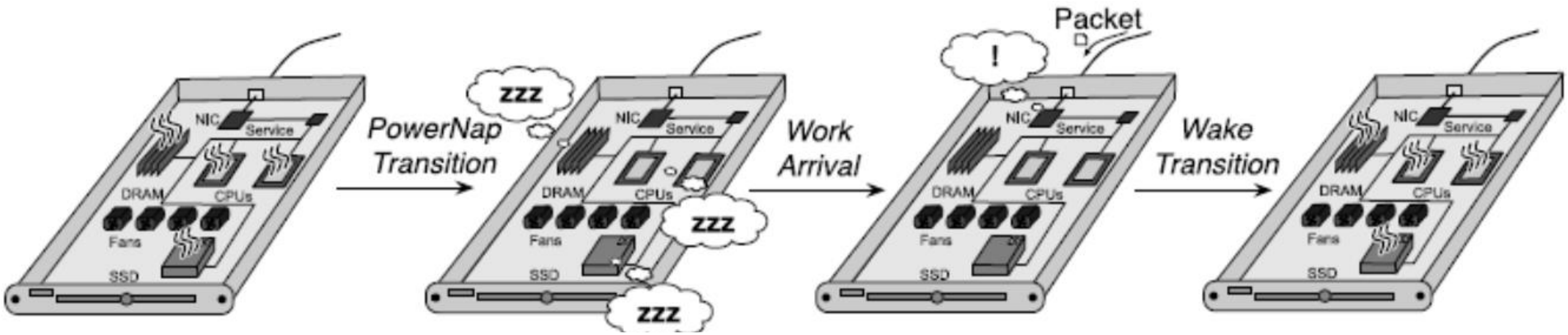
- **A server has many components, including CPU, fans, disk, memory, etc.**

- **DVFS can be highly effective in reducing CPU power. However, CPUs account for a portion of total system power. See typical server power breakdowns for the IBM p670, Sun UltraSparc T2000, and a generic server by Google.**




- **We need an approach that manage the power in the entire server, e.g., transition into a low-power state or sleeping state when there is no job.**

# PowerNap for a Server




Server operates at full performance to finish existing work

System components nap while server is idle

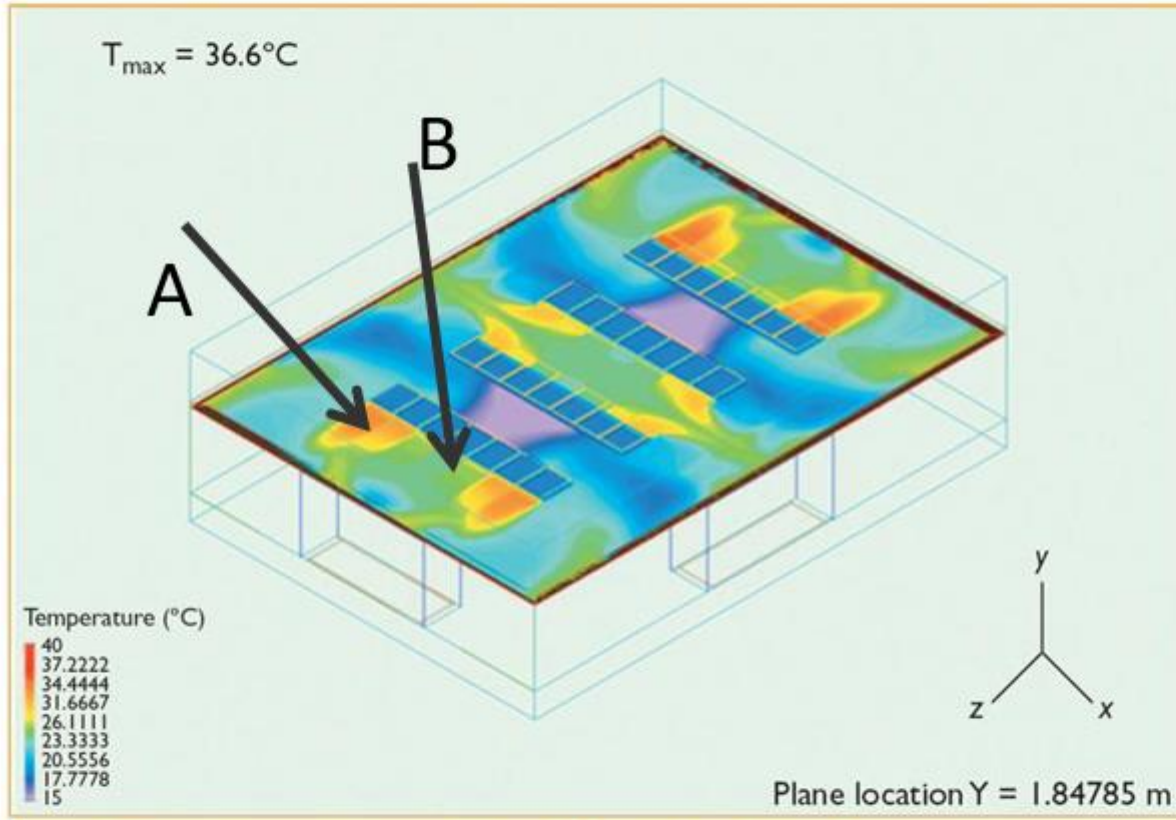
Detect the arrival of work

Server returns to full performance to finish work as quickly as possible

- **Each time the server is done with all pending work, it transits to *the nap state*.**
- **In the nap state: nearly all system components enter sleep mode, which are already available in many components. Power consumption is low, no processing can occur. Components that signal the arrival of new work, or expiration of a software timer remain partially powered.**
- **In the active state: When new work arrives, the system wakes and transitions back to the active state. When the work is complete, the system returns to the nap state.**

# Data Center Level - Workload Migration

- **Observation: different workloads can result in different power consumption.**
- **Reason: too many computation tasks are running in Zone A while only few tasks in Zone B.**
- **Q: how to solve this?**

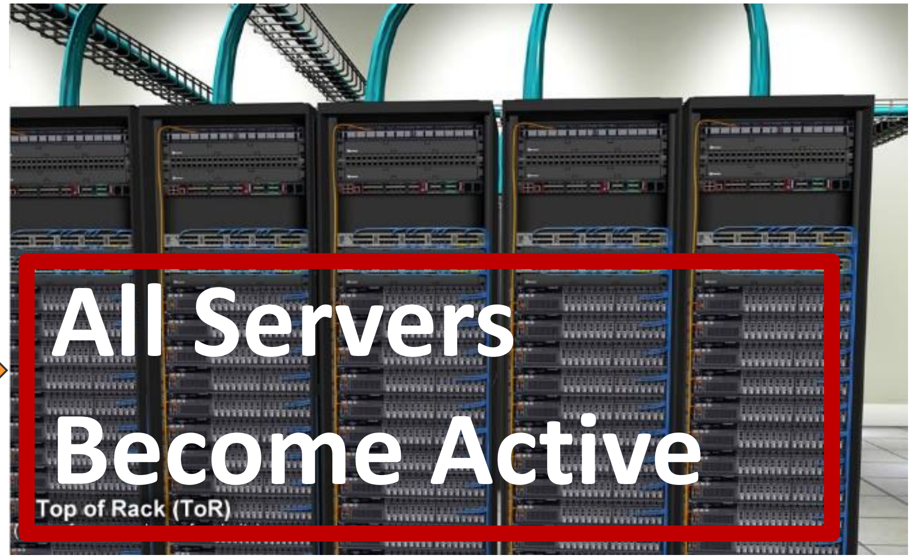



Temperature distribution in data center

- **Solution: moving some computation tasks from Zone A to Zone B to have lower overall power consumption**

# Data Center Level – Dynamic Component Deactivation

World Cup




**Main idea:** Allow servers to be dynamically turned off to save energy and only turn on minimum servers to finish tasks.

Midnight

# Inter Data Centers Level: geographical load balancing

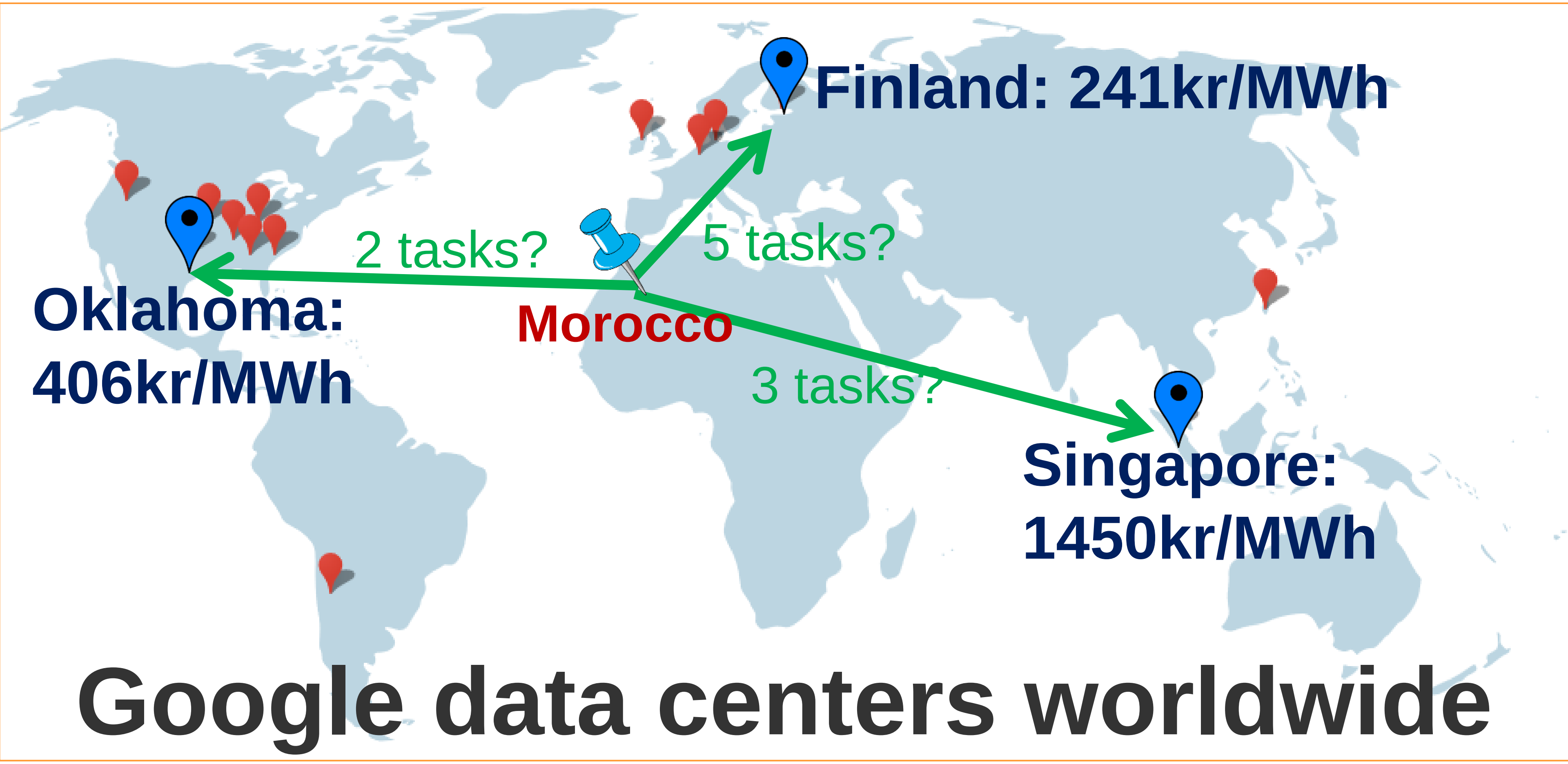
- **Q: what is the difference between these locations?**

# Inter Data Centers Level: exploiting location diversity

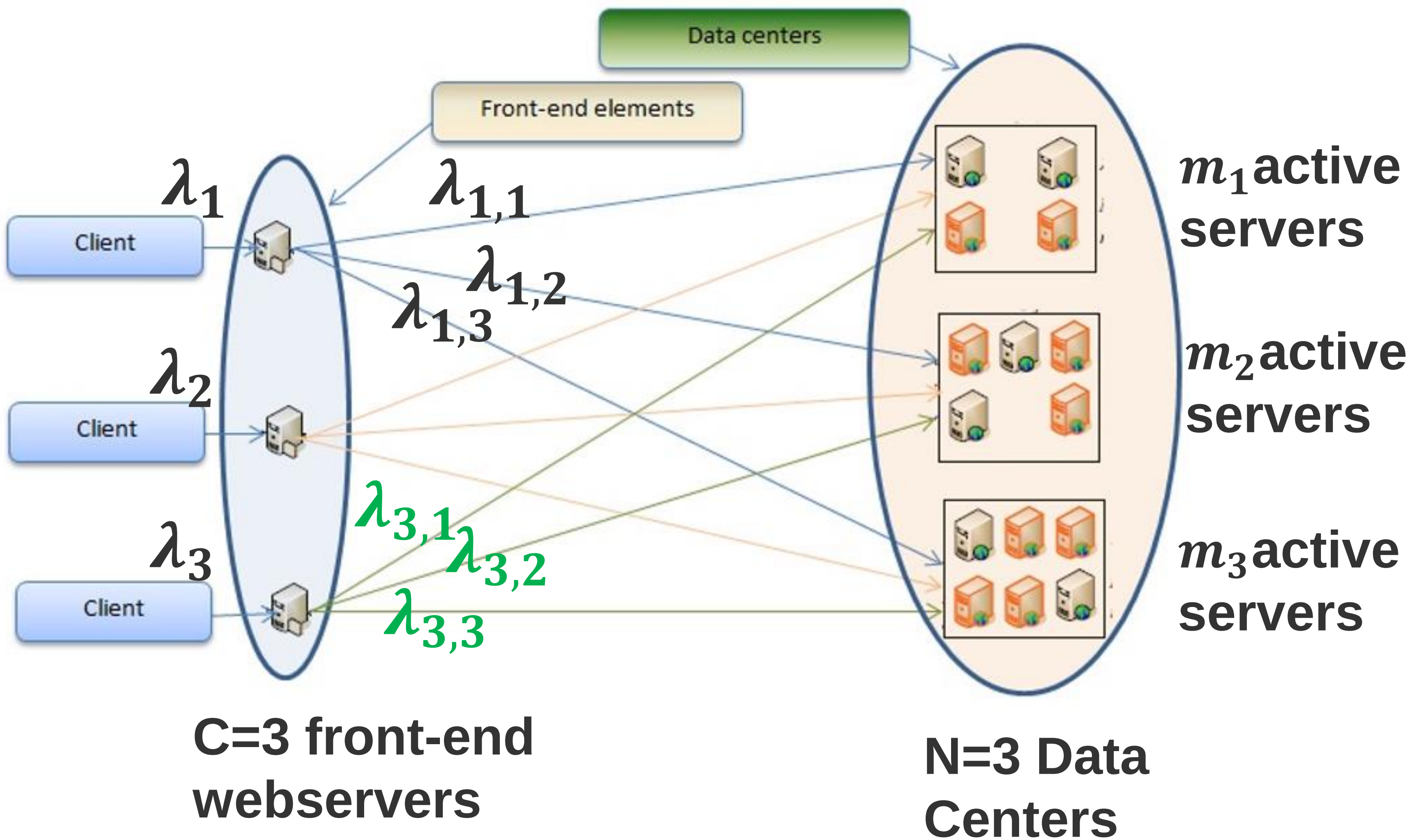
- **Different geographical distance from service requests**
  - **Your requests may be directed to the data center in Finland since you are geographically close to Finland**
- **Different working load**
  - **Your requests may be directed to the data center where there is low working load**
- **Different electricity price**
  - **Your requests may be directed to a data center with low electricity price to reduce energy cost**
- **Different renewal energy sources availability, greenness, and CO2 emission**
  - **Your requests may be directed to the data center where renewable energy is readily available**

# An Example: allocating tasks to minimize energy cost (similar as demand response concept in Lecture 3)

- **Three locations have different electricity prices. We need to allocate computation tasks to different locations to minimize the total energy cost in all three data centers**



# An Example with N=3 Data Centers



# Energy Cost Problem – Workload Constraint

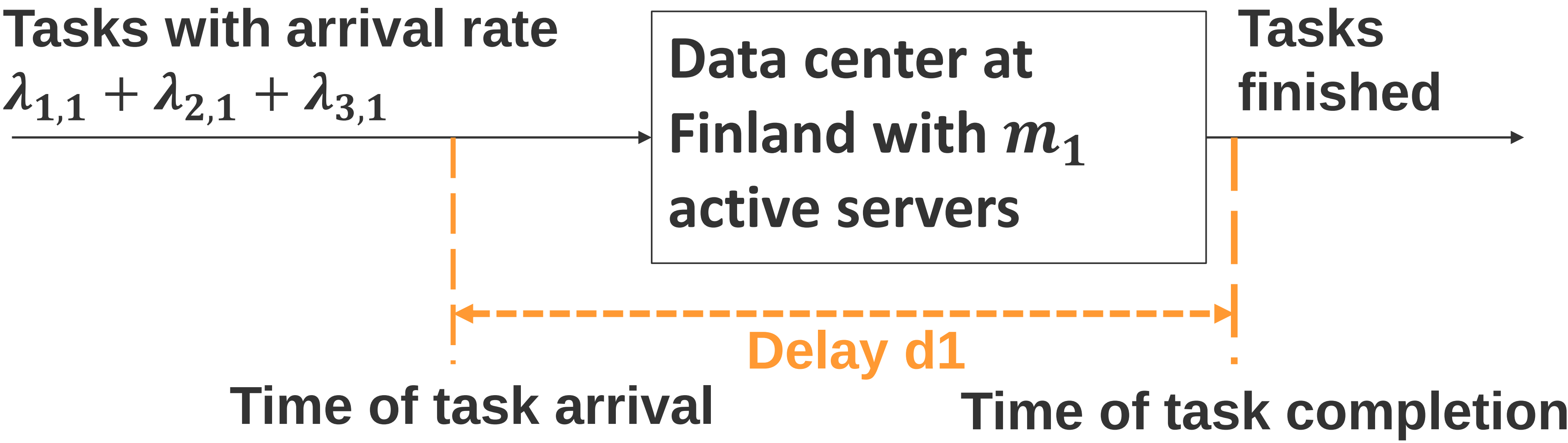
- **A client request is first handled by a front-end Web server, then it is forwarded to one server at a specific location of the data center to be processed. The request arrival rate from front-end Web server *j* to data center *i* is $\boldsymbol{\lambda_{j,i}}$. We denote the requests demand at each front-end Web server *j* as $\boldsymbol{\lambda_j}$ $(\boldsymbol{j = 1, 2, \dots C})$. Therefore we have:**

$$\sum_{i=1}^{N} \lambda_{j,i} = \lambda_j; j = 1,2 \dots C$$

- **At each data center, there are usually hundreds or even thousands servers to afford large number of requests. However, the number of active servers $\boldsymbol{m_i}$ should not be larger than the total number of servers $\boldsymbol{M_i}$ at each data center *i*. Therefore, we have**

$$m_i \leq M_i; i = 1,2 \dots N$$

# Energy Cost Problem – delay requirement




- $m$ active servers in a data center will deal with tasks from all customers.
- When all requests go to Finland with the lowest electricity price, the energy cost may be very low. However, the customers may have to wait for a very long time to get response which is not favorable.
- Hence, there is a constraint related to the allowed latency, e.g., 1 sec. That is, the service delay $d_1$ should not be longer than the allowed latency $D_1$.

# Energy Cost Minimization

- **Energy cost minimization:**

$$\min_{\lambda} \sum_{h=1}^{24} \underline{\left(m_1 P_1^h + m_2 P_2^h + m_3 P_3^h\right)}$$

Cost from all data centers in hour *h*

**Subject to**

$$\sum_{i=1}^{N} \lambda_{j,i} = \lambda_j; j = 1,2 \ldots C$$

$$m_i \leq M_i; i = 1,2 \ldots N$$

$$d_i \leq D_i; i = 1,2 \ldots N$$

– **where $P_i^h$ denote the price of electricity at datacenter i at hour *h*.**

- **Q: Is this a linear programming optimization problem?**
  - **No, the delay constraint is not linear. More interest? Need to read a queueing theory book and M/G/m queueing model**

# MORE CONSIDERATIONS…

# Data Centers Use Renewable Energy as Power Sources

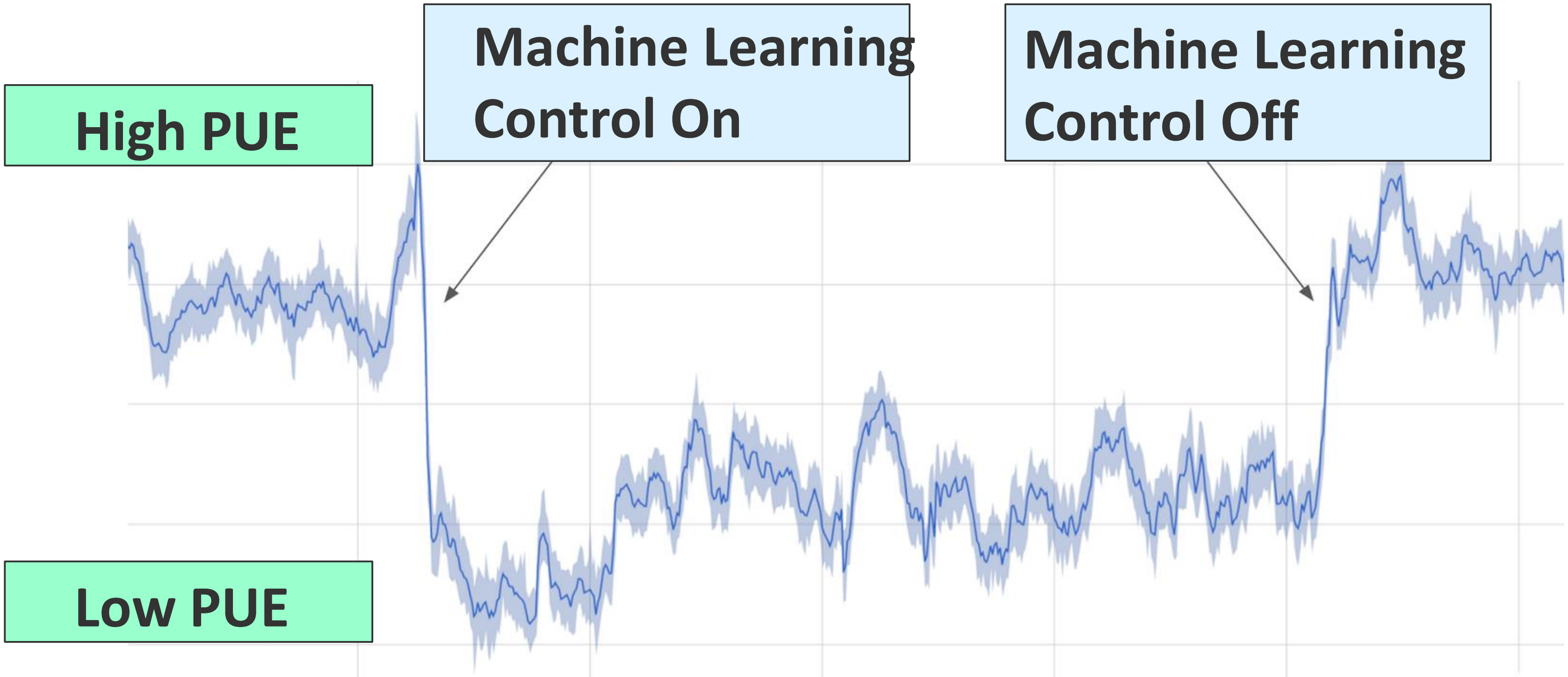
- **Apple plans to build a 200 MW solar array to power its data center in Reno, Nevada**

- **Q: what are the main challenges data centers face in using solar power?**

- **Reliability: because of solar power's intermittency, data centers must be prepared to store it or supplement it. Centers typically use electricity from solar panels to power daytime operations, and apply any excess to charge UPS (uninterruptible power supply) systems. <u>The real challenge</u> isn't in finding alternatives to supplement solar power, but in having the intelligence to optimize the use of each power source.**

- **Quality: The second issue must be addressed in order to protect sensitive IT assets i.e., power quality to stabilize against fluctuations is important.**

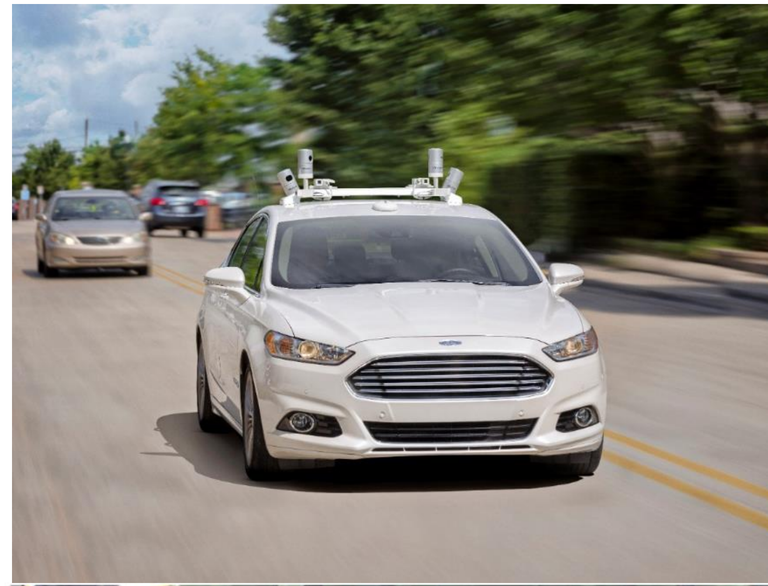
# Google’s DeepMind cut its Energy Bills by 40%




- “…build a better predictive model that essentially uses less energy to power the cooling system by more accurately predicting when the incoming computation load is likely to land,“
- The DeepMind team collected data for five years and created a prediction model for how much energy would be needed by the data center based on the amount of server usage that was likely.

# Green mini-Data Center in Self-driving Cars

- **Ford's self-driving car road test**
- **Q: why do we need mini-data center in self-driving car?**



- **A self-driving  car generate 1 GB/second data and it requires real-time processing to make correct decisions.**
- **Computation equipment in the car**

# References


- **“Er, what is a data center”, Intellect, TechUK.** **https://www.techuk.org/images/documents/Data_Centres_-_CCA/Note_03_Er_what_is_a_data_centre.pdf**

- **A. Rahman, X. Liu and F. Kong, "A Survey on Geographic Load Balancing based Data Center Power Management in the Smart Grid Environment", in IEEE Communications Surveys and Tutorials (COMST), vo.16, no.1, 2014.**