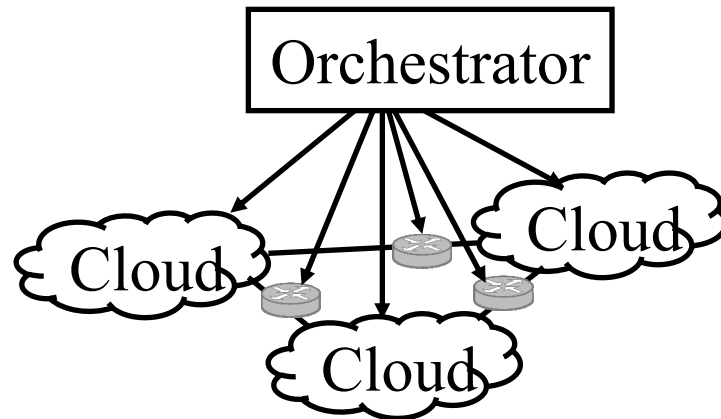


# Trends and Issues in Softwarization of Networks: What's In, What's Out



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Keynote at IEEE Conference on Network Softwarization,  
Montreal, Canada, June 26, 2018

These slides and recording of this talk are available on-line at:

<http://www.cse.wustl.edu/~jain/talks/netsoft.htm>



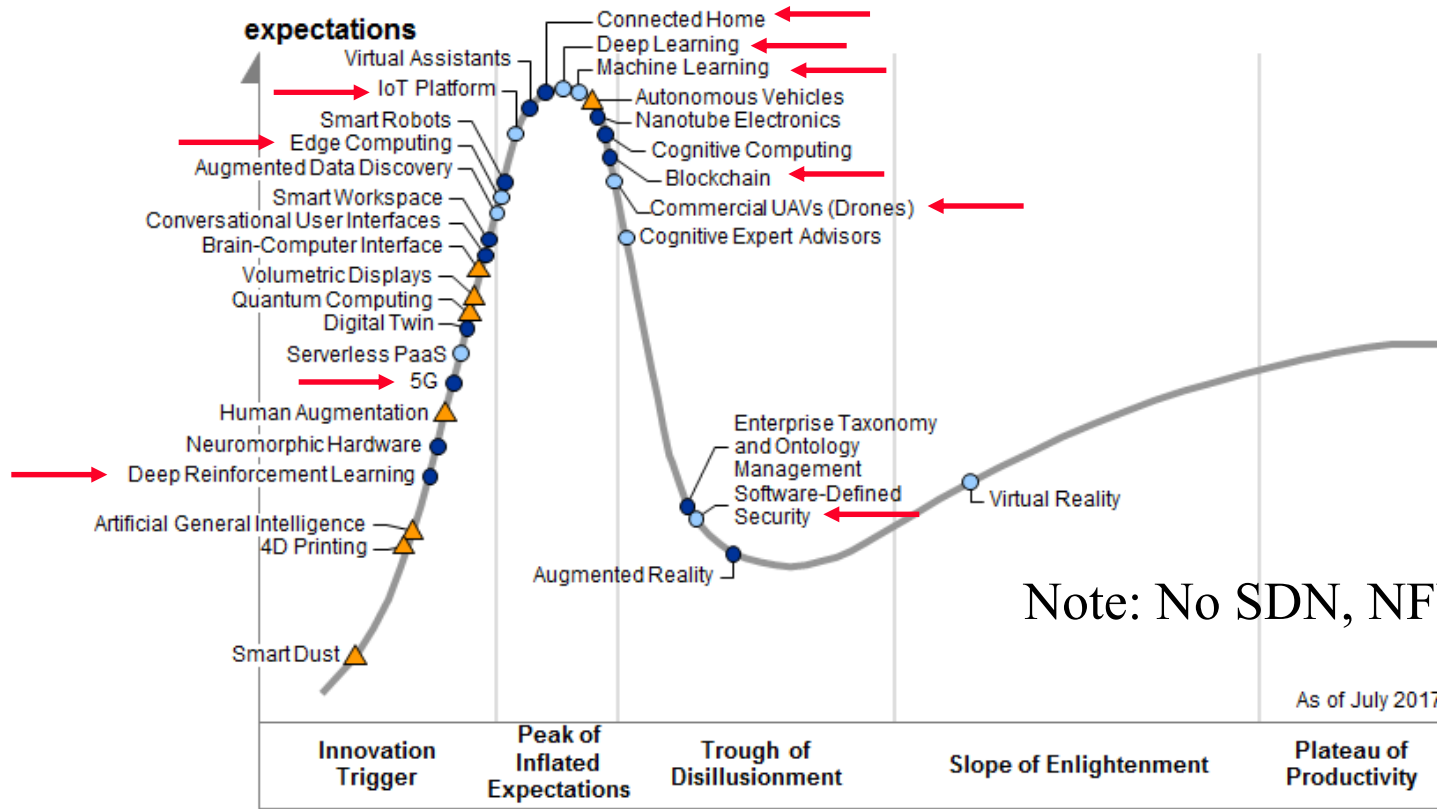
1. What has changed in the last five years?
2. What has happened to SDN, NFV, and Clouds?
3. What's in, what's out?

# Selecting the Right Problems

- ❑ Important question for **students**, academics, entrepreneurs, and companies
- ❑ Goal: To impact
- ❑ Follow the **paradigm shifts**:
  - 1980: Ethernet
  - 1990: ATM Networks
  - 2000: Optical Networks
  - 2005: Wireless Networks
  - 2010: Next Generation Internet/SDN
  - 2013: Multi-Cloud Computing
  - 2018: Whatever is being **hyped** this year?



# Gartner Hype Cycle 2017



Note: No SDN, NFV, ...

As of July 2017

VC investment ← | Acquisitions By large corporations | → Mass Production

Ref: Gartner, "Hype Cycle for Emerging Technologies, 2017," July 2017, [subscribers only]

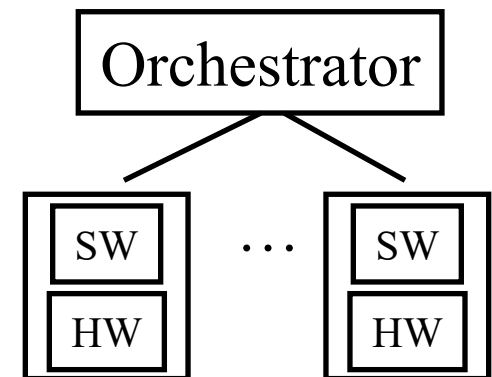
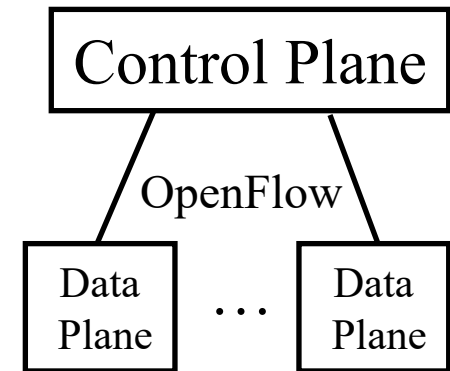
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<http://www.cse.wustl.edu/~jain/talks/netsoft.nfm>

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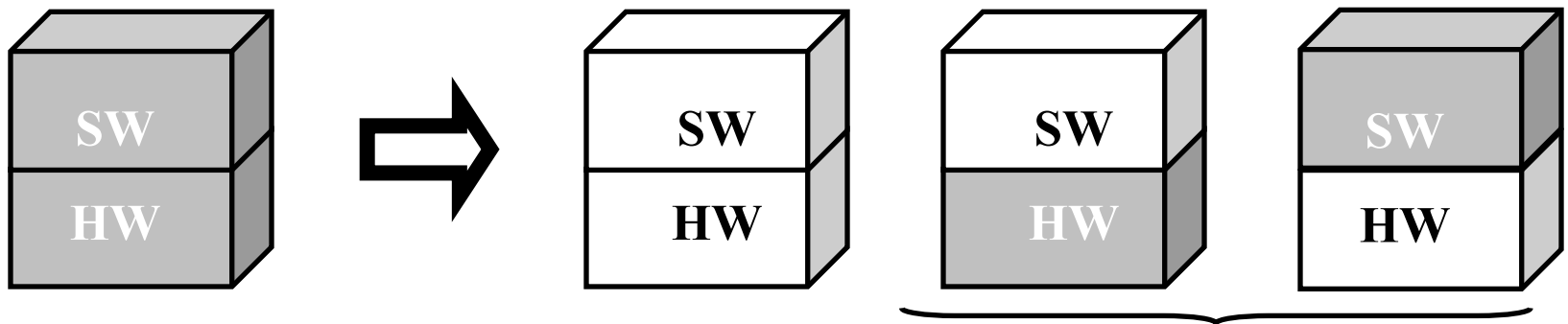
# Trend 1: SDN to Disaggregation

- ❑ SDN was invented in 2009
- ❑ Then: SDN:
  - Separation of control and data planes
  - Centralization of Control
  - Standard Protocol between the planes
- ❑ Now: Software Defined = **Disaggregation** of HW/SW
  - Commodity hardware
  - Software that runs on commodity HW
  - Legacy protocols survive



# Disaggregation: Black Box to White Box

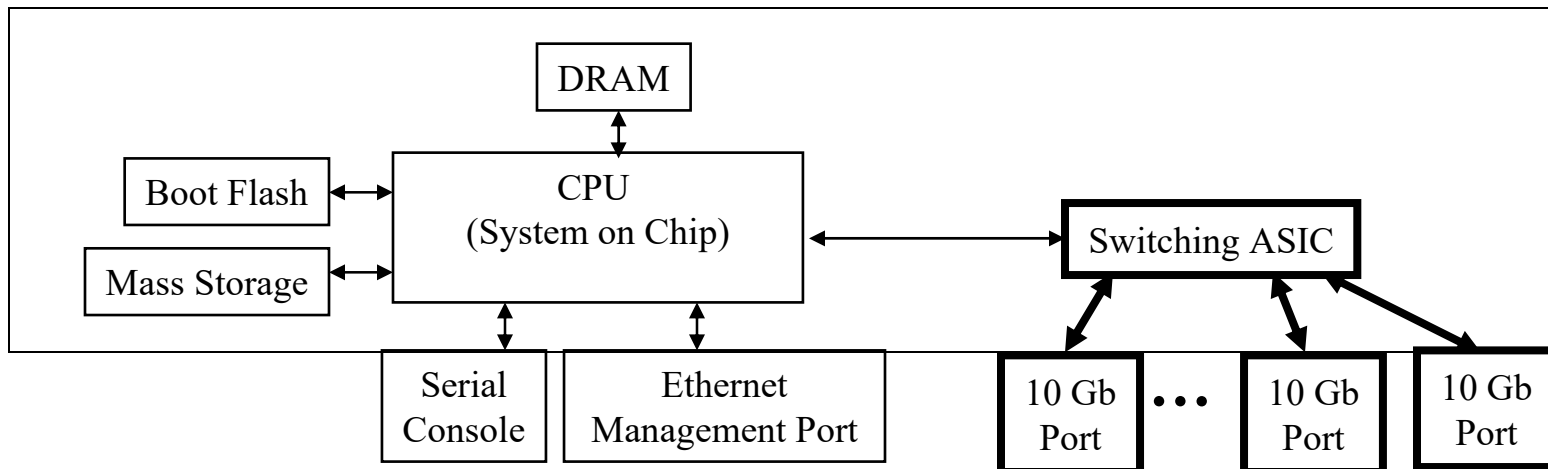
- ❑ All specialization and differentiation via software  
⇒ White box networking
- ❑ **Black Box**: Proprietary HW with Proprietary SW
- ❑ **White Box**: Open Source Hardware and Software
- ❑ Software on a different hardware ⇒ hardware can change  
Different software on a hardware ⇒ Software can change
- ❑ **Bright Box**: Branded White box =  
Branded SW on open HW or Open SW on Branded HW



Ref: A. Lerner, "Branded Switching + White-Box Switching = Brite-Box Switching," Nov 14, 2014,  
<https://blogs.gartner.com/andrew-lerner/2014/11/19/britefuture/>

# White Box Switches

- ❑ Switches by EdgeCore Networks (ACTON), Quanta, HPE, DNI, Dell, Mellanox, Delta Agema, Celestica, Alpha Networks, Ingrasys, Inventec, Netberg
- ❑ Switching ASICs by Broadcom, Marvell, Intel/Fulcrum, Mellanox, Barefoot, and Cavium
- ❑ CPUs: Intel Rangeley/Atom, Freescale, ARM A9



Ref: ONL Hardware Support and Certification, <http://www.opennetlinux.org/hcl>  
Washington University in St. Louis <http://www.cse.wustl.edu/~jain/talks/netsoft.htm>

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# Trend 2: Separation of Control to Orchestration of Policies

Separation and Centralization of Control Plane

Orchestration of Policies

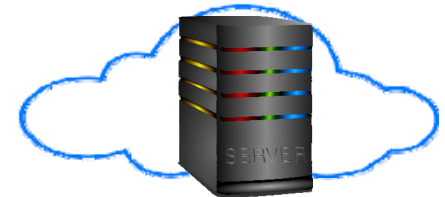


Micromanagement is not scalable



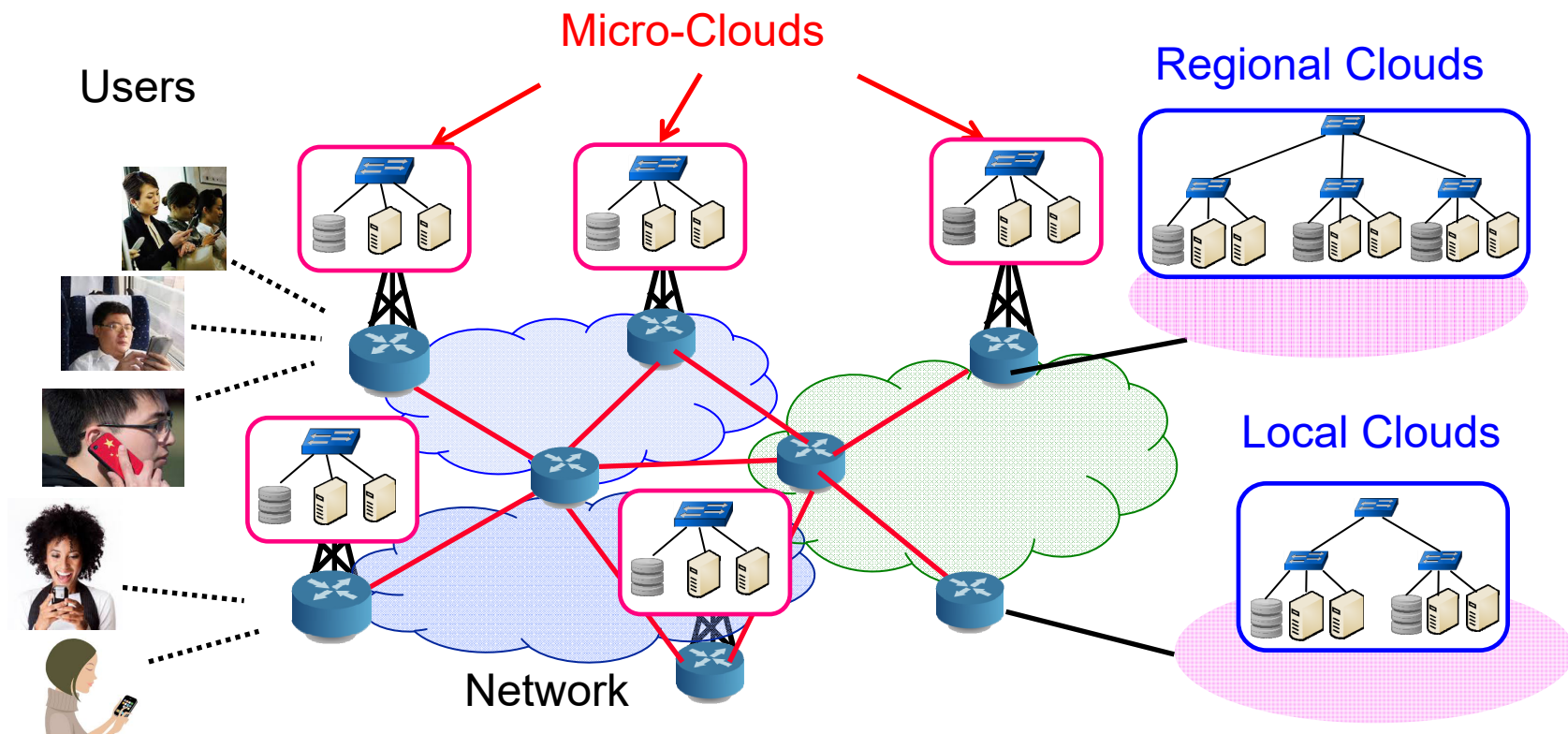
# Trend 3: Clouds to Micro-Clouds

- ❑ Cloud computing was invented in 2006
- ❑ Then: Cloud = Large Data Center  
Multiple VMs managed by a cloud management system (OpenStack)
- ❑ Today: Cloud = Computing using virtual resources
  - $\mu$ Cloud = Cloud in a server with multiple VMs.
  - VMs managed via cloud management SW, e.g., OpenStack



# Trend 4: Core to Edge Computing

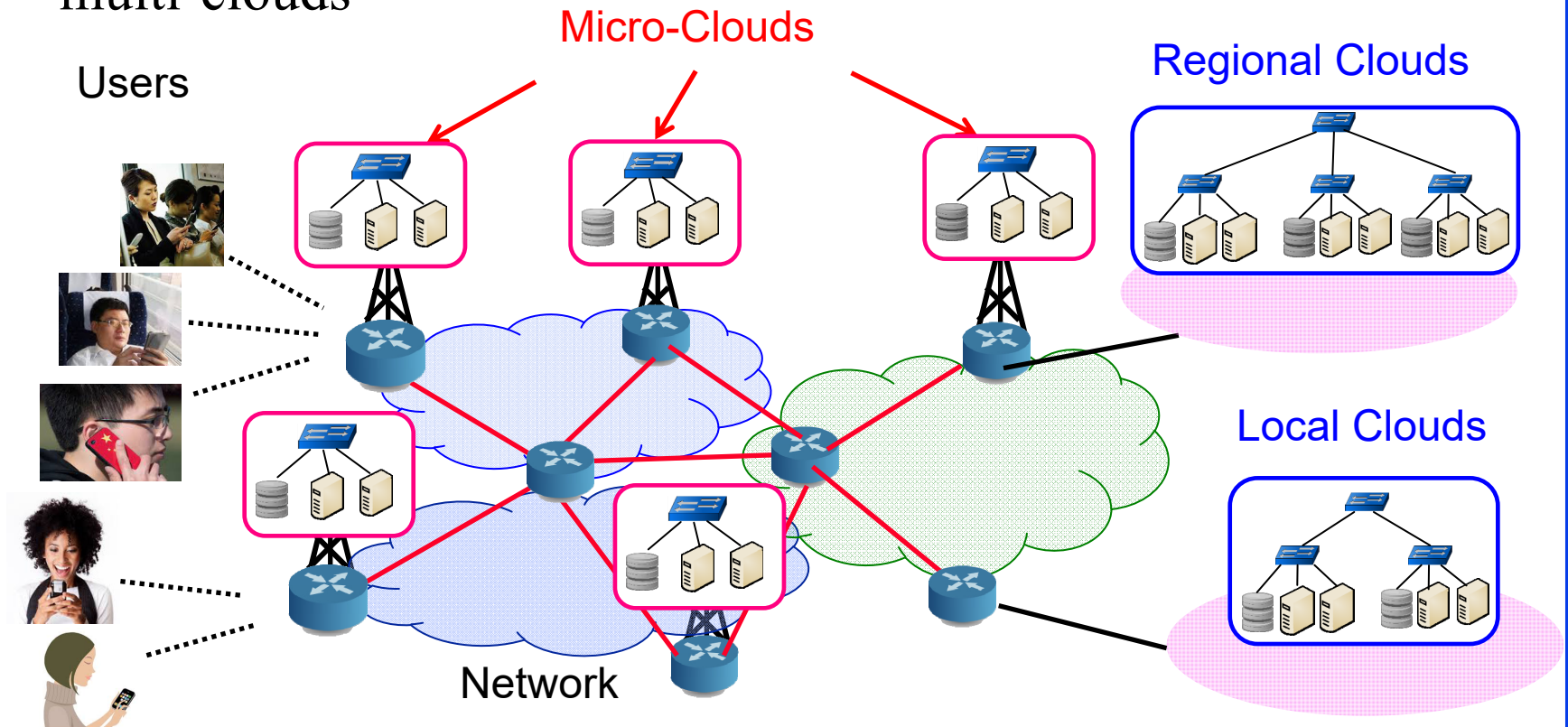
- To service mobile users/IoT, the computation needs to come to edge  $\Rightarrow$  Mobile Edge Computing



Ref: Lav Gupta, Raj Jain, H. Anthony Chan, "Mobile Edge Computing - an important ingredient of 5G Networks," IEEE Softwarization Newsletter, March 2016, <http://www.cse.wustl.edu/~jain/papers/mec16.htm>

# Trend 5: Services to Micro-Services

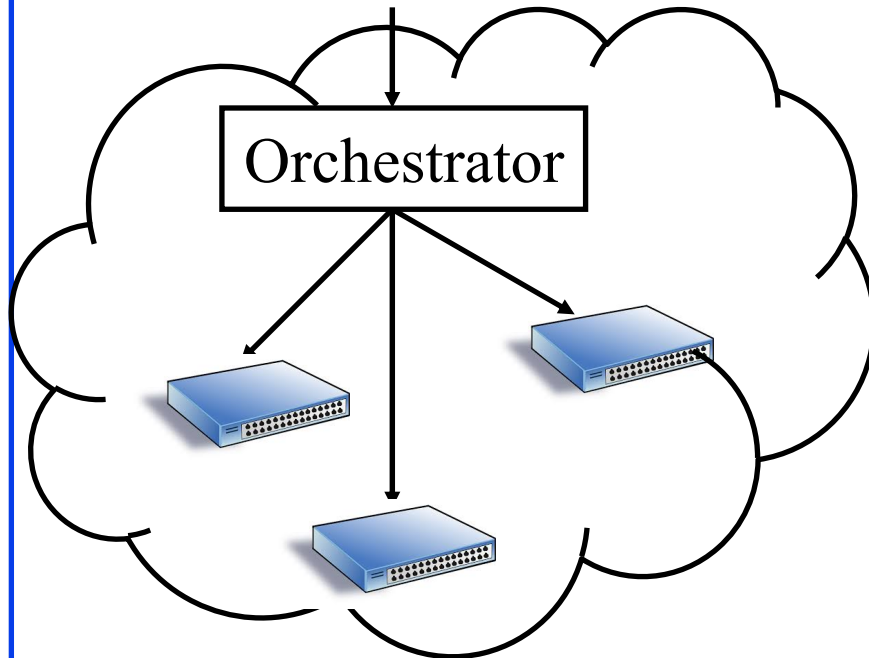
- ❑ **Decomposition:** Applications are broken in to smaller pieces that can be developed, tested, and run in isolation on multi-clouds



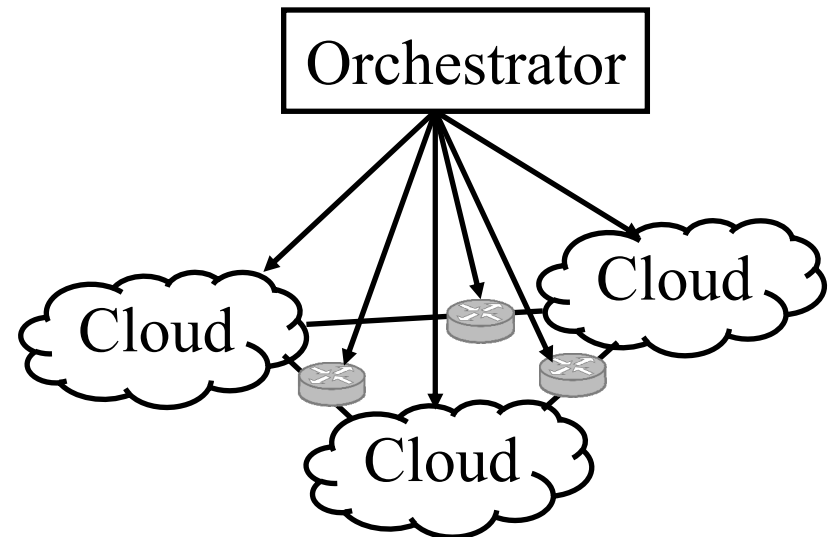
# Trend 6: Orchestration of Switches to Orchestration of Multi-Cloud

- ❑ Orchestrating devices to Orchestrating Clouds
- ❑ Micro-Service placement and optimization in multi-clouds

Datacenter Applications



Global Applications



Ref: Subharthi Paul, Raj Jain, Mohammed Samaka, Jianli Pan, "Application Delivery in Multi-Cloud Environments using Software Defined Networking," Computer Networks Special Issue on cloud networking and communications, December 2013,

<http://www.cse.wustl.edu/~jain/papers/comnet14.htm>

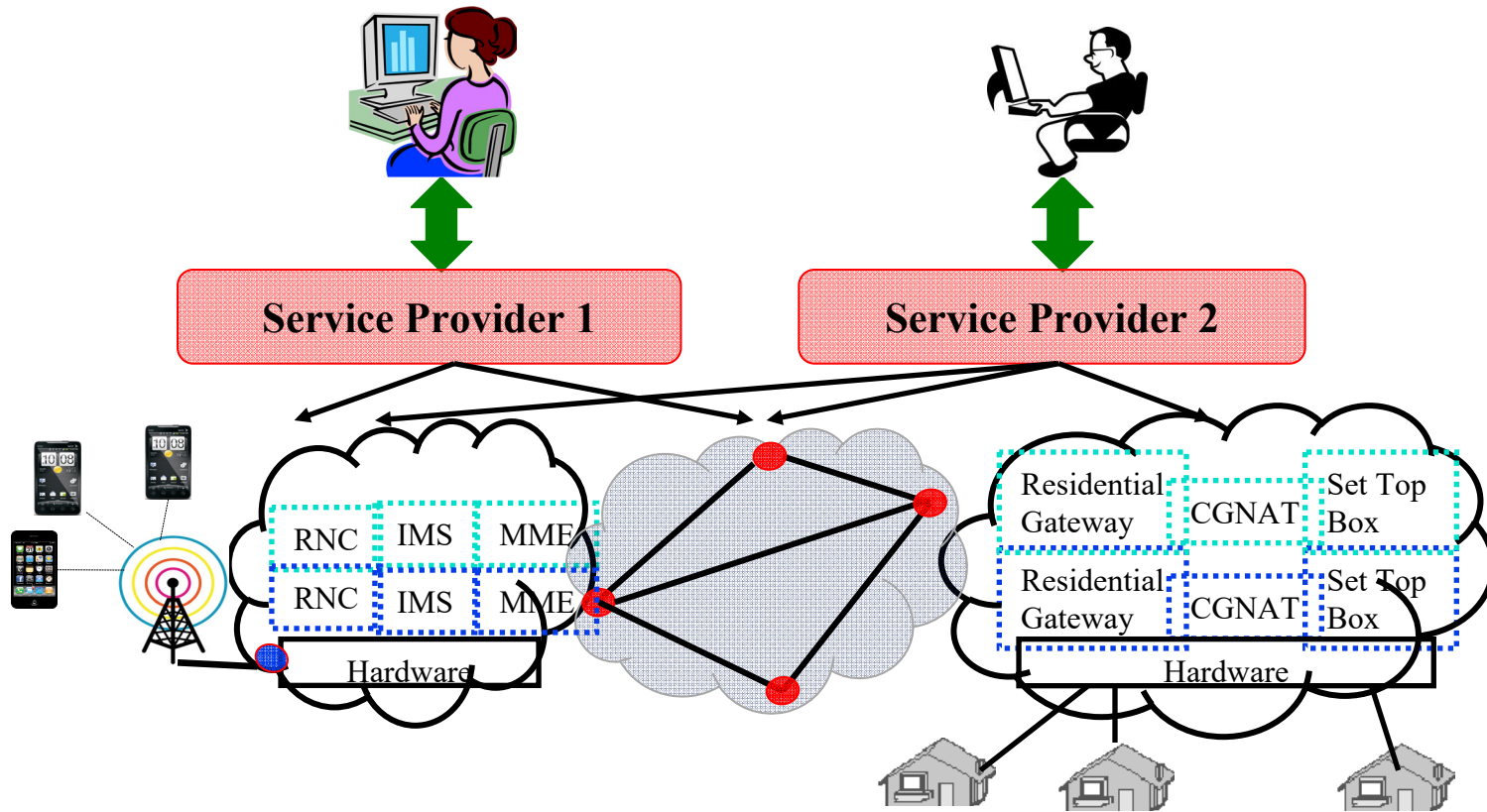
Washington University in St. Louis

<http://www.cse.wustl.edu/~jain/talks/netsoft.htm>

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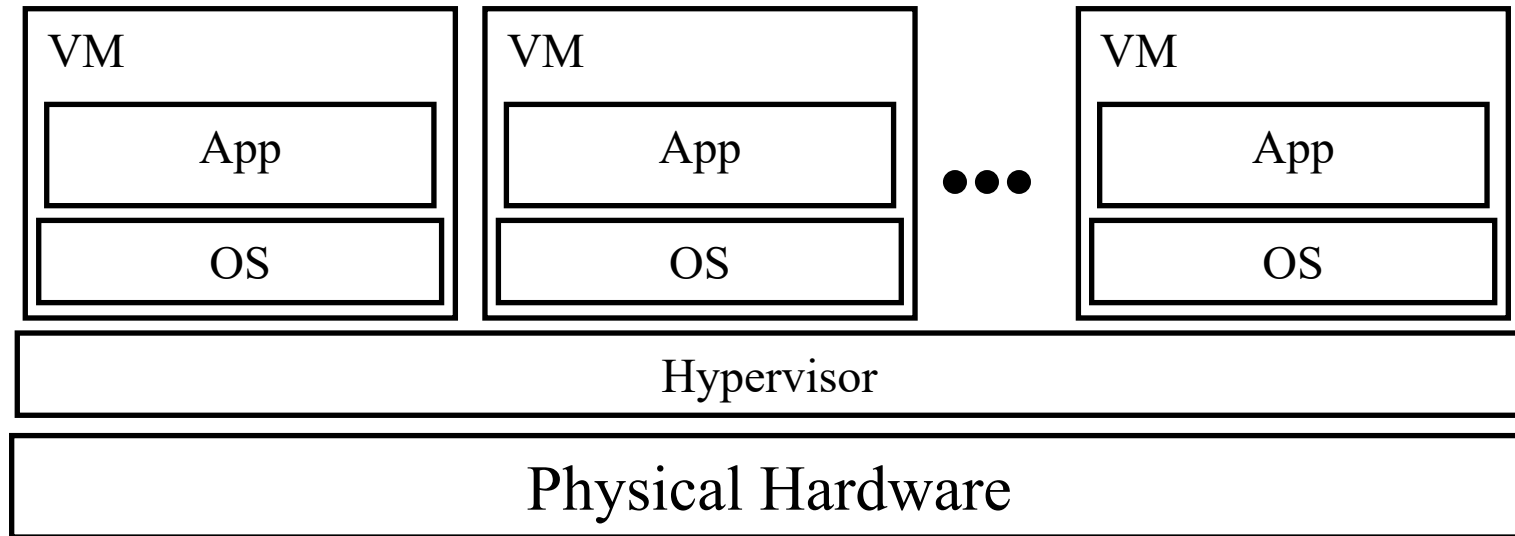
# Network Function Virtualization (NFV)

- Network Functions on Virtual Machines in a cloud



Ref: Raj Jain and Subharthi Paul, "Network Virtualization and Software Defined Networking for Cloud Computing - A Survey," IEEE Communications Magazine, Nov 2013, pp. 24-31, [http://www.cse.wustl.edu/~jain/papers/net\\_virt.htm](http://www.cse.wustl.edu/~jain/papers/net_virt.htm)

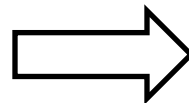
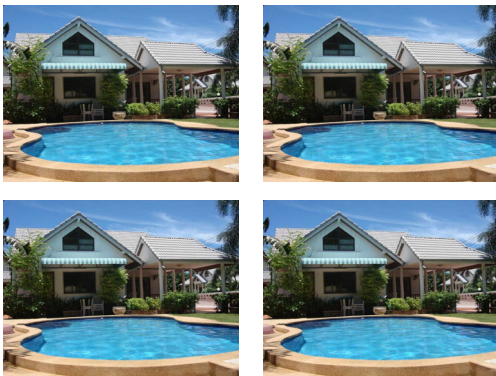
# Problems with Virtual Machines



- ❑ Each VM requires an operating system (OS)
  - Each OS requires a license  $\Rightarrow$  **CapEx**
  - Each OS has its own compute and storage overhead
  - Needs maintenance, updates  $\Rightarrow$  **OpEx**
  - **VM Tax** = added CapEx + OpEx

# Trend 7: Virtualization to Containerization

- ❑ Run many apps in the same virtual machine
  - These apps share the OS and its overhead
  - Can't access each other's resources without explicit permission
  - Like apartments in a complex  $\Rightarrow$  Containers



# Kata Containers

- ❑ Containers do have less security than VMs
- ❑ Kata Containers = VM + Container hybrid
- ❑ Combines “Intel Clear Containers” and “HyperV runV”
- ❑ Open source project under OpenStack Foundation
- ❑ Performance like containers, isolation and security like VMs
- ❑ Package once and run anywhere
  - VMware, Google, and Amazon are all moving towards this approach

Ref: <https://katacontainers.io/>

<https://www.forbes.com/sites/janakirammsv/2017/12/11/why-kata-containers-is-good-for-the-industry-and-customers/2/#3d8cc2e9404f>



# Standards are Slow

- ❑ Initially, Standards  $\Rightarrow$  Interoperability  
Iff all companies implement the same way
- ❑ Standards = Compromises  $\Rightarrow$  We agree to disagree  
All differing opinions are part of the standard as option  
Different companies choose different options  
 $\Rightarrow$  No Interoperability
- ❑ Need Interoperability organizations
  - WiFi  $\Rightarrow$  Approves the subset of standard that is mandatory
- ❑ All this introduces delay  
 $\Rightarrow$  The standard out of date when it is ready for implementation
- ❑ IEEE 802.11ah-2016 Long-Range WiFi for IoT. Started 2010.  
Taken over by competition: ZigBee, LoraWAN, ...

# Standards are not Open

- ❑ Open  $\Rightarrow$  Anyone can implement it without fee
- ❑ IETF allows “non-discriminatory and reasonable licensing fee”  
 $\Rightarrow$  Not really open
- ❑ Open Source Initiative (OSI) Criteria:
  - No intentional secrets
  - Free and publicly available
  - All patents must be royalty-free for unrestricted use
  - No license agreements, NDA, or paperwork to implement
  - Not dependent on non-open standards

# Trend 8: Standards to Open Source SW

- ❑ Standardization to Rough Consensus and Running Code
- ❑ IETF has ~100 working groups  
Open Linux Foundation has >100 open source networking projects. Their website can't be kept uptodate.
- ❑ 4 Opens:
  - Open Source
  - Open Design
  - Open Development
  - Open Community

# Blockchains

- ❑ Blockchain is the technology that made Bitcoin secure
- ❑ Blockchain was invented by the inventor of Bitcoin
- ❑ After Bitcoin became successful, people started looking into the technology behind Bitcoin and found:
  - Blockchain is the key for its success
  - Two complete strangers can complete a transaction/contract without a third party

# Example of a Contract: Wedding



# Wedding (Cont)

## ❑ Centralized Trust



- ❑ Centralized registry
- ❑ Single point of failure
- ❑ Easier to hacked

## ❑ Distributed Trust



- ❑ Decentralized
- ❑ No single point of failure
- ❑ Very difficult to hack

# Trend 9: Centralized to Distributed

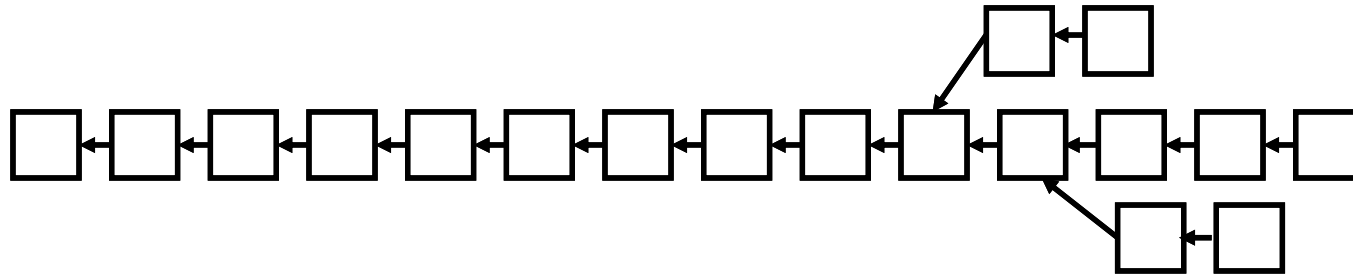
- ❑ **Trend:** Make everything decentralized with no central point of trust
- ❑ Two perfect strangers can exchange money, make a contract without a trusted third party
- ❑ Decentralized systems are
  1. More reliable: Fault tolerant
  2. More secure: Attack tolerant
  3. No single bottleneck  $\Rightarrow$  Fast
  4. No single point of control  $\Rightarrow$  No monopoly
- ❑ Blockchain is one way to do this among **untrusted multi-domain** systems.

Time is a cycle: Distributed vs. Centralized debate

# Blockchains

## □ How is it done?

- A singly linked chain of blocks of verified signed transactions is replicated globally on millions of nodes
- You will have to change millions of nodes to attack/change



- ## □ Who is interested: Banks, Hospitals, Venture Capitalists, ...
- ⇒ Researchers, students, ...



# Examples of Centralized Systems

- ❑ **Banks:** Allow money transfer between two accounts
- ❑ **Currency:** Printed and controlled by the government
- ❑ **Stock Exchanges:** Needed to buy and sell stocks
- ❑ **Networks:** Certificate Authorities, DNS
- ❑ In all cases:
  1. There is a central third party to be trusted
  2. Central party maintains a large database of information  
⇒ Attracts Hackers
  3. Central party may be hacked ⇒ affects millions
  4. Central party is a single point of failure.  
Can malfunction or be bribed.

# Networking Applications of Blockchains

## ❑ Multi-Domain Systems:

- Multiple Cloud Service Providers
- Multiple cellular providers
- Multi-Interface devices: WiFi, Cell, Bluetooth, ...
- BGP: BGP Authentication

## ❑ Globally Centralized Systems:

- DNS
- Public Key Infrastructure
  - ❑ Certificate Authorities issue certificates
  - ❑ Single Point of Failure
  - ❑ Example: Diginotar – Dutch CA compromised in 2011

Explore blockchains for multi-domain/centralized systems

# Smart Everything



Smart Watch



Smart TV



Smart Car



Smart Health



Smart Home



Smart Kegs



Smart Space



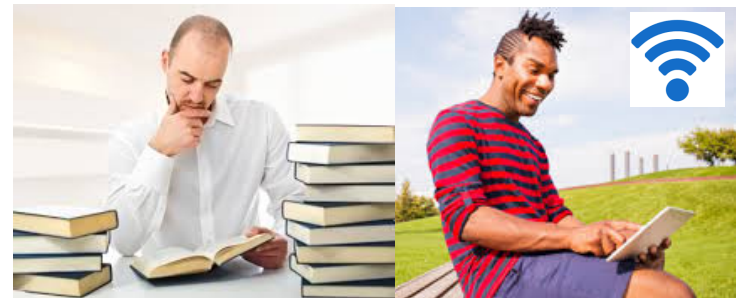
Smart Industries



Smart Cities

# What's Smart?

- ❑ Old: Smart = Can think  $\Rightarrow$  Computation  
= Can Recall  $\Rightarrow$  Storage
- ❑ Now: Smart = Can find quickly, Can Delegate  
 $\Rightarrow$  Communicate = Networking
- ❑ Smart Grid, Smart Meters, Smart Cars, Smart homes, Smart Cities, Smart Factories, Smart Smoke Detectors, ...

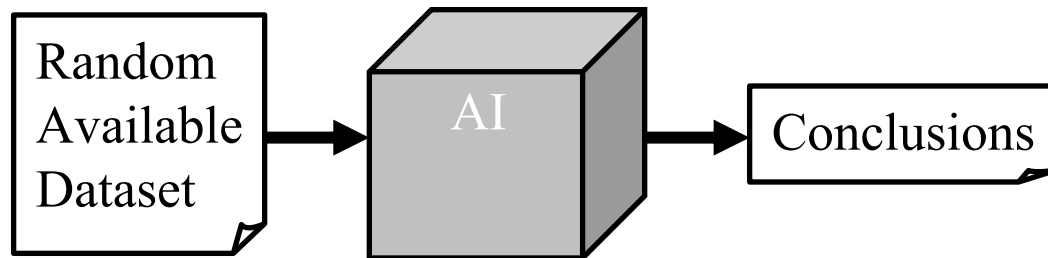


Not-Smart

Smart

# Trend 10: Smart to Intelligent

- ❑ AI everywhere
- ❑ Issue: AI is currently a blackbox
- ❑ AI algorithms are developed without knowledge of the system
- ❑ AI algorithms are used without knowledge of the system
- ❑ No idea of where the input came from  
⇒ No idea of why the results are what they are
- ❑ Garbage-In, Garbage-Out  
Random-In, Random-Out



# Trend 11: Managed to Self-Driven Networks

- ❑ **Self-Discover:** Find its components
- ❑ **Self-Organize and Self-configure:** Trending. Predict.
- ❑ **Auto-Manage** = Auto-BSS (bill)/Auto-OSS (provision)
- ❑ **Self-Monitor:** Counters and Probes. Telemetry
- ❑ **Self-Diagnose and Self-Heal:** Self-Report to human operator

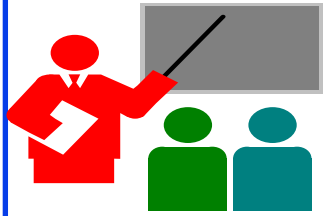


**Network Manager**

# Intent-Based Policy Management

- ❑ **Intent:** Tell what you want. Not how you want it done.  
E.g., Tell Google maps where you want to go. Not how to.
- ❑ **Invariance:** Intent doesn't change if the network changes, devices fail, ...
- ❑ **Portability:** Independent of infrastructure, equipment vendors, service providers, protocols used, media used, ...
- ❑ **Compose-ability:** Can use any infrastructure, ...
- ❑ **Scalable:** From one to billions. Single controllers not scalable.
- ❑ Action requires context: Actions need to adopt to changes in infrastructure
- ❑ OpenDaylight has a new project on Network Intent Composition (NIC)

Ref: <https://www.sdxcentral.com/articles/contributed/network-intent-summit-perspective-david-lenrow/2015/02/>  
[https://wiki.opendaylight.org/view/Project\\_Proposals:Network\\_Intent\\_Composition](https://wiki.opendaylight.org/view/Project_Proposals:Network_Intent_Composition)



# Summary

#	Past	Present/Future
1	SDN	Disaggregation
	Proprietary Black Boxes	Standardized White Boxes
2	Control	Orchestration
3	Clouds	Micro-Clouds
4	Core	Edge
5	Services	Micro-services
6	Orchestration of Switches	Orchestration of Multi-Cloud
7	Virtualization	Containerization
8	Standards	Open-Source SW
9	Centralized	Distributed
10	Smart	Intelligent
11	Managed	Self-Driven

1. Networking is changing faster than PhD research cycles
2. For impact/success, publishing is not sufficient.  
Implement your research in open source SW.



# Related Papers

## Multi-Cloud:

- ❑ Deval Bhamare, Mohammed Samaka, Aiman Erbad, Raj Jain, Lav Gupta, H. Anthony Chan, "**Optimal Virtual Network Function Placement and Resource Allocation in Multi-Cloud Service Function Chaining Architecture**," Computer Communications, Vol. 102, April 2017, pp. 1-16, <http://www.cse.wustl.edu/~jain/papers/comcom17.htm>
- ❑ Deval Bhamare, Raj Jain, Mohammed Samaka, Aiman Erbad, "**A Survey on Service Function Chaining**," Journal of Network and Computer Applications, Vol. 75, Nov 2016, pp. 138-155, <http://www.cse.wustl.edu/~jain/papers/jnca16.htm>
- ❑ Lav Gupta, Prof Raj Jain, Prof Mohammed Samaka, Prof Aiman Erbad, and Dr. Deval Bhamare, "**Performance Evaluation of Multi-Cloud Management and Control Systems**," Recent Advances in Communications and Network Technology, 2016, Vol. 5, Issue 1, pp. 9-18, <http://www.cse.wustl.edu/~jain/papers/racnt.htm>
- ❑ Subharthi Paul, Raj Jain, Mohammed Samaka, Aiman Erbaud, "**Service Chaining for NFV and Delivery of other Applications in a Global Multi-Cloud Environment**," 21st Annual International Conference on Advanced Computing and Communications (ADCOM) 2015, Chennai, India, September 18-20, 2015, [http://www.cse.wustl.edu/~jain/papers/adn\\_in15.htm](http://www.cse.wustl.edu/~jain/papers/adn_in15.htm)

# Related Papers (Cont)

## Edge Computing:

- ❑ Lav Gupta, Raj Jain, H. Anthony Chan, "**Mobile Edge Computing - an important ingredient of 5G Networks**," IEEE Softwarization Newsletter, March 2016, <http://sdn.ieee.org/newsletter/march-2016/mobile-edge-computing-an-important-ingredient-of-5g-networks>
- ❑ Deval Bhamare, Aiman Erbad, Raj Jain, Mohammed Samaka, "**Automated Service Delivery Platform for C-RANs**," The IEEE Third International Workshop on Mobile Cloud Computing systems, Management, and Security (MCSMS) 2017, Valencia Spain, May 8-11, 2017, <http://www.cse.wustl.edu/~jain/papers/mcsms17.htm>,

# Related Papers (Cont)

## Micro-Services:

- ❑ Deval Bhamare, Mohammed Samaka, Aiman Erbad, Raj Jain, Lav Gupta, **"Exploring Micro-Services for Enhancing Internet QoS,"** Transactions on Emerging Telecommunications Technologies, Accepted June, 2018, ISSN: 2161-3915, DOI: 10.1002/ett.3445, [http://www.cse.wustl.edu/~jain/papers/ms\\_ett18.htm](http://www.cse.wustl.edu/~jain/papers/ms_ett18.htm)
- ❑ Deval Bhamare, Aiman Erbad, Raj Jain, Maede Zolanvari, Mohammed Samaka, **"Efficient Virtual Network Function Placement Strategies for Cloud Radio Access Networks,"** Computer Communications, Volume 127, May 2018, pp. 50-60, ISSN 0140-3664, DOI: [10.1016/j.comcom.2018.05.004](https://doi.org/10.1016/j.comcom.2018.05.004)
- ❑ Deval Bhamare, Mohammed Samaka, Aiman Erbad, Raj Jain, Lav Gupta, H. Anthony Chan, **"Multi-Objective Scheduling of Micro-Services for Optimal Service Function Chains,"** International Conference on Communications (ICC 2017), May 21-25, 2017, <http://www.cse.wustl.edu/~jain/papers/icc17.htm>

# Related Papers (Cont)

## Micro-Services (Cont):

- ❑ Deval Bhamare, Raj Jain, Mohammed Samaka, Gabor Vaszkun, Aiman Erbad, "**Multi-Cloud Distribution of Virtual Functions and Dynamic Service Deployment: OpenADN Perspective**," 2015 IEEE International Conference on Cloud Engineering (IC2E), Tempe, AZ, March 9-13, 2015, pp. 299-304, [http://www.cse.wustl.edu/~jain/papers/vm\\_dist.htm](http://www.cse.wustl.edu/~jain/papers/vm_dist.htm)
- ❑ Deval Bhamare, Raj Jain, Mohammed Samaka, Aiman Erbad, "**A Survey on Service Function Chaining**," Journal of Network and Computer Applications, Vol. 75, Nov 2016, pp. 138-155, ISSN: 10848045, DOI: 10.1016/j.jnca.2016.09.001, <http://www.cse.wustl.edu/~jain/papers/jnca16.htm>

# Related Papers (Cont)

## AI for Networking:

- ❑ Lav Gupta, M. Samaka, Raj Jain, Aiman Erbad, Deval Bhamare, H. Anthony Chan, "**Fault and Performance Management in Multi-Cloud Based NFV using Shallow and Deep Predictive Structures**," 26th International Conference on Computer Communications and Networks (ICCCN 2017), Vancouver, Canada, July 31-Aug 3, 2017, <http://www.cse.wustl.edu/~jain/papers/icccn17.htm>
- ❑ Tara Salman, Deval Bhamare, Aiman Erbad, Raj Jain, Mohammed Samaka, "**Machine Learning for Anomaly Detection and Categorization in Multi-cloud Environments**," The 4th IEEE International Conference on Cyber Security and Cloud Computing (IEEE CSCloud 2017), New York, June 26-28, 2017, <http://www.cse.wustl.edu/~jain/papers/cscloud.htm>
- ❑ Lav Gupta, Mohammed Samaka, Raj Jain, Aiman Erbad, Deval Bhamare, Chris Metz, "**COLAP: A Predictive Framework for Service Function Chain Placement in a Multi-cloud Environment**," The 7th IEEE Annual Computing and Communication Workshop and Conference (CCWC), Las Vegas, Jan 9-11, 2017, [http://www.cse.wustl.edu/~jain/papers/clp\\_ccwc.htm](http://www.cse.wustl.edu/~jain/papers/clp_ccwc.htm)
- ❑ Deval Bhamare, Tara Salman, Mohammed Samaka, Aiman Erbad, Raj Jain, "**Feasibility of Supervised Machine Learning for Cloud Security**," 3rd International Conference on Information Science and Security (ICISS2016), December 19th - 22nd, 2016, Pattaya, Thailand,, <http://www.cse.wustl.edu/~jain/papers/iciss16.htm>

# Related Papers (Cont)

## IoT:

- Tara Salman, Raj Jain, "A Survey of Protocols and Standards for Internet of Things," Advanced Computing and Communications, Vol. 1, No. 1, March 2017, [http://www.cse.wustl.edu/~jain/papers/iot\\_accs.htm](http://www.cse.wustl.edu/~jain/papers/iot_accs.htm)

# Related Talks/Class Lectures

- ❑ Raj Jain, “**CSE 570: Recent Advances in Networking,**” Spring 2018, <http://www.cse.wustl.edu/~jain/cse570-18/index.html>
- ❑ Raj Jain, "**Blockchains: Networking Applications,**" An invited talk at the 38th IEEE Sarnoff Symposium, Newark, NJ, Sep 19, 2017, [http://www.cse.wustl.edu/~jain/talks/blc\\_srnf.htm](http://www.cse.wustl.edu/~jain/talks/blc_srnf.htm)
- ❑ Raj Jain, "**The Catch-up Game: Quest for the Impact,**" Keynote at ACM SIGCOMM 2017, Los Angeles, CA, August 22, 2017, <http://www.cse.wustl.edu/~jain/talks/sigcomm.htm>
- ❑ Raj Jain, "**Multi-Cloud Global Application Delivery for Smart Cities,**" International Summit on Smart World and Smart Cities, Fremont, CA, USA, Aug 5, 2017, <http://www.cse.wustl.edu/~jain/talks/smrtwrlld.htm>

# List of Acronyms

- ❑ API            Application Programming Interface
- ❑ CapEx        Capital Expenditure
- ❑ CE            Community Edition
- ❑ CLI            Command Language Interface
- ❑ CNCF        Cloud Native Computing Foundation
- ❑ DCT           Docker Content Trust
- ❑ EE            Enterprise Edition
- ❑ ID            Identifier
- ❑ OCI            Open Cloud Initiative
- ❑ OpEx        Operational Expenses
- ❑ OS            Operating System
- ❑ TCP           Transmission Control Protocol
- ❑ VM            Virtual Machine
- ❑ VXLAN       Virtual eXtended Local Area Network



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