Internet, Multi-Cloud, Wireless, and Network Security Research at Washington University in St. Louis

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These slides are available on-line at:

http://www.cse.wustl.edu/~jain/talks/cs13117.htm

Overview

1. Why study networking?

2. Current Issues in Networking

3. Our research projects

4. Related networking research and courses

Networking = "Plumbing"

❑ Networking is the "plumbing" of computing

❑ Almost all areas of computing are network-based.

> Distributed computing

> Big Data

> Cloud Computing

> Internet of Things

> Smart Cities

❑ Networking is the backbone of computing.

Networking is already great!

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Networking is Fueling All Sectors of Economy

❑ Networking companies are among the most valued companies: Apple, AT&T, Samsung, Verizon, Microsoft, China Mobile, Alphabet, Comcast, NTT, IBM, Intel, Cisco, Amazon, Facebook, …

⇒ All tech companies that are hiring currently are networking companies

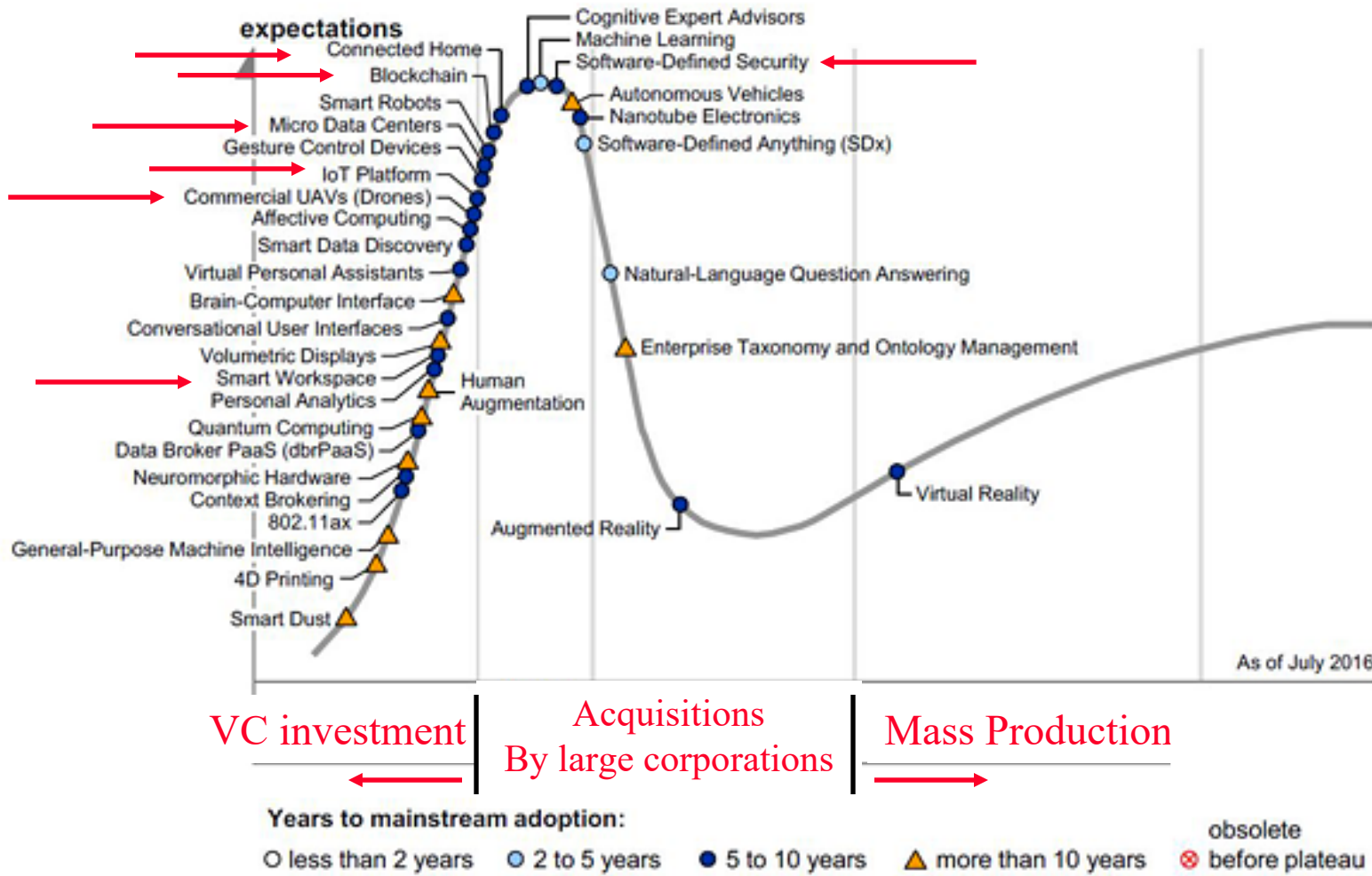❑ Note: Apple became highly valued only after it switched from computing to communications (iPhone)

Networking = Economic Indicator

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Selecting the Right Field

❑ Important question for **student**, academics, entrepreneurs, and companies

❑ Goal: To impact

❑ Follow the **paradigm shifts**:

➢ 1980: Operating Systems

➢ 1990: Performance Analysis

➢ 2000: Networking

➢ 2013: Multi-Cloud Computing

➢ 2017: Whatever is being **hyped** this year?

Gartner Hype Cycle 2016

expectations

- Cognitive Expert Advisors
- Machine Learning
- Software-Defined Security
- Connected Home
- Blockchain
- Smart Robots
- Autonomous Vehicles
- Nanotube Electronics
- Micro Data Centers
- Gesture Control Devices
- Software-Defined Anything (SDx)
- IoT Platform
- Commercial UAVs (Drones)
- Affective Computing
- Smart Data Discovery
- Virtual Personal Assistants
- Brain-Computer Interface
- Natural-Language Question Answering
- Conversational User Interfaces
- Volumetric Displays
- Smart Workspace
- Enterprise Taxonomy and Ontology Management
- Personal Analytics
- Human Augmentation
- Quantum Computing
- Data Broker PaaS (dbrPaaS)
- Neuromorphic Hardware
- Context Brokering
- 802.11ax
- General-Purpose Machine Intelligence
- 4D Printing
- Virtual Reality
- Augmented Reality
- Smart Dust

As of July 2016

VC investment | Acquisitions By large corporations | Mass Production

Years to mainstream adoption:
○ less than 2 years ◔ 2 to 5 years ● 5 to 10 years △ more than 10 years ⊗ obsolete before plateau

Ref: Gartner, "Hype Cycle for Emerging Technologies, 2016," July 2016, [subscribers only], gartner.com/document/3383817

Trend 1: 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
$\qquad\qquad$ = Can Recall $\Rightarrow$ Storage

❑ Now: Smart = Can find quickly, Can Delegate
$\Rightarrow$ Communicate = Networking

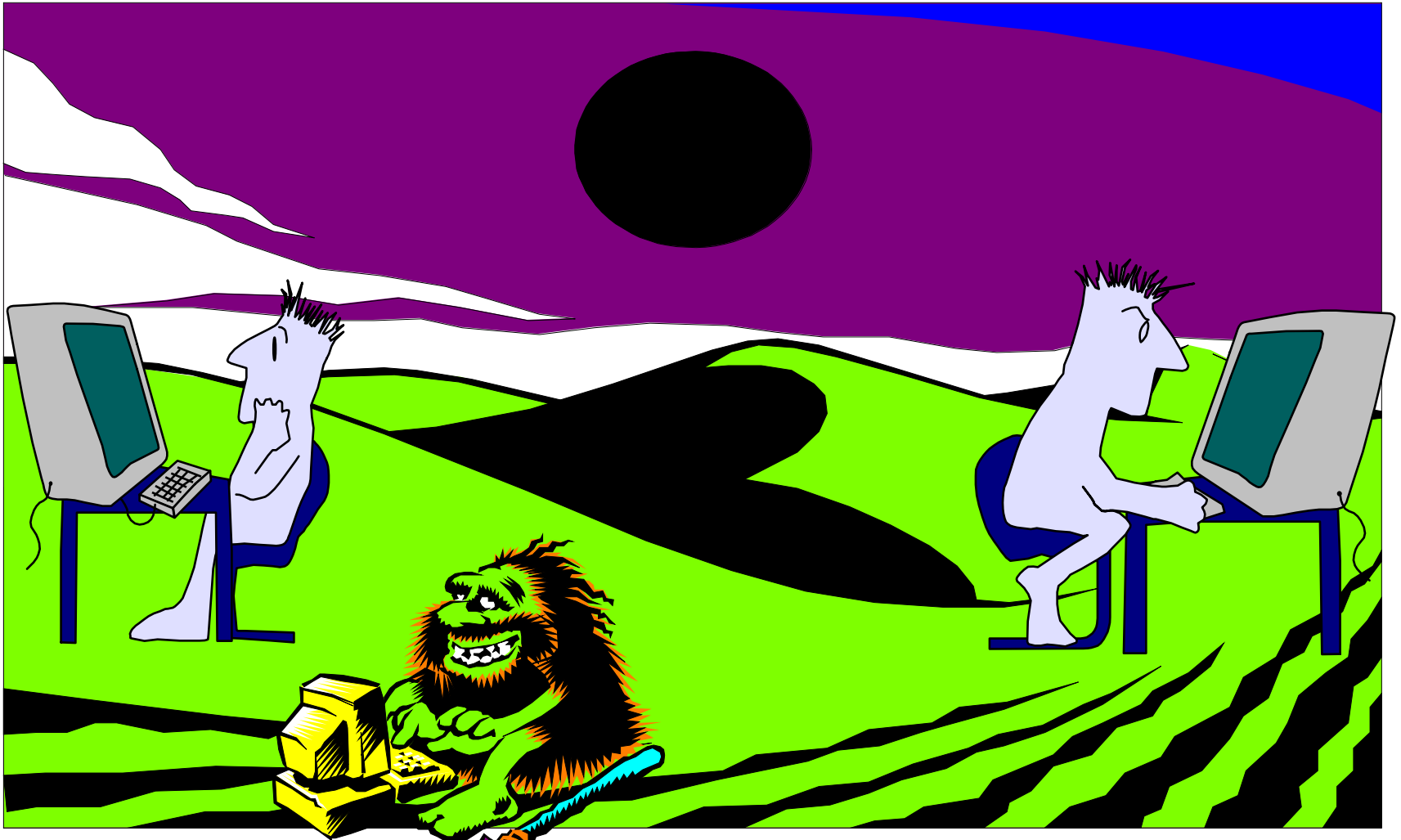These slides and recording of this talk are available on-line at:
http://www.cse.wustl.edu/~jain/talks/aeect17.htm

❑ Smart Grid, Smart Meters, Smart Cars, Smart homes, Smart Cities, Smart Factories, Smart Smoke Detectors, …
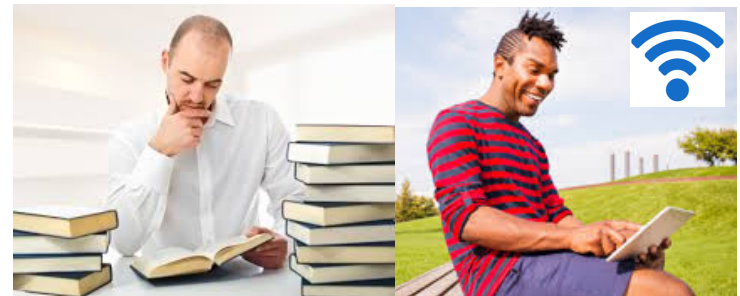
Not-Smart   Smart

Cavemen of 2050

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Cloud Computing

❑ August 25, 2006: Amazon announced EC2 ⇒ Birth of Cloud Computing in reality (Prior theoretical concepts of computing as a utility)
$10 B in 2016, a growth rate of 49% with 17% margins, much higher than the overall Amazon business

❑ Cloud Computing:
- ➢ Applications through Internet (Google Docs)
- ➢ Computing through Internet (Amazon EC3)
- ➢ Storage and backup through Internet (iCloud, Google Drive)

Trend 2: Micro-Cloud Computing

❑ 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

  ➢ µCloud = Cloud in a server with multiple VMs.

  ➢ Each VM with Multiple Containers ⇒ Multiple Services
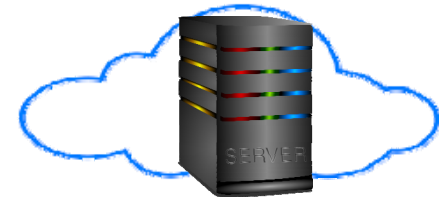
Mobile/Wireless

❑ June 29, 2007: Apple announced iPhone
⇒ Birth of Mobile Internet, Mobile Apps

➢ Almost all services are now mobile apps: Google, Facebook, Bank of America, …

❑ Wireless (WiFi) is ubiquitous (Intel Centrino)

❑ New Developments:

➢ 5G: 1Gbps

➢ Vehicular Networking

Trend 3: Mobile Edge Computing

❑ To service mobile users/IoT, the computation needs to come to edge ⇒ Mobile Edge Computing
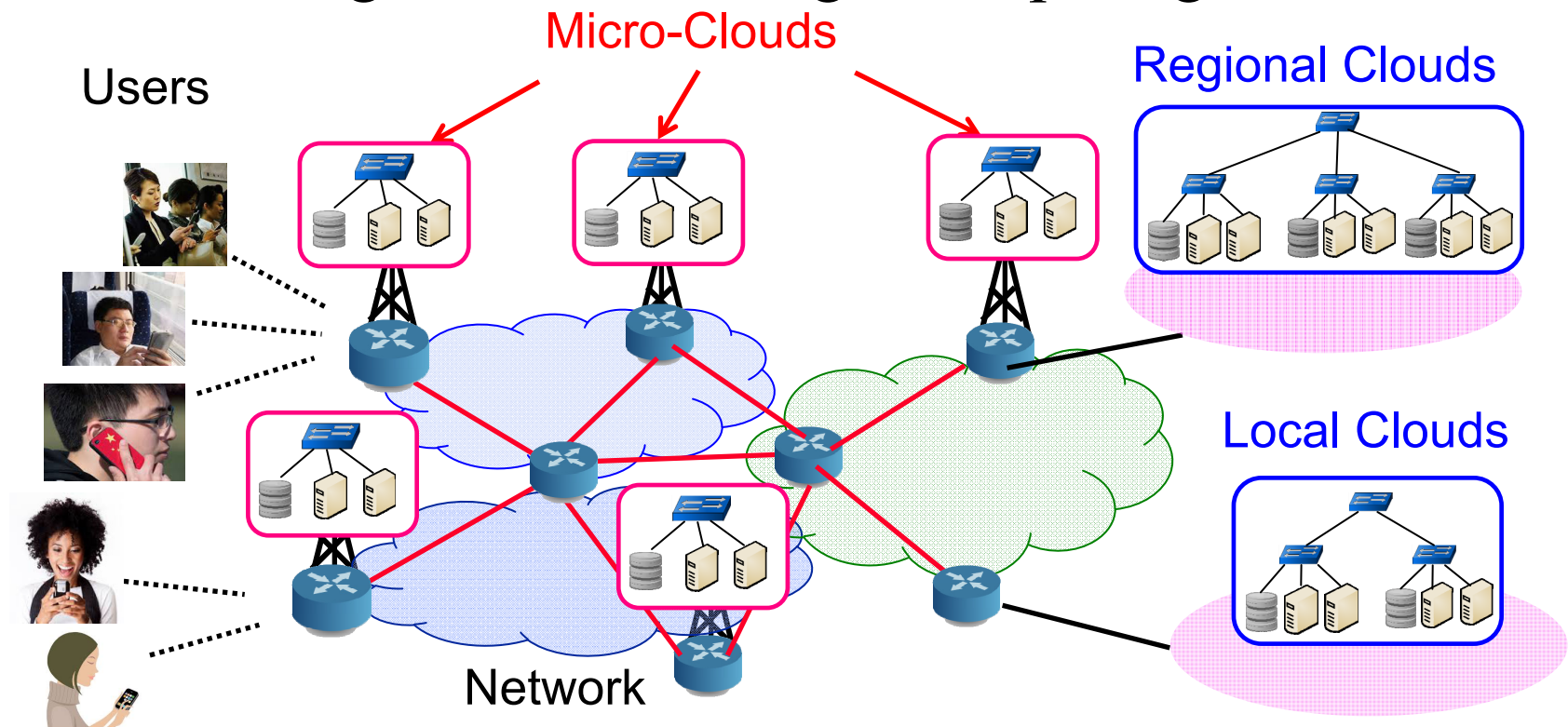
Ref: Lav Gupta, Raj Jain, H. Anthony Chan, "Mobile Edge Computing - an important ingredient of 5G Networks," IEEE Softwarization Newsletter, March 2016, http://www.cse.wustl.edu/~jain/papers/mec16.htm
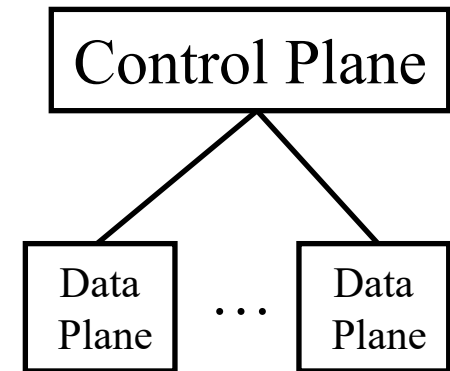http://www.cse.wustl.edu/~jain/talks/cs13117.htm

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Trend 4: Micro-Services

❑ All major applications, such as, Facebook, Netflix, etc. consist of a number of micro-services that are instantiated on demand on virtual machines

Micro-Clouds

Regional Clouds

Users

Local Clouds

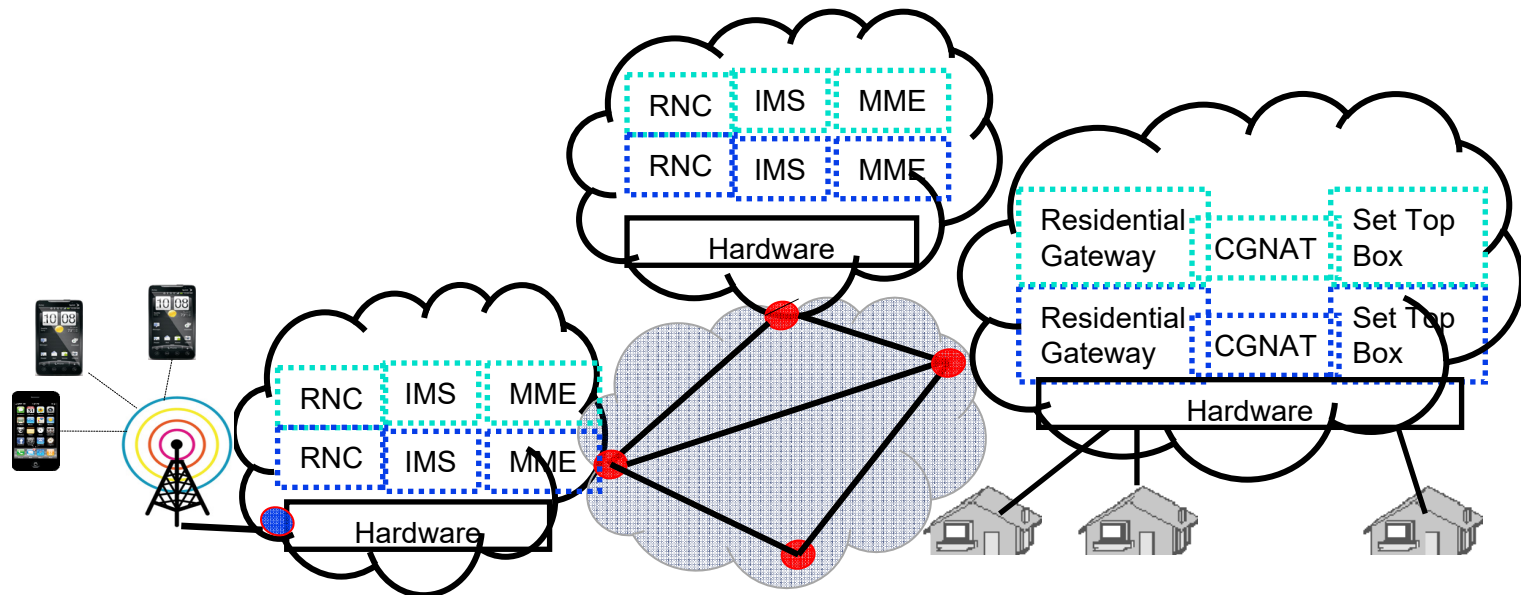Network
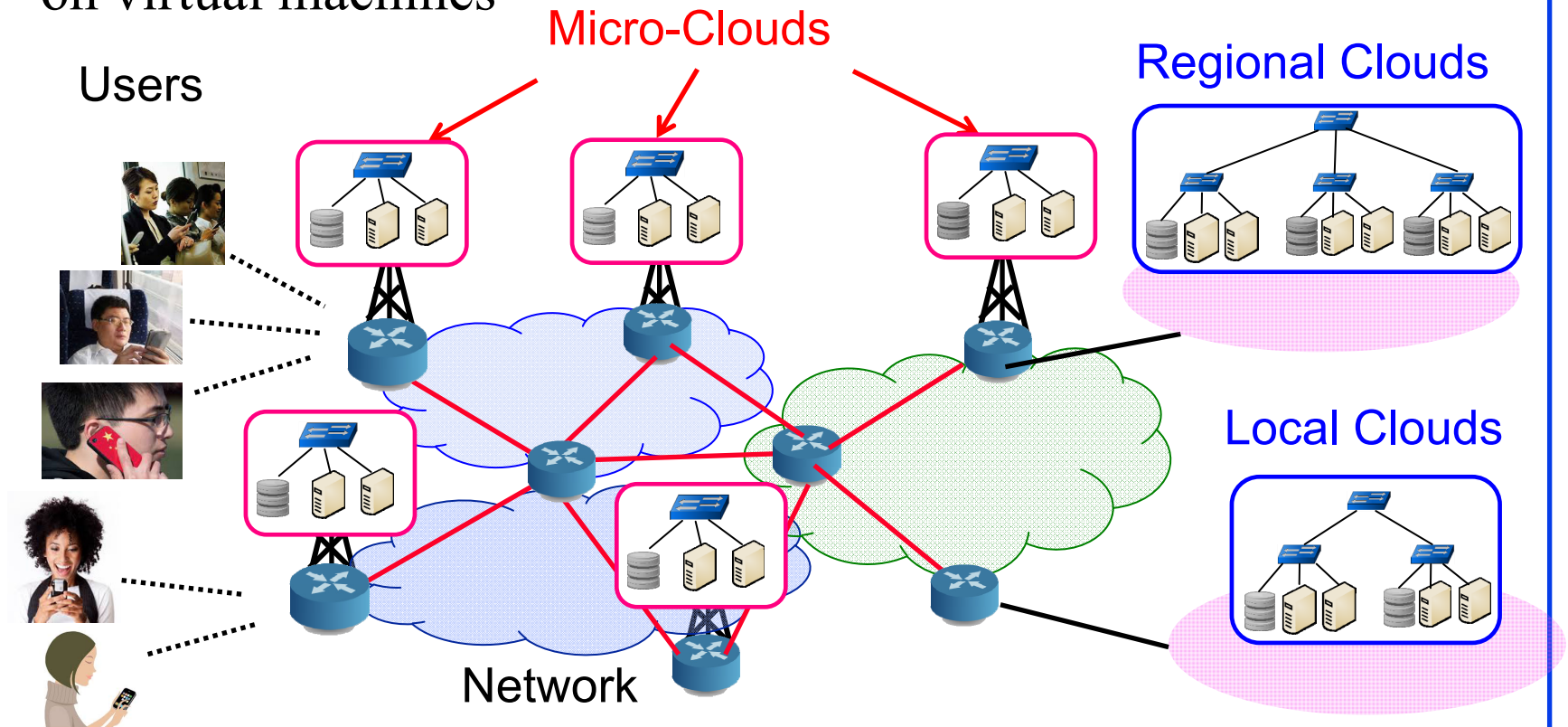
Trend 5: Software Defined Everything

- ❑ SDN was invented in 2009
- ❑ Then: SDN:
  - ➢ Separation of control and data planes
  - ➢ Centralization of Control
  - ➢ Standard Protocol between the planes
- ❑ Now: Software Defined Everything (SDE) = **Disaggregation** of hw/sw
  - ➢ Commodity hardware
  - ➢ Software that runs on commodity hw
  - ➢ Open Source Software
    ⇒ Service industry
  - ➢ Controller replaced by Orchestrator
  - ➢ Centralization of policies

```
          ┌───────────────┐
          │ Control Plane │
          └───────────────┘
           /             \
    ┌──────┐           ┌──────┐
    │ Data │   ...     │ Data │
    │ Plane│           │ Plane│
    └──────┘           └──────┘


          ┌───────────────┐
          │ Orchestrator  │
          └───────────────┘
           /             \
    ┌──────┐           ┌──────┐
    │ SW   │   ...     │ SW   │
    ├──────┤           ├──────┤
    │ HW   │           │ HW   │
    └──────┘           └──────┘
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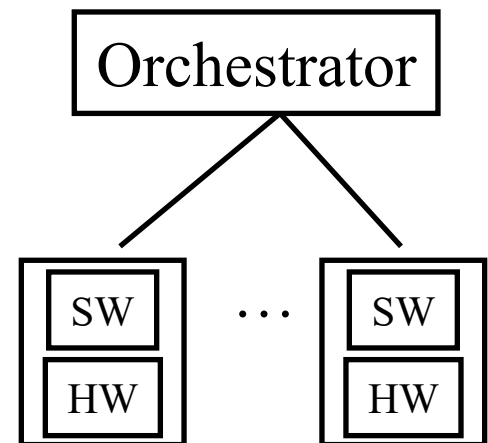
Ref: D. M Batista, G. Blair, F. Kon, R. Boutaba, D. Hutchison, R. Jain, R. Ramjee, C. Rothenberg, "Perspectives on software-defined networks: interviews with five leading scientists from the networking community" Journal of Internet Services and Applications 2015, 6:22, http://www.cse.wustl.edu/~jain/papers/jisa15.htm

http://www.cse.wustl.edu/~jain/talks/cs13117.htm

Trend 6: Multi-Cloud for 5G: NFV

❑ NFV = Network Function Virtualization
Use of clouds by telecom carriers

❑ Problem: Where to place which function and move as the traffic pattern changes ⇒ Service Function Chaining
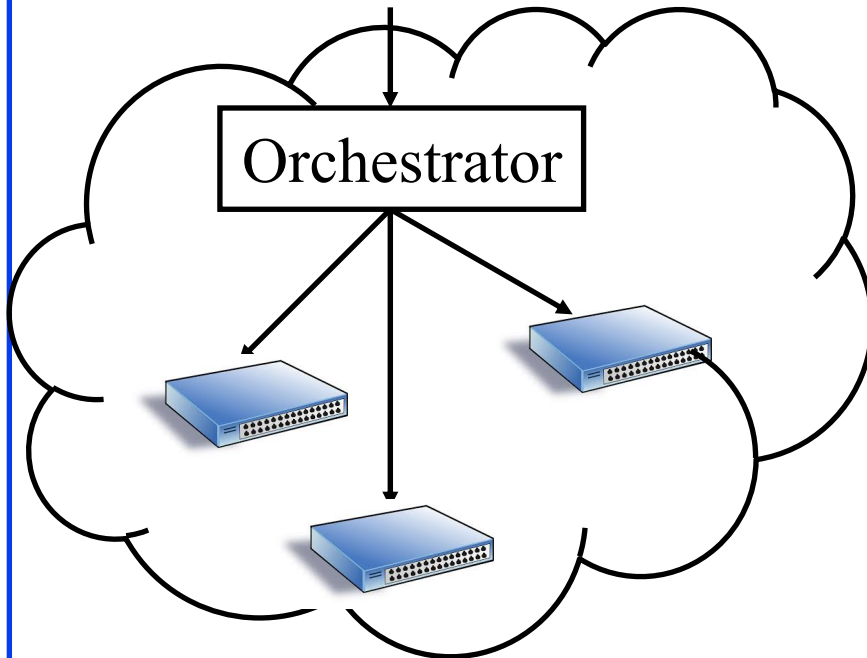

Ref: Raj Jain and Subharthi Paul, "Network Virtualization and Software Defined Networking for Cloud Computing - A Survey,"
IEEE Communications Magazine, Nov 2013, pp. 24-31, http://www.cse.wustl.edu/~jain/papers/net_virt.htm
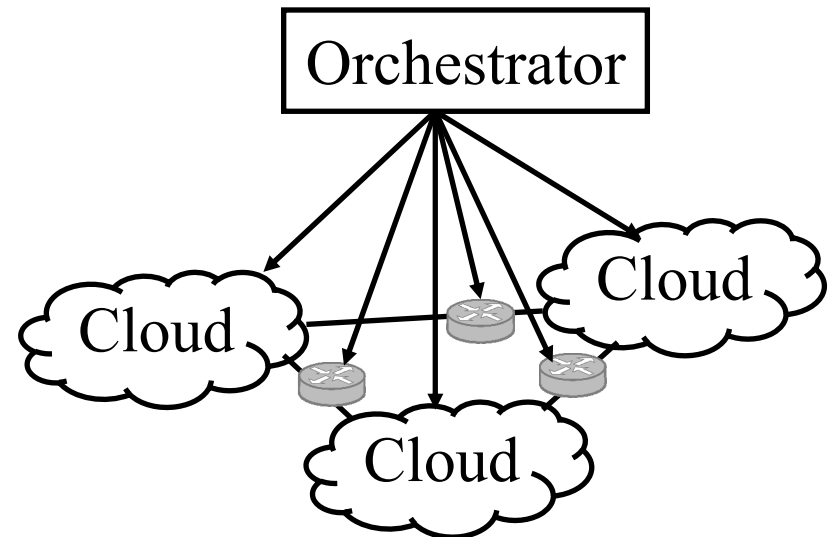http://www.cse.wustl.edu/~jain/talks/cs13117.htm

Trend 7: Software Defined Multi-Cloud

❑ Orchestrating devices to Orchestrating 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
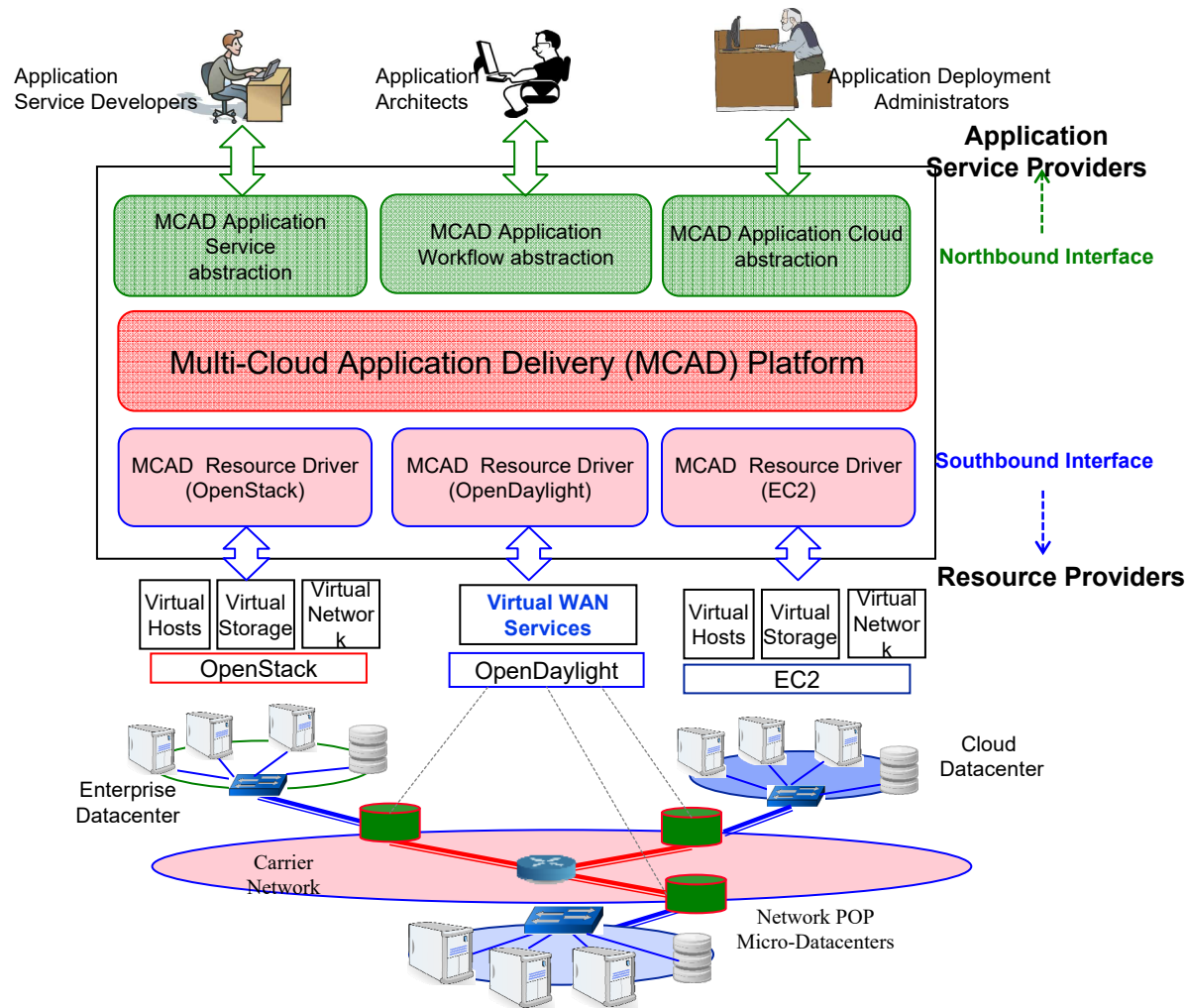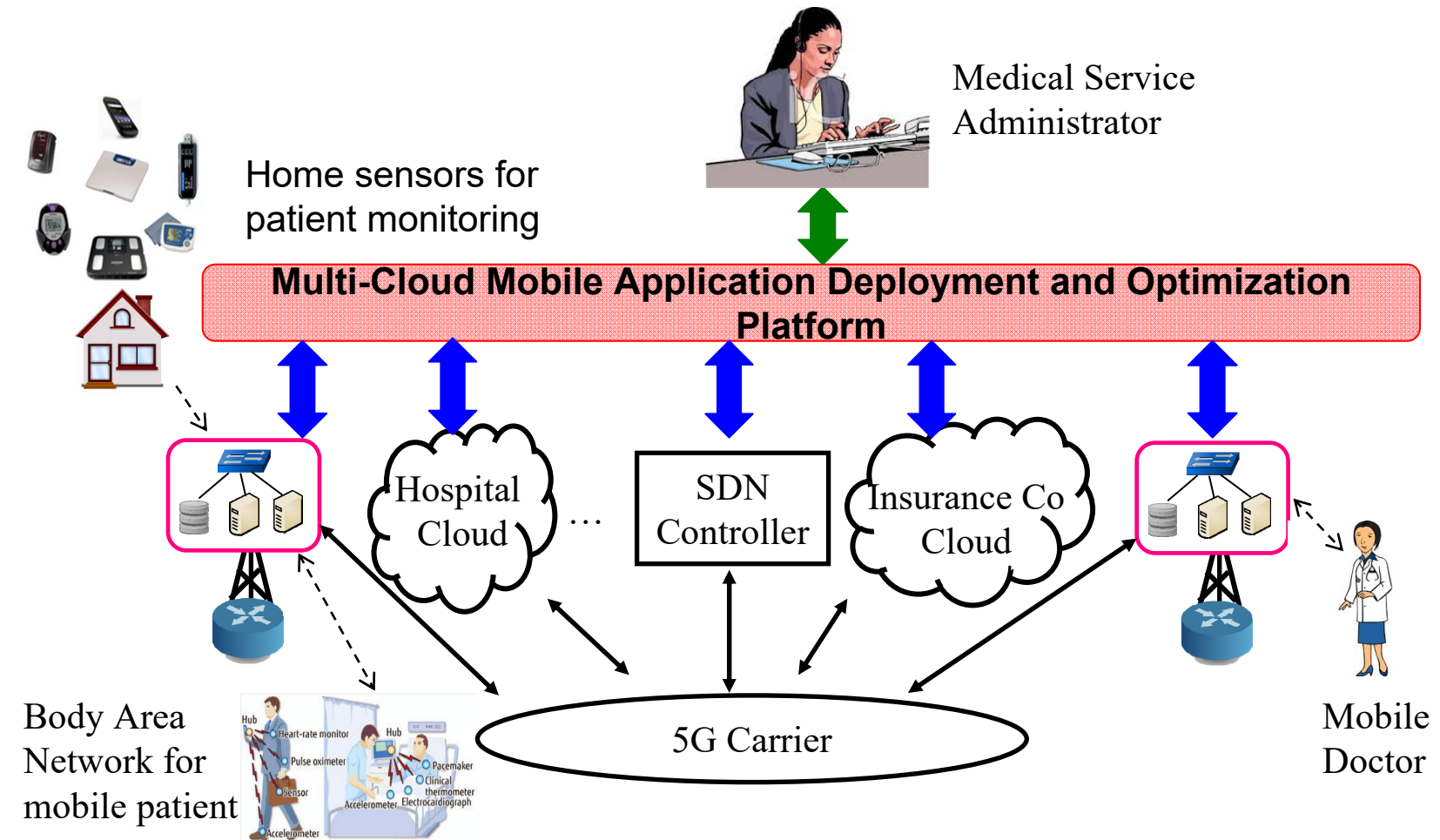
OpenADN Multi-Cloud Management

Ref: Lav Gupta, Raj Jain, Mohammed Samaka, "Analysis of Application Delivery Platform for Software Defined Infrastructures," International Journal of Communication Networks and Distributed Systems, 2016, Vol. 5, http://www.cse.wustl.edu/~jain/papers/ijcnds16.htm

http://www.cse.wustl.edu/~jain/talks/cs13117.htm

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Mobile Healthcare Use Case

Home sensors for patient monitoring

Medical Service Administrator

Multi-Cloud Mobile Application Deployment and Optimization Platform

Hospital Cloud … SDN Controller Insurance Co Cloud

Body Area Network for mobile patient

5G Carrier

Mobile Doctor

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Trend 9: Security & Cyber Warfare

❑ Security of computers, companies, smart grid, and nations

❑ Nation States are penetrating other nations computers
  5^{th} domain of warfare (after land, sea, air, space)

❑ In 2010, US set up US Cyber Command

❑ UK, China, Russia, Israel, North Korea have similar centers

❑ Many cyber wars: North Korea vs. USA, Israel vs. Syria, South Korea vs. North Korea, India vs. Pakistan, …

Old

New

Ref: http://en.wikipedia.org/wiki/Cyber_war

http://www.cse.wustl.edu/~jain/talks/cs13117.htm ©2017 Raj Jain

Internet of Harmful Things

Researchers at DEFCON 3, hacked a smart toilet, making it flush incessantly and closing the lid repeatedly and unexpectedly. Causing a **Denial of Service** Attack.

Ref: http://www.computerworld.com/article/2486502/
security0/worm-may-create-an-internet-of-harmful-things--says-symantec--take-note--amazon-.html
http://www.cse.wustl.edu/~jain/talks/cs13117.htm

Washington University in St. Louis

DEFCON

❑ Hacker's conference

❑ Held in Las Vegas every July

❑ 20,000+ attendees

❑ All anonymous

Washington University in St. Louis

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DEFCON 2017

- Hacking voting machines
- Hack connected vehicles
- Hacking the cloud
- Hacking travel routers
- Clone RFID in real time
- Breaking the Uber badge ciphers
- Counterfeit hardware security devices, RSA tokens
- Fool antivirus software using AI
- How to track government spy planes
- Break bitcoin hardware wallets
- DARPA Cyber Grand Challenge (2015, 2016)
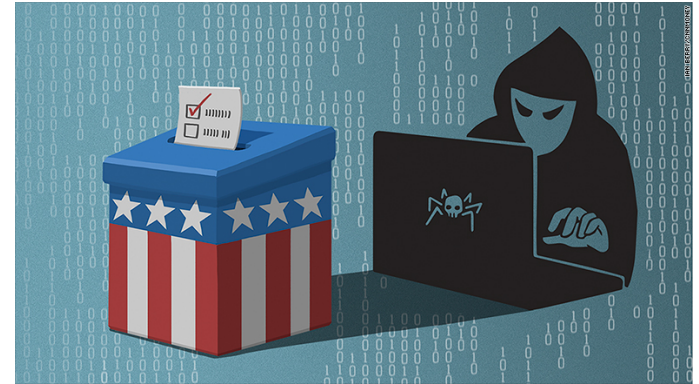
Confidentiality
Integrity
Authentication

Teaching CIA methods w/o hacking is not sufficient

Trend 10: 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 without a third party

Example of a Contract: Wedding
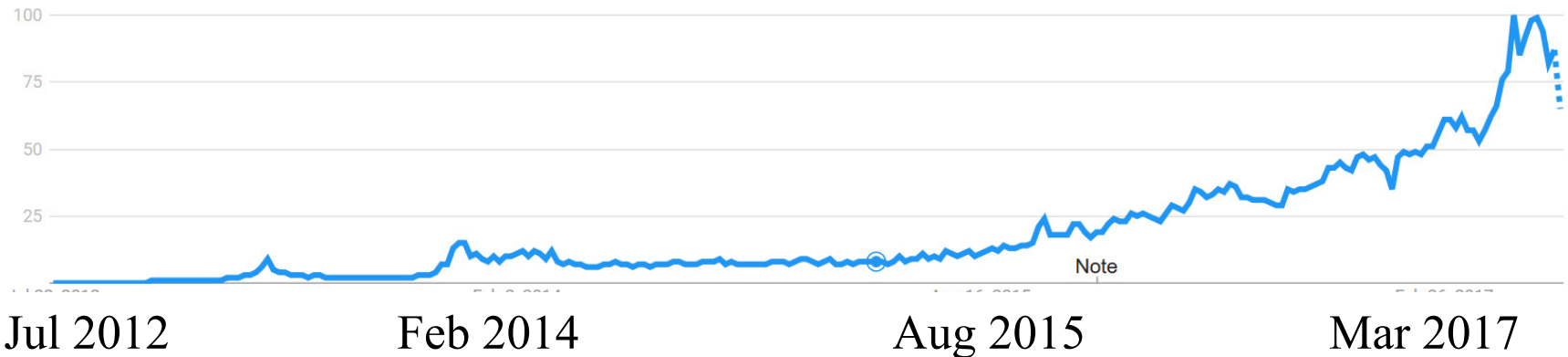
Wedding (Cont)

❏ Centralized

❏ Decentralized

❏ Centralized registry

❏ Single point of failure

❏ Easier to hacked

❏ Decentralized

❏ No single point of failure

❏ Very difficult to hack

Google Trend: Blockchains

Jul 2012   Feb 2014   Aug 2015   Mar 2017

❑ Countries with most interest in Blockchains:
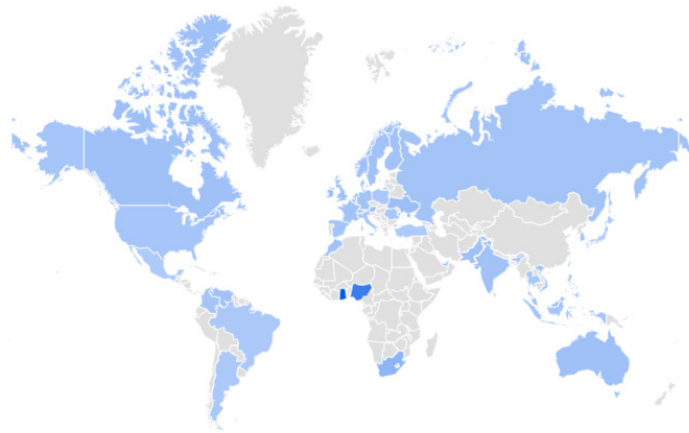
1	Ghana	100
2	Nigeria	68
3	Singapore	25
4	Hong Kong	22
5	South Africa	20

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Trend: Centralized to Decentralized

❑ **Trend**: Make everything decentralized with no central point of control

❑ 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
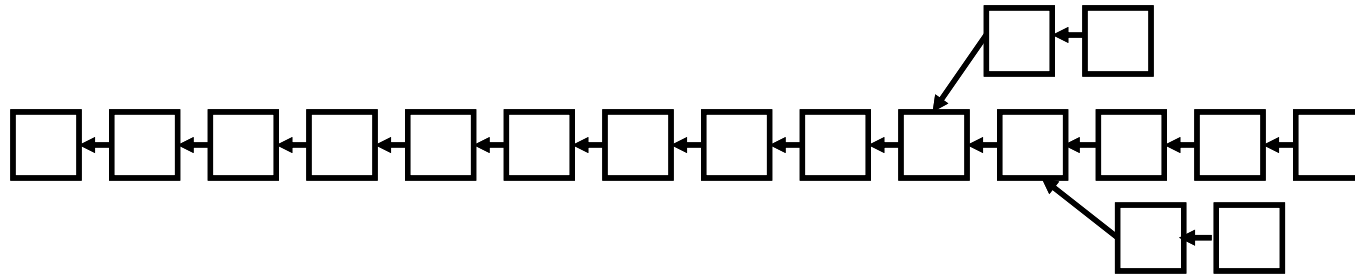
❑ **Who** is interested: Banks, Hospitals, Venture Capitalists, …
  ⇒ Researchers, students, …

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 $\Rightarrow$ Attracts Hackers
3. Central party may be hacked $\Rightarrow$ affects millions
4. Central party is a single point of failure. Can malfunction or be bribed.

Ref: A. Narayanan, et al, "Bitcoin and Cryptocurrency Technologies," Princeton University Press, 2016, 304 pp.

Blockchains For Cities

❑ Land titles

❑ Vehicle registries

❑ Business license

❑ Criminal records

❑ Passports

❑ Birth certificates

❑ Death certificates

❑ Building permits

❑ Gun permits

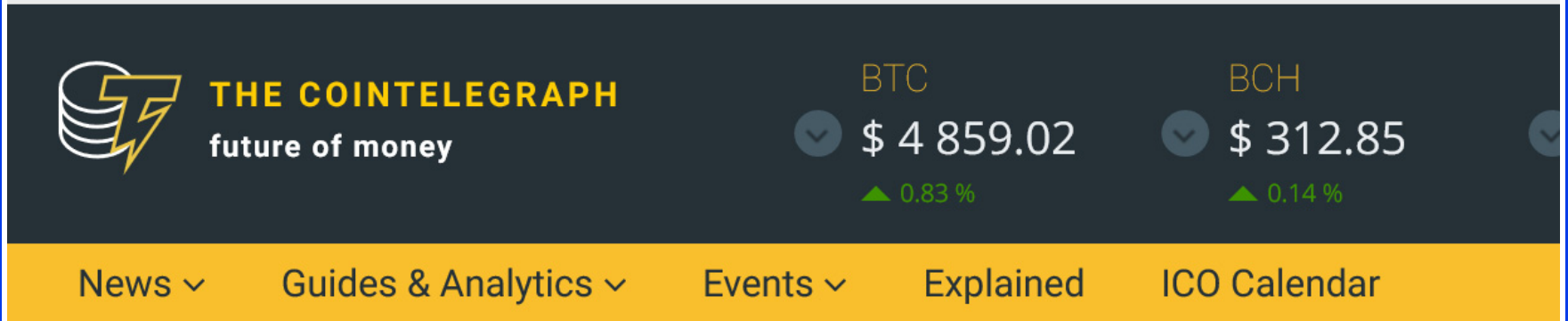Ref: http://ledracapital.com/blog/2014/3/11/Bitcoin-series-24-the-mega-master-blockchain-list

Blockchains for Cities (Cont)

THE COINTELEGRAPH
future of money

BTC
$ 4 859.02
▲ 0.83 %

BCH
$ 312.85
▲ 0.14 %

News ∨   Guides & Analytics ∨   Events ∨   Explained   ICO Calendar

By Joshua Althauser   9 HOURS AGO

Indian State Uses Blockchain Technology to Stop Land Ownership Fraud

Networking Applications of Blockchains

❑ Multi-Domain Systems:

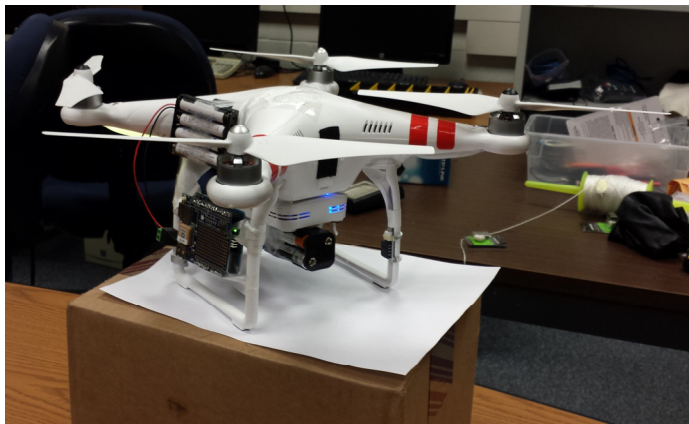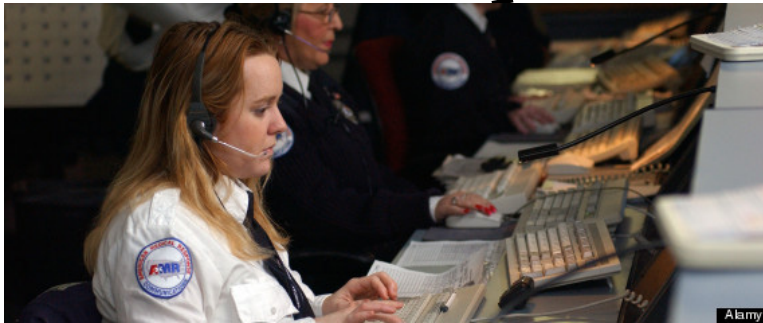   ➢ Multiple Cloud Service Providers

    ➢ Multiple cellular providers

    ➢ Multi-Interface devices: WiFi, Cell, Bluetooth, …

    ➢ BGP: BGP Authentication

❑ Globally Centralized Systems:

    ➢ DNS

    ➢ Certificate Authorities

Explore blockchains for multi-domain/centralized systems

Communication using UAVs

http://www.cse.wustl.edu/~jain/talks/cs13117.htm

Key Distinction of Our Research

❑ Goal: Impact to the real-world
DECbit congestion indication in almost
all networking architectures since its
invention

❑ Funded by industry partners:
Intel, Cisco, Broadcom, Boeing, …

❑ Impact real-world by participating in
standards organizations and industry forums:
ATM Forum, IEEE Standards, American National
Standards Institute (ANSI), Internet Engineering Task
Force (IETF), WiMAX Forum

❑ Work on long term as well as short term research

Networking Courses at WUSTL

1. **CSE 473: Introduction To Computer Networks** (every fall) – Prerequisite for all other networking classes

2. CSE 521S: Wireless Sensor Networks

3. CSE 537S: Mobile Computing

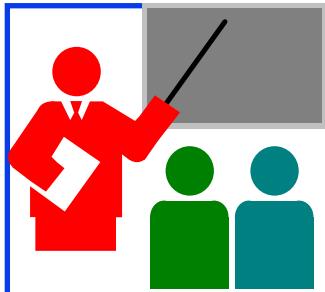4. **CSE 570S: Advanced Networking:** Clouds, Big Data, SDN, IoT (Spring 2018)

5. **CSE 574S**: **Wireless and Mobile Networking** (Fall 2018)

6. **CSE 571S: Network Security** (Spring 2019)

7. CSE 7700: Research Seminar On Networking and Communications

Summary

1. Computer networking is the backbone of all computing $\Rightarrow$ Cyber age. Networking companies are the leading edge.

2. Smart $\neq$ High-Speed Computation,
   Smart $\neq$ Big Data Storage,
   Smart = Networked

3. Clouds are getting smaller, Carriers and enterprises moving to clouds, leading to clouds everywhere $\Rightarrow$ multi-cloud

4. Our MCAD abstracts/virtualizes the cloud interfaces and allows automated management of security and other policies of multi-cloud applications

5. We are working on:
   1. Multi-Cloud
   2. IoT Security
   3. UAV Protocols

References: Class Recordings

❑ Recordings of all of my classes and talks are available on YouTube and on my website:

1. CSE 473: Introduction to Computer Networks, http://www.cse.wustl.edu/~jain/cse473-16/index.html

2. CSE 571S: Network Security, http://www.cse.wustl.edu/~jain/cse571-17/index.html

3. CSE 574S: Wireless Networks, http://www.cse.wustl.edu/~jain/cse574-16/index.html

4. CSE 567: Computer Systems Analysis http://www.cse.wustl.edu/~jain/cse567-17/index.html

5. CSE 570: Recent Advances in Networking http://www.cse.wustl.edu/~jain/cse570-15/index.html

Recent Papers

- Xin Li, M. Samaka, H. A. Chan, D. Bhamare, L. Gupta, C. Guo, and Raj Jain, **"Network Slicing for 5G: Challenges and Opportunities**," IEEE Internet Computing, Vol. 21, Issue 5, September 18, 2017, pp. 20-27, http://www.cse.wustl.edu/~jain/papers/slic_ic.htm

- D. Bhamare, M. Samaka, A. Erbad, Raj Jain, L. Gupta, H. A. 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

- T. 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

- L. Gupta, Raj Jain, H. A. 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

- L. Gupta, Raj Jain, and G. Vaszkun, **"Survey of Important Issues in UAV Communication Networks**," IEEE Communications Surveys and Tutorials, Volume PP, Issue 99, November 3, 2015, http://www.cse.wustl.edu/~jain/papers/uav_comst.htm

Recent Talks

❑ Raj Jain, "**Current Trends in Networking With Applications to Internet of Things and Smart Cities**," Keynote at 2017 IEEE Jordan Conference on Applied Electrical Engineering and Computing Technologies (AEECT), Amman, Jordan, October 12, 2017, http://www.cse.wustl.edu/~jain/talks/aeect17.htm

❑ 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

❑ 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, "**Unmanned Aerial Systems: Networking Applications, Challenges and Issues**," Keynote at Midwest Drone Introduction, St. Louis, MO, October 15, 2016, http://www.cse.wustl.edu/~jain/talks/unmanned.htm

❑ Raj Jain, "**Smart Cities: Technological Challenges and Issues**," IEEE CS Keynote at 21st Annual International Conference on Advanced Computing and Communications (ADCOM) 2015, Chennai, India, September 19, 2015, Chennai, India, September 18, 2015, http://www.cse.wustl.edu/~jain/talks/smrtcit.htm

Acronyms

- ❑ ABR   Available Bit Rate
- ❑ ACM   Automatic Computing Machinery
- ❑ ADCOM   Advanced Computing
- ❑ AI   Artificial Intelligence
- ❑ ANSI   American National Standards Institute
- ❑ API   Application Programming Interface
- ❑ AT&T   American Telephone and Telegraph
- ❑ ATM   Asynchronous Transfer Mode
- ❑ BGP   Border Gateway Protocol
- ❑ CA   California
- ❑ CGNAT   Carrier Grade Network Address Translator
- ❑ CIA   Confidentiality, Integrity, Authentication
- ❑ CS   Computer Science
- ❑ CSE   Computer Science and Engineering
- ❑ DARPA   Defense Advanced Research Project Agency
- ❑ DECbit   Digital Equipment Corporation Bit

Acronyms (Cont)

- DECT — Digital Enhanced Cordless Telecommunications
- DEFCON — D-E-F (sequential letters of the alphabet) Conference
- DNS — Domain Name Service
- DSL — Digital Subscriber Line
- EC2 — Asynchronous Transfer Mode
- ECN — Explicit congestion notification
- EFCI — Explicit Forward Congestion Indication
- FTTH — Fiber to the Home
- GIS — Geographical Information Systems
- GPS — Global Positioning Systems
- HW — Hardware
- IBM — International Business Machine Corporation
- iCloud — Apple's Cloud Service
- IEEE — Institution of Electrical and Electronic Engineering
- IETF — Internet Engineering Task Force
- IMS — Internet Multimedia System
- IoT — Internet of Things

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Acronyms (Cont)

- IP   Internet Protocol
- LAN   Local Area Network
- MCAD   Multi-Cloud Application Delivery
- MME   Multi-media Multicasting Entity
- MO   Missouri
- NFC   Near-Field Communications
- NVF   Network Function Virtualization
- NJ   New Jersey
- NTT   Nippon Telephone and Telegraph
- OpenADN   Open Application Delivery Networking
- PHY   Physical Layer
- POP   Point of Presense
- PP   Pages
- RFID   Radio Frequency Identifier
- RNC   Radio Network Controller
- RSA   Rivest, Silverman, Adleman
- SDE   Software Define Everything

Acronyms (Cont)

- SDN   Software Defined Networking
- SIGCOMM   Special Interest Group in Data Communications
- SOA   Service Oriented Architecture
- SW   Software
- TCP   Transmission Control Protocol
- TV   Television
- UAV   Unmanned Aerial Vehicle
- UK   United Kingdom
- ULE   Ultra Low Energy
- VC   Virtual Circuit
- VM   Virtual Machine
- WAN   Wide Area Network
- WiFi   Wireless Fidelity
- WiMAX   Worldwide Interoperability for Microwave Access
- WUSTL   Washington University in St. Louis
- XML   Extended markup language

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