Introduction to Internet of Things

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These slides and audio/video recordings of this class lecture are at:
http://www.cse.wustl.edu/~jain/cse574-20/

Student Questions

Overview

1. What are Things?
2. Business Opportunities for IoT
3. IoT Research Challenges
4. Recent Protocols for IoT
5. Datalink Issues

Note: This is first of a series of class lectures on IoT.

Student Questions

What are Things?

- Thing = Not a computer
- Phone, watches, thermostats, cars, Electric Meters, sensors, clothing, band-aids, TV,…
- Anything, Anywhere, Anytime, Anyway, Anyhow (5 A's)

Ref: http://blog.smartthings.com/iot101/iot-adding-value-to-peoples-lives/

Student Questions

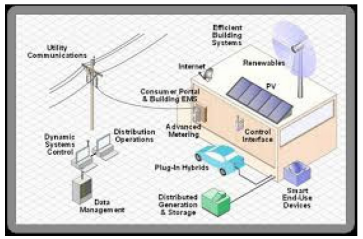
Internet of Things

- Less than 1% of things around us is connected.
  Refrigerator, car, washing machine, heater, a/c, garage door, should all be connected but are not.
- From 10 Billion today to 50 Billion in 2020
  Should include processes, data, things, and people.
- $14 Trillion over 10 years
  ⇒ Third in the list of top 10 strategic technologies by Gartner
  (After Mobile devices, Mobile Apps, but before Clouds, …)
- a.k.a. **Internet of Everything** by Cisco
  Smarter Planet by IBM

Ref: "Gartner Identifies Top 10 Strategic Technologies,"
http://www.cioinsight.com/it-news-trends/gartner-identifies-top-10-strategic-technologies.html
Ref: J. Bradley, "The Internet of Everything: Creating Better Experiences in Unimaginable Ways," Nov 21, 2013,
http://blogs.cisco.com/ioe/the-internet-of-everything-creating-better-experiences-in-unimaginable-ways/#more-131793

Student Questions

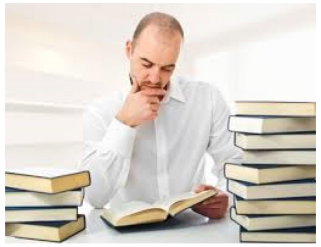
Sample IoT Applications

 Smart Grid	 Smart Health	 Smart Home
 Smart Cities	 Smart Industries	 Smart TV
 Smart Watch	 Smart Car	 Smart Kegs

Student Questions

What's Smart?

- IoT = Instrument, Interconnect, Intelligently process (3 I's)
- Old: Smart = Can think ⇒ Can compute
- Now: Smart = Can find quickly, Can Delegate
  ⇒ Communicate = Networking
- Smart Grid, Smart Meters, Smart Cars, Smart homes, Smart Cities, Smart Factories, Smart Smoke Detectors, …

Not-Smart 

Smart 

- Smart = Apply the latest **technology** to solve problems

Student Questions

Why IoT Now?

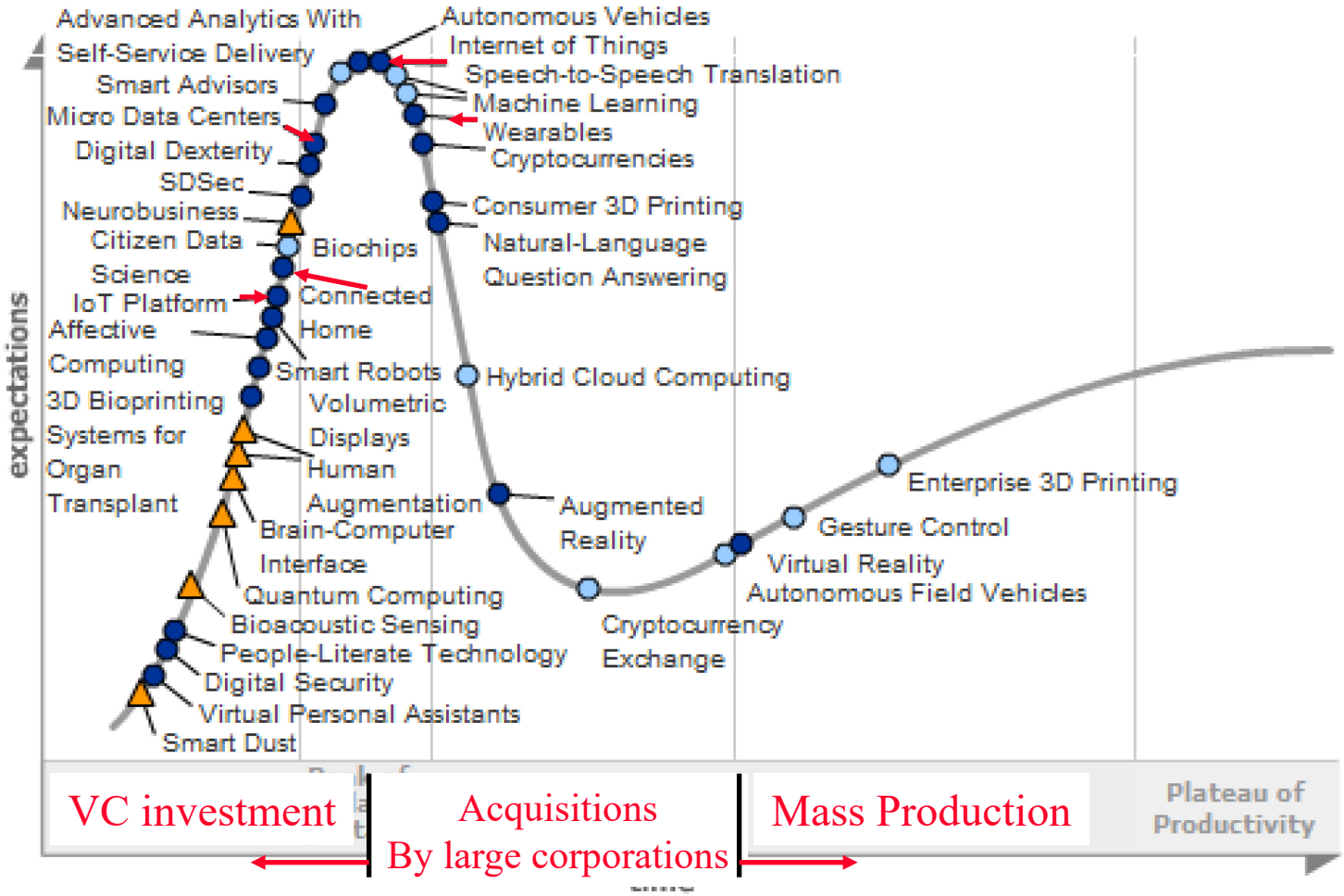
- IoT = Sensing + Communication + Computation

1. Micro-Sensors: Temperature, Moisture, Pressure, air quality, …
2. Tags: Radio Frequency Id (RFID), Quick Response (QR) Codes, …
3. Energy Efficient Communication: Small or no batteries, Personal area communication (PAN), Bluetooth, ZigBee, …
4. Micro-Computing: Micro multi-core chips, Raspberry Pi, Intel Galileo, Arduino, …
5. Cloud Computing: Little or no local computing
6. Open/Small operating systems: Linux

Ref: CTIA, "Mobile Cyber security and the Internet of Things," http://www.ctia.org/docs/default-source/default-document-library/ctia-iot-white-paper.pdf

Student Questions

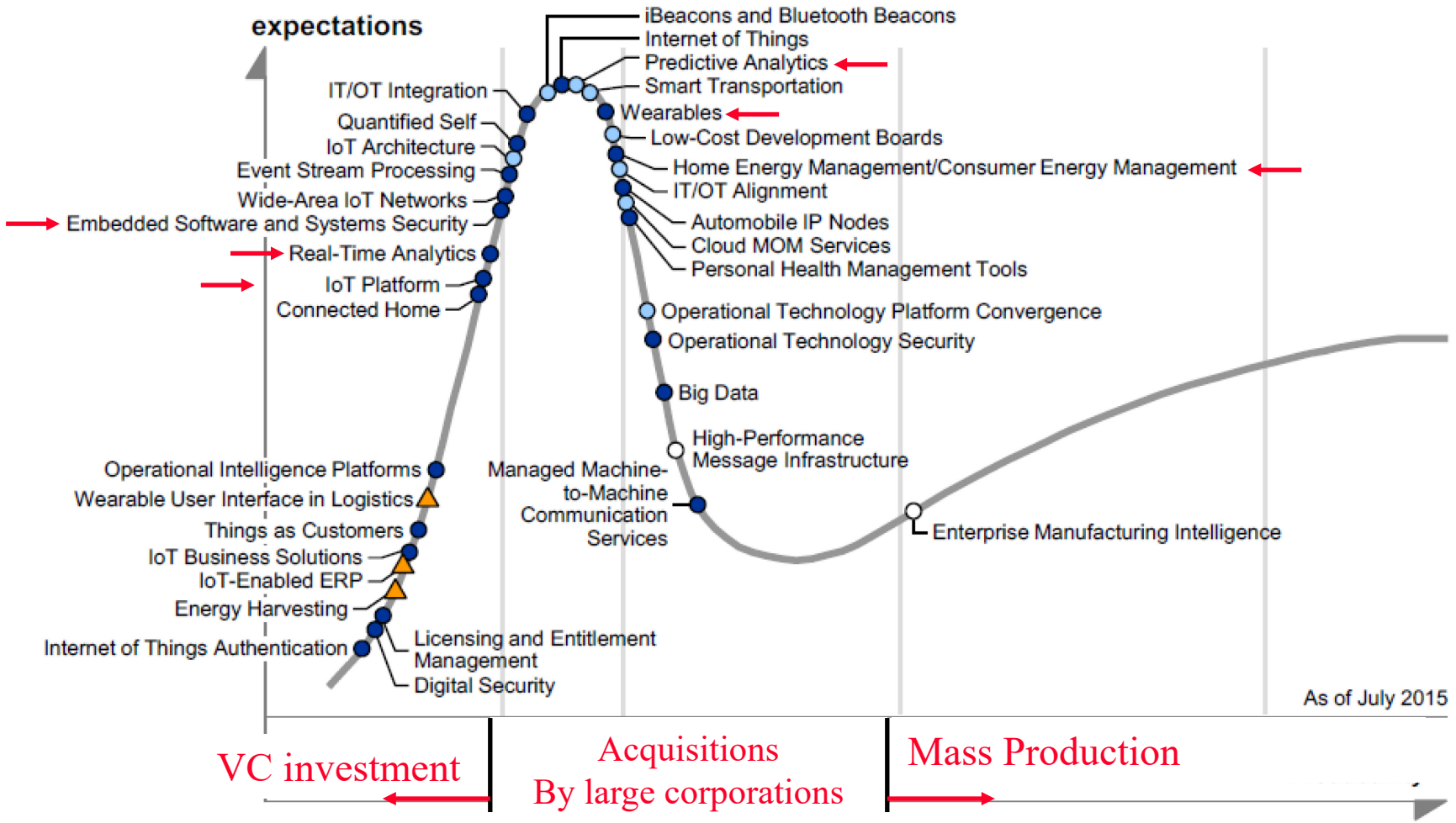
Gartner Hype Cycle 2015



Ref: Gartner, "Hype Cycle for Emerging Technologies, 2015," July 2015, [Available to subscribers only], http://www.gartner.com/document/3100227?ref=QuickSearch&sthkw=hype%20cycle%202015&refval=156919648&qid=fe61993355944ace1c8c01ec2df676d9

Student Questions

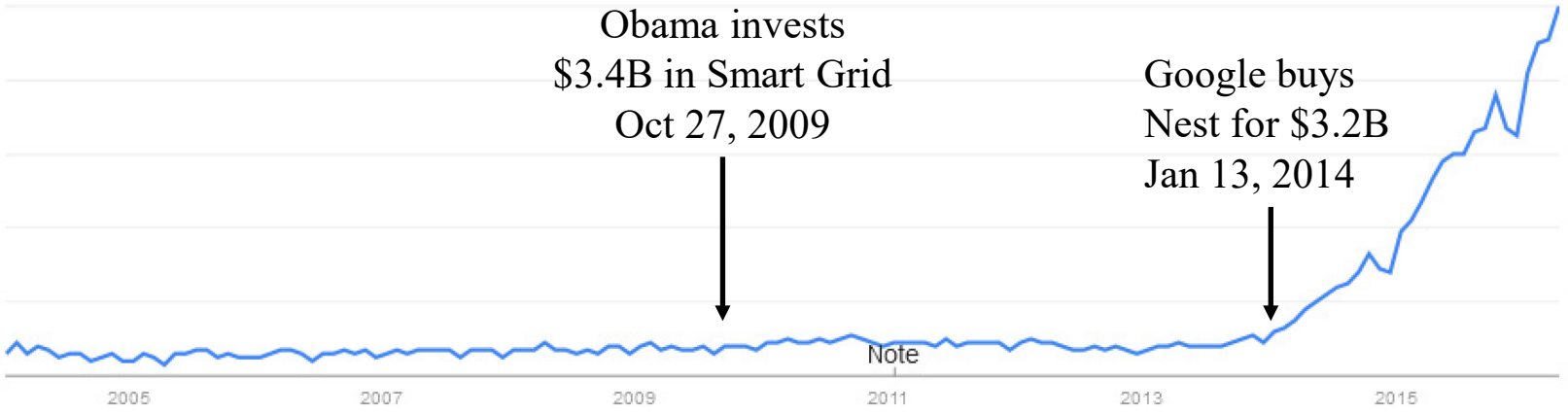
Gartner's Hype Cycle For IoT 2015



Ref: A Velosa, et al, "Hype Cycle for the Internet of Things, 2015" Gartner Report, G00272399, July 2015, 69 pp.

Student Questions

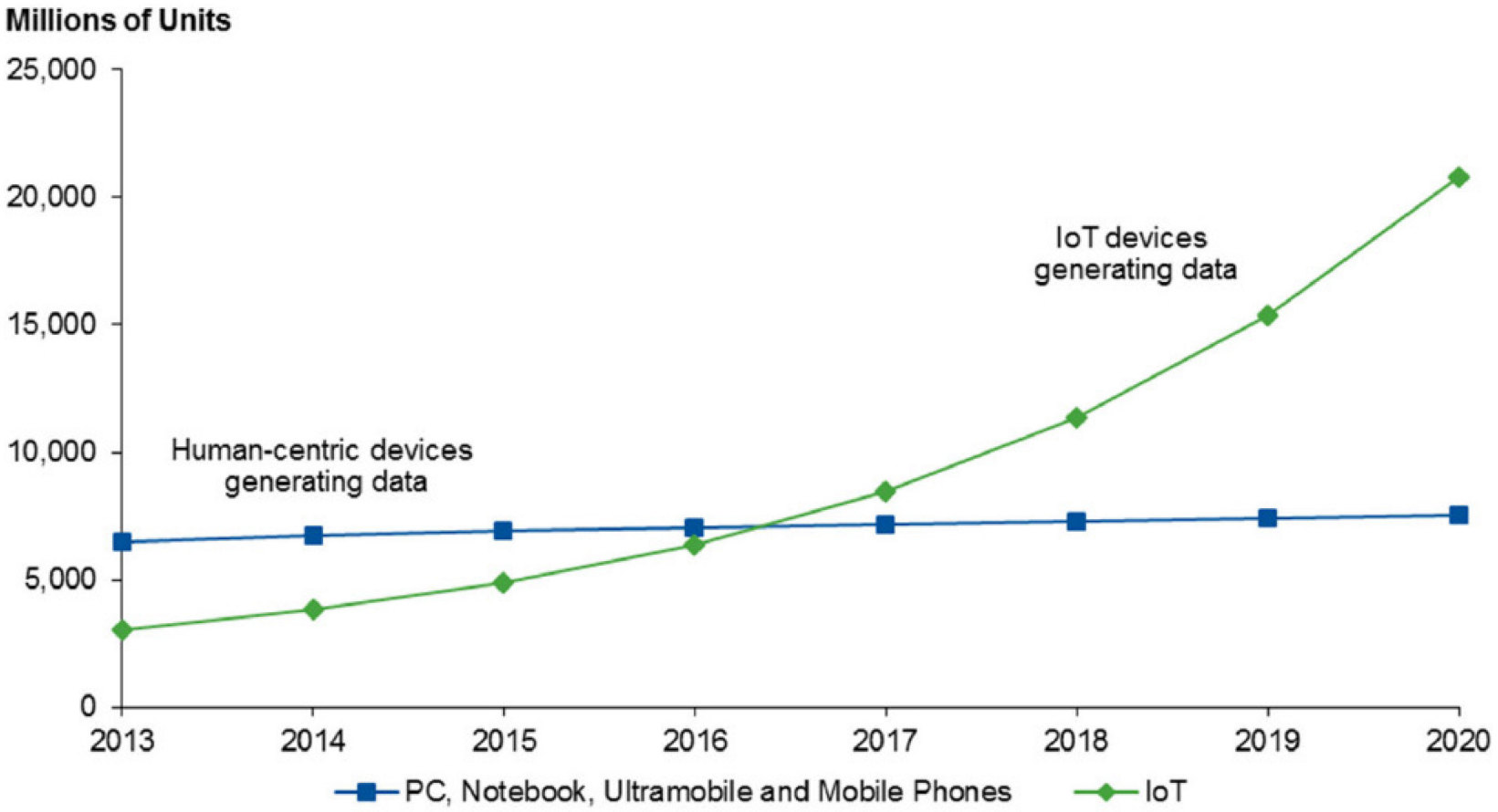
Google Trends



- Around for 10 years
- IERC-European Research Cluster on the Internet of Things funded under 7th Framework in 2009
  ⇒ "Internet of European Things"
- US interest started in 2009 w $3.4B funding for **smart grid** in American Recovery and Reinvestment Act of 2009

Student Questions

Computing vs. IoT



- 21 Billion devices by 2020

Ref: M. Moran, "Why the Internet of Things Will Dwarf Social (Big Data)," Gartner Report #G00289622, February 2016

Student Questions

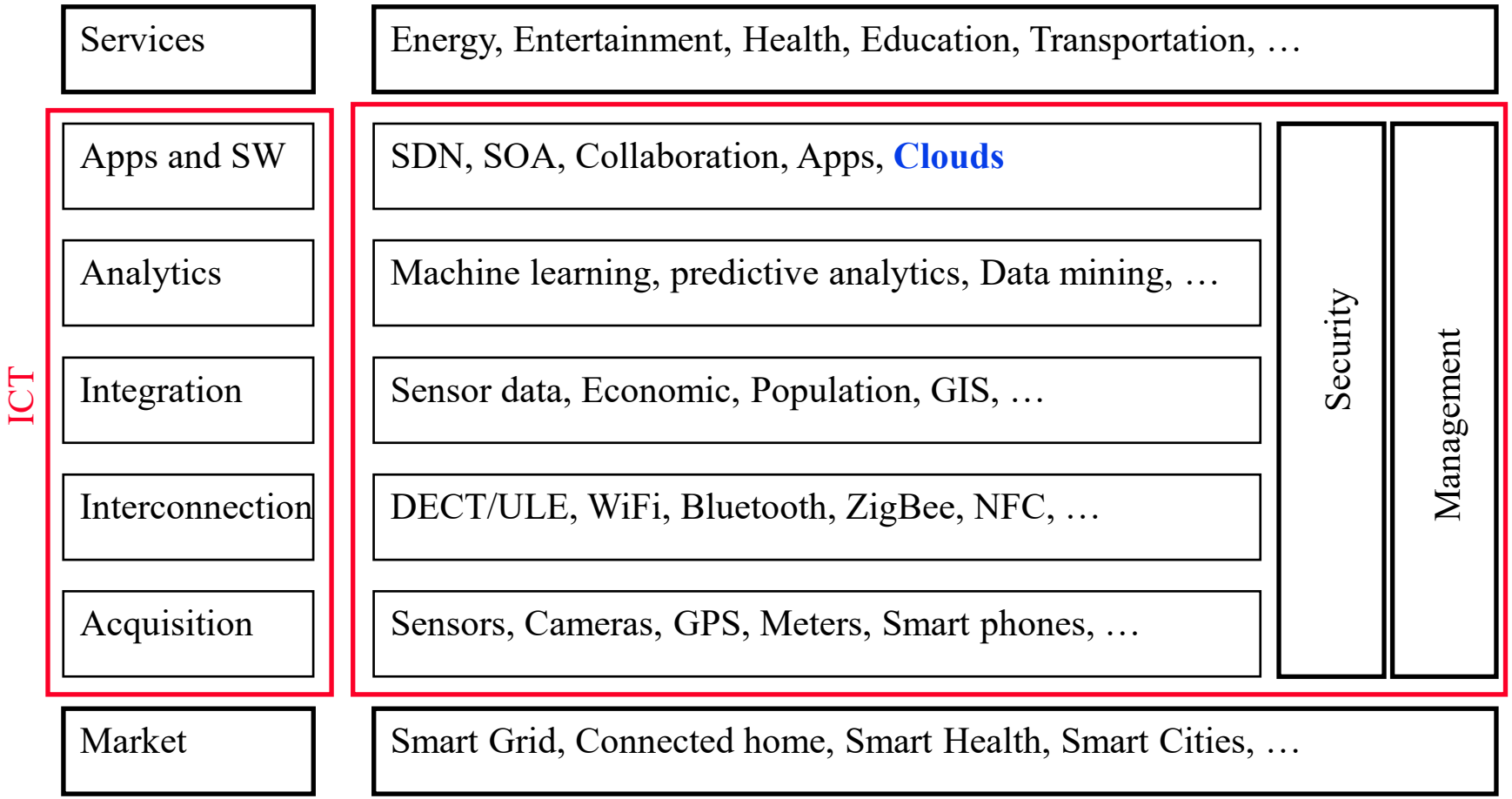
IoT Business Opportunity

- $1.7 Trillion by 2020 - IDC
- $7.1 Trillion - Gartner
- $10-15 Trillion just for Industrial Internet – GE
- $19 Trillion – Internet of Everything - Cisco

Ref: http://www.forbes.com/sites/gilpress/2014/08/22/internet-of-things-by-the-numbers-market-estimates-and-forecasts/
http://www.forbes.com/sites/gilpress/2014/08/22/internet-of-things-by-the-numbers-market-estimates-and-forecasts/

Student Questions

A 7-Layer Model of IoT



Student Questions

Areas of Research for IoT

1. **PHY**: Smart devices, sensors giving real-time information, *Energy Harvesting*
2. **Datalink**: WiFi, Bluetooth, ZigBee, 802.11ah, …
   Broadband: DSL, FTTH, Wi-Fi, 5G, …
3. **Routing**: *Multiple interfaces,* Mesh networking, …
4. **Analytics**: Big-data, data mining, Machine learning, Predictive analytics, …
5. **Apps & SW**: SDN, SOA, Cloud computing, Web-based collaboration, Social networking, HCI, Event stream processing, …
6. **Applications**: Remote health, On-line education, on-line laboratories, …
7. **Security:** Privacy, Trust, Identity, Anonymity, …

Student Questions

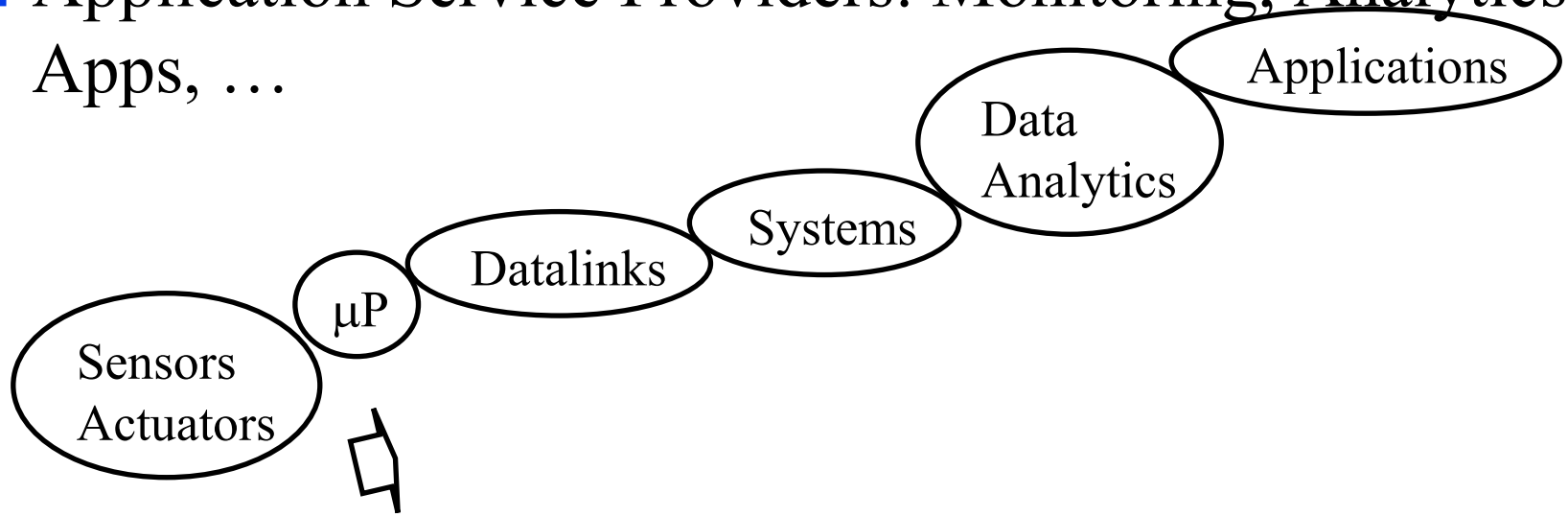
IoT is a Data ($) Mine

Ref: https://www.pinterest.com/iofficecorp/humor/

Student Questions

Business Opportunities

- Components: Sensors, wireless radios, protocols,
- Smart Objects: Smart TV, Camera, Watch, …
- Systems: Buildings, Cars, Health, …
- Network service providers: ISP
- Application Service Providers: Monitoring, Analytics, Apps, …



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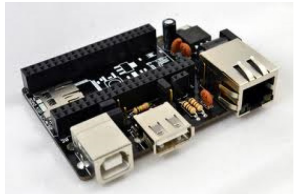
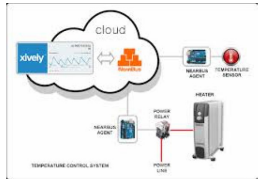
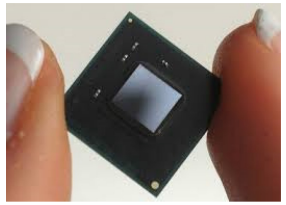
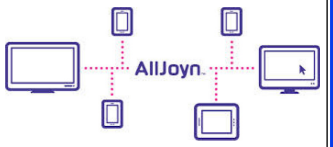
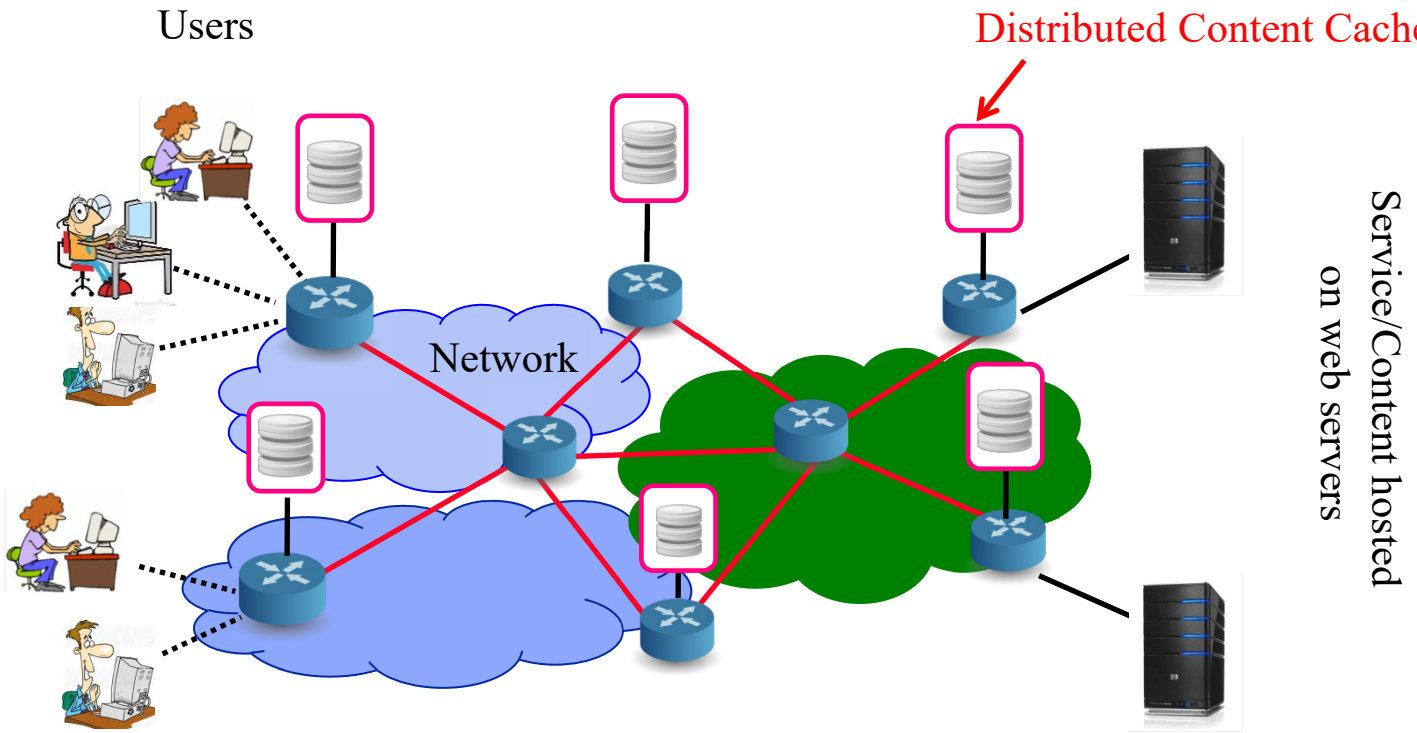
Recent IoT Products

 NEST Thermostat	 Corventis: Wireless Cardiac Monitor	 WEMO Remote	 Tractive Pet Tracker
 Ninja Blocks	 Revolve Home Automation	 ThingWorx Application Platform	 Lings Cloud Platform
 Mbed Development Platform	 Xively Remote Access API	 Intel Quark Processor	 AllJoyn S/W Framework

Student Questions

Past: Data in the Edge

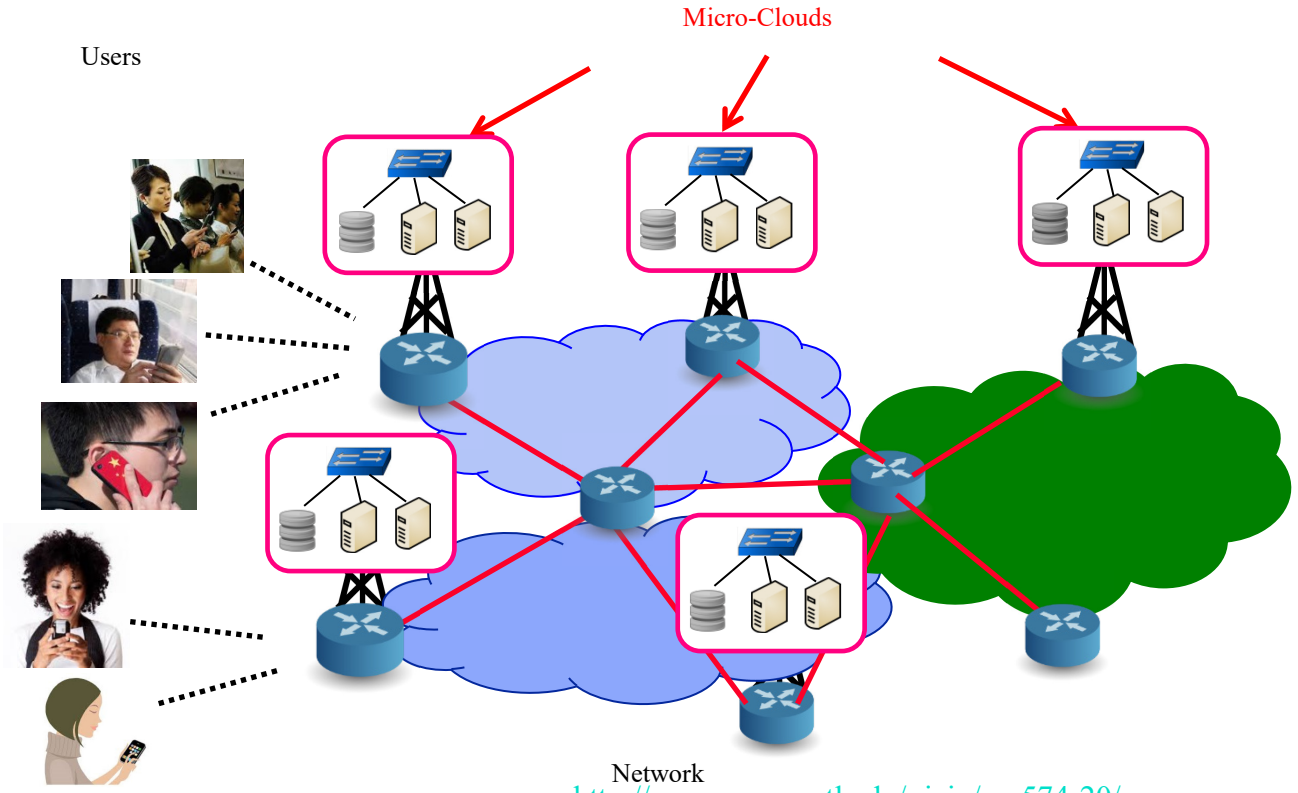
- To serve world-wide users, latency was critical and so the data was replicated and brought to edge



Student Questions

Trend 2: Computation in the Edge

- To service mobile users/IoT, the computation needs to come to edge ⇒ Mobile Edge Computing, Fog Computing

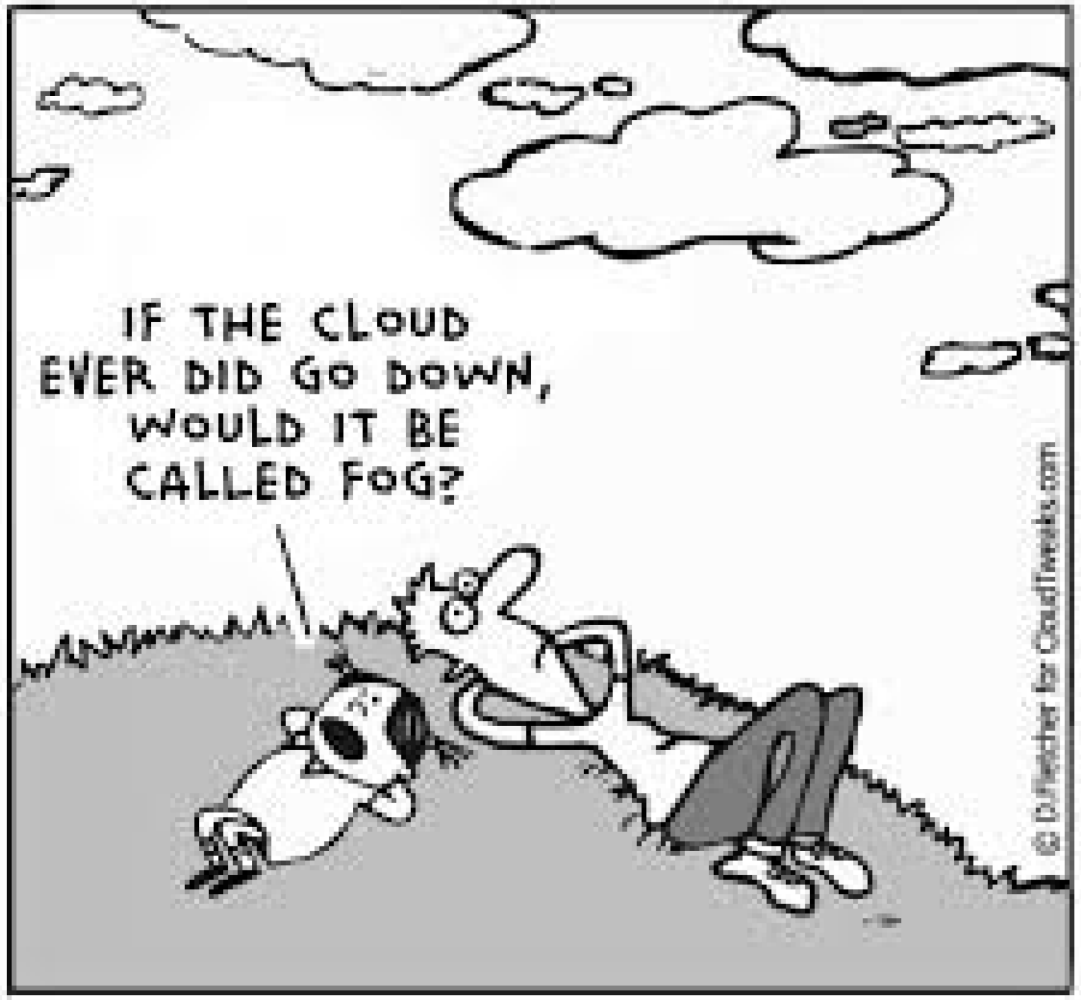


Student Questions

- Is edge computing related to CDNs like Cloudflare?

Content Distribution Networks (CDN) started with "Storage" by replicating websites all over the world to provide quick response. Edge computing takes it further by providing computation closer to the users.

Fog Computing

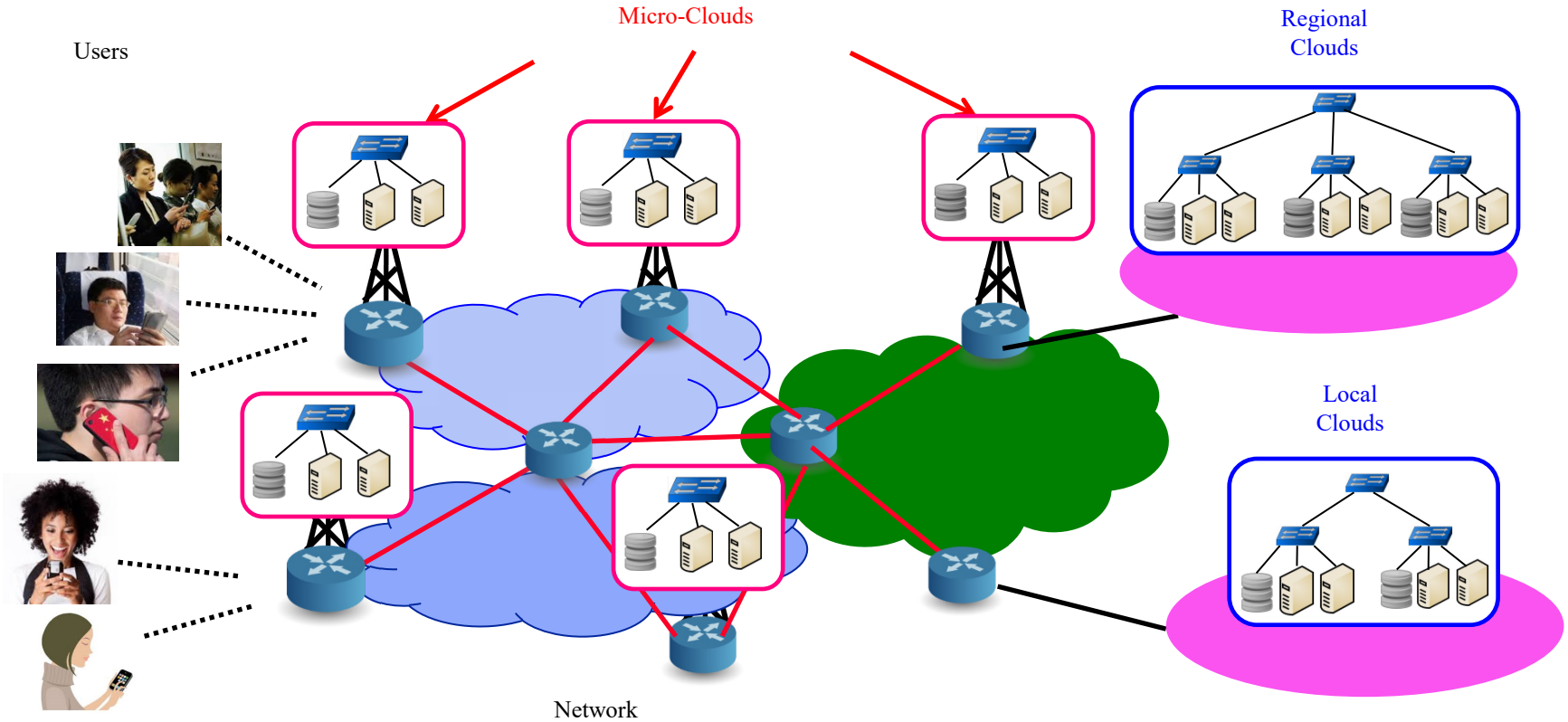


Ref: http://community.spiceworks.com/topic/254392-fog-computing-replaces-cloud-as-new-tech-buzzword

Student Questions

Trend 3: Multi-Cloud

- Larger and infrequent jobs serviced by local and regional clouds ⇒ Fog Computing



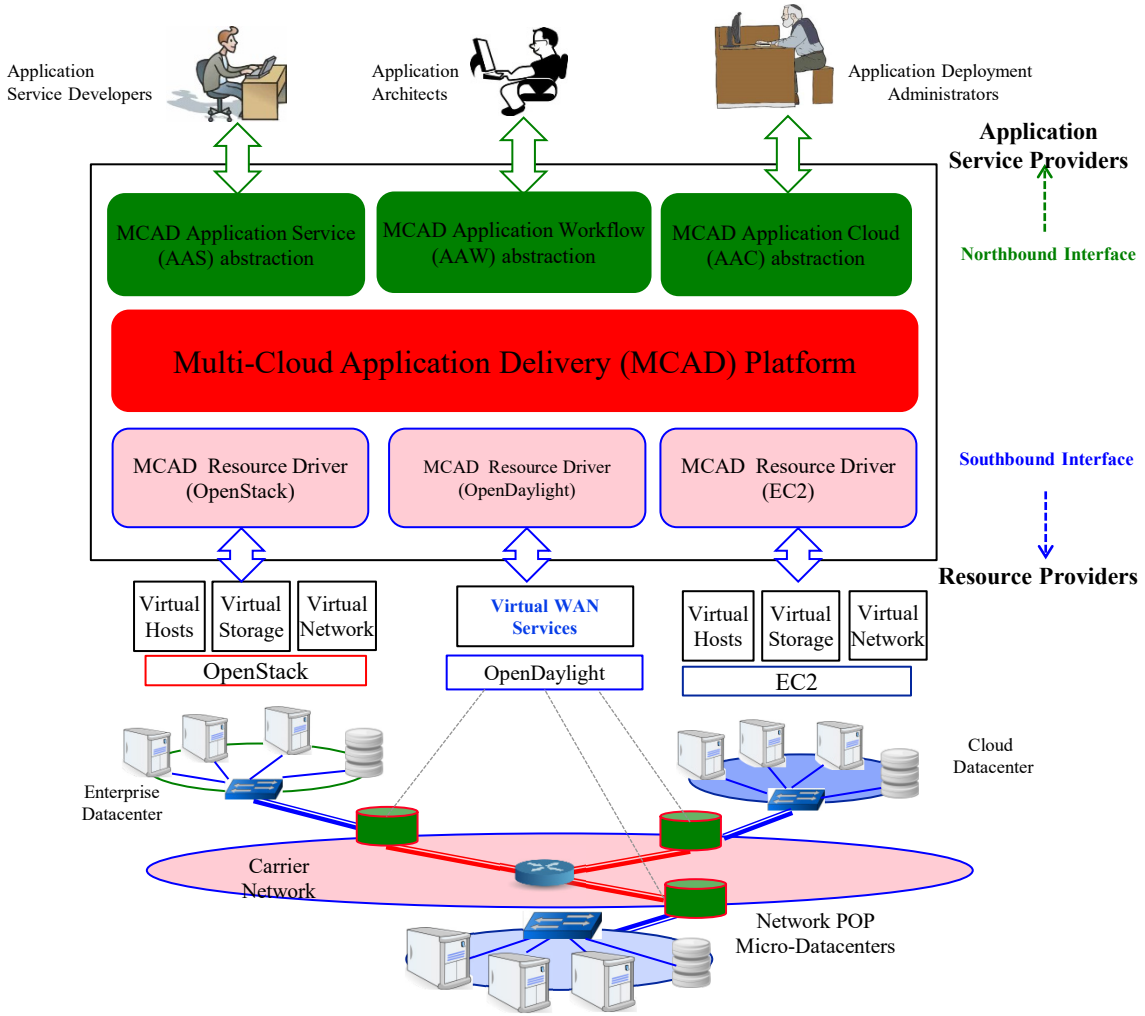
Ref: Subharthi Paul, Raj Jain, Jianli Pan, Jay Iyer, and Dave Oran, "**OpenADN: A Case for Open Application Delivery Networking**," Proceedings of International Conference on Computer Communications and Networks (ICCCN) 2013, Nassau, Bahamas, July 30-Aug 2, 2013, http://www.cse.wustl.edu/~jain/papers/adn_ic3n.htm

Student Questions

- Can you post a reference link for the MCAD platform? What are some use cases for this platform outside of IoT?

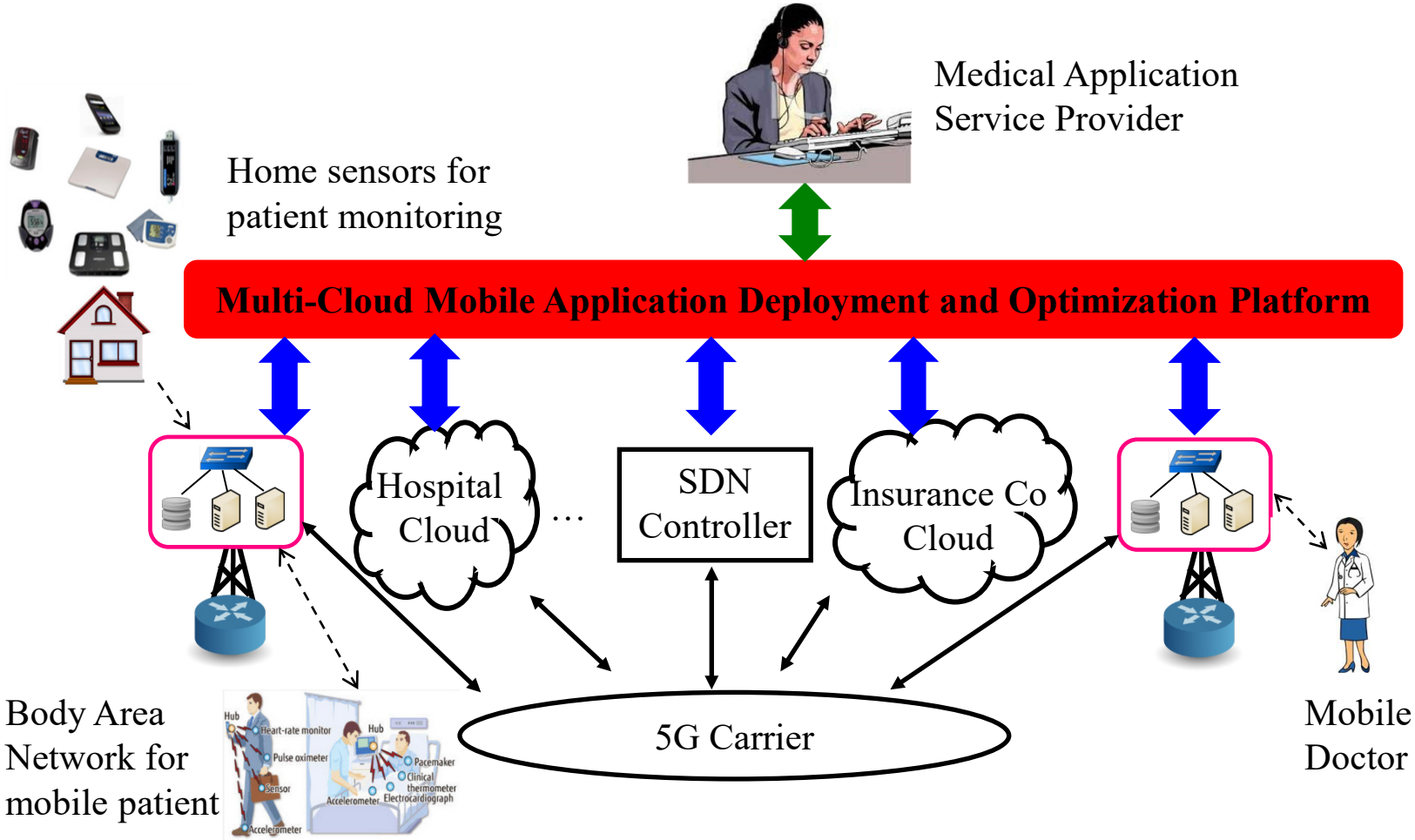
I have added the reference on the left. It was initially called OpenADN. It was a testbed in our lab. Multi-cloud computing is now very common.

Software Defined Multi-Cloud Application Management



Student Questions

Mobile Healthcare Use Case



Student Questions

Legacy IoT Protocols

- **BACnet**: Building Automation and Control Network
- **LonWorks**: Local Operating Network (like BACnet)
- **ModBus**: Modicon (Schneider Electric)'s Serial Bus (www.modbus.org)
- **KNX**: Home and Building Automation Standard
- **Z-Wave**: Wireless Communication for Home Automation
- **M-Bus**: Bus for remote reading of gas and electric meters
- **ANSI CI12.20**: Electric Meter Accuracy and Performance
- **DLMS**: Device Language Message Specification
- **COSEM**: Company Specification for Energy Metering
- **DALI**: Digital Addressable Lighting Interface
- **EIB**: European Installation Bus
- **WirelessHART**: Wireless Highway Addressable Remote Transducer Protocol (www.hartcomm.org)

Ref: IEC 61158: Fieldbus for use in industrial control systems, Part 1 to 6, 2008

Student Questions

Recent Protocols for IoT

Session	MQTT, SMQTT, CoRE, DDS, AMQP , XMPP, CoAP, IEC,…	Security	Management
Network	Encapsulation 6LowPAN, 6TiSCH, 6Lo, Thread…	IEEE 1888.3, TCG, Oath 2.0, SMACK, SASL, EDSA, ace, DTLS, Dice, …	IEEE 1905, IEEE 1451, IEEE 1377, IEEE P1828, IEEE P1856
	Routing RPL, CORPL, CARP		
Datalink	**WiFi, 802.11ah, Bluetooth Low Energy,** Z-Wave, **ZigBee Smart, DECT/ULE, 3G/LTE**, NFC, **Weightless,** HomePlug GP, **802.15.4e, G.9959, WirelessHART, DASH7, ANT+, LTE-A, LoRaWAN,** ISA100.11a, DigiMesh, WiMAX, …		

Ref: 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

Student Questions

Standardization

- Almost every standards body is working on IoT:
  - IEEE: 802.11, 802.15.4, HomePlug
  - ZigBee Alliance: ZigBee Smart
  - Bluetooth SIG: Bluetooth Smart
  - IETF: RPL, 6LowPAN
  - ITU:
  - ETSI: DECT/ULE
  - IPSO, …
  - 3GPP
- Seven organizations joined together to avoid duplication: ARIB, ATIS, CCSA, ETSI, TIA, TTA, TTC ⇒ oneM2M

Ref: http://www.onem2m.org

Student Questions

- What are some differences in creating a protocol designed to connect computers vs IoT devices?

Same as connecting a tiny Raspberri Pi vs Connecting a Supercomputer. Very low power and very low computing capability are just two issues to begin the discussion.

Datalink Issues

- Energy efficiency
  - ⇒ Need to decrease energy/bit by a factor of 1000
  - Energy/bit has gone down by a factor of 2 per year
  - Either wait ten years or design better protocols
- Small messages ⇒ Need low overhead
- Limited computing ⇒ Light weight protocols
  ⇒ lightweight Encryption, authentication, security
- Quality of Information (QoI)

Student Questions

- What is the difference between QoI and QoS?

Quality of Service is measured by the delay and throughput. QoI is measured by accuracy and correctness.

Power per MB

Type	Bit rate	TX Power	mJoules/MB
802.11b	11Mb	50mW	36.4
802.11g	54Mb	50mW	7.4
802.11a	54Mb	200mW	29.6
802.15.1 Bluetooth	1Mb	1mW	8.0
802.15.3	55Mb	200uW	0.03

- Once connected, Bluetooth classic maintains connections even when there is no data. Low power but not low enough.

Student Questions

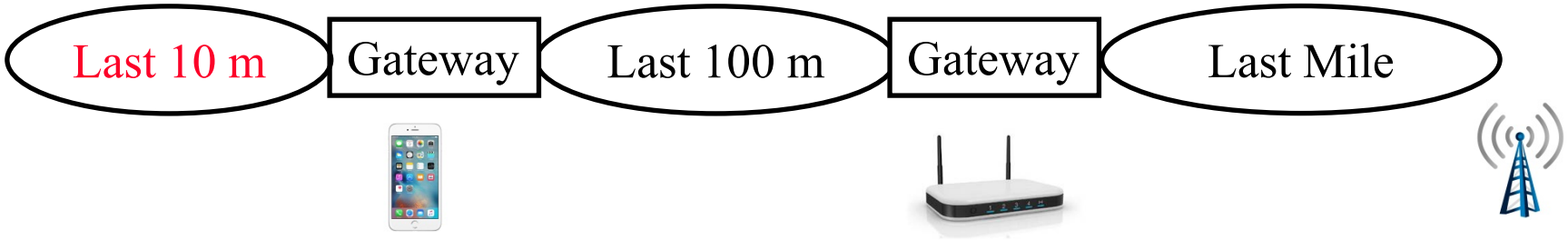
Networking Issues

- Large number ⇒ 32-bit or 48-bit addressing not sufficient
- 32-bit IPv4 addresses too small
- 48-bit IEEE 802 too small
- 128-bit IPv6 addresses too large. Tiny things do not have energy to transmit such large addresses.
- 16-bit local addresses and 64-bit global addresses
- 6LowPAN, 6-to-NonIP

Student Questions

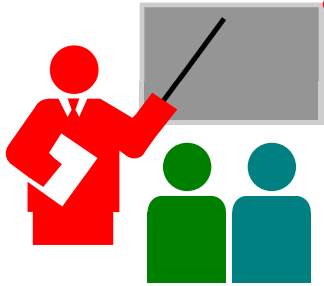
Last 100m Protocols

- The Last Mile: Mobile and Broadband Access revolution
  Smart Grid, Smart Cities, Smart Industries
- The last 100m: Smart home
- The last 10 meter: Smart Healthcare, Smart Wearable's



Student Questions

Summary



1. Less than 1% of things are connected
   ⇒ IoT is a big opportunity for academics and industry
2. Smart Grid and Energy management is leading the change.
3. Smartness comes from communication capability since the computation can be delegated
4. Right at the knee: Academic and Startup Research opportunities in almost subfields of computing including hardware development, data analytics, security, and networking.
5. Cloud computing everywhere leads to fog computing and multi-cloud computing ⇒ AppFabric

Student Questions

Reading List

- 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
- Honbo Zhou, "The Internet of Things in the Cloud: A Middleware Perspective," CRC Press, October 2012, 391 pp., ISBN:978-1-4398-9299-2 (Safari Book).
- Olivier Hersent; David Boswarthick; Omar Elloumi, "The Internet of Things: Key Applications and Protocols," John Wiley & Sons, February 1, 2012, 370 pp., ISBN:978-1-119-99435-0 (Safari Book).

Optional:

- Francis daCosta, "Rethinking the Internet of Things: A Scalable Approach to Connecting Everything," Apress, January 2014, 192 pp., ISBN:1-4302-5740-7 (Safari Book).
- Hakima Chaouchi, "The Internet of Things: Connecting Objects," John Wiley & Sons, June 2010, 288 pp., ISBN:978-1-848-21140-7 (Safari Book).
- Nitesh Dhanjani, "Abusing the Internet of Things," O'Reilly Media, Inc., August 2015, 250 pp., ISBN:978-1-4919-0233-2 (Safari Book).

Student Questions

Wikipedia Links

- https://en.wikipedia.org/wiki/Fog_computing
- https://en.wikipedia.org/wiki/Internet_of_Things
- https://en.wikipedia.org/wiki/IPSO_Alliance
- https://en.wikipedia.org/wiki/Machine_to_machine
- https://en.wikipedia.org/wiki/Multicloud
- https://en.wikipedia.org/wiki/Nearables
- https://en.wikipedia.org/wiki/Smart_device
- https://en.wikipedia.org/wiki/SmartThings
- https://en.wikipedia.org/wiki/Ubiquitous_computing
- https://en.wikipedia.org/wiki/Wearable_technology
- https://en.wikipedia.org/wiki/Web_of_Things

Student Questions

Wikipedia Links (Cont)

- http://en.wikipedia.org/wiki/ANT%2B
- http://en.wikipedia.org/wiki/Near_field_communication,
- http://en.wikipedia.org/wiki/Weightless_%28wireless_communications%29
- https://en.wikipedia.org/wiki/Highway_Addressable_Remote_Transducer_Protocol
- https://en.wikipedia.org/wiki/Li-Fi
- https://en.wikipedia.org/wiki/LoRaWAN
- https://en.wikipedia.org/wiki/Thread_(network_protocol)
- https://en.wikipedia.org/wiki/Weightless_(wireless_communications)

Student Questions

Acronyms

- 3GPP Third Generation Partnership Project
- 6LowPAN IPv6 over Low Powered Personal Area Network
- 6Tisch IPv6 over TSCH mode of IEEE 802.15.4e
- AAC Application Architecture
- AAS Application Service
- AAW Application Workflow
- AMQP Advanced Message Queueing Protocol
- ANSI American National Standards Institute
- ANT A proprietary open access multicast wireless sensor network
- ANT+ Interoperability function added to ANT
- API Application Programming Interface
- ARIB Association of Radio Industries and Businesses (Japan)\
- ATIS Alliance for Telecommunications Industry Solutions
- BACnet Building Automation and Control Network
- CARP Common Address Redundancy Protocol
- CI12.20 ANSI Standard for Electric Meter Accuracy and Performance
- CoAP Constrained Application Protocol

Student Questions

Acronyms (Cont)

- COSEM Company Specification for Energy Metering
- CPS Cyber Physical Systems
- CRC Cyclic Redundancy Check
- CTIA Cellular Telecommunication Industries Association
- DALI Digital Addressabel Lighting Interface
- DARPA Defense Advance Research Project Agency
- DASH7 ISO 18000-7 RFID standard for sensor networks
- DECT Digital Enhanced Cordless Communication
- DLMS Device Language Message Specification
- DSL Digital Subscriber Line
- DTLS Datagram Transport Layer Security
- EC2 Elastic Compute Cloud 2 (by Amazon)
- ETSI European Telecommunications Standards Institute
- FTTH Fiber to the home
- GE General Electric

Student Questions

Acronyms (Cont)

- GIS Geographical Information Systems
- GP GreenPHY
- GPS Global Positioning System
- GreenPHY Green Physical Layer
- HomePlug-GP HomePlug Green PHY
- IBM International Business Machines
- ICT Information and Communications Technology
- IDC Name of a company
- IEEE Institute for Electrical and Electronic Engineers
- IERC IoT-European Research Cluster
- IETF Internet Engineering Task Force
- IoT Internet of Things
- IP Internet Protocol
- IPSO IP for Smart Objects
- IPv4 Internet Protocol version 4
- IPv6 Internet Protocol version 6

Student Questions

Acronyms (Cont)

- ISP Internet Service Provider
- ITU International Telecommunications Union
- KISS Keep it simple stupid
- KNX Building automation protocol
- MB Mega-byte
- MCAD Multi-Cloud Application Deployment Platform
- MQTT Message Queue Telemetry Transport
- NEST Name of a product
- NFC Near field communication
- NIH National Institute of Health
- NITRD Networking and Info Tech Research and Development
- NonIP Non-Internet Protocol
- NSF National Science Foundation
- oneM2M One Machine to Machine
- PAN Personal area network
- PoP Point of Presence

Student Questions

Acronyms (Cont)

QoI	Quality of information
QR	Quick Response
RFID	Radio Frequency Identifier
RPL	Routing Protocol for Low Power and Lossy Networks
RX	Receiver
SASL	Simple Authentication and Security Layer
SDN	Software Defined Networking
SIG	Special Interest Group
SMACK	Stuttgart Modified Amateur radio CRC-KISS
SOA	Software-oriented Architecture
SW	Software
TCG	Technical Committee G
TSCH	Time-Slotted Channel Hopping
TV	Television
TX	Transmitter
ULE	Ultra Low Energy

Student Questions

Acronyms (Cont)

- US United States
- VC Venture Capital
- WAN Wide Area Network
- WiFi Wireless Fidelity
- WiMAX Worldwide Interoperability for Microwave Access
- WirelessHART Wireless Highway Addressable Remote Transducer Protocol
- XML eXtensible Markup Language
- ZB Ziga-Byte

Student Questions

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Raj Jain
http://rajjain.com

http://www.cse.wustl.edu/~jain/cse574-20/j_10iot.htm

Student Questions

Related Modules

CSE567M: Computer Systems Analysis (Spring 2013),
https://www.youtube.com/playlist?list=PLjGG94etKypJEKjNAa1n_1X0bWWNyZcof

CSE473S: Introduction to Computer Networks (Fall 2011),
https://www.youtube.com/playlist?list=PLjGG94etKypJWOSPMh8Azcgy5e_10TiDw

Recent Advances in Networking (Spring 2013),
https://www.youtube.com/playlist?list=PLjGG94etKypLHyBN8mOgwJLHD2FFIMGq5

CSE571S: Network Security (Fall 2011),
https://www.youtube.com/playlist?list=PLjGG94etKypKvzfVtutHcPFJXumyyg93u

Video Podcasts of Prof. Raj Jain's Lectures,
https://www.youtube.com/channel/UCN4-5wzNP9-ruOzQMs-8NUw

Student Questions