Introduction to Internet of Things

Raj Jain
Washington University in Saint Louis
Saint Louis, MO 63130
Jain@cse.wustl.edu

These slides and audio/video recordings of this class lecture are at:
http://www.cse.wustl.edu/~jain/cse574-22/

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 the first of a series of class lectures on IoT.

Student Questions

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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/

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Internet of Things

- Less than 1% of things around us are connected.
  The refrigerator, car, washing machine, heater, a/c, and garage door, should all be connected but are not.
- From 10 Billion today to 50 Billion in 2020.
  It includes processes, data, things, and people.
- $14 Trillion over ten 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

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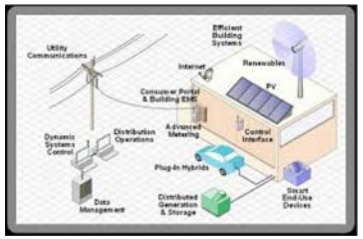
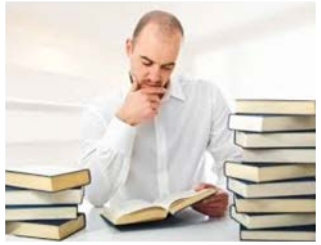
Sample IoT Applications

 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

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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

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- What is PAN? Is it something similar to PBSS?

WAN, LAN, PAN.
Personal area network.
Bluetooth is a PAN.

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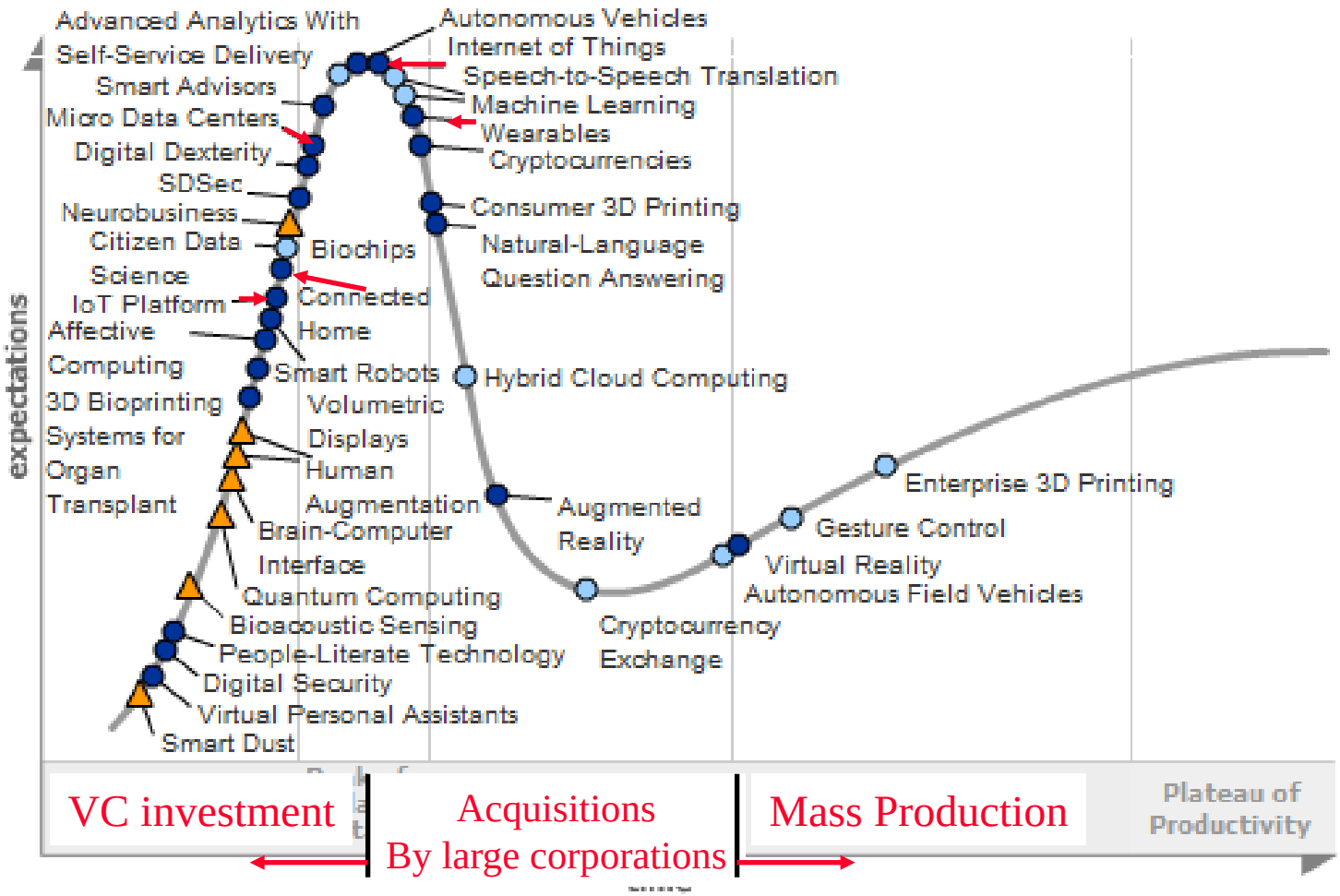
Gartner Hype Cycle 2015



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

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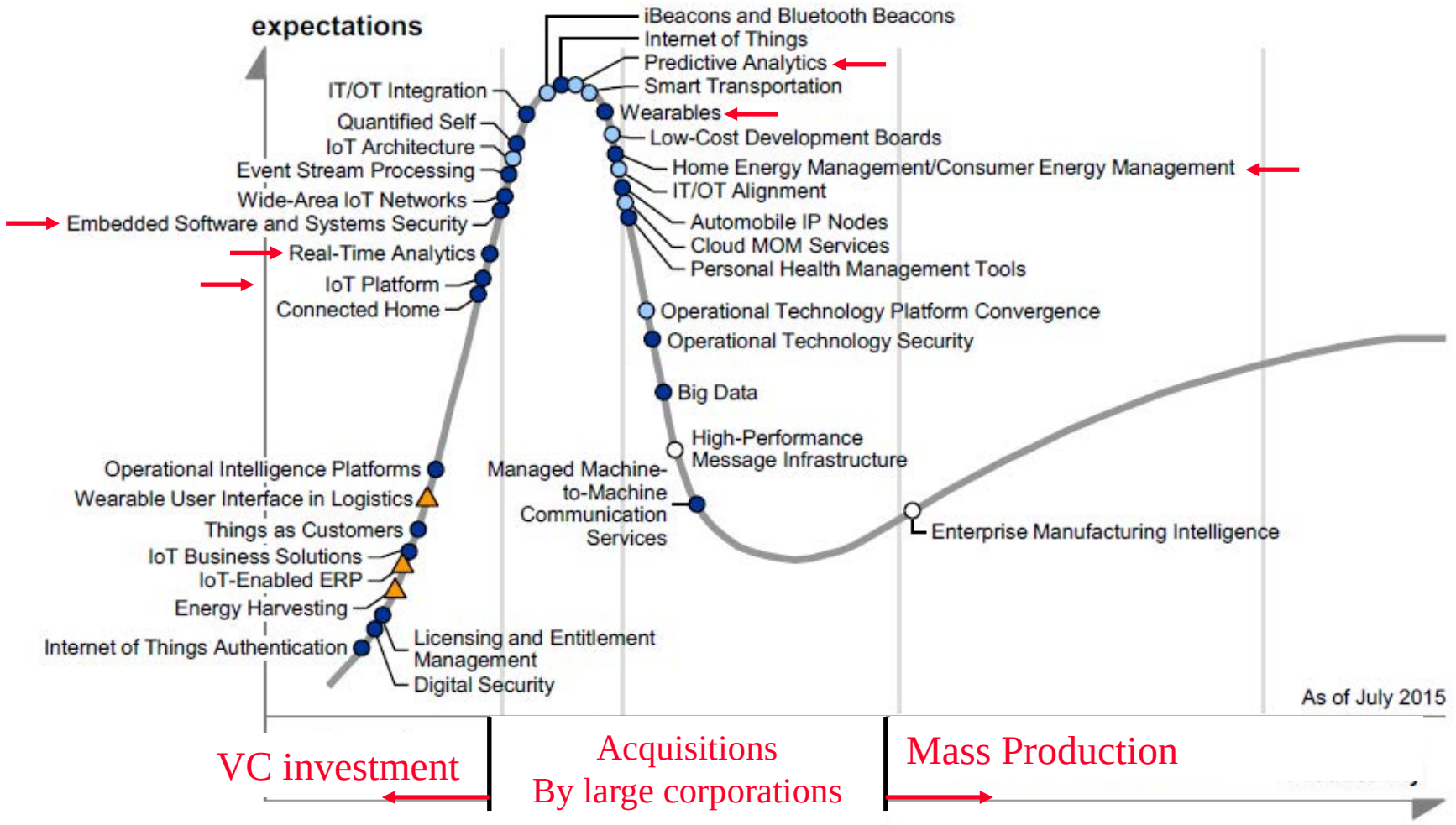
Gartner's Hype Cycle For IoT 2015



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

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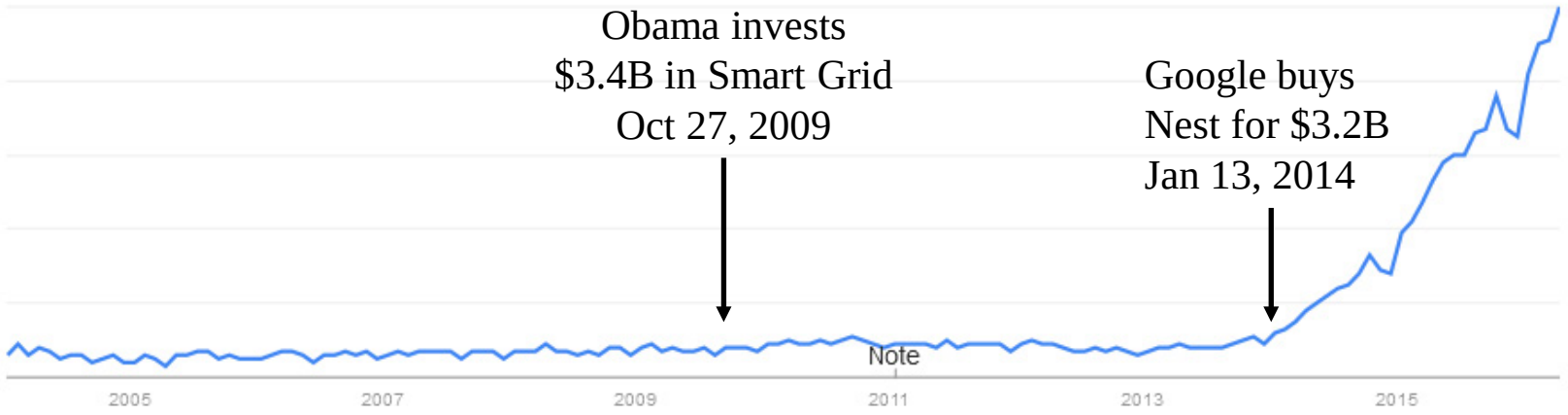
Google Trends



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

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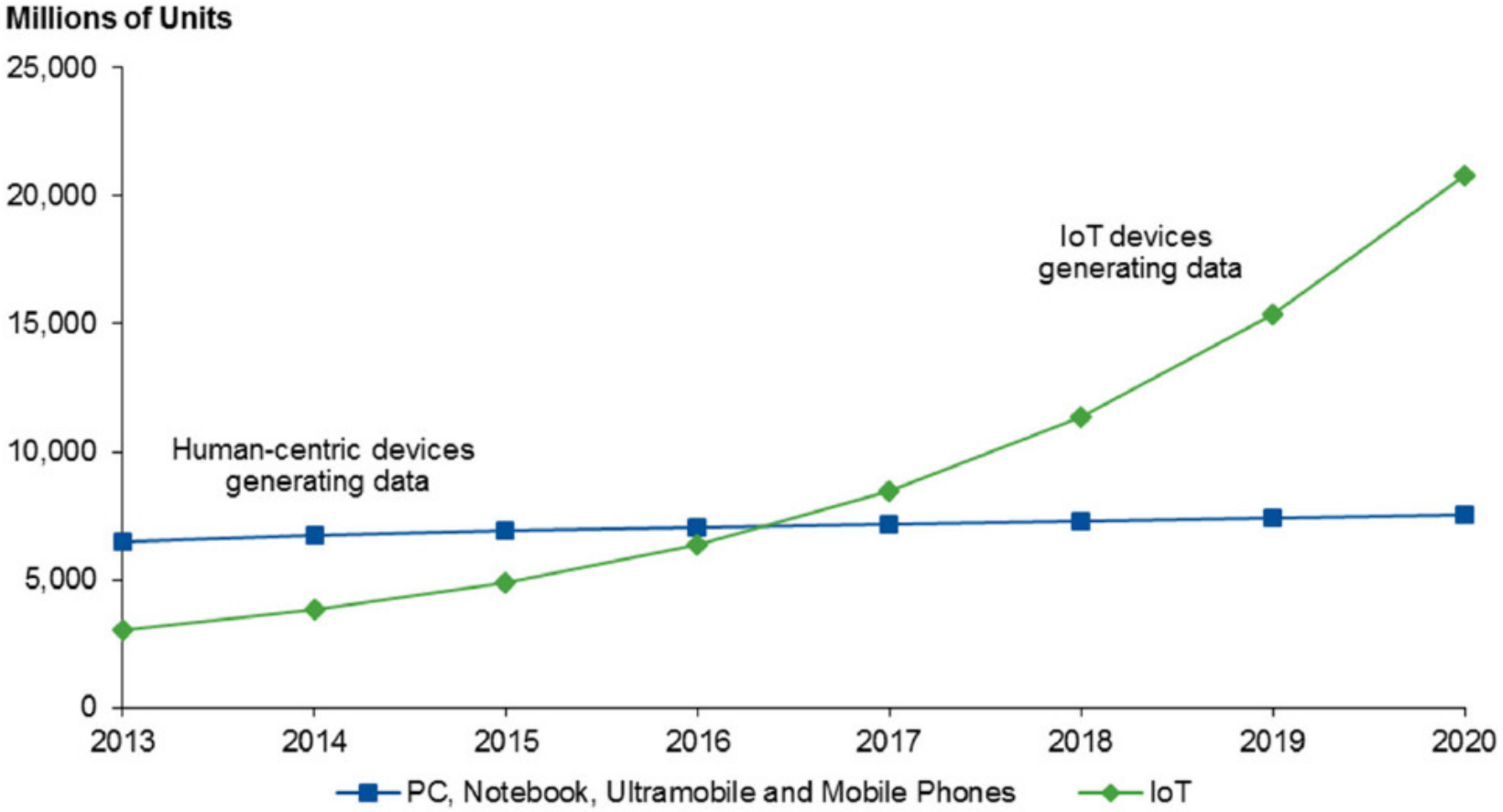
Computing vs. IoT



- 21 Billion devices by 2020

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

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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/

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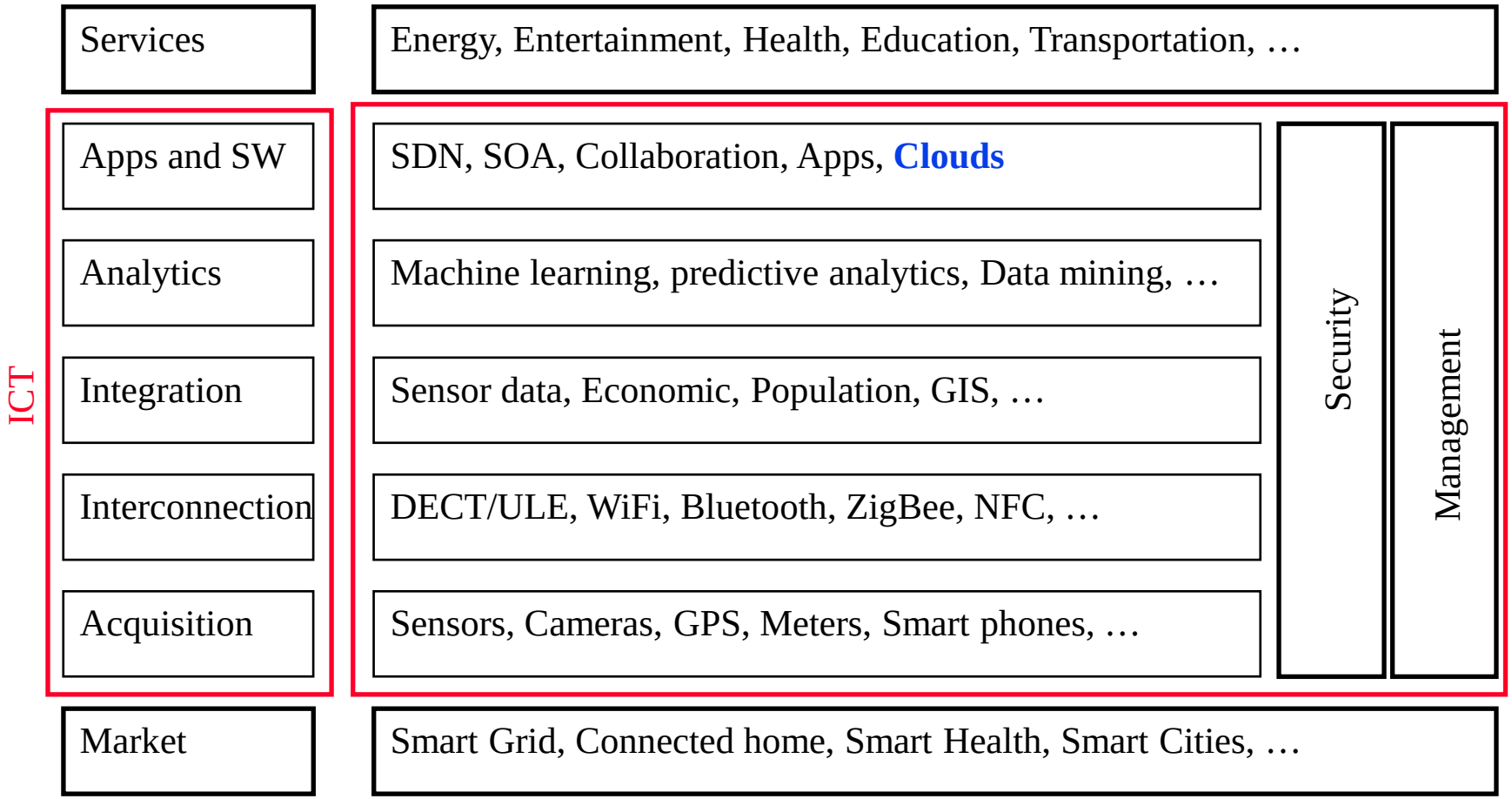
A 7-Layer Model of IoT



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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, Online education, online laboratories, …
7. **Security:** Privacy, Trust, Identity, Anonymity, …

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IoT is a Data ($) Mine

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

Student Questions

- How much privacy do users care about? People don't want Alexa listening to them. Are they okay with other smart device data use?

Everyone is different. Many free services are supported by selling data. Free browser extensions and free apps are such examples.

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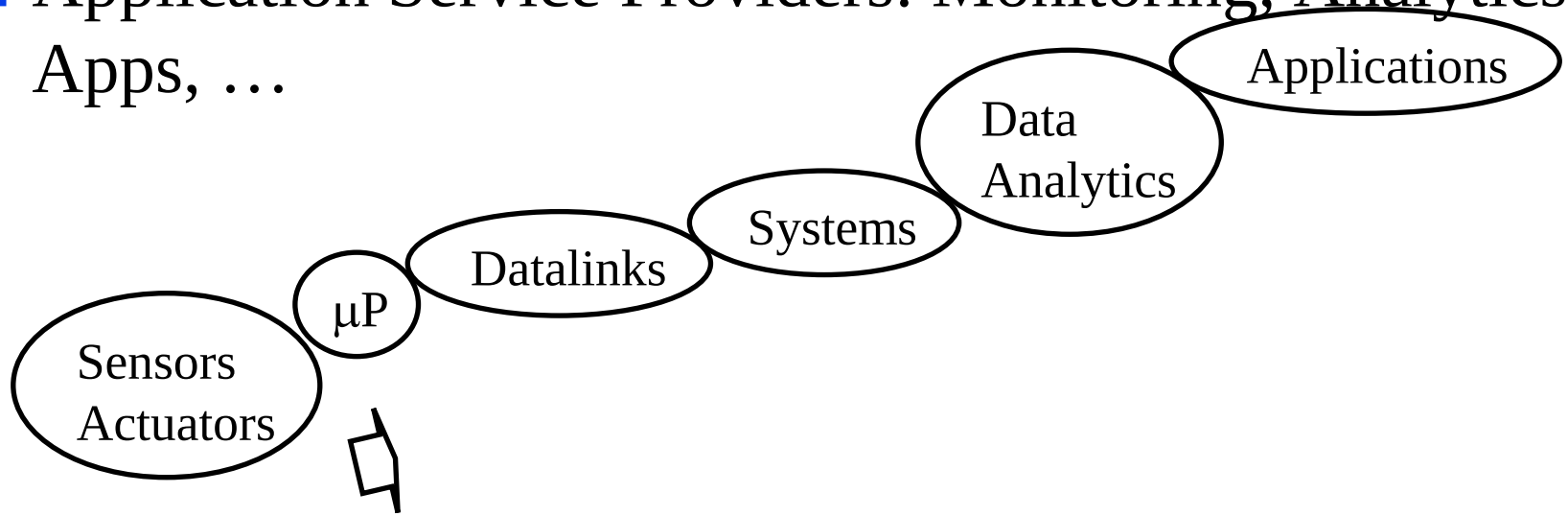
Business Opportunities

- 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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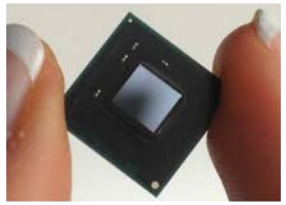
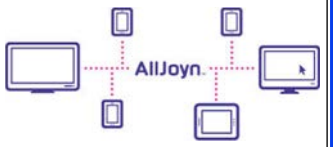
Recent IoT Products

 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

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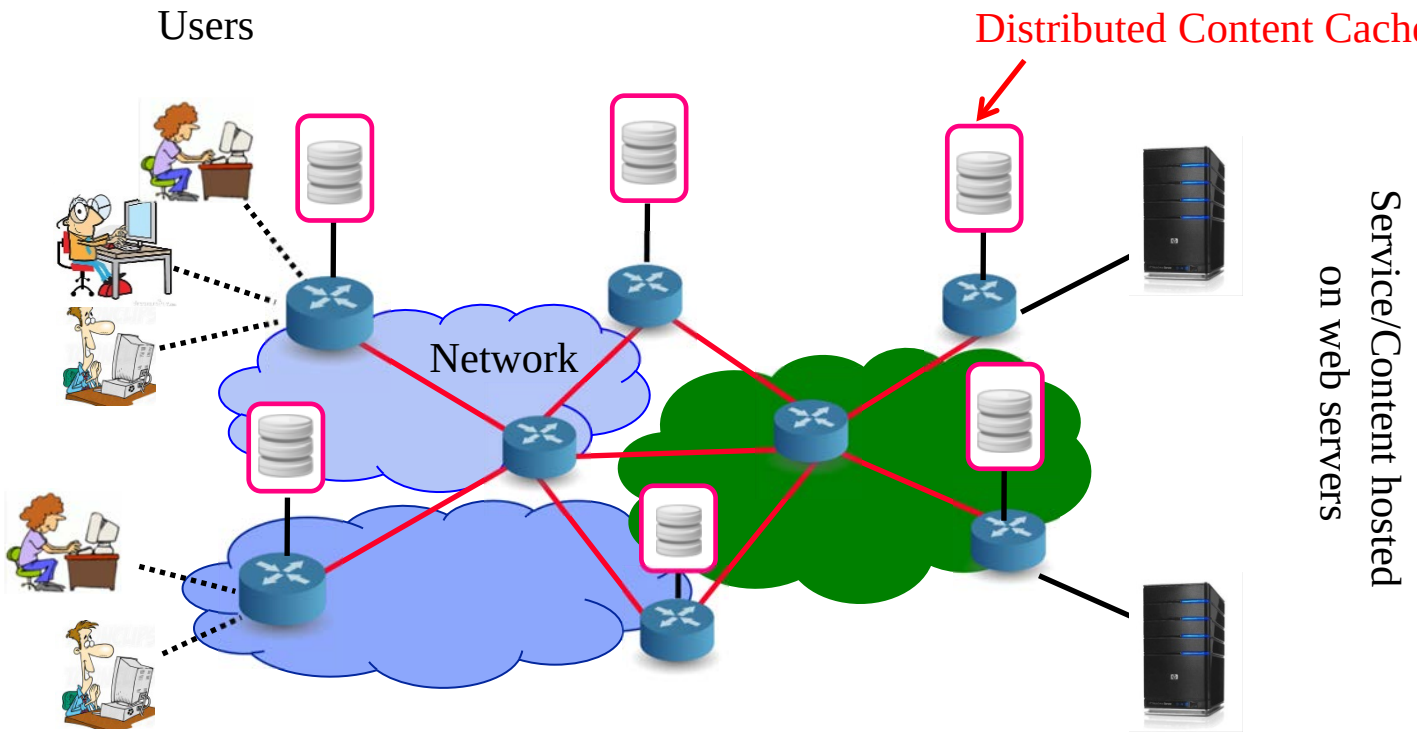
Past: Data in the Edge

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



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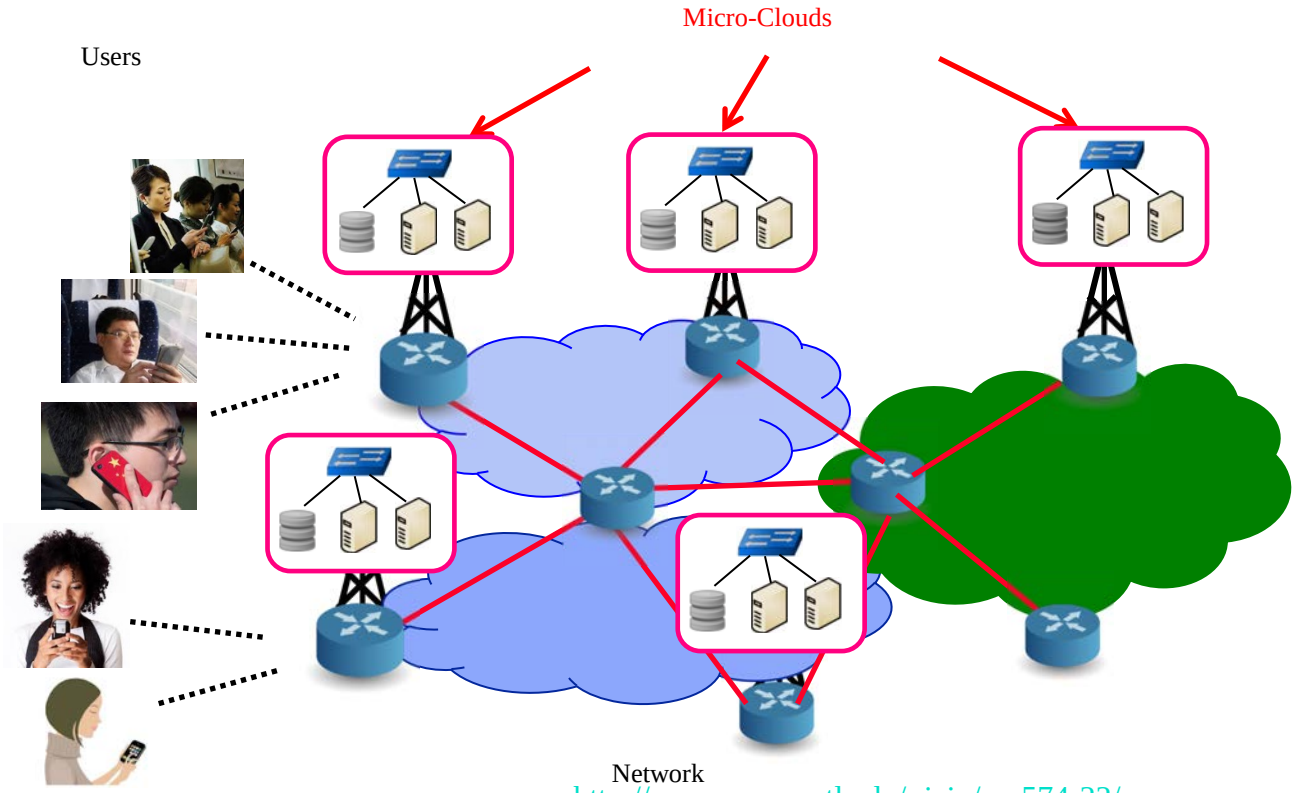
Trend 2: Computation in the Edge

- 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.

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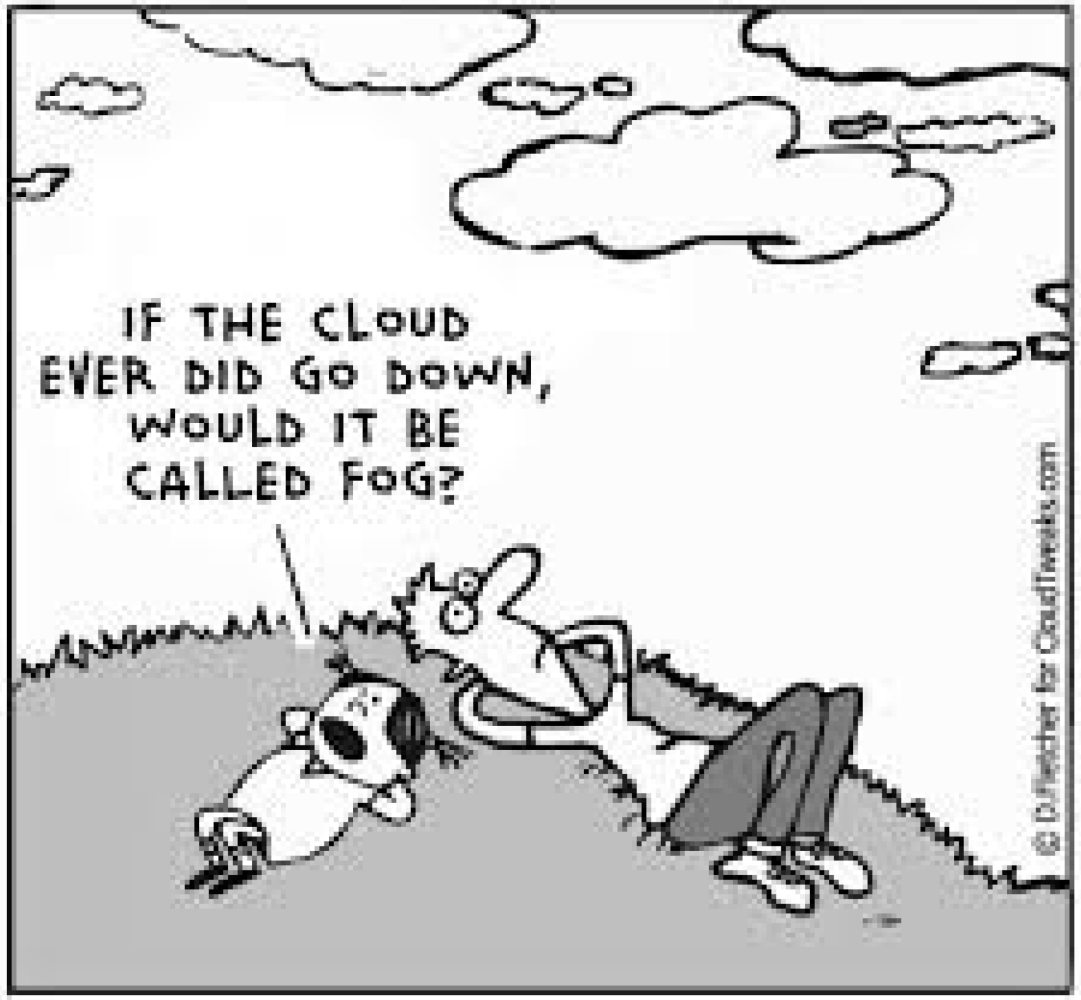
Fog Computing



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

Student Questions

- For Fog and Edge computing, do we have any standard definition?
  No. There is no standard definition of fog computing.
- Is fog computing equal to multi-cloud?

No. Fog = computing everywhere = Clouds everywhere

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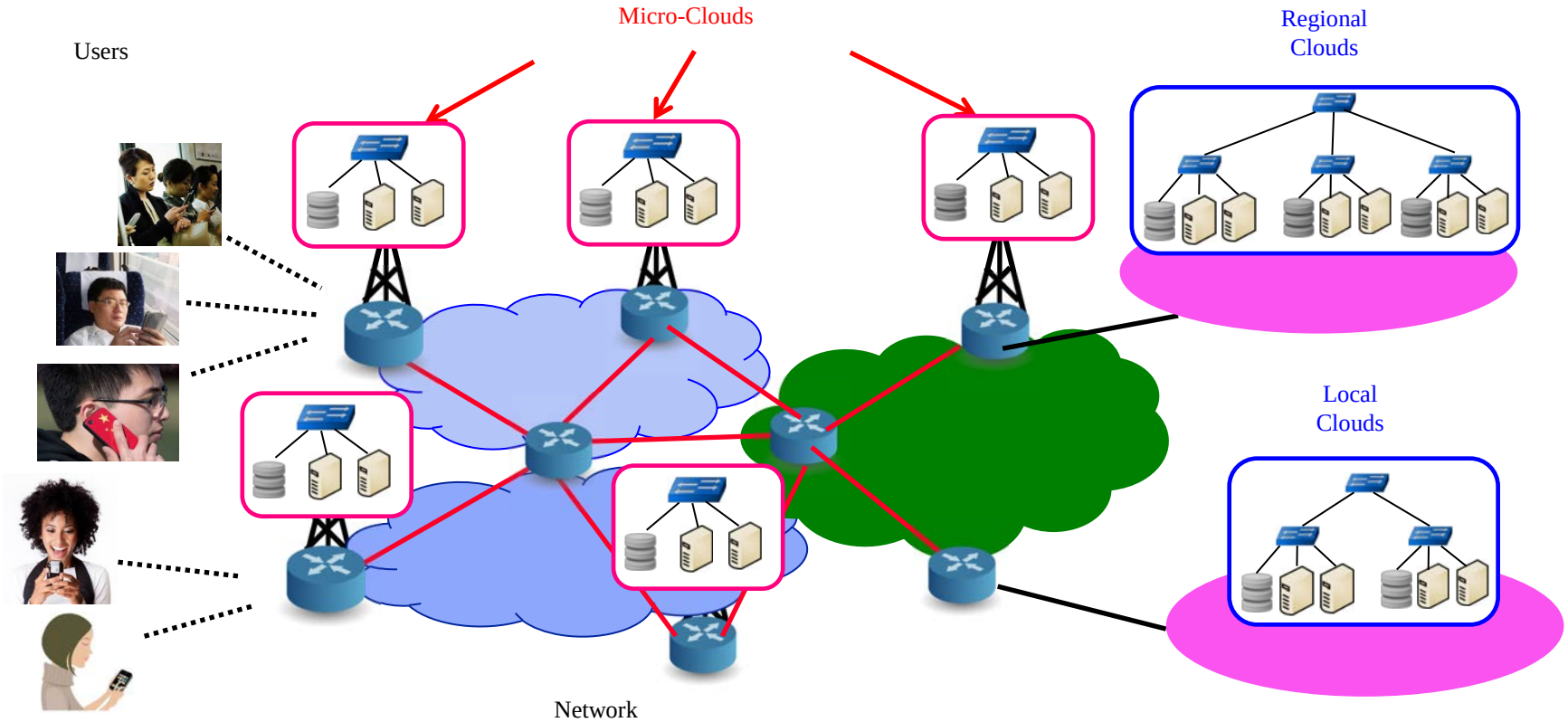
Trend 3: Multi-Cloud

- 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

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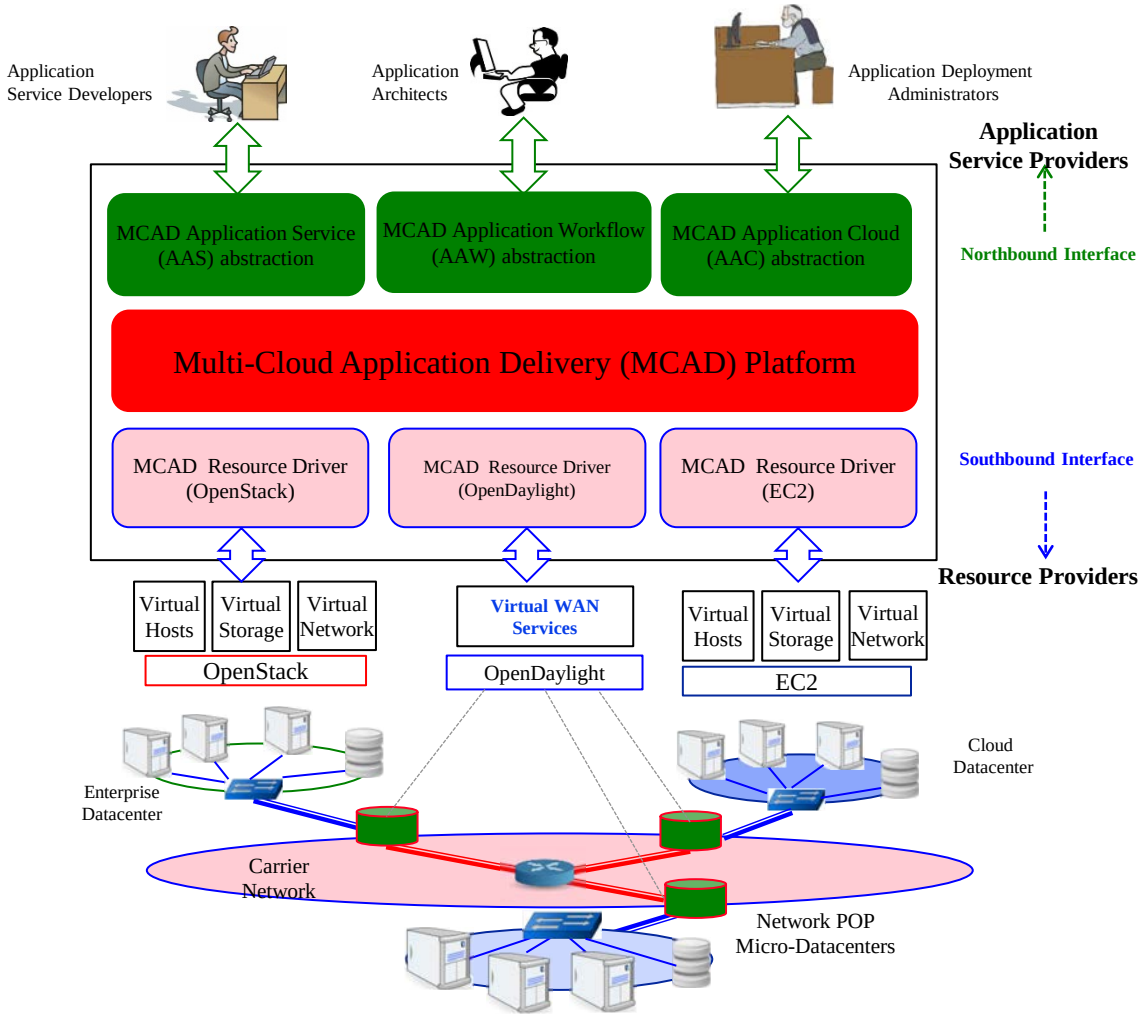
Student Questions

- 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



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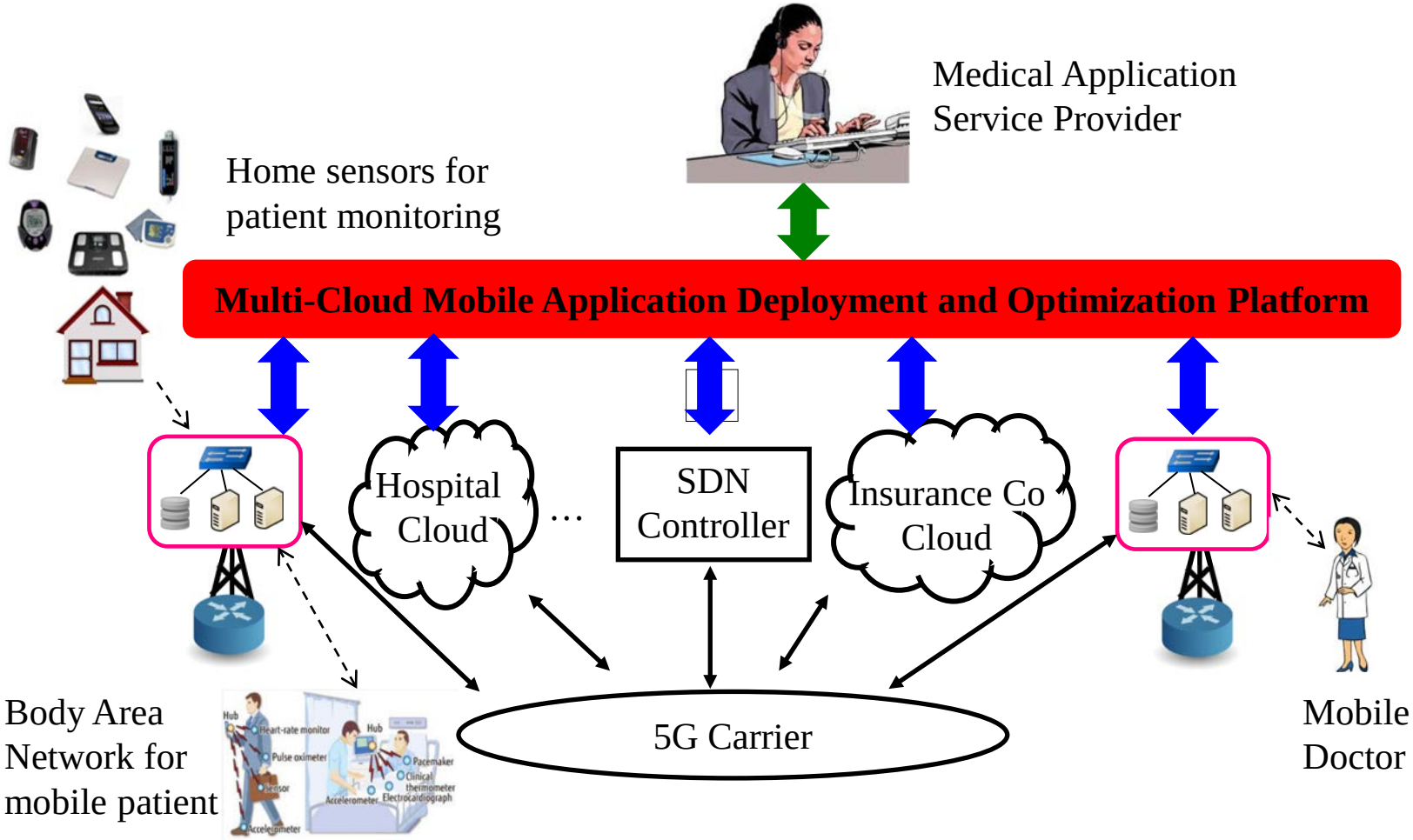
Mobile Healthcare Use Case



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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

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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

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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.

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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 ⇒ Lightweight 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.

- How do we measure energy/bit? Is this the computational energy the hardware uses to process the data traffic, or is it the energy required to transmit by the antennas?

Energy includes both computation and transmission. Based on battery usage.

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

- Are we required to know the math behind this table?

No.

End of Q

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Networking Issues

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

Student Questions

- For one device, does it have a local address and a global address at the same time?

Yes. Like your pet name and a legal name.

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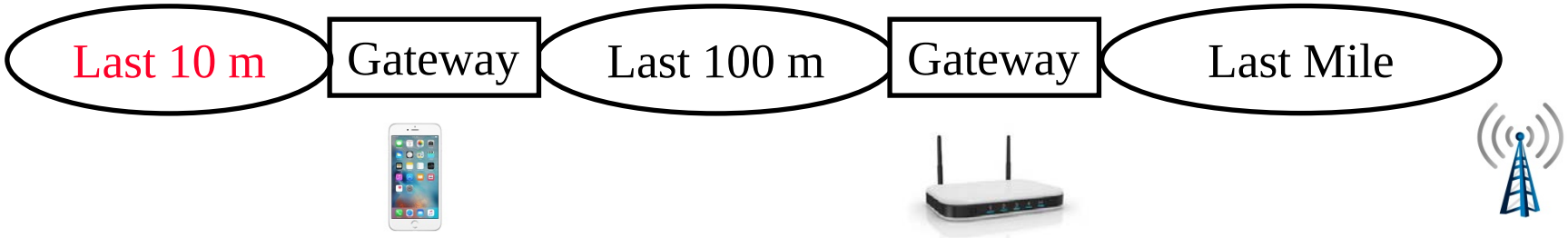
Last 100m Protocols

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



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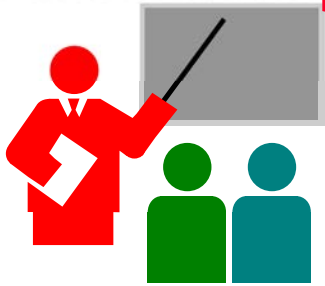
Summary



1. Less than 1% of things are connected
   ⇒ IoT is a big opportunity for academics and the 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

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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).

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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

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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)

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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

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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

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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

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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

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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

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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

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http://rajjain.com

http://www.cse.wustl.edu/~jain/cse574-22/j_10iot.htm

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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),
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Student Questions

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