

# 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



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



# 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,"

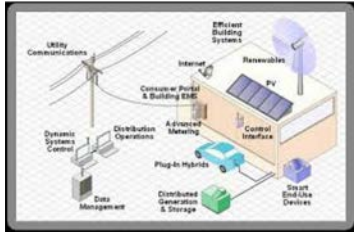
<http://www.cioinsight.com/it-news-trends/gartner-identifies-top-10-strategic-technologies.html>

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

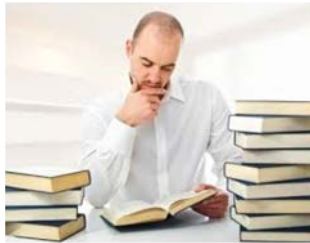
## Student Questions



# What's Smart?

- ❑ IoT = Instrument, Interconnect, Intelligently process (3 I's)
- ❑ Old: Smart = Can think  $\Rightarrow$  Can compute
- ❑ 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



- ❑ 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>

<http://www.cse.wustl.edu/~jain/cse574-22/>

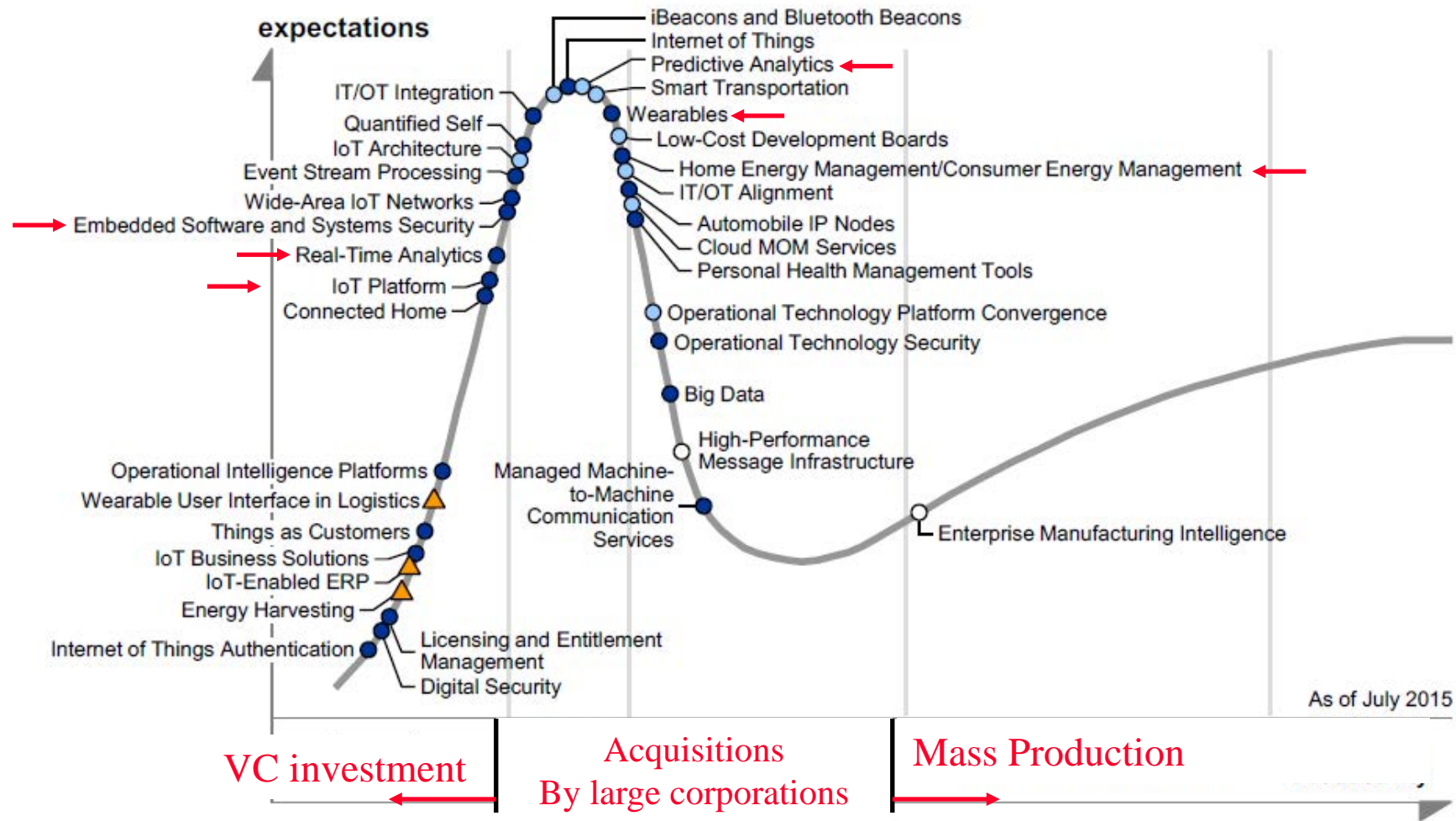
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## Student Questions





# Gartner's Hype Cycle For IoT 2015



## Student Questions

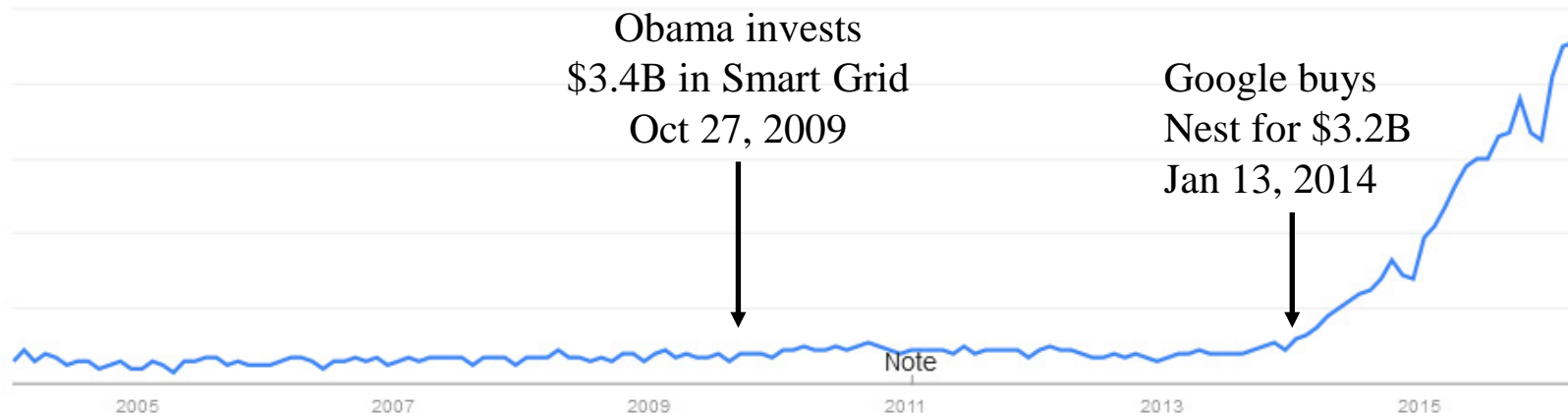
Ref: A Velosa, et al, "Hype Cycle for the Internet of Things, 2015" Gartner Report, G00272399, July 2015, 69 pp.

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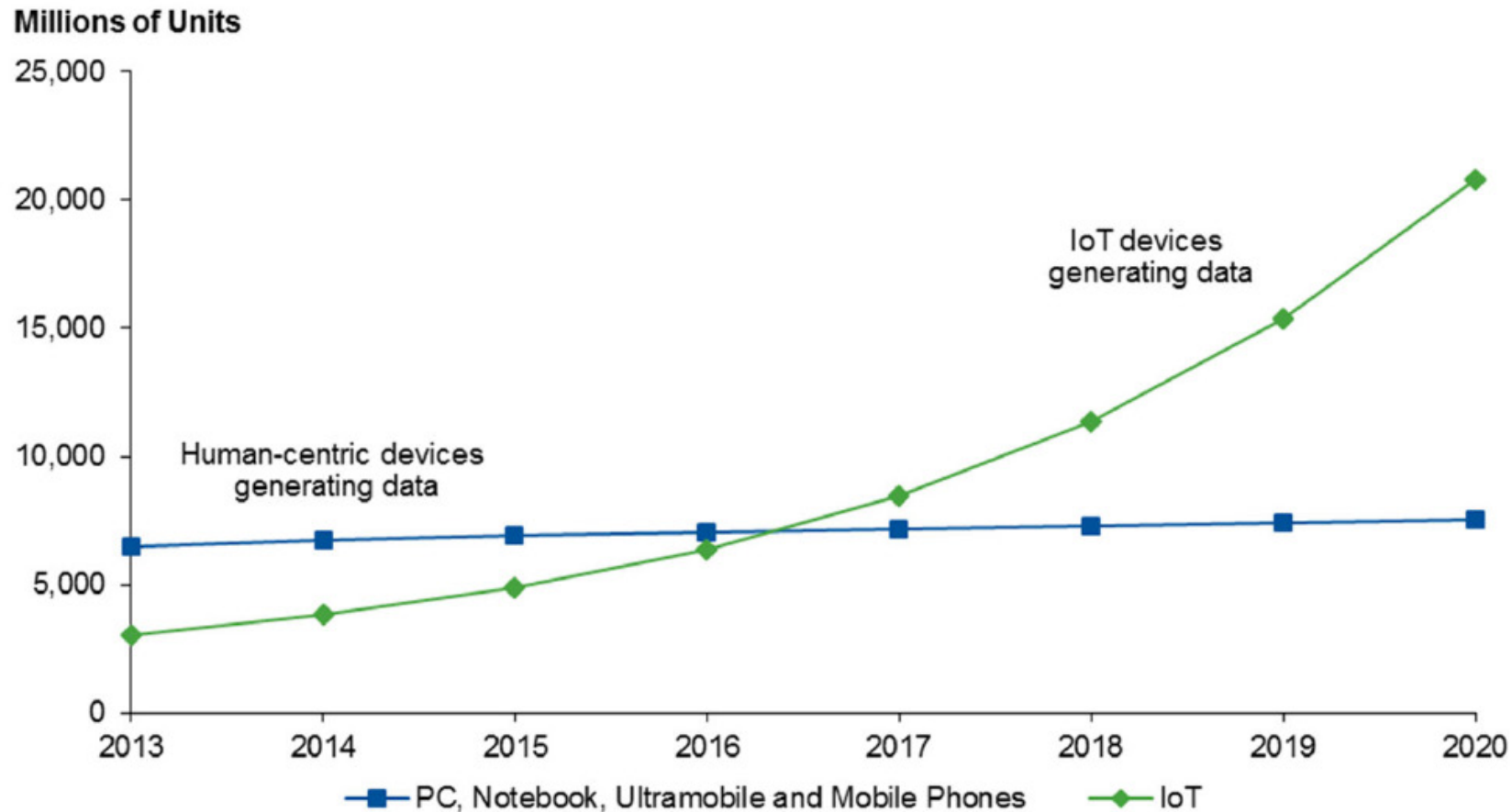
# Google Trends



- ❑ Around for 10 years
- ❑ IERC-European Research Cluster on the Internet of Things funded under 7<sup>th</sup> 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

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# IoT Business Opportunity

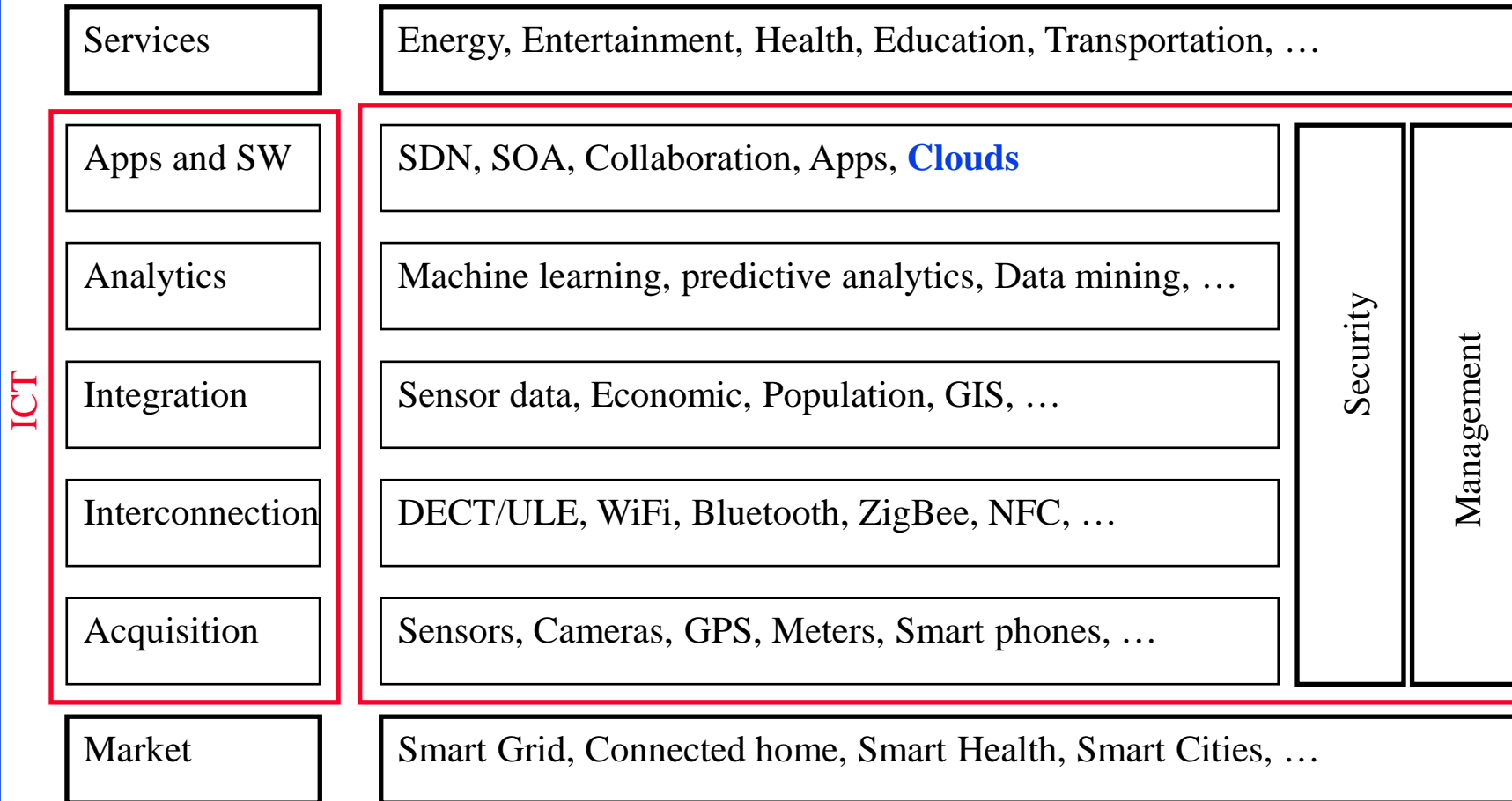


- ❑ \$1.7 Trillion by 2020 - IDC
- ❑ \$7.1 Trillion - Gartner
- ❑ \$10-15 Trillion just for Industrial Internet – GE
- ❑ \$19 Trillion – Internet of Everything - Cisco

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/>

## 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, ...

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# IoT is a Data (\$) Mine



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

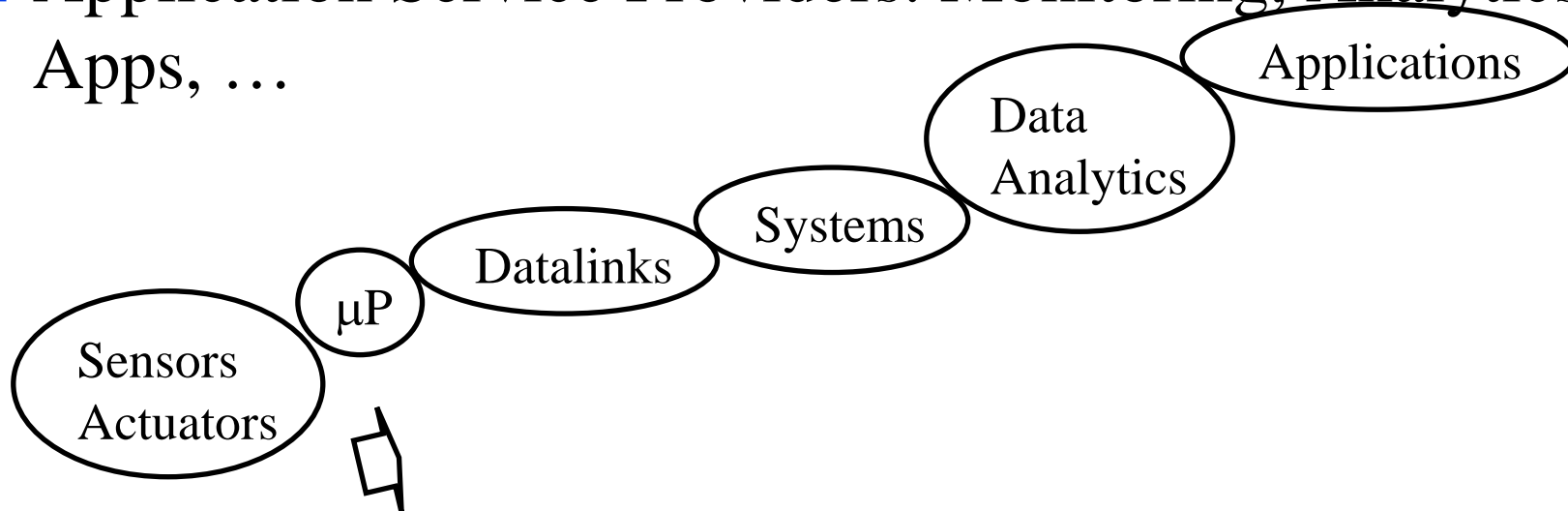
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# Business Opportunities

- ❑ 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, ...



## Student Questions

# Recent IoT Products



NEST Thermostat



Corventis: Wireless Cardiac Monitor



WEMO Remote



Tractive Pet Tracker



Ninja Blocks



Revolve Home Automation



ThingWorx Application Platform



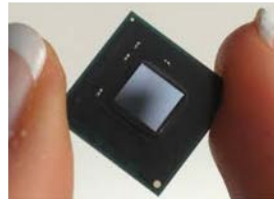
Lings Cloud Platform



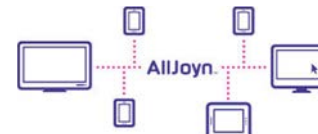
Mbed Development Platform



Xively Remote Access API



Intel Quark Processor

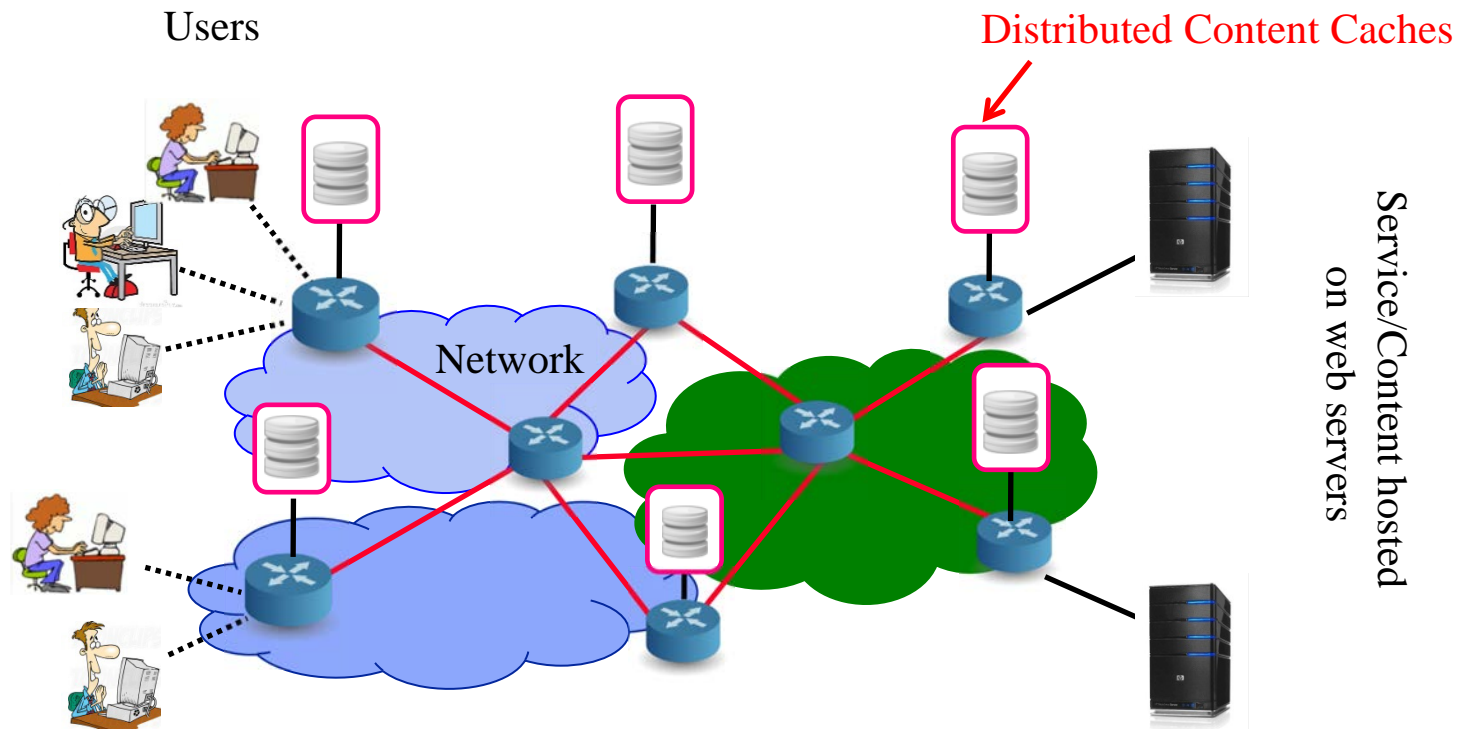


AllJoyn S/W Framework

## Student Questions

# Past: Data in the Edge

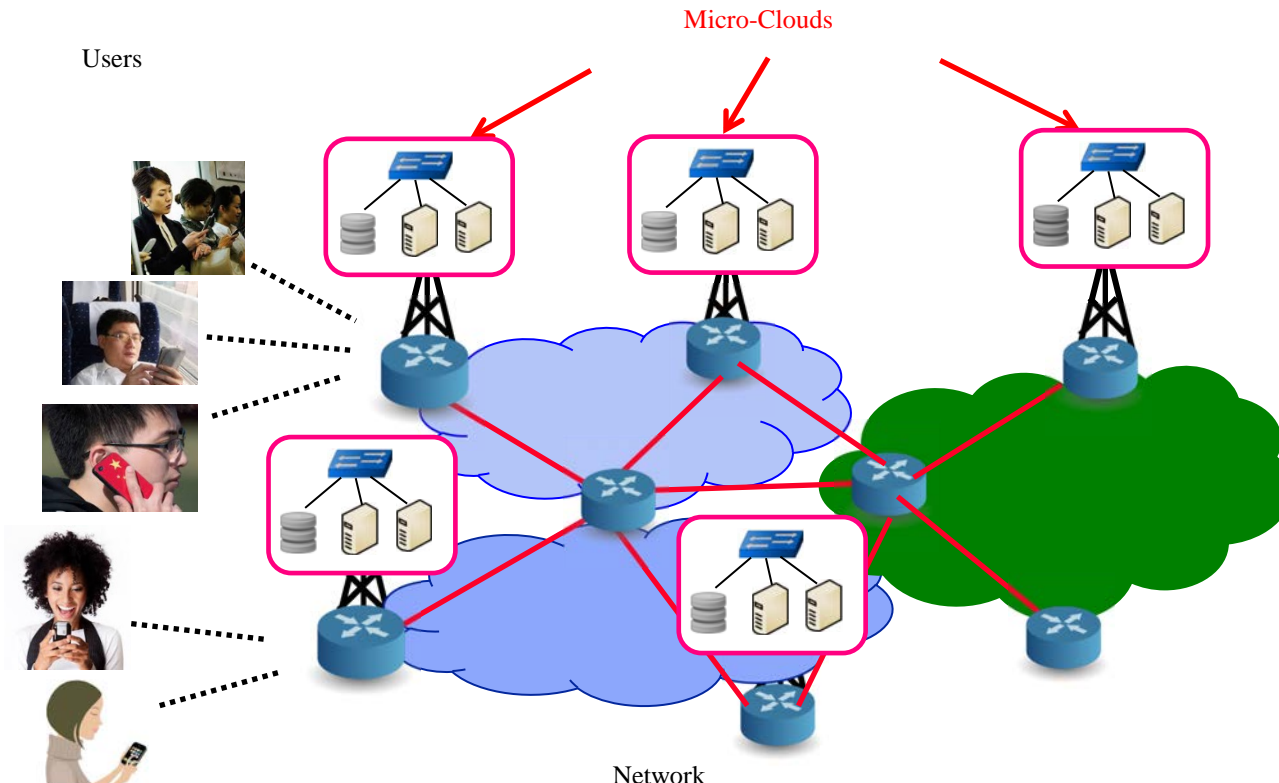
- ❑ To serve world-wide users, latency was critical and so the data was replicated and brought to edge



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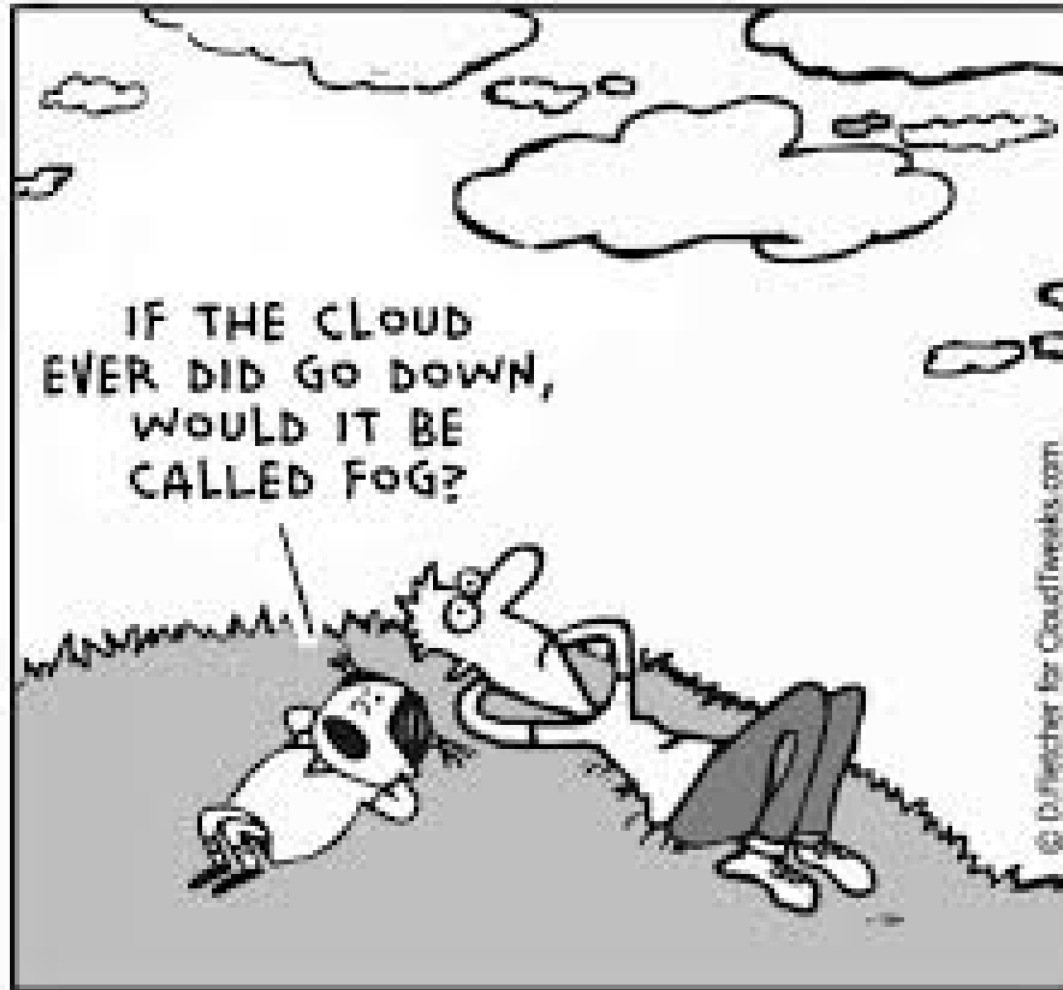
# Trend 2: Computation in the Edge

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



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# Fog Computing



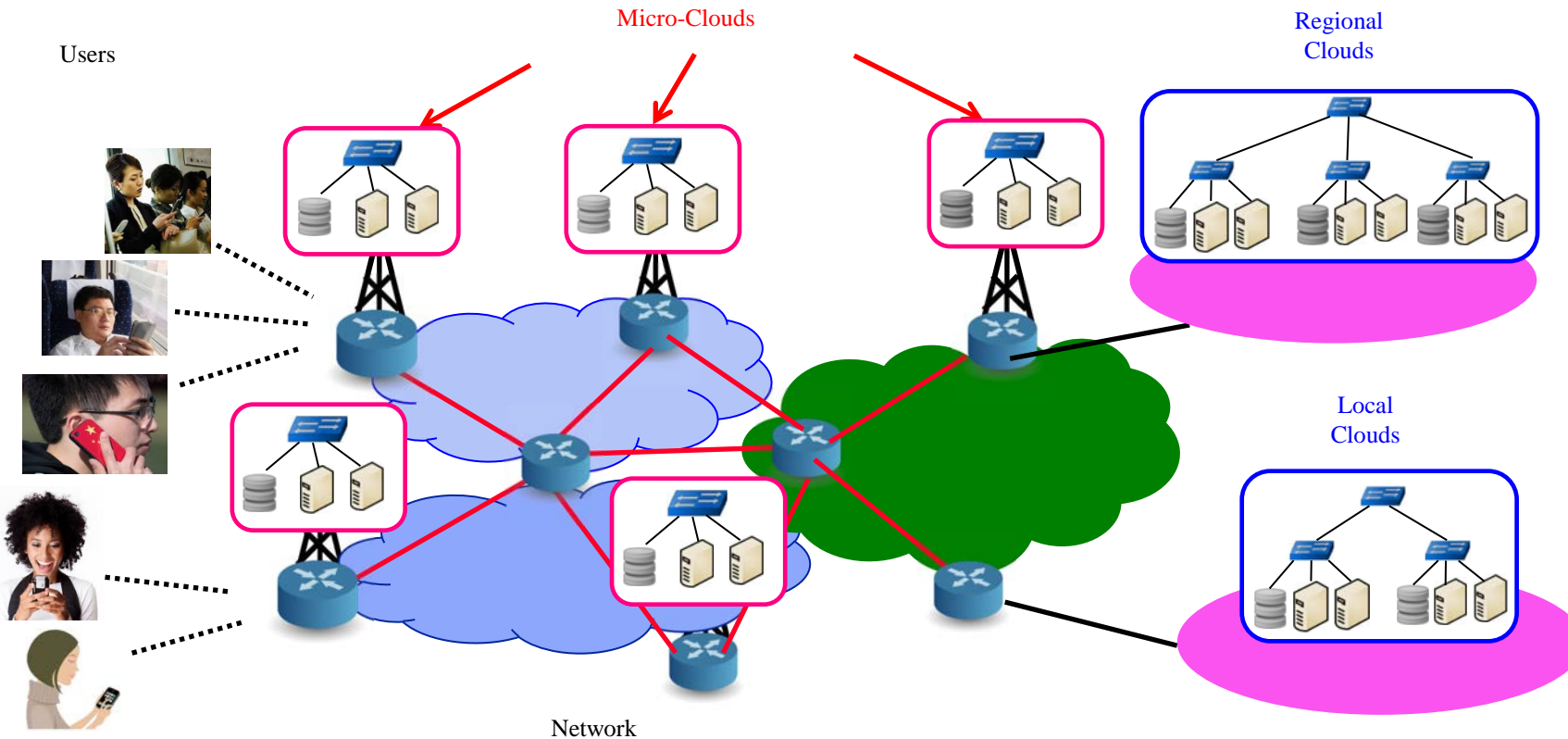
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Ref: <http://community.spiceworks.com/topic/254392-fog-computing-replaces-cloud-as-new-tech-buzzword>



# Trend 3: Multi-Cloud

- ❑ Larger and infrequent jobs serviced by local and regional clouds  $\Rightarrow$  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](http://www.cse.wustl.edu/~jain/papers/adn_ic3n.htm)

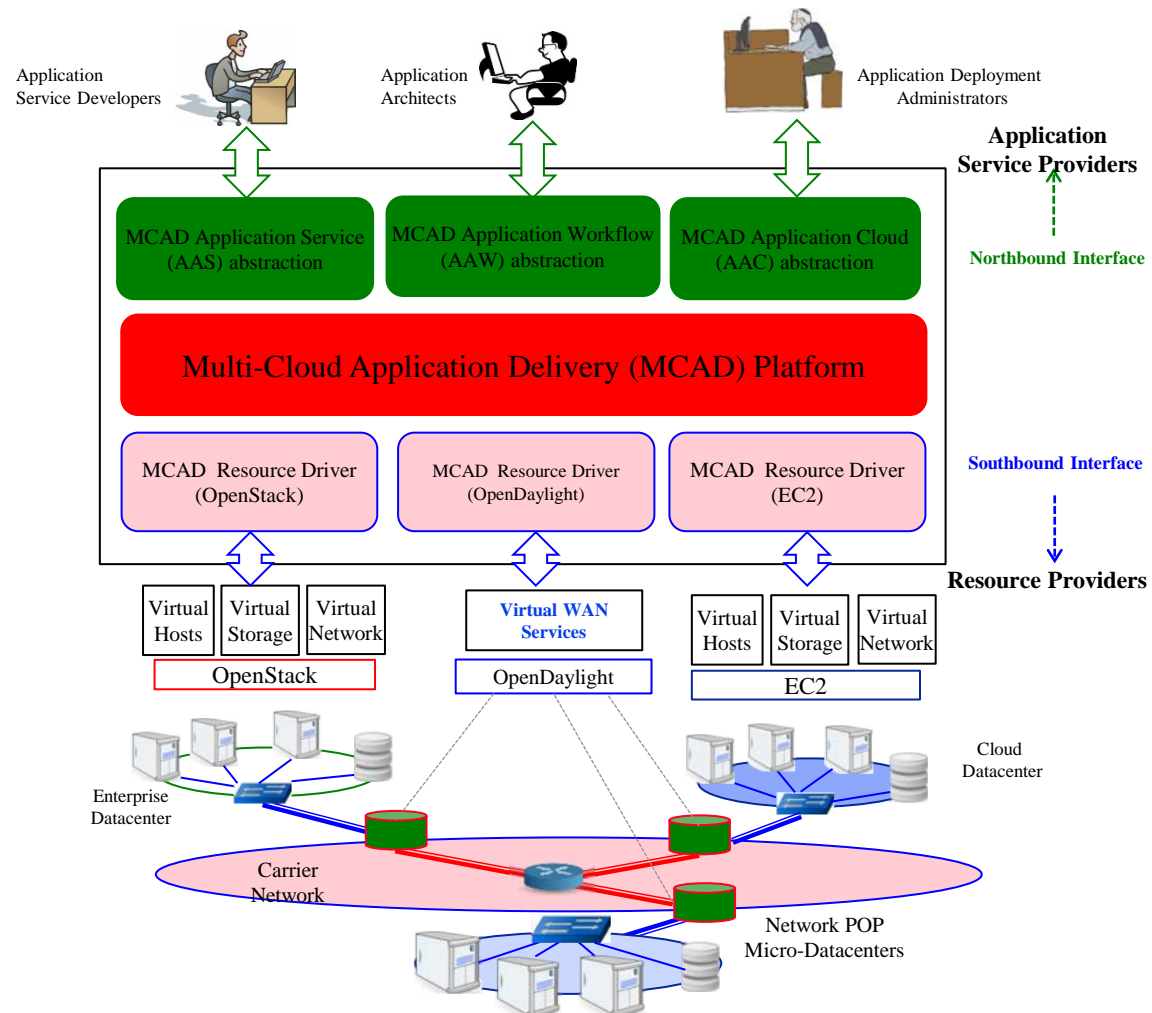
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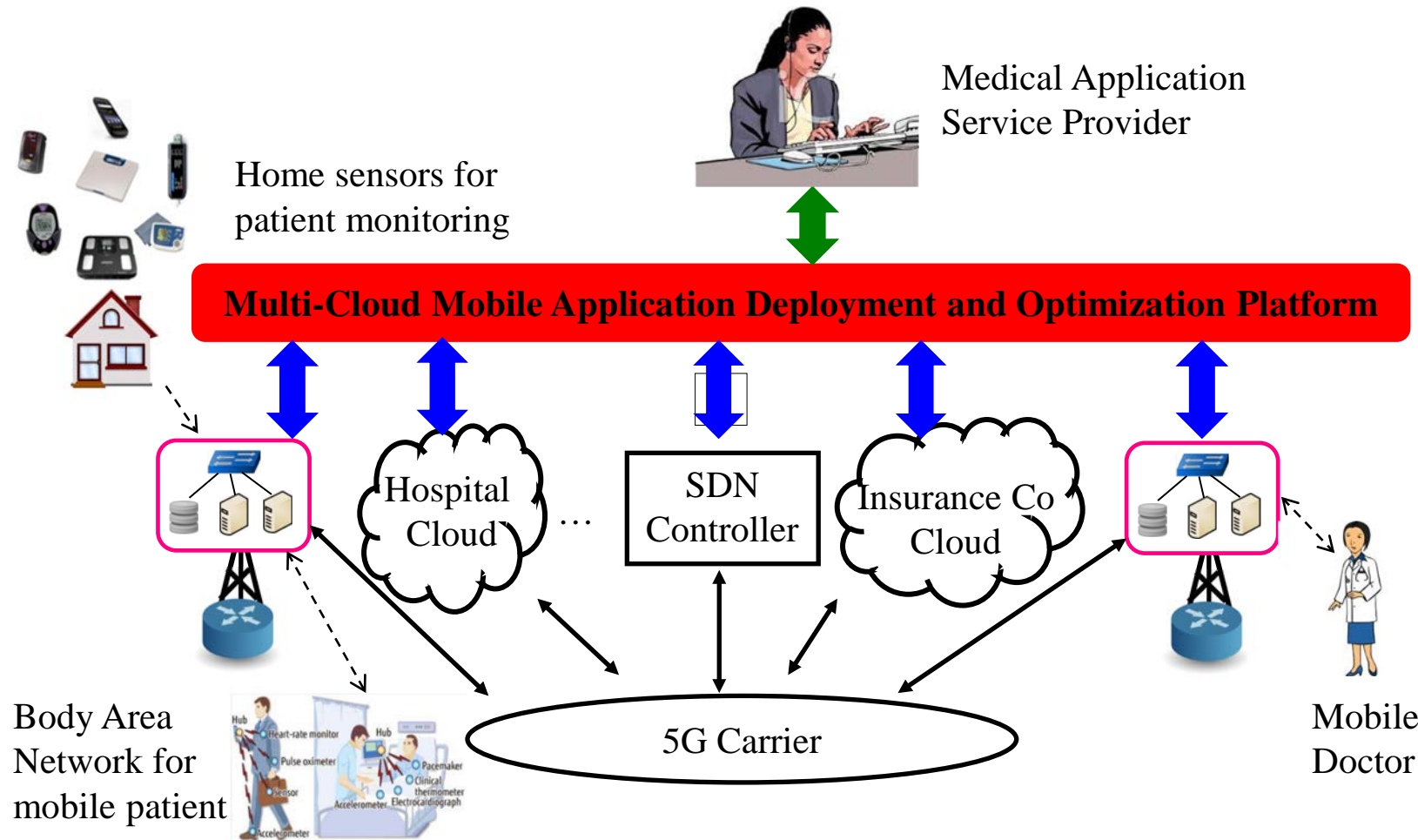
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# Software Defined Multi-Cloud Application Management



## 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](http://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](http://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	<p>Encapsulation 6LowPAN, 6TiSCH, 6Lo, Thread...</p> <p>Routing RPL, CORPL, CARP</p>	IEEE 1888.3, TCG, Oath 2.0, SMACK, SASL, EDSA, ace, DTLS, Dice, ...	IEEE 1905, IEEE 1451, IEEE 1377, IEEE P1828, IEEE P1856
Datalink	<p>WiFi, <b>802.11ah</b>, <b>Bluetooth</b> Low Energy, Z-Wave, <b>ZigBee Smart</b>, DECT/ULE, 3G/LTE, NFC, Weightless, HomePlug GP, <b>802.15.4e</b>, <b>G.9959</b>, <b>WirelessHART</b>, <b>DASH7</b>, <b>ANT+</b>, <b>LTE-A</b>, <b>LoRaWAN</b>, ISA100.11a, DigiMesh, WiMAX, ...</p>		

## Student Questions

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](http://www.cse.wustl.edu/~jain/papers/iot_accs.htm)

# 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, TTA, TTC ⇒ oneM2M

Ref: <http://www.onem2m.org>

## Student Questions



# Datalink Issues

- ❑ Energy efficiency
  - $\Rightarrow$  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  $\Rightarrow$  Need low overhead
- ❑ Limited computing  $\Rightarrow$  Light weight protocols
  - $\Rightarrow$  lightweight Encryption, authentication, security
- ❑ Quality of Information (QoI)

## Student Questions

# 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

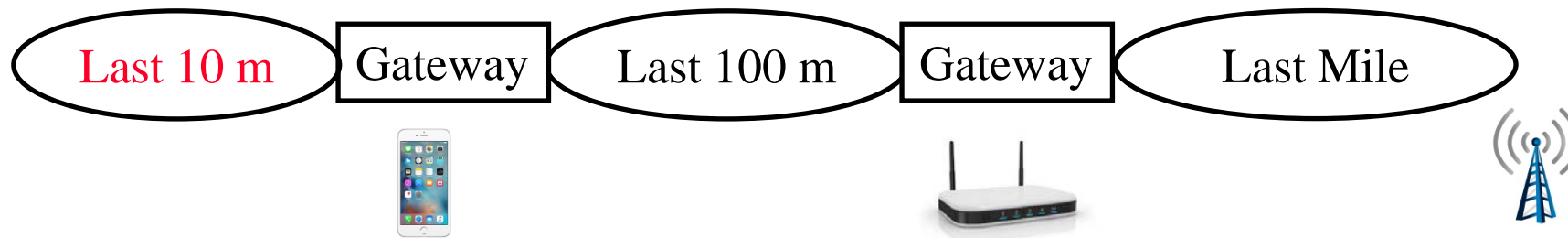
# Networking Issues

- ❑ Large number  $\Rightarrow$  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

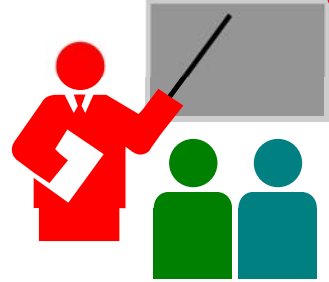
# Last 100m Protocols

- ❑ 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](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/Fog_computing)
- ❑ [https://en.wikipedia.org/wiki/Internet\\_of\\_Things](https://en.wikipedia.org/wiki/Internet_of_Things)
- ❑ [https://en.wikipedia.org/wiki/IPSO\\_Alliance](https://en.wikipedia.org/wiki/IPSO_Alliance)
- ❑ [https://en.wikipedia.org/wiki/Machine\\_to\\_machine](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/Smart_device)
- ❑ <https://en.wikipedia.org/wiki/SmartThings>
- ❑ [https://en.wikipedia.org/wiki/Ubiquitous\\_computing](https://en.wikipedia.org/wiki/Ubiquitous_computing)
- ❑ [https://en.wikipedia.org/wiki/Wearable\\_technology](https://en.wikipedia.org/wiki/Wearable_technology)
- ❑ [https://en.wikipedia.org/wiki/Web\\_of\\_Things](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/Near_field_communication),
- ❑ [http://en.wikipedia.org/wiki/Weightless\\_%28wireless\\_communications%29](http://en.wikipedia.org/wiki/Weightless_%28wireless_communications%29)
- ❑ [https://en.wikipedia.org/wiki/Highway\\_Addressable\\_Remote\\_Transducer\\_Protocol](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/Thread_(network_protocol))
- ❑ [https://en.wikipedia.org/wiki/Weightless\\_\(wireless\\_communications\)](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 Addressable 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

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[http://www.cse.wustl.edu/~jain/cse574-22/j\\_10iot.htm](http://www.cse.wustl.edu/~jain/cse574-22/j_10iot.htm)



# Related Modules



CSE567M: Computer Systems Analysis (Spring 2013),  
[https://www.youtube.com/playlist?list=PLjGG94etKypJEKjNAa1n\\_1X0bWWNyZcof](https://www.youtube.com/playlist?list=PLjGG94etKypJEKjNAa1n_1X0bWWNyZcof)

CSE473S: Introduction to Computer Networks (Fall 2011),  
[https://www.youtube.com/playlist?list=PLjGG94etKypJWOSPMh8Azcg5e\\_10TiDw](https://www.youtube.com/playlist?list=PLjGG94etKypJWOSPMh8Azcg5e_10TiDw)



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

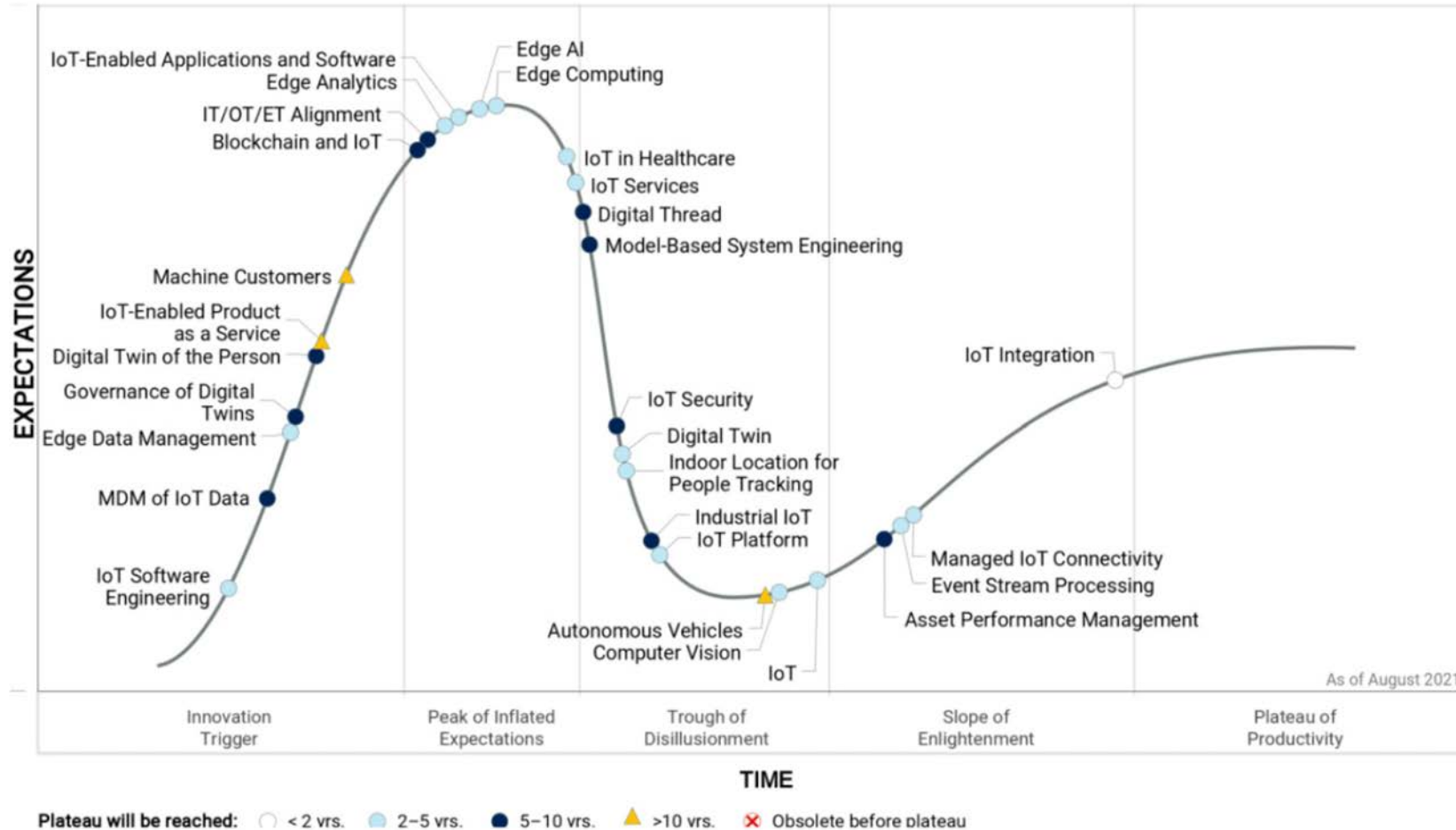
CSE571S: Network Security (Fall 2011),  
<https://www.youtube.com/playlist?list=PLjGG94etKypKvzfVtutHcPFJXumyyg93u>



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

## Student Questions

# Hype Cycle for IoT 2021



## Student Questions

Ref: B. Lheureux, et al., "Hype Cycle for the Internet of Things, 2021," Gartner Report ID G00747575, 6 August 2021, 103 pp.

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<http://www.cse.wustl.edu/~jain/cse574-22/>

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