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/cse570-23/

Student Questions

Overview

1. What are Things?
2. What's Smart and Why IoT Now?
3. IoT Research Challenges, including Datalink and Networking Issues
4. Recent Protocols for IoT
5. Fog Computing and Multi-Cloud Management

Note: This is part 1 of a series of class lectures on IoT. MQTT, 6LowPAN, and RPL are covered in other parts.

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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Student Questions

- About the definition of a thing, how to define if a device is a computer? Modern smartphones are essentially a computer. They have Von Neumann architecture and run on UNIX or Linux-based OS (highly modified), are they computers? Is a thermostat running Linux a computer?

Things = Not a computer in 2008

Internet of Things

- Less than 1% of things around us were connected in 2013.
  The refrigerator, car, washing machine, heater, a/c, and garage door should all be connected, but maybe not.
- From 10 Billion in 2013 to 50 Billion in 2020.
  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 and mobile Apps, but before Clouds, …)
- a.k.a. **Internet of Everything** by Cisco
  Smarter Planet by IBM

Student Questions

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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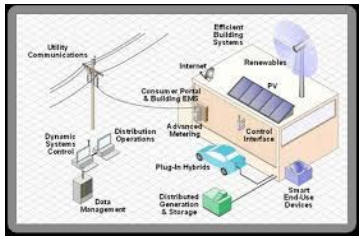
Sample IoT Applications

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

Student Questions

- ❑ How is a smart car IOT?

Most of the new cards today are smart.

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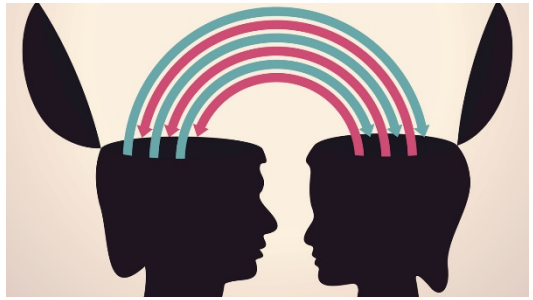
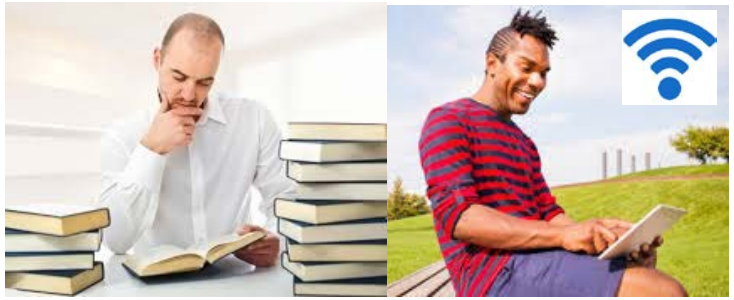
What's Smart?

- Old: Smart = Can think ⇒ Computation
  = Can Recall ⇒ Storage
- 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

Student Questions

- Is the only device that can connect to the Internet a smart device? Why can it not be LAN?

Any networking is fine.

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

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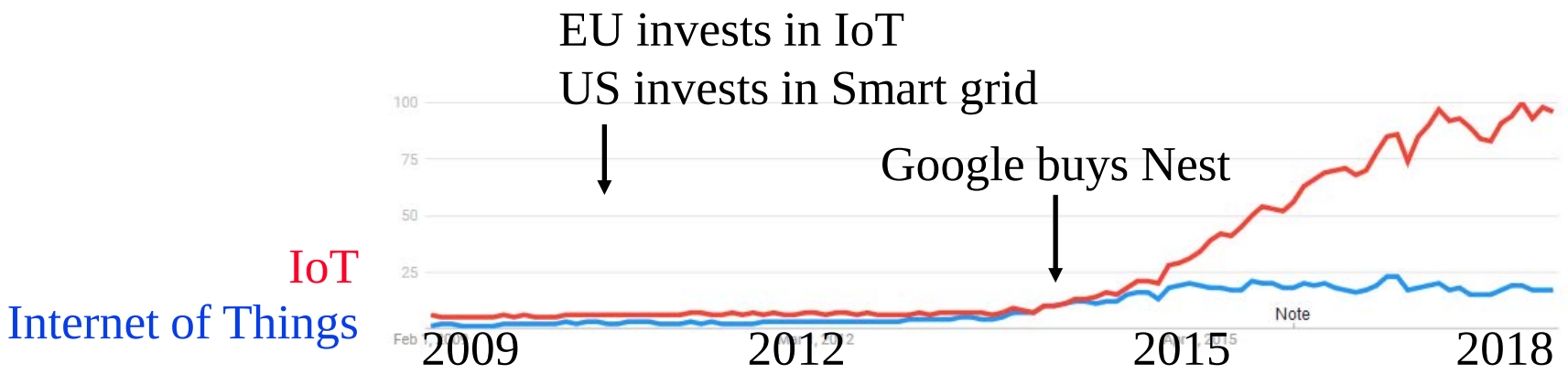
Google Trends



- 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 with $4B funding for **smart grid** in the American Recovery and Reinvestment Act of 2009
- Venture capital interest jumped when Google bought Nest for $3.2B in 2014.

Student Questions

- Were any significant contributions to IoT development or applications in use today from the smart grid funding?

Yes, it started IoT research in the USA only then. Smart Grid is still a current IoT research application.

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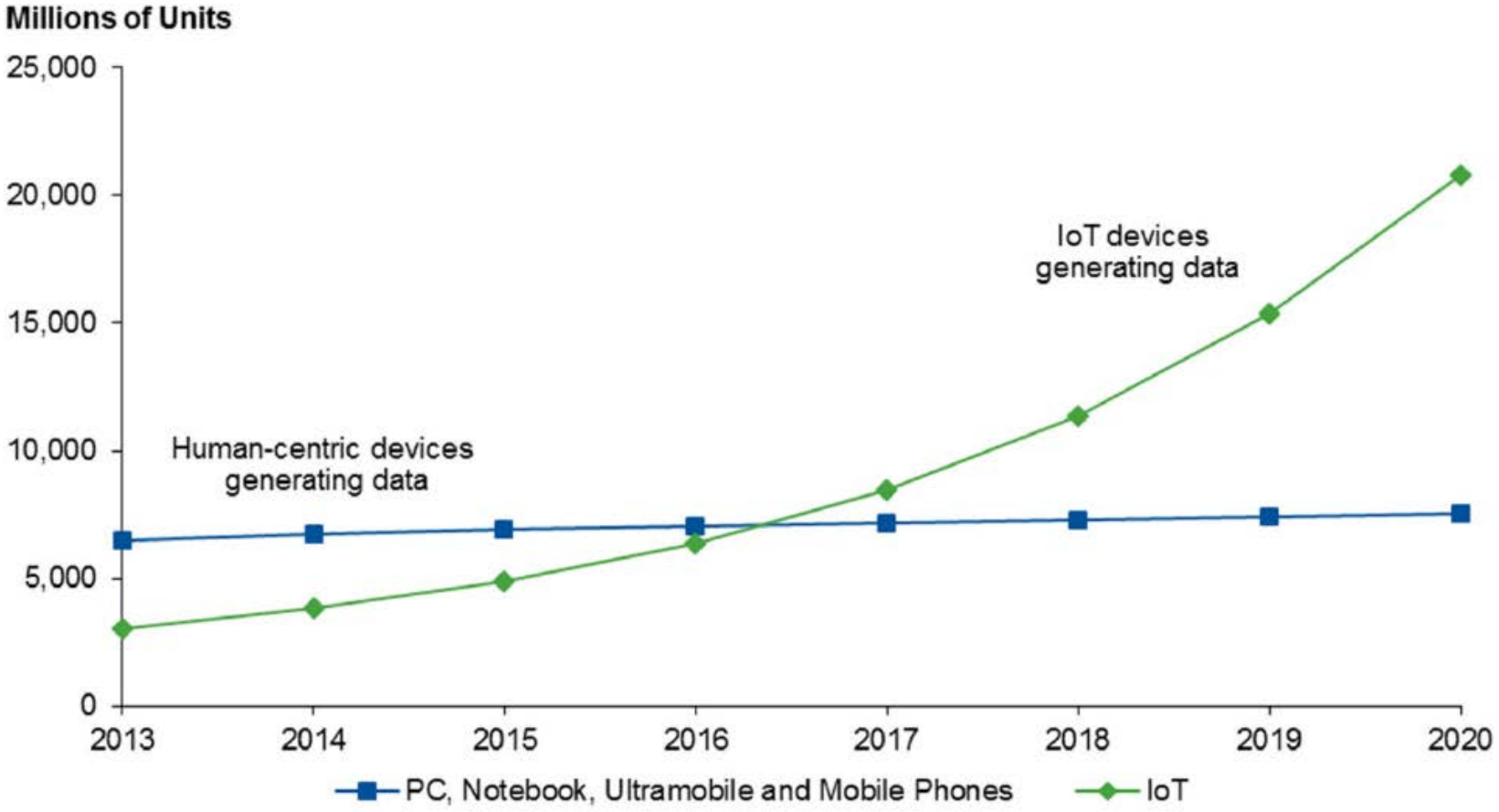
Computing vs. IoT



- 21 Billion devices by 2020

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

Student Questions

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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

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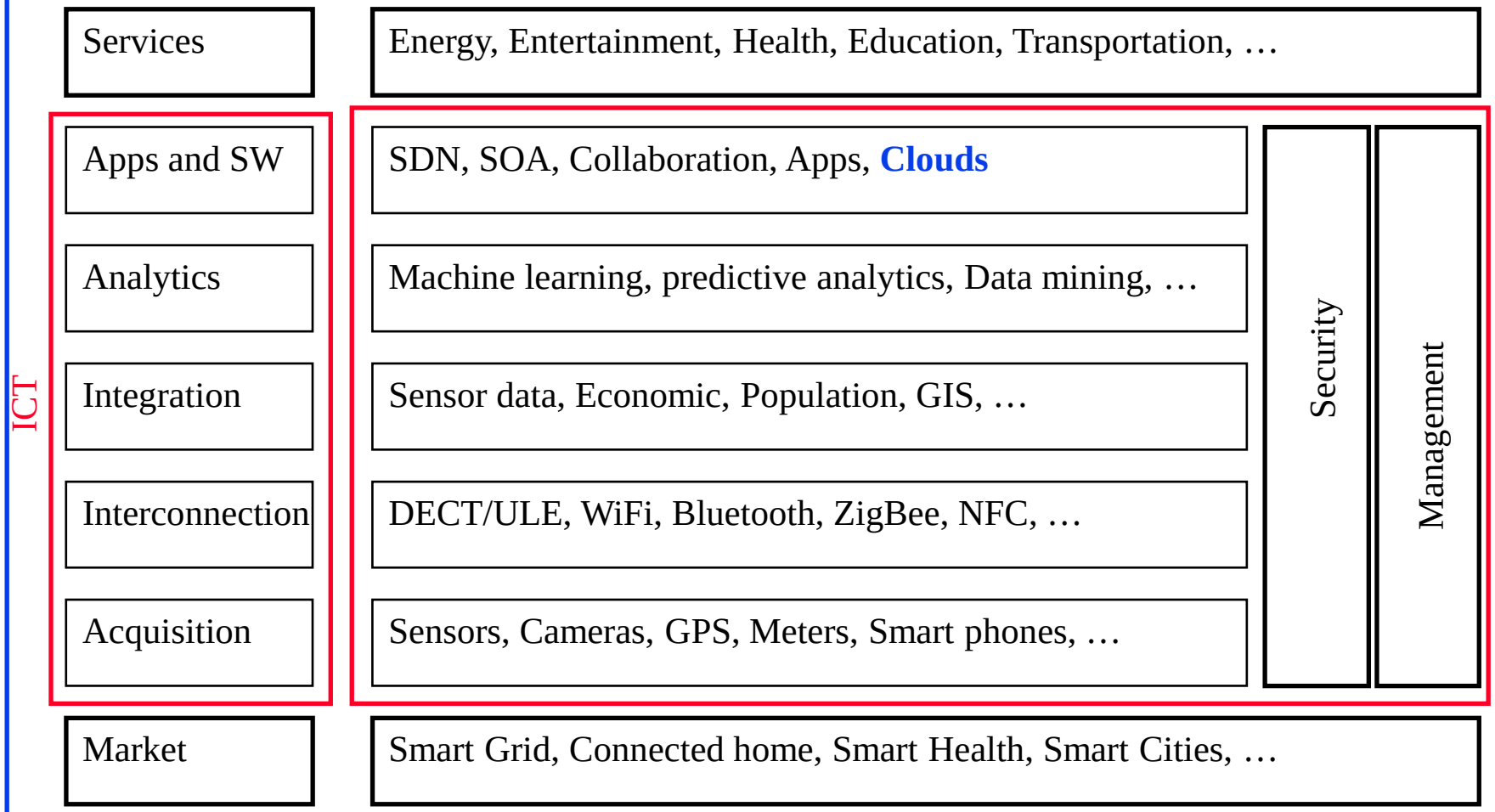
A 7-Layer Model of IoT



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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, …

Student Questions

- What's the most popular IoT research area?

There is no one area. Every field, computer science, Electrical Engineering, and Energy, has its favorites. My team works on the security of IoT using AI, Quantum, and Blockchain.

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Internet of Harmful Things

As researchers did recently at Black Hat, imagine someone hacking your connected toilet, making it flush incessantly, and closing the lid repeatedly and unexpectedly.

News

Worm may create an Internet of Harmful Things, says Symantec (Take note, Amazon)

Security firm Symantec says it has found a Linux worm aimed at Internet of Things devices

By Patrick Thibodeau
December 3, 2013 01:22 PM ET Add a comment

Share 6 +1 Like 7 More

Computerworld - Security researchers are gradually raising warnings that the Internet of Things will increase, by multitudes, the number of things that can be hacked and attacked.

The Hitchcockian plotlines are endless. Replace *The Birds* with flying Amazon delivery drones. Or imagine, as researchers did recently at Black Hat, someone hacking your connected toilet, making it flush incessantly and closing the lid repeatedly and unexpectedly.

Student Questions

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Privacy Issue: Beacons

- Advertising based on proximity
- Peripherals (your phone) broadcast its presence if Bluetooth is turned on
- The primary aim of these broadcasts is to allow device discovery
- Advertising packets consist of a header and max 27B of payload with multiple TLV-encoded data items
  - May include signal strength, ⇒ Distance
- iOS7 iPhones can send/receive iBeacons
- It can be used for customized advertising, indoor location, geofencing
- PayPal uses this to identify you.
  You can pay using a PIN and your phone.

Student Questions

- Airdrop between Apple's devices, is this kind of IoT?

Yes. It's networking using Bluetooth.

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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

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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 power requirements standardized per protocol, or are these numbers hardware-dependent?

These are typical numbers. There is no standard.

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Networking Issues

- Large number ⇒ 32-bit or 48-bit addressing not sufficient
- 32-bit IPv4 addresses are too small
- 48-bit IEEE 802 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

- Can you elaborate on IoT devices' local and global addresses?

Local Addresses have to stay within the local network. They need to be recognized and are dropped outside the local network.

- What kind of address is the local address? Is it assigned by the local network (e.g., a wireless router)?

The local network administrator assigns it. For example, a router on "Floor 3 closet 5."

- What about global addresses? Is it similar to the MAC address?

Public IP addresses are Global. They are globally unique and can be forwarded by any global device. Private IP addresses are not global.

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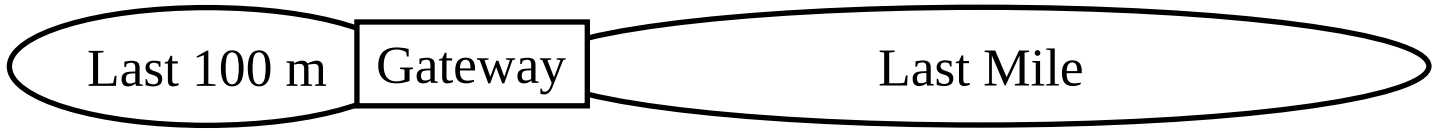
Last 100m Protocols

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



Student Questions

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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

Student Questions

- Though they are still in use, they will eventually be abandoned, right? Since no one is going to use them for new devices?

Yes. But old technologies take a long time to die.

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IoT Ecosystem

Applications	Smart Health, Smart Home, Smart Grid Smart Transport, Smart Workspaces, …	**Security** TCG, Oath 2.0, SMACK, SASL, ISASecure, ace, CoAP, DTLS, Dice	**Management** IEEE 1905, IEEE 1451, …
Session	**MQTT**, CoRE, DDS, AMQP , …		
Network	Encapsulation **6LowPAN**, 6TiSCH, … Routing **RPL**, CORPL, CARP		
Datalink	WiFi, Bluetooth Smart, ZigBee Smart, Z-Wave, DECT/ULE, 3G/LTE, NFC, Weightless, **HomePlug GP**, 802.11ah, **802.15.4**, G.9959, WirelessHART, DASH7, ANT+ , LoRaWAN, …		
Software	Mbed, Homekit, AllSeen, IoTvity, ThingWorks, EVRYTHNG , …		
Operating Systems	Linux, Android, Contiki-OS, TinyOS, …		
Hardware	ARM, **Arduino**, Raspberry Pi, ARC-EM4, Mote, Smart Dust, Tmote Sky, …		

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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Student Questions

- Why did you categorize MQQT and DDS as session protocols, and why do you not have a transport layer? Mainly because DDS messages can be transported over UDP, and as far as I know, it has no "session" concept.

In the ISO OSI model, a session was defined as something to that particular invocation of an application. The transport layer was defined as the protocol between two endpoints. Session and Application also run end-to-end. So, there needs to be more clarity between Session and Transport. MQTT is a session protocol that requires transport.

- This slide is an excellent summary of IoT. What layer do you think researchers should focus on? And in what direction? *Depends on your interest. All layers need new ideas.*
- What is the role of the session? *See above.*

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: oneM2M (see below)
  - ETSI: DECT/ULE
  - IPSO, …
- Seven organizations joined together to avoid duplication: ARIB, ATIS, CCSA, ETSI, TIA, TTA, TTC ⇒ oneM2M

Student Questions

- So, Bluetooth and Bluetooth LE are different protocols?

Different versions of the same protocol. A Bluetooth LE device will interwork with older Bluetooth devices but not vice versa.

Ref: http://www.onem2m.org

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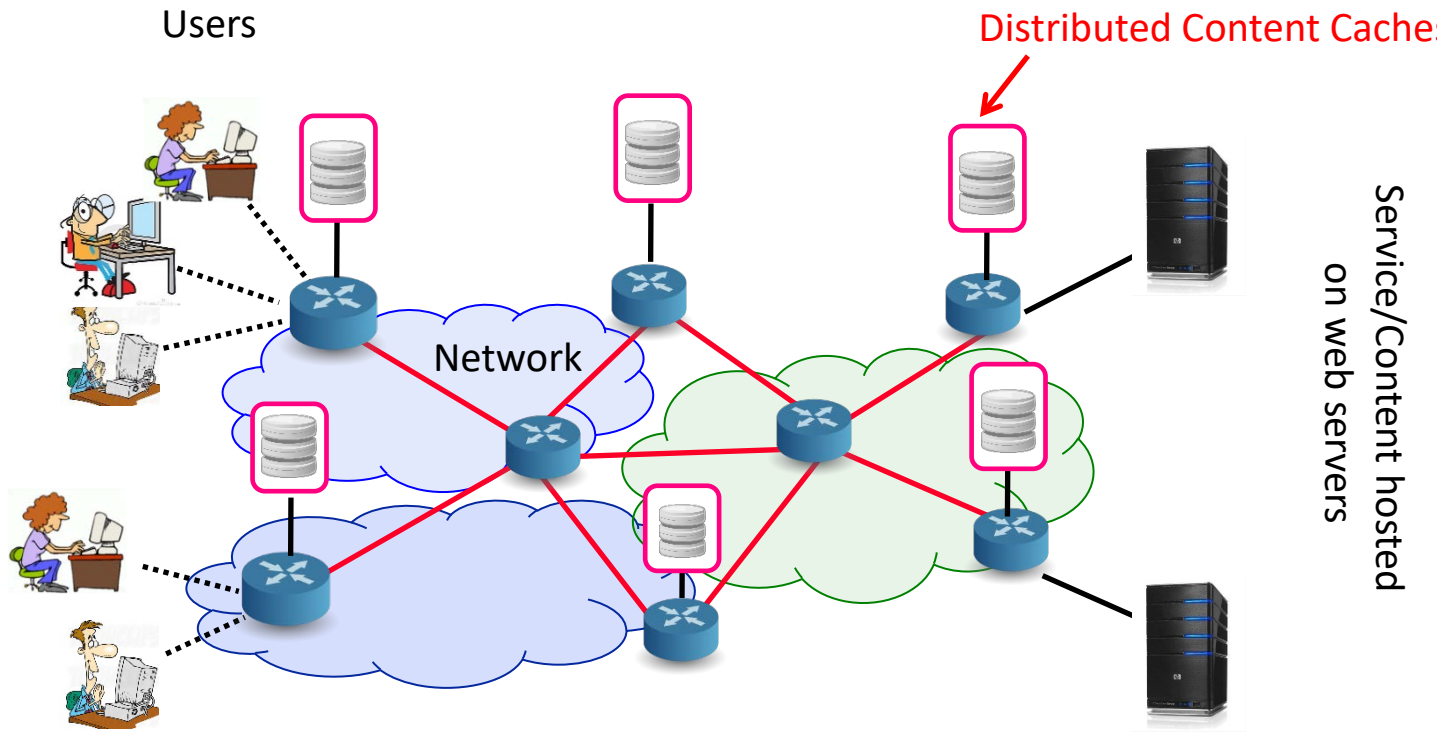
Past: Data in the Edge

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



Student Questions

- Is the push button the same as the Duo mobile application?

"Push" is not a button. It is how the information comes to you. You can pull the info from the net, or the net can push it to you.
Duo is simply a two-factor authentication verifying that you have the phone with you.

- Which way is more secure for the users?

Push and pull are both equally insecure.
Two-factor authentication makes both more secure.

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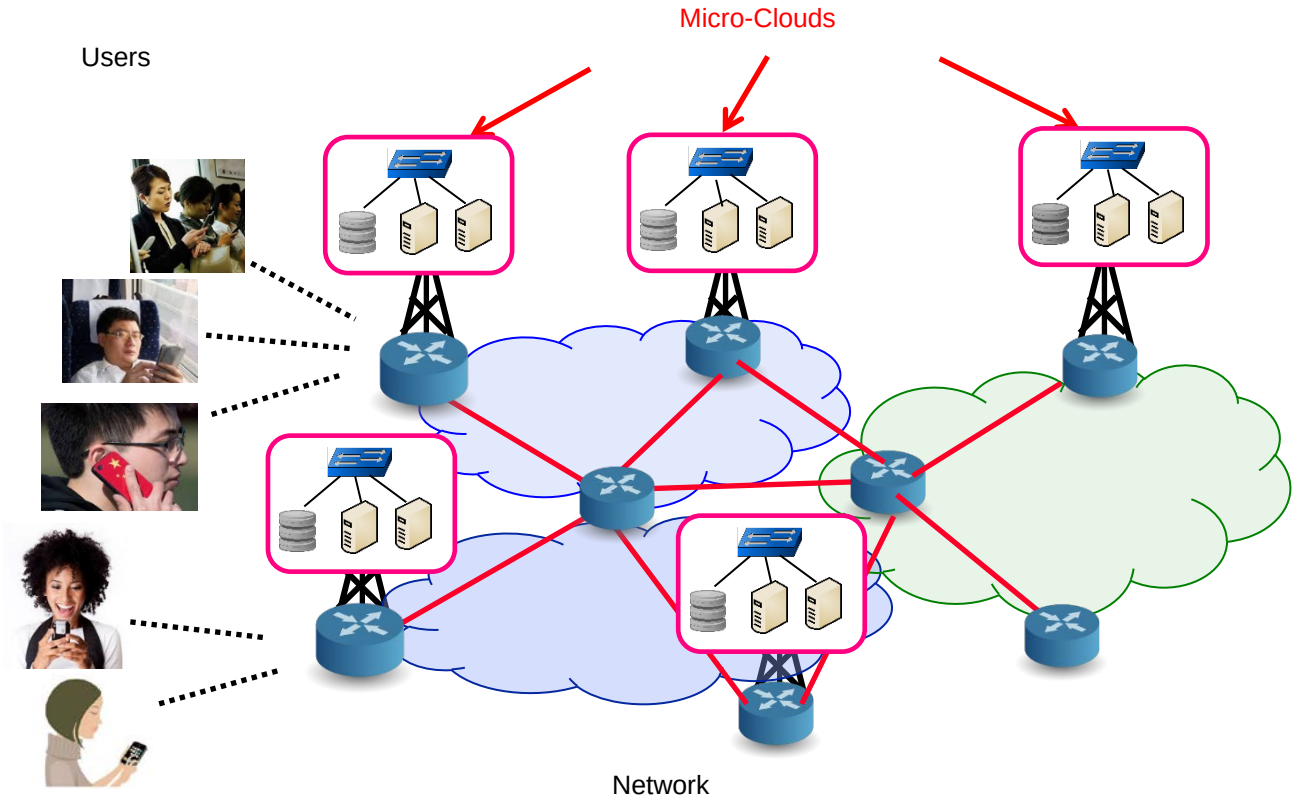
Trend: Computation in the Edge

- To service mobile users/IoT, the computation needs to come to the edge ⇒ Micro-cloud on the tower
  ⇒ Mobile-Edge Computing



Student Questions

- Does computation in the edge mean that people are able to keep their private data in their local terminals, or do those internet firms still need to store our data in their data centers where machine learning models are trained?

Internet firms keep your data in their clouds so they can make money from storage and also sell your information to advertisers.

- Could you please give us some examples of Computation in the Edge in our daily life?

Most of the computation in smart devices today is an example of "Computation in the Edge," motion detection.

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Trend: Computation in the Edge

- To service mobile users/IoT, the computation needs to come to the edge ⇒ Micro-cloud on the tower
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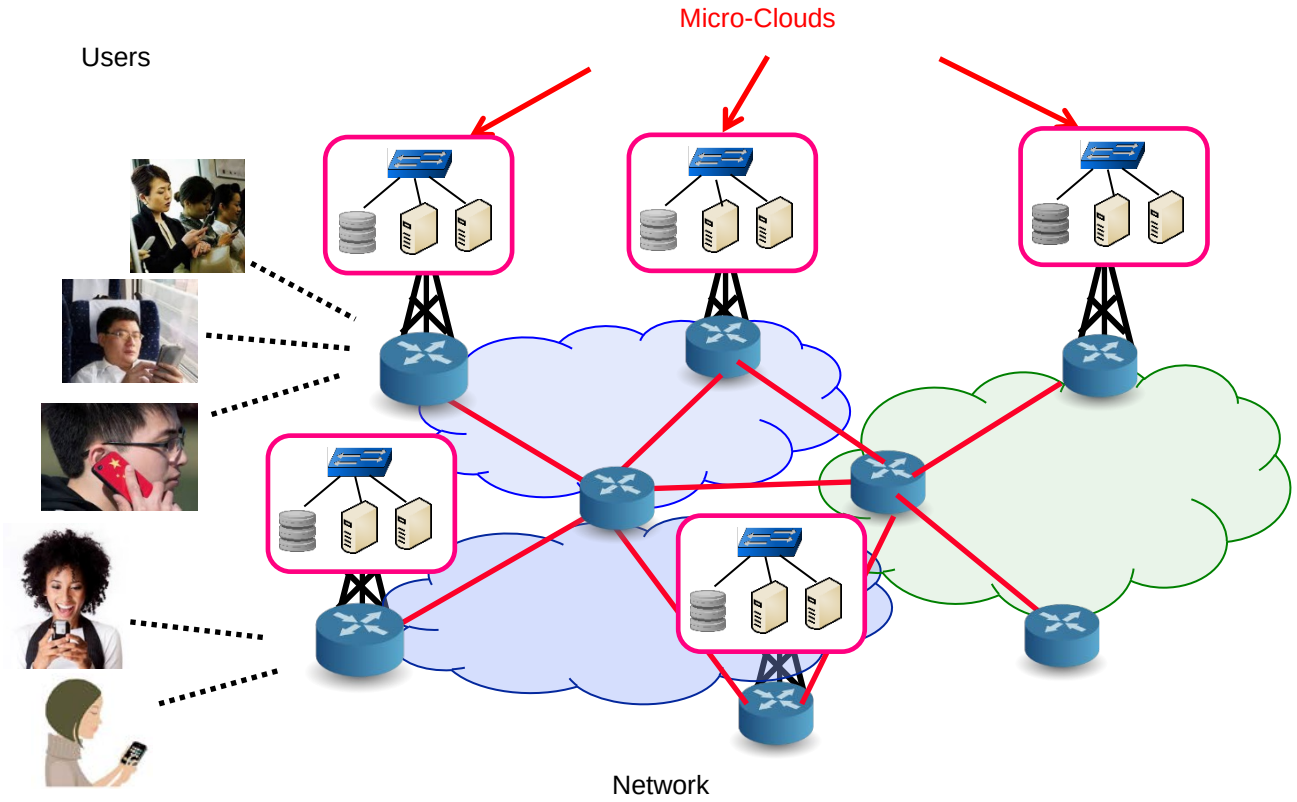

Student Questions

- So the edge's micro cloud still does the computation on the edge's computer and will not send the computation request to a data center or some company's server? Does this mean an edge needs to be able to compute/process many different services (e.g., handling service requests from different applications)?

Edge clouds take care of a bulk (not all) of the common types of computations and send the rest to the central cloud.

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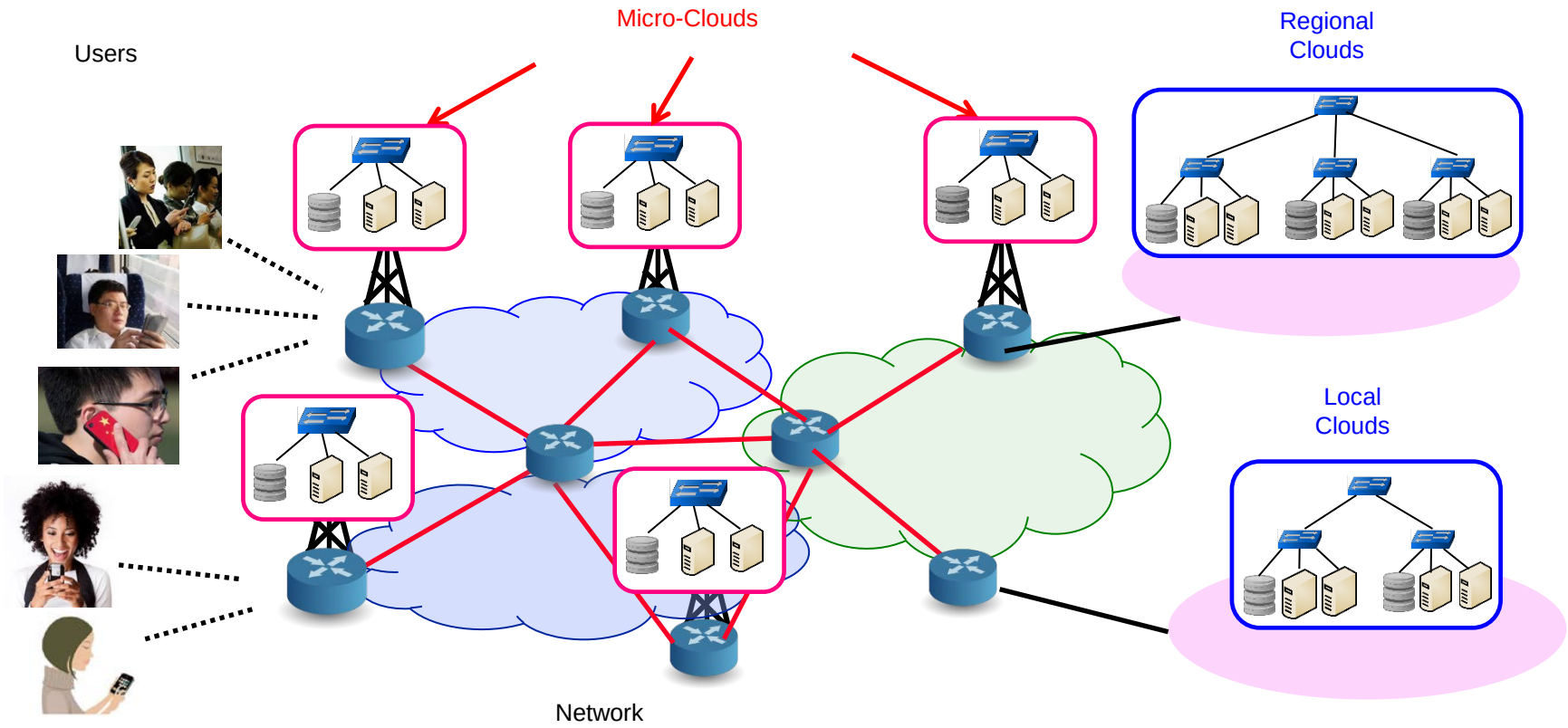
Trend: Multi-Cloud

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



Student Questions

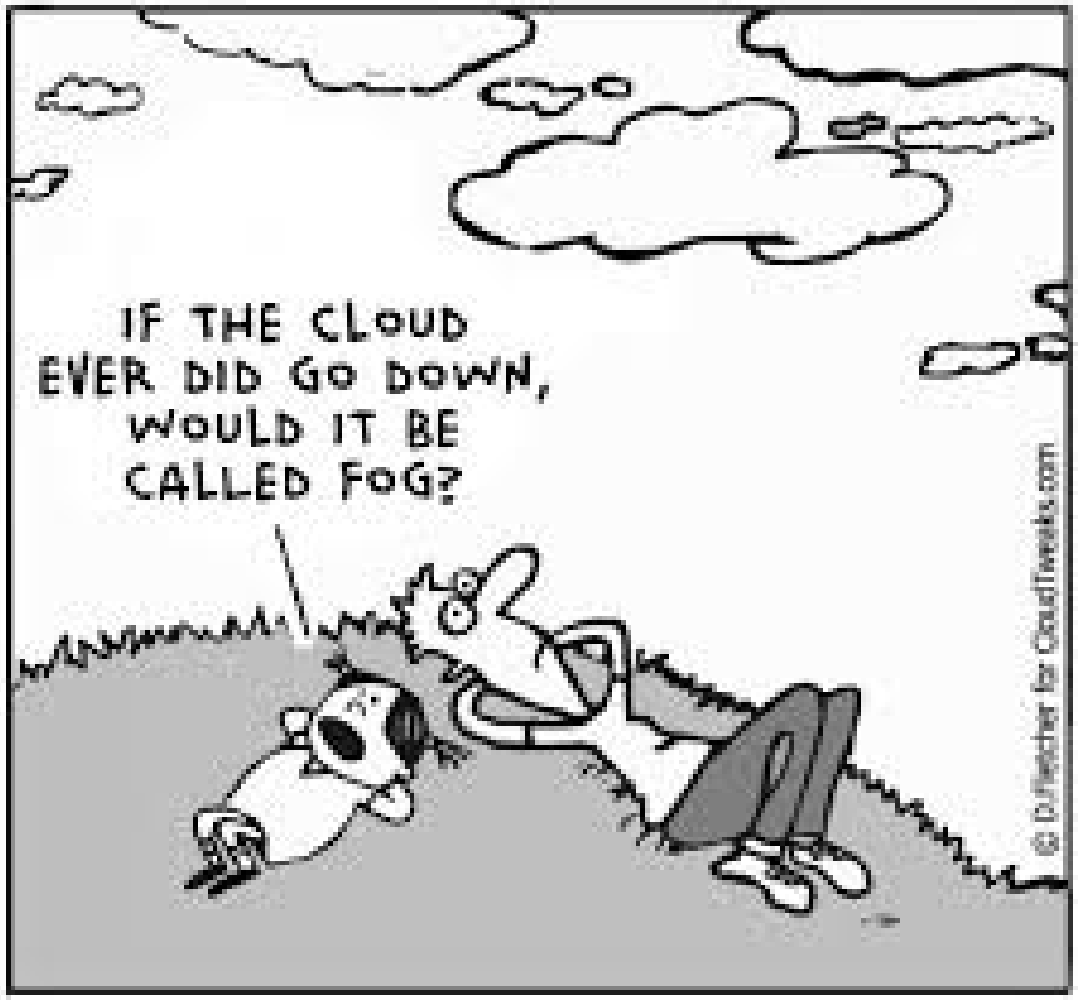
- Can you give some FOG computing examples? How do you fix the problem of the FOG going down?

It is just more layers of clouds. A component going down disrupts the service to that component's users only. Higher layers are designed with higher resiliency.

- Does multi-cloud mean lower computing and less storage of edge?

Yes.

Fog Computing



Student Questions

- Would fog computing be a subset of cloud computing?

If you include edge clouds as clouds, then yes.

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

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Fog Computing (Cont)

- Location Aware and Location Sensitive
  ⇒ Low latency ⇒ Computing in microclouds
  ⇒ Computing in the edge ⇒ Computing everywhere
  ⇒ Fog
- Geographically distributed => Everywhere/Anywhere
- Large Scale
- Mobility
- Real-Time

Student Questions

- Fog computing is a kind of cloud computing that is smaller, closer to us, and more responsive. Is this understanding correct?

Fog is closer to us. It is closer to what we now call "edge clouds."

- Can any cloud/data center perform fog computing if it is close enough to the IoT devices? Is fog computing defined as a location rather than hardware or protocols?

Yes, but lower layers are less powerful and more straightforward.

- Is the security issue also involved in the fog computing?

Yes, a lot. That's what we are working on right now.

Ref: F. Bonomi, et al., "Fog Computing and Its Role in the Internet of Things," ACM MCC'12, August 17, 2012, Helsinki, Finland

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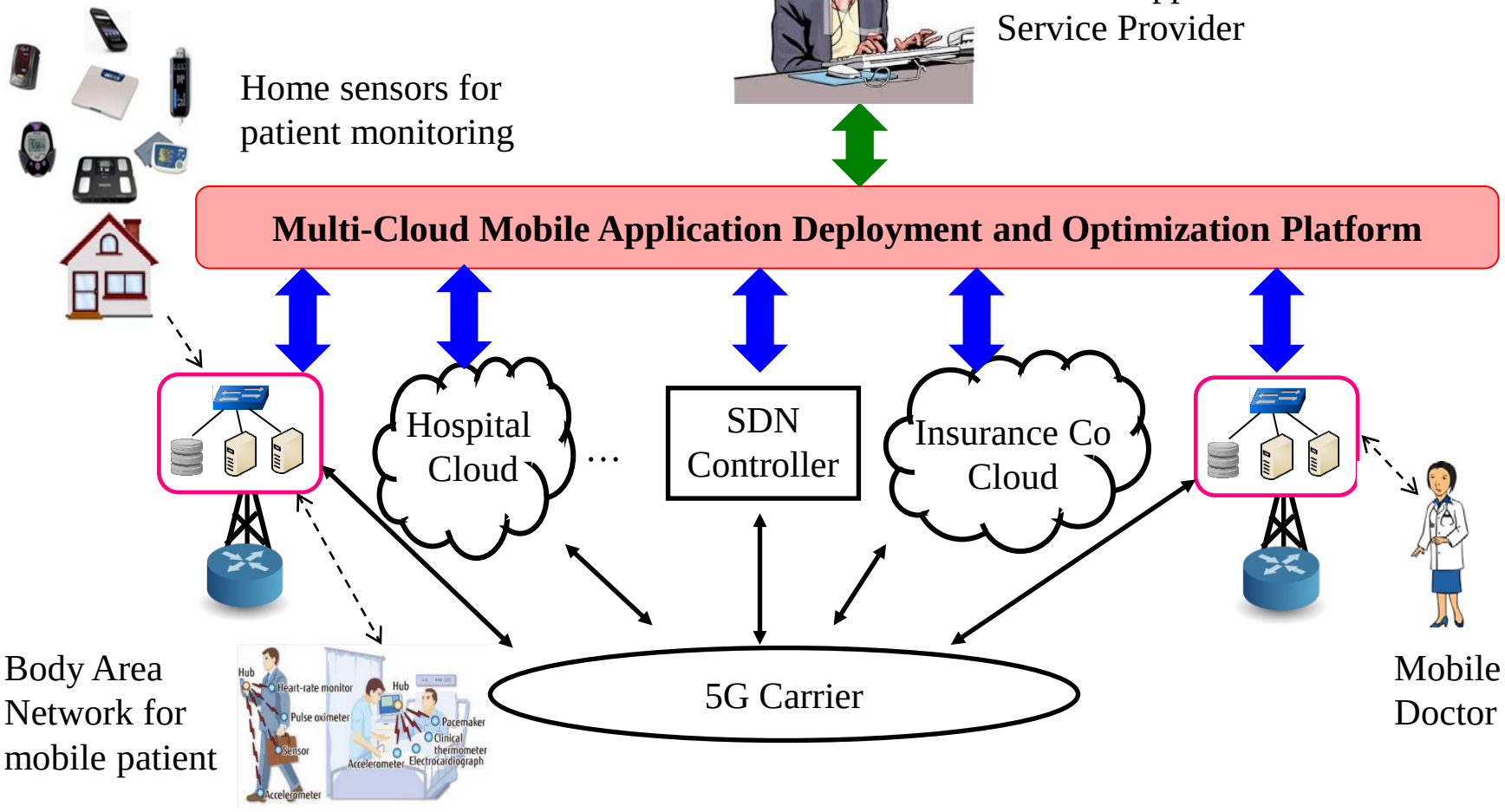
Mobile Healthcare Use Case



Student Questions

- Is there a difference between Fog computing and the edge devices we discussed?

Edge devices and clouds are different. Your phone is an edge device. The tower may be a cloud.

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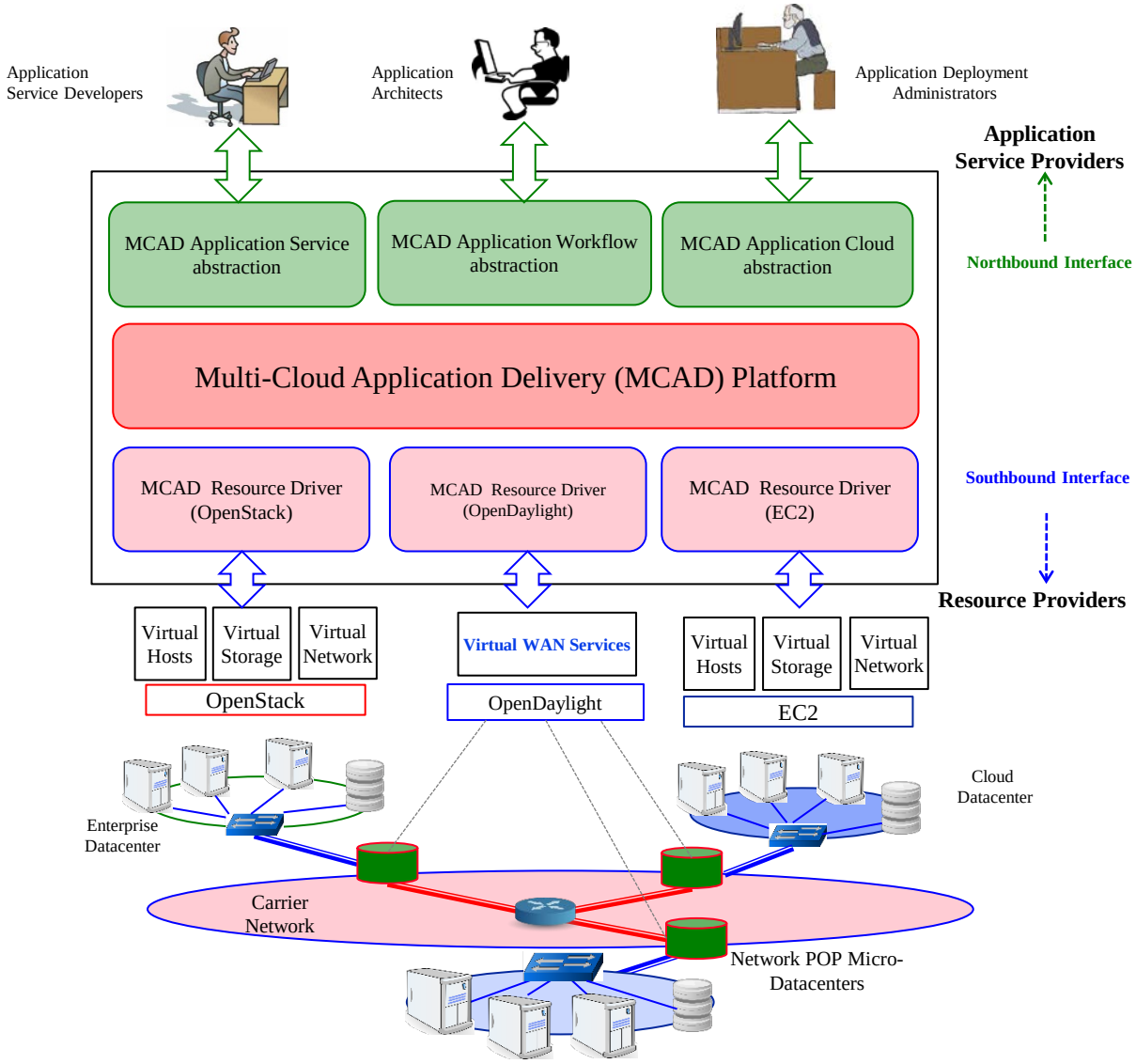
Multi-Cloud Management



Student Questions

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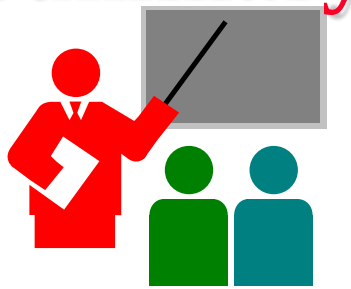
Summary



1. Less than 1% of things are connected
   ⇒ IoT is a big opportunity for academics and industry
2. Smart Grid and Energy management lead 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 all subfields of computing, including hardware development, data analytics, security, and networking.
5. Cloud computing everywhere leads to fog computing and multi-cloud computing ⇒ our MCAD project

Student Questions

- You said in the slide that IoT is a big opportunity, and then what do you think of the future for network equipment vendors like Cisco?

Cisco is selling routers and switches for the cloud. So, the future is bright.

- Is it still less than 1%? Since so many "intelligent furniture/devices/gears" are out?

It has increased significantly. But I don't have the recent stats.

  - To confirm that over 50% of devices are IoT now?

No. That seems too high.

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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

Student Questions

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References

- 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).
- 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

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Wikipedia Links

- https://en.wikipedia.org/wiki/Fog_computing
- https://en.wikipedia.org/wiki/Industrial_Internet
- 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

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Acronyms

- 6LowPAN IPv6 over Low Powered Personal Area Network
- ACM Automatic Computing Machinery Association
- 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)
- BACnet Building Automation and Control Network
- CI12.20 ANSI Standard for Electric Meter Accuracy and Performance
- CoAP Constrained Application Protocol
- COSEM Company Specification for Energy Metering
- CPS Cyber Physical Systems
- CPU Central Processing Unit
- CTIA Cellular Telecommunication Industries Association
- DARPA Defense Advance Research Project Agency
- DASH7 ISO 18000-7 RFID standard for sensor networks

Student Questions

Acronyms (Cont)

- DECT Digital Enhanced Cordless Communication
- DLMS Device Language Message Specification
- DoE Department of Energy
- EC2 Elastic Compute Cloud 2 (by Amazon)
- ETSI European Telecommunications Standards Institute
- EU European Union
- FP7 Framework Program 7
- GP GreenPHY
- GreenPHY Green Physical Layer
- HomePlug-GP HomePlug Green PHY
- IEEE Institute for Electrical and Electronic Engineers
- IERC IoT-European Research Cluster
- IETF Internet Engineering Task Force
- iOS iPhone Operating System
- IoT Internet of Things
- IP Internet Protocol

Student Questions

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Acronyms (Cont)

IPSO	IP for Smart Objects
IPv4	Internet Protocol version 4
IPv6	Internet Protocol version 6
ISP	Internet Service Provider
ITU	International Telecommunications Union
KNX	Building automation protocol
MB	Mega-byte
MCAD	Multi-Cloud Application Deployment Platform
MQTT	Message Queue Telemetry Transport
NASA	National Aeronautical and Space Administration
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

Student Questions

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Acronyms (Cont)

- OAuth Open Authorization protocol from IETF
- oneM2M One Machine to Machine
- ONR Office of Naval Research
- PAN Personal area network
- PIN Personal Identification Number
- PLC Power Line Communication
- PoP Point of Presence
- QoI Quality of information
- QR Quick Response
- RFID Radio Frequency Identifier
- RPL Routing Protocol for Low Power and Lossy Networks
- SDN Software Defined Networking
- SIG Special Interest Group
- SOA Service Oriented Architecture
- TLV Type-Length-Value
- TV Television
- UK United Kingdom

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Acronyms (Cont)

- ULE Ultra Low Energy
- US United States
- VC Venture Capital
- WAN Wide Area Network
- WiFi Wireless Fidelity
- XML eXtensible Markup Language
- ZB Ziga-Byte

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https://www.youtube.com/playlist?list=PLjGG94etKypJEKjNAa1n_1X0bWWNyZcof

CSE473S: Introduction to Computer Networks (Fall 2011),

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

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