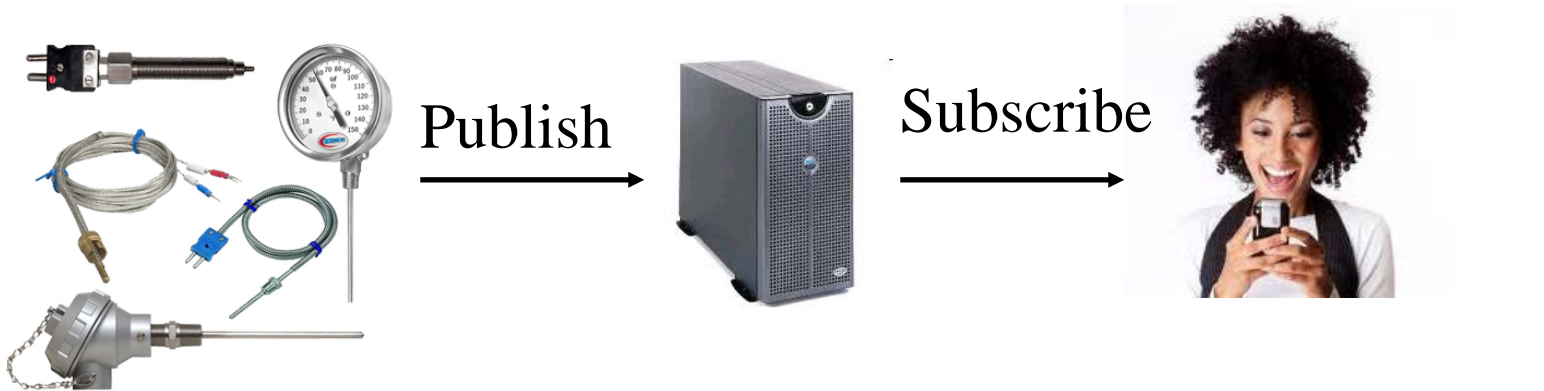


Messaging Protocols for Internet of Things: MQTT



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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



- ❑ MQ Telemetry Transport (MQTT)
 - MQTT Concepts
 - MQTT Application 2
 - MQTT vs. HTTP
- ❑ Hardware for IoT

- ❑ Note: This is 4th in a series of lectures on the Internet of Things.
Please see the URL on the first slide and every slide for other lectures of this series.

Student Questions

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 , ... | | |
| Routing | 6LowPAN , RPL , 6Lo, 6tsch, Thread, 6-to-nonIP , ... | | |
| 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, EVERYTHING , ... | | |
| Operating Systems | Linux, Android, Contiki-OS, TinyOS, ... | | |
| Hardware | ARM, Arduino , Raspberry Pi, ARC-EM4, Mote, Smart Dust, Tmote Sky, ... | | |

Student Questions

MQ Telemetry Transport (MQTT)

- ❑ Lightweight messaging protocol for M2M communication
- ❑ Telemetry = Tele-Metering = Remote measurements
- ❑ Invented and sponsored by IBM.
Now Open source. Open Source libraries available.
- ❑ MQ originated from the “message queueing (MQ)” architecture used by IBM for service-oriented networks. There is **no** queueing in MQTT.
- ❑ Telemetry data goes from devices to a server or broker.
Uses a publish/subscribe mechanism.
- ❑ Lightweight = Low network bandwidth and small code footprint

Ref: https://en.wikipedia.org/wiki/MQ_Telemetry_Transport

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Student Questions

❑ Does MQTT support offline messages?
Offline can mean many things. The sensor (publisher), broker, network, or user (subscriber) can be offline. All brokers store messages, so as long as they are up, messages will be available later for retrieval. Some sensors (e.g., video cameras) have local storage. If so, it can store data for a limited time. Users are mostly offline anyway. They come back once in a while and see important notifications.

❑ Can you give a small review on M2M communication?

M2M=Machine-to-Machine used in industrial automation

❑ What programming languages are the open source libraries available in?

I don't know. But Python and C++ are the popular languages.

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Student Questions

- ❑ What does a small code footprint mean, and how does the design of a lightweight protocol achieve that?

*Small number of lines of code.
Protocol weight refers to the protocol overhead, not the lines of code.*

- ❑ What is "code footprint"?
Lines of code

MQTT (Cont)

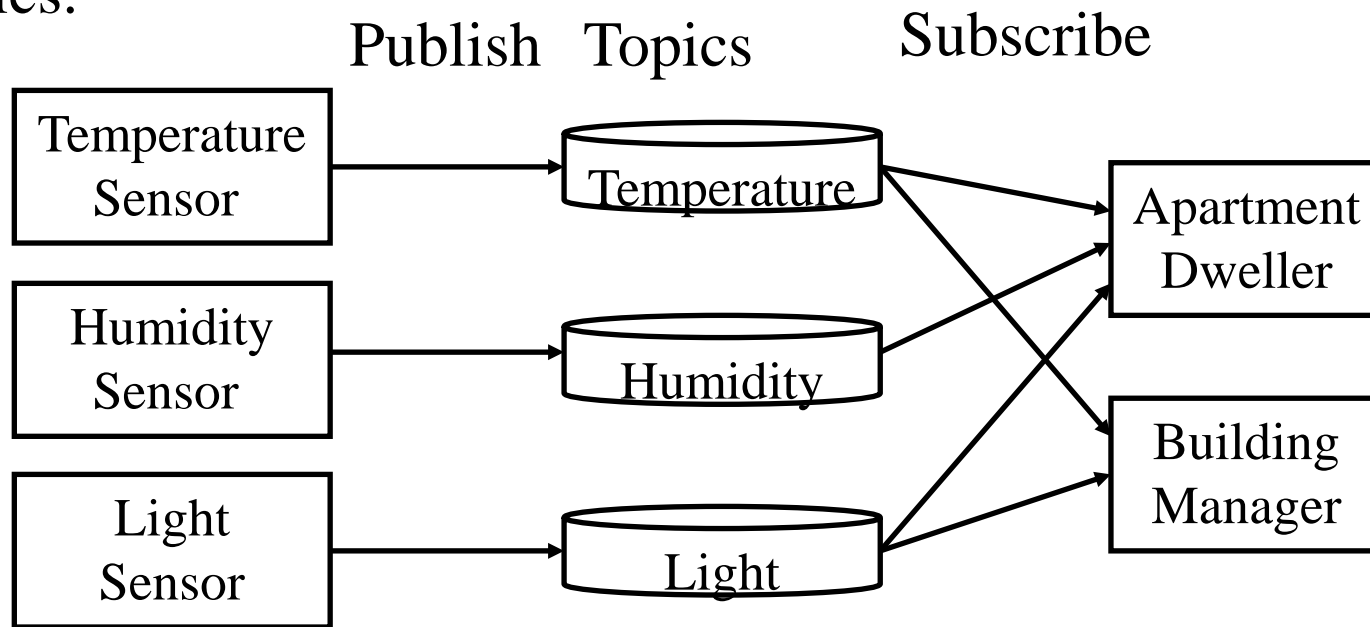
- ❑ Facebook Messenger uses MQTT to minimize battery usage. Several other applications in medical and environmental applications
- ❑ Many open-source implementations of clients and brokers are available
 - Really small message broker (RSMB): C
 - Mosquitto
 - Micro broker: Java-based for PDAs, notebooks

Student Questions

- ❑ What are brokers for?
Publishing uses publishers, brokers, and users, just like the book market. Brokers distribute the information.

MQTT Concepts

- ❑ **Topics/Subscriptions:** Messages are published to topics. Clients can subscribe to a topic or a set of related topics
- ❑ **Publish/Subscribe:** Clients can subscribe to or publish to topics.



Student Questions

- ❑ Does traffic essentially flow in one direction from the sensors to the databases? From databases to subscribers, is the traffic bi-directional?

All traffic is bidirectional, but the majority of the packets are flowing in a downward direction with sensors on the top and users on the bottom.

- ❑ Can you explain the difference between publish vs. subscribe regarding how the client uses it and how the broker uses it?

As in the book business.

Ref: V. Lampkin, et al., "Building Smarter Planet Solutions with MQTT and IBM WebSphere MQ Telemetry,"

IBM Redbooks, SEP-2012, ISBN: 0738437085, 268 pp., (Safari Book), <http://www.redbooks.ibm.com/redbooks/pdfs/sg248054.pdf>

MQTT Concepts (Cont)

- ❑ **Quality of Service Levels:** Three levels:
 - 0 = At most once (Best effort, No Ack),
 - 1 = At least once (Acked, retransmitted if ack not received),
 - 2 = Exactly once [Request to send (Publish), Clear-to-send (Pubrec), message (Pubrel), ack (Pubcomp)]
- ❑ **Retained Messages:** The server keeps messages even after sending them to all subscribers. New subscribers get the retained messages

Student Questions

- ❑ For the retained msg, by the subscribers here, you mean “IoT devices,” not “users,” correct? This policy led to an attack on (azure and Google Cloud) details are in a paper called “Burglars’ IoT Paradise.”

Subscribers = Users

Publishers = IoT devices

Brokers = IoT service providers, e.g., Amazon for Amazon cameras.

- ❑ Is there any specific ruling on what and how long the messages should be kept? If the server keeps all messages indefinitely, that would not be economical for IoT.

As long as the user pays. Brokers provide many different subscription plans.

MQTT Concepts (Cont)

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Student Questions

- ❑ What types of devices would use QoS 2?

See the list

- ❑ So the server knows when there is a new subscriber?

They don't. Only brokers know it when the subscriber joins the broker.

- ❑ Is it the new subscriber who asks for the retained messages, or does the server proactively send the retained message to new subscribers?

Subscribers get only what they request.

- ❑ What is Ack?

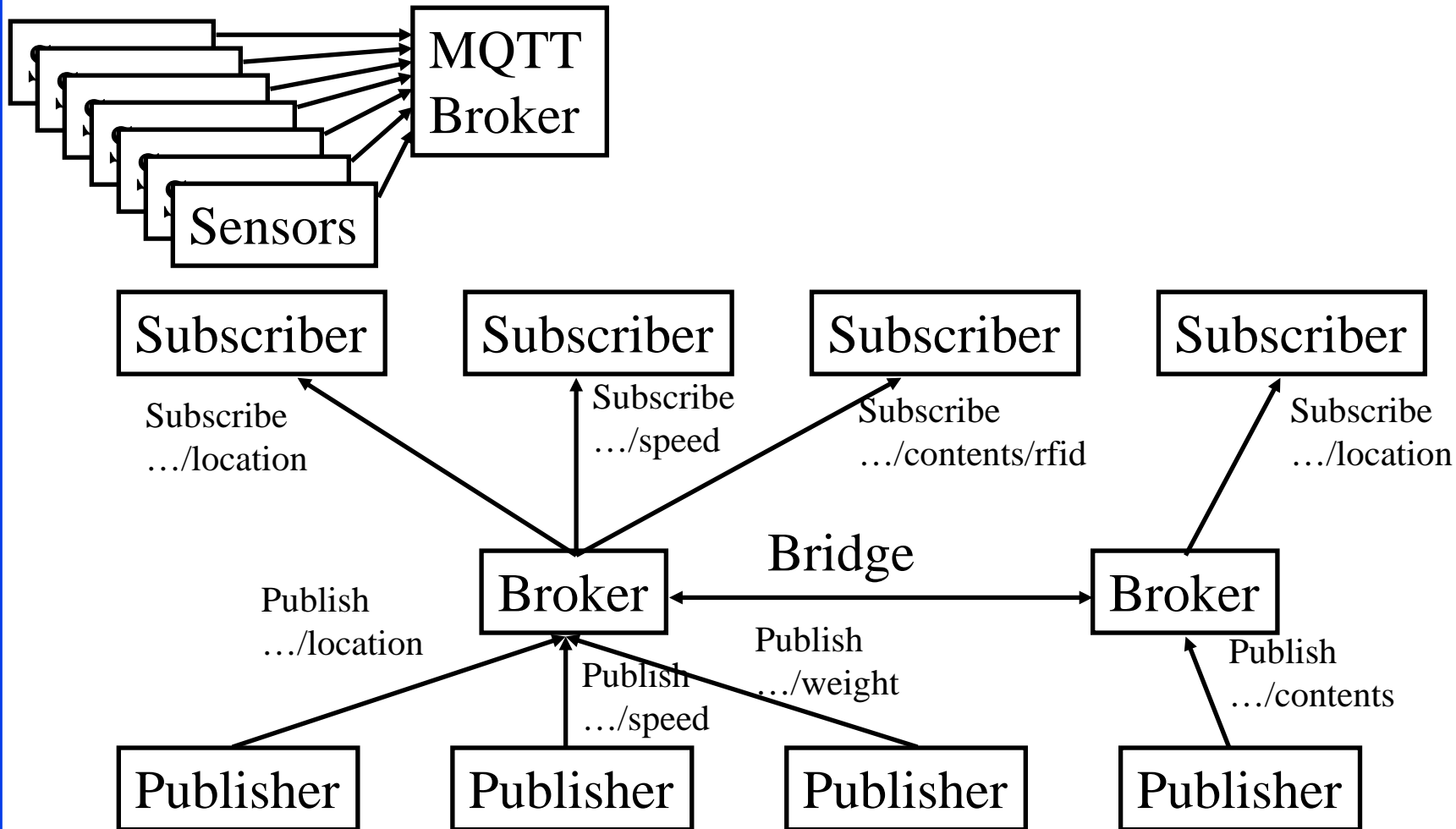
Acknowledgment

MQTT Concepts (Cont)

- ❑ **Clean Sessions** and **Durable Connections**: At connection set up:
Clean session flag \Rightarrow all subscriptions are removed on disconnect
Otherwise, subscriptions remain in effect after disconnection
 \Rightarrow Subsequent messages with high QoS are stored for delivery after reconnection
- ❑ **Wills**: At connection, a client can inform that it has a will or a message that should be published if unexpected disconnection
 \Rightarrow Alarm if the client loses connection
- ❑ Periodic **keep alive** messages \Rightarrow If a client is still alive
- ❑ **Topic Trees**: Topics are organized as trees using / character
/# matches all sublevels
/+ matches only one sublevel

Student Questions

MQTT Example



Student Questions

- ❑ What does a broker do? I could not find its definition in the MQTT specification <https://docs.oasis-open.org/mqtt/mqtt/v5.0/os/mqtt-v5.0-os.html> Can it have a queue?

Brokers work on behalf of many publishers. They are more potent than publishers. Yes, they can have a queue.

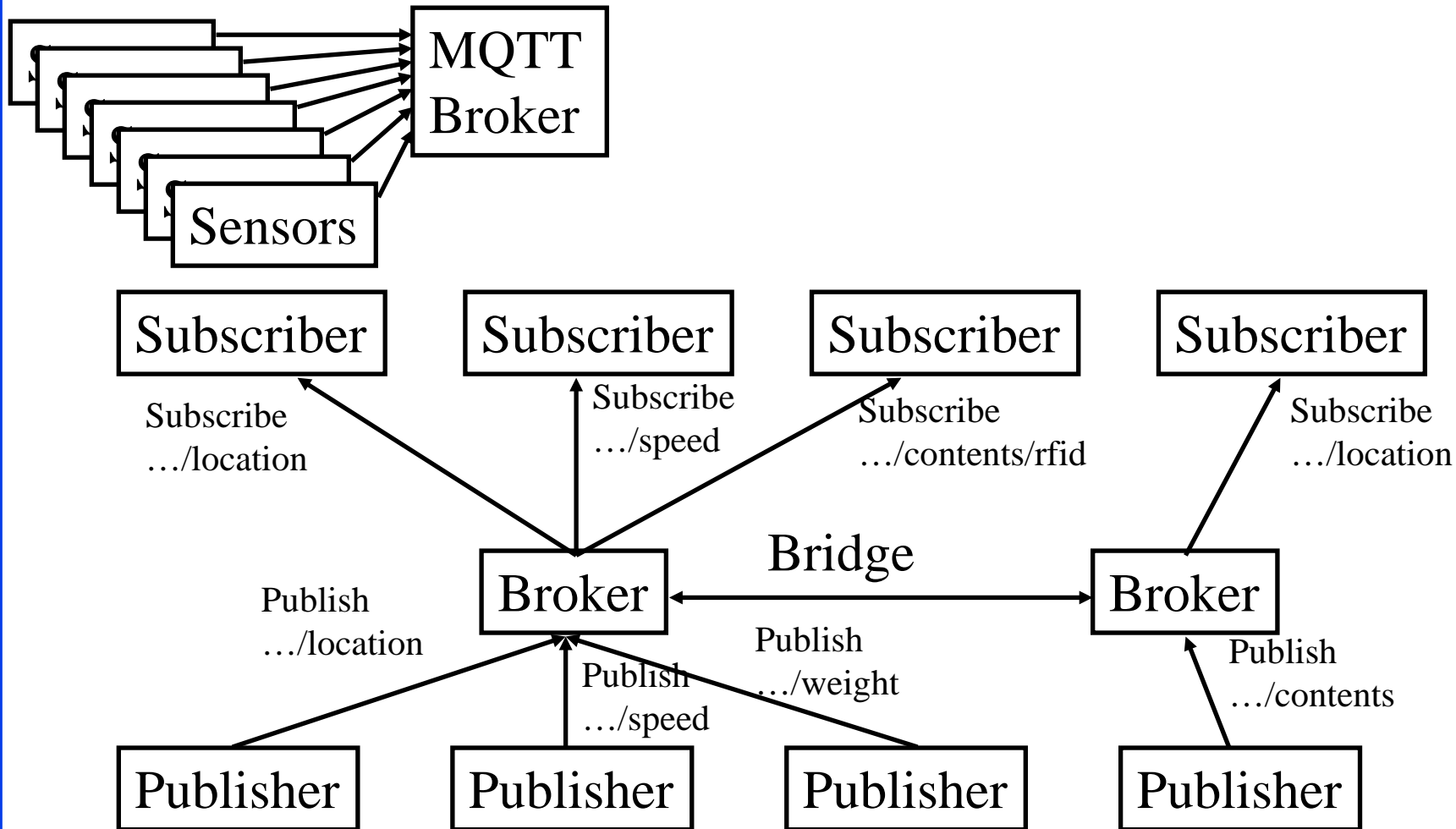
- ❑ Why are the two brokers connected? Is it for backup?

Load balancing, ownership, specialization, additional services. For example, many IoT providers work with Amazon Alexa, so Alexa is also a broker.

- ❑ If subscriber_1 subscribes to the topic "device/location" and subscriber_2 to "device/speed," if a publisher wants to publish messages to all those two subscribers simultaneously, which topic should it publish to?

Your example has two topics. Publishers will publish both topics. Sometimes, two publishers are required if each topic requires a different publisher.

MQTT Example



Student Questions

- ❑ Could you explain the broker's function in the MQTT?

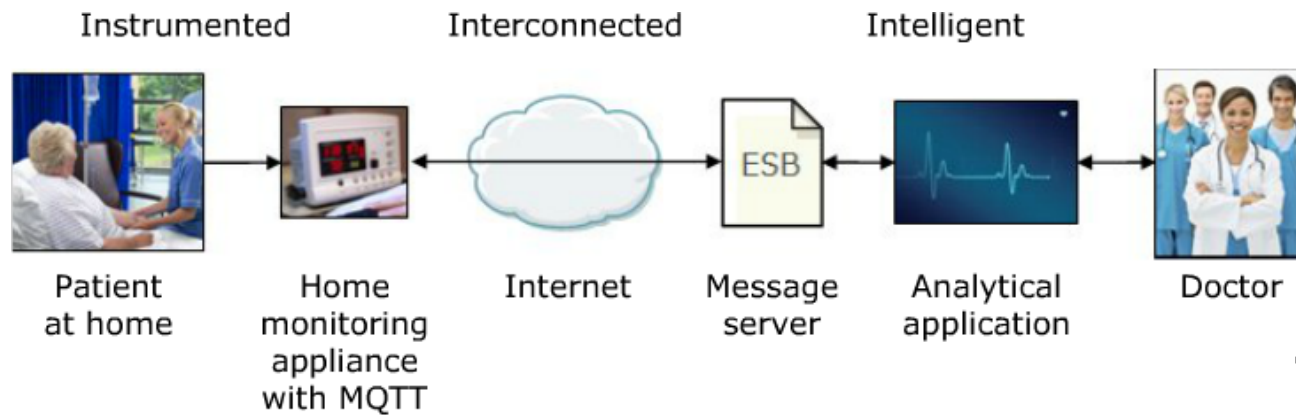
See the previous slide.

- ❑ Can you show who would be on this diagram in the Facebook messenger example?

Reading and writing messages on Facebook would be more like server-client communication. One user would be the publisher. The Facebook server is the broker. Other users are the subscribers.

MQTT Application Examples

- ❑ Home pacemaker monitoring solution
 - Sensors on patient
 - Collected by monitoring equipment in the home (broker) using MQTT
 - Subscribed by a computer in the hospital
 - Alert the doctor if anything is out of order



Student Questions

- ❑ What should be the Quality of Service Levels of this example?

Doctors and patients determine and specify the alert conditions. QoS also includes speed and resolution. It is determined by the cost of the system, e.g., high-cost cameras provide 4K-high-resolution video.

- ❑ Does MQTT specify any security implementations for its packets transmitted? And are there any standard security protocols used for it?

There are tons of protocols for IoT security. See Slide 13.3

MQTT vs. HTTP

| | MQTT | HTTP |
|-------------------|------------------------------|-------------------|
| Design | Data centric | Document centric |
| Pattern | Publish/Subscribe | Request /Response |
| Complexity | Simple | More Complex |
| Message Size | Small. Binary with 2B header | Large. ASCII |
| Service Levels | Three | One |
| Libraries | 30kB C and 100 kB Java | Large |
| Data Distribution | 1 to zero, one, or n | 1 to 1 only |

- ❑ Open source, <http://www.eclipse.org/paho/>
- ❑ Clients available in .NET, Perl, Python, REXX, Rube,
- ❑ Also, for Arduino, Mbed, Nanode, Netduino

Ref: V. Lampkin, et al., "Building Smarter Planet Solutions with MQTT and IBM WebSphere MQ Telemetry,"

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Student Questions

- ❑ Can you explain the difference between 'data-centric' and 'document-centric'?

Data= computer-to-computer

Documents = user-to-user or computer-to-user or user-to-computer. Documents are designed for humans.

- ❑ Does the fact that MQTT uses a broker provide any advantages or disadvantages compared to HTTP?

Sensors do not need multi-user server capability.

This is an MQTT advantage.

- ❑ The publish/subscribe means the information changes in the client who publishes. The client who subscribes will immediately change at the same time. Is that correct?

No. Publish=Provide information

Subscribe = Interested in information.

IoT devices publish, and human users subscribe.

- ❑ What is REXX used for?

Restructured Extended Executor is a programming language that can be interpreted or compiled.

MQTT vs. HTTP

| | MQTT | HTTP |
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Student Questions

- ❑ Can MQTT and HTTP be integrated to communicate between IoT devices and web services?

They usually are. You get a web interface to manage your device.

- ❖ Are Rube, Arduino, Mbed, Nanode, and Netduino all programming languages?

No. These are hardware platforms.

IoT Hardware

1. Single-Board Microcontrollers
2. Single-Board Computers
3. Single-Board AI Engines

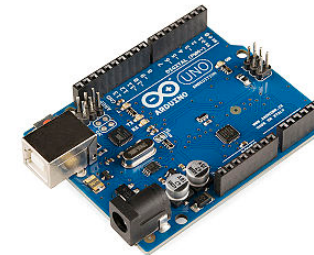
Student Questions

Single-Board Microcontrollers

❑ Arduino:

- Open-source hardware/software
- The name derived from Arduin of Ivrea (a King of Italy 1002-14)
- Can use a variety of microprocessors
 - ❑ Many different products and form factors
- Standard digital and analog I/O pins
 - ❑ Interface to many shields: Expansion boards for motors, Ethernet, GPS, Display, ...
- Arduino IDE in Java w programming in C or C++
- Applications: Oscilloscope, Drone, Phone, ...

- ❑ 100+ microcontrollers listed on Wikipedia



Student Questions

- ❑ Can we treat Arduino as a computer?
Generally, Arduino is used as an I/O device.
- ❑ Could you give some examples of something an Arduino can do but Raspberry Pi can't, and vice versa?

Raspberry Pi is a computer. You can run several versions of Linux on Raspberry Pi and attach Ethernet, Monitor, mouse, and keyboard to it. Arduino is generally connected to a Raspberry Pi for these functions.

Ref: <https://en.wikipedia.org/wiki/Arduino> , https://en.wikipedia.org/wiki/Comparison_of_single-board_microcontrollers

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<http://www.cse.wustl.edu/~jain/cse570-23/>

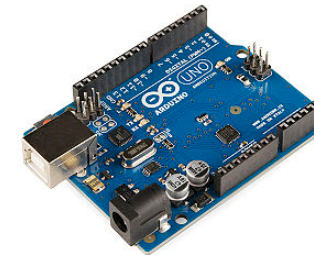
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Student Questions

- ❑ I recently came across a paper discussing a messaging protocol for IoT using Apache Kafka. While this paper presented a unique case, MQTT is generally the preferred choice for IoT. Apache Kafka, known for its high-throughput capabilities, is utilized by several large web companies. What are some primary reasons for this difference between the Web and IoT?

Kafka is for stream processing and not for management.

Ref: <https://en.wikipedia.org/wiki/Arduino> , https://en.wikipedia.org/wiki/Comparison_of_single-board_microcontrollers

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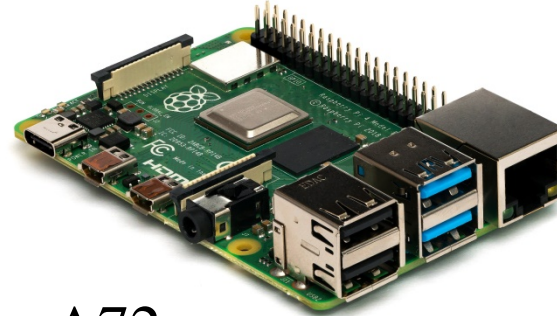
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Single-Board Computers

❑ Raspberry Pi

- Currently, V4 Model B
- Dual 4K displays
- 1.5 GHz 64-bit Quad-core ARM Cortex-A72
- Up to 4 GB RAM
- Supports Linux, Windows 10 (IoT Core), FreeBSD, etc.
- MicroSDHC, USB3, Gigabit Ethernet, 802.11ac Wi-Fi, Bluetooth
- Low cost: Around \$35

❑ See a list of 100+ other such computers on Wikipedia



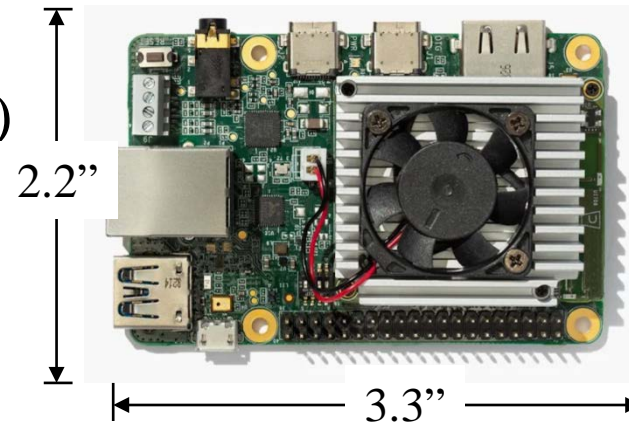
Student Questions

Ref: https://en.wikipedia.org/wiki/Single-board_computer, https://en.wikipedia.org/wiki/Raspberry_Pi, <https://www.raspberrypi.org/>, https://en.wikipedia.org/wiki/Comparison_of_single-board_computers

Single-Board AI Engines

❑ Google Coral Development Board

- Edge Tensor Processing Unit (TPU)
- Machine learning accelerator
- Cryptographic co-processor
- Gigabit Ethernet, Wi-Fi, Bluetooth
- USB, MicroSD
- HDMI, 3.5mm Audio
- Supports Mendel Linux, TensorFlow Lite, ...
- Low cost: Below \$150



❑ Similar offerings from Nvidia (Jetson Nano) and others

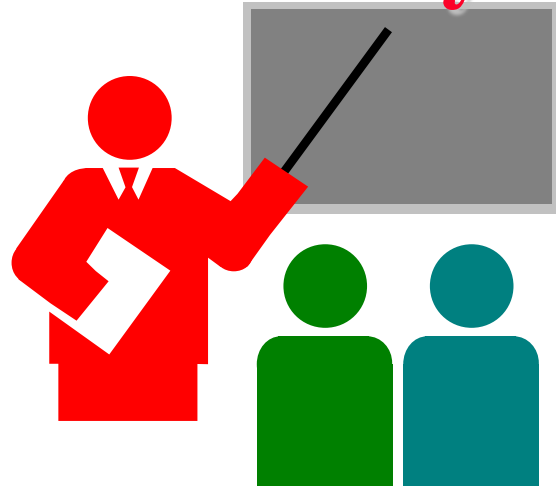
Ref: <https://coral.withgoogle.com/docs/dev-board/datasheet/>, https://en.wikipedia.org/wiki/Tensor_processing_unit

Student Questions

- ❑ Is TPU a combination of CPU and GPU?
Or does it have to be a single one?
GPUs are designed for graphics, which require millions of pixels to be processed in parallel. This makes them suitable for AI, where millions of data points must be processed. TPU is a CPU with instructions and capacity for tensor processing, so it does not need a GPU for AI.

- ❑ The TPU only uses Python, correct?
Not really.
- ❑ Since AI Engines need more work, does it mean they will contain more libraries?
No. AI engines only contain compiled code to execute. The code development is done on a separate machine.

Summary



1. MQTT is a protocol used to publish and subscribe sensor information
2. Lightweight, low code size, open source
3. Hardware for IoT is moving from small controllers to intelligent Edge TPUs

Student Questions

- Are there any security implications of the protocol since it is lightweight?
Yes. IoT security is a topic of research. MQTT is one component in the IoT protocol chain that can be broken.
-

Reading List

- ❑ V. Lampkin, et al., “Building Smarter Planet Solutions with MQTT and IBM WebSphere MQ Telemetry,” IBM Redbooks, SEP-2012, ISBN: 0738437085, 268 pp.,
<http://www.redbooks.ibm.com/redbooks/pdfs/sg248054.pdf>

Wikipedia Links

- ❑ https://en.wikipedia.org/wiki/MQ_Telemetry_Transport
- ❑ <https://en.wikipedia.org/wiki/Arduino>
- ❑ https://en.wikipedia.org/wiki/Comparison_of_single-board_computers
- ❑ https://en.wikipedia.org/wiki/Comparison_of_single-board_microcontrollers
- ❑ https://en.wikipedia.org/wiki/Raspberry_Pi
- ❑ https://en.wikipedia.org/wiki/Single-board_computer
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Student Questions

References

- ❑ <http://www.eclipse.org/paho/>
- ❑ <https://coral.withgoogle.com/docs/dev-board/datasheet/>
- ❑ <https://www.raspberrypi.org/>

Student Questions

Acronyms

- ❑ .NET Microsoft's software framework
- ❑ 3G Third Generation
- ❑ AMQP Advanced Queueing Message Protocol
- ❑ ARC-EM4 Name of a Product
- ❑ ARM Acorn RISC Machine
- ❑ ASCII American Standard Code for Information Exchange
- ❑ AVR Name of Atmel 8-bit RISC processor
- ❑ CoAP Constrained Application Protocol
- ❑ DDS Data Distribution Service
- ❑ DECT Digital Enhanced Cordless Telecommunication
- ❑ DTLS Datagram Transport Level Security
- ❑ GP Green Physical Layer
- ❑ GPS Global Positioning System
- ❑ HTTP Hypertext Transfer Protocol
- ❑ IDE Integrated Development Environment
- ❑ IEEE Institution of Electrical and Electronics Engineers

Student Questions

Acronyms (Cont)

- ❑ IoT Internet of Things
- ❑ IP Internet Protocol
- ❑ ISASecure Security Certification by ISCI
- ❑ ISCI ISA Security Compliance Institute
- ❑ kB Kilo Byte
- ❑ LoRaWAN Long-Range Wide Area Network
- ❑ LTE Long-Term Evolution
- ❑ MQ Message Queueing
- ❑ MQTT MQ Telemetry Transport
- ❑ NFC Near Field Communication
- ❑ PDA Personal Digital Assistant
- ❑ QoS Quality of Service
- ❑ REXX REstructured eXtended eXecutor (an interpreted programming language)
- ❑ RPL Routing over Low-Power and Lossy
- ❑ RSMB Really small message broker

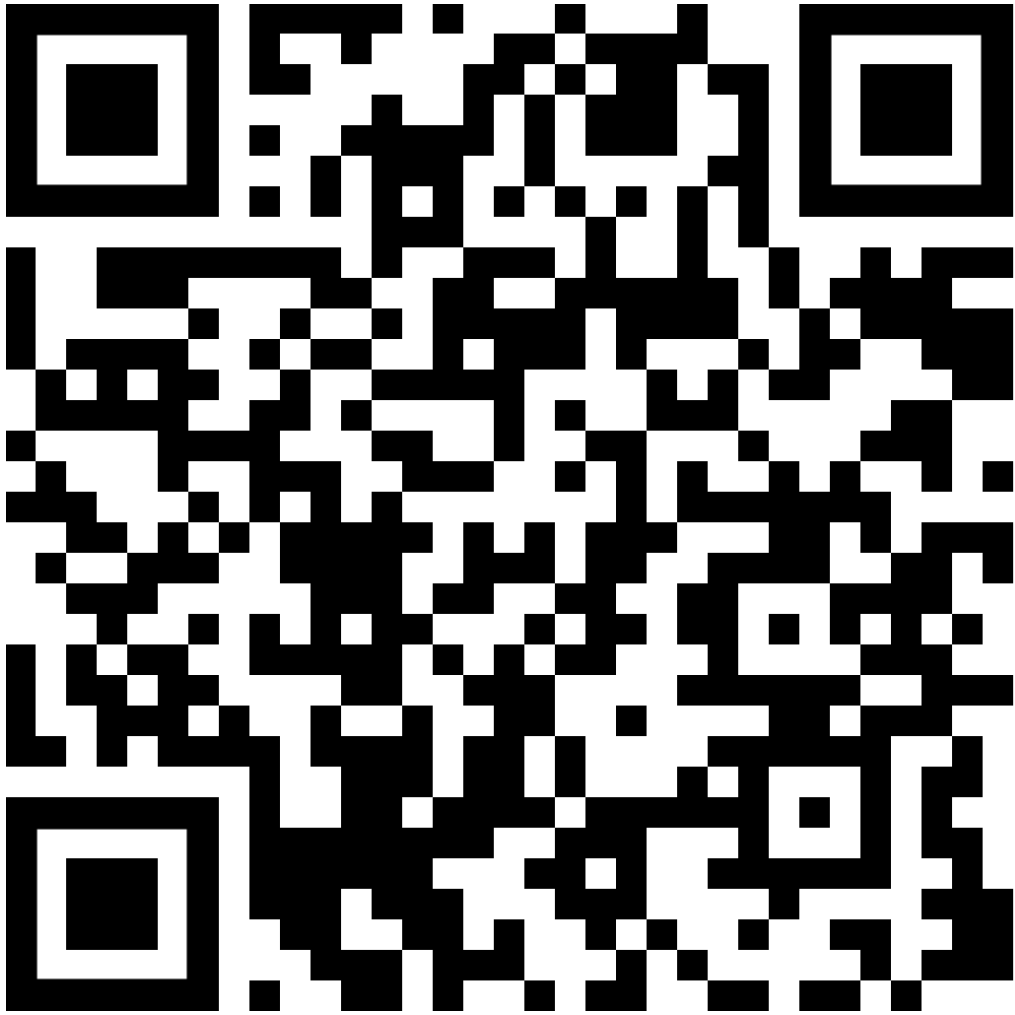
Student Questions

Acronyms (Cont)

- ❑ SASL Simple Authentication and Security Layer
- ❑ SDHC Secure Digital High-Capacity
- ❑ SMACK Simplified Mandatory Access Control Kernel
- ❑ TCG Trusted Control Group
- ❑ TPU Tensor Processing Unit
- ❑ TinyOS Tiny Operating System
- ❑ ULE Ultra-Low Energy
- ❑ URL Uniform Resource Locator
- ❑ WiFi Wireless Fidelity
- ❑ WirelessHART Wireless Highway Addressable Remote Transducer Protocol

Student Questions

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http://www.cse.wustl.edu/~jain/cse570-23/m_13mqt.htm

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http://www.cse.wustl.edu/~jain/cse570-23/m_13mqt.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



 Wireless and Mobile Networking (Spring 2016),

https://www.youtube.com/playlist?list=PLjGG94etKypKeb0nzyN9tSs_HCd5c4wXF

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