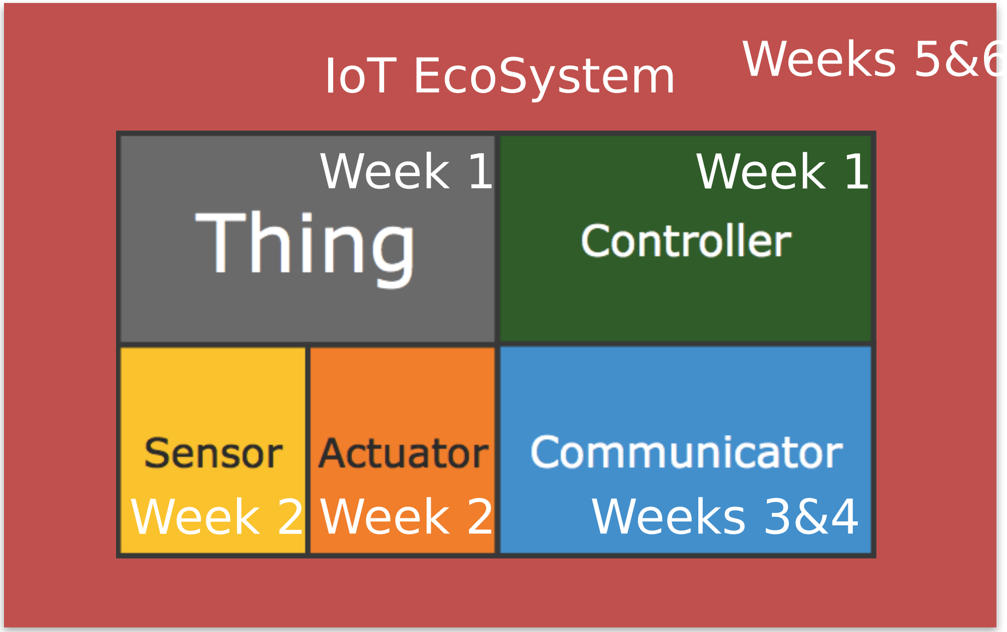
Internet-of-Things (IoT)

INTERNET of Things



IoT EcoSystem

Weeks 5&6

Thing

Week 1

Controller

Week 1

Sensor

Week 2

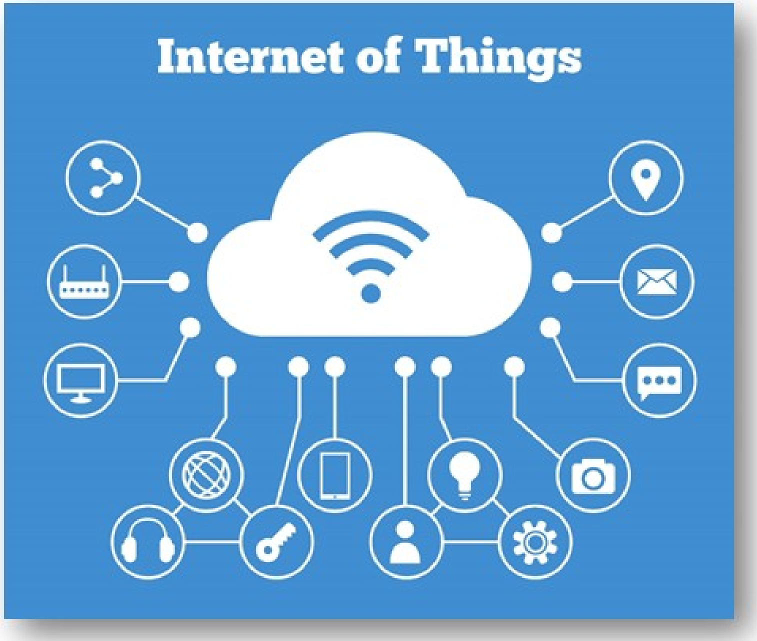
Actuator

Week 2

Communicator

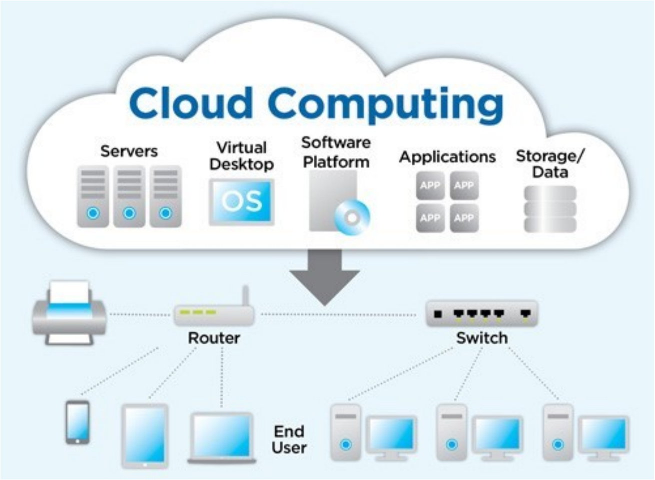
Weeks 3&4

What is Cloud Computing?



What is Cloud Computing?

- Delivery of computing **services**
  - servers
  - storage
  - analytics
  - databases
  - networking
  - and much more...



- Another definition: network-based computing taking place over the Internet, while hiding complexity of underlying infrastructure using simple APIs

What is Cloud Computing?

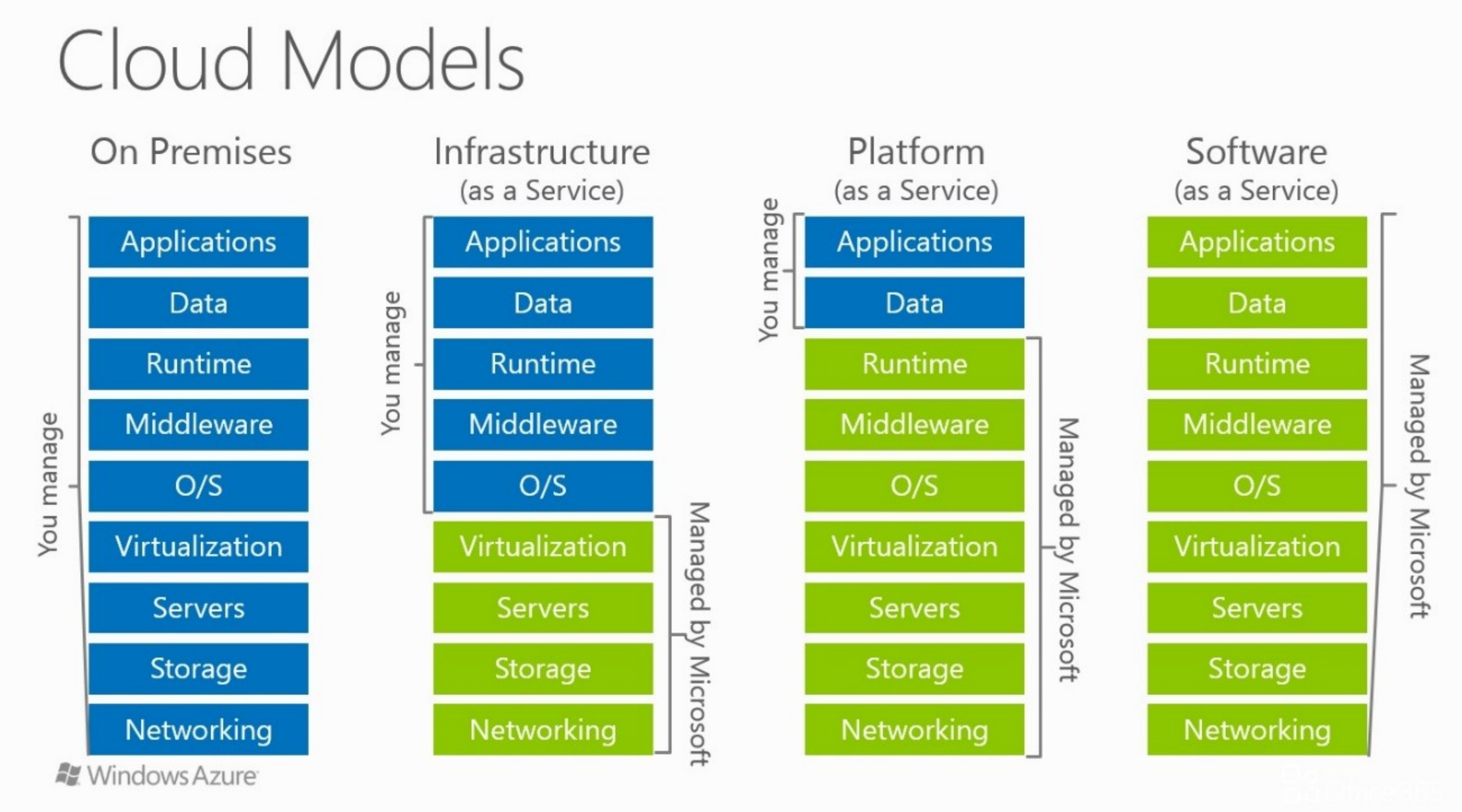
- Collection/group of **integrated and networked hardware, software, and Internet infrastructure** (called a platform)

- Platforms provide **on demand** services that are **always on** and **accessible anytime** and **anywhere**

What is Cloud Computing?

- Advantages:
  - New applications
  - Anytime/anywhere access
  - Homogeneity
  - Virtualization
  - Resilient
  - Cost
  - Sharing, collaboration
  - Management/maintenance
  - Security
  - …

Cloud Models: IaaS, PaaS, SaaS



Cloud Models

On Premises

You manage

Applications
Data
Runtime
Middleware
O/S
Virtualization
Servers
Storage
Networking

Infrastructure
(as a Service)

You manage

Applications
Data
Runtime
Middleware
O/S

Managed by Microsoft

Virtualization
Servers
Storage
Networking

Platform
(as a Service)

You manage

Applications
Data

Managed by Microsoft

Runtime
Middleware
O/S
Virtualization
Servers
Storage
Networking

Software
(as a Service)

Managed by Microsoft

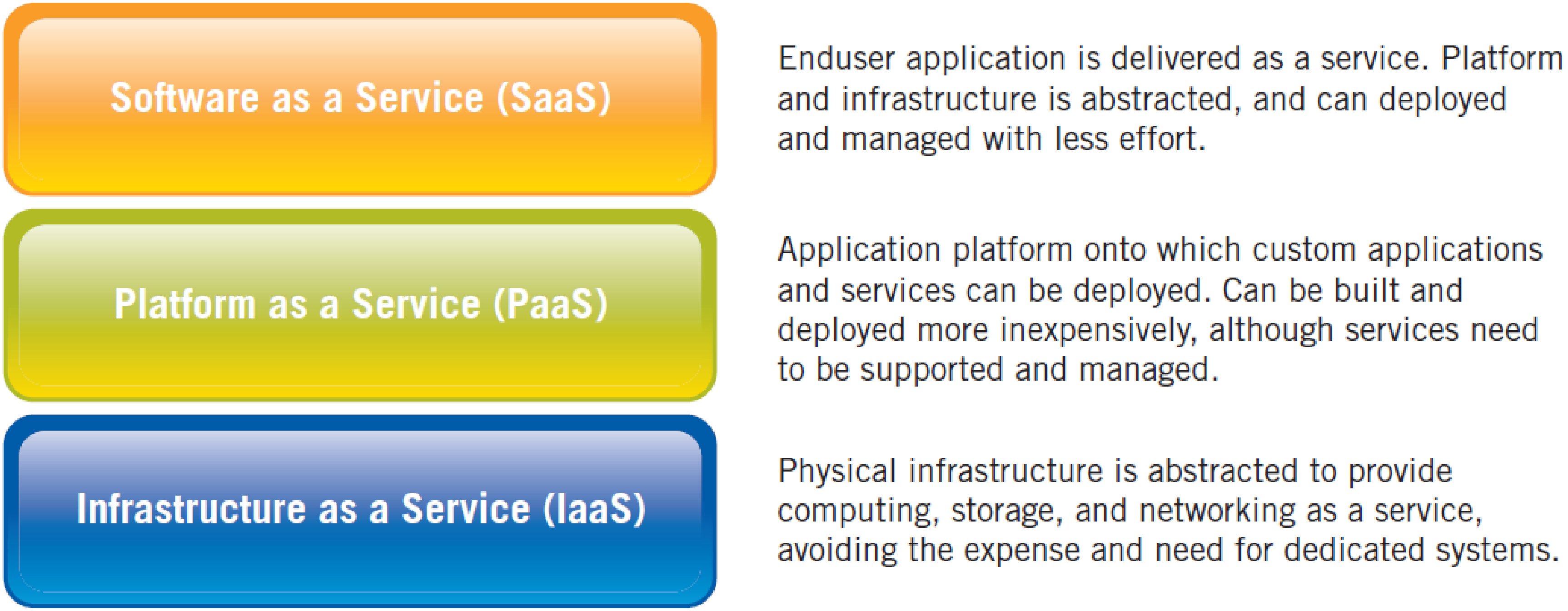
Applications
Data
Runtime
Middleware
O/S
Virtualization
Servers
Storage
Networking

Windows Azure

Definitions

- **Virtualization:** creation of a virtual resource such as a server, desktop, operating system, file, storage, or network
- **Middleware:** software that acts as a bridge between an operating system or database and applications, especially on a network
- **Runtime:** software designed to support the execution of computer programs

IaaS, PaaS, SaaS



Software as a Service (SaaS)

Enduser application is delivered as a service. Platform and infrastructure is abstracted, and can deployed and managed with less effort.

Platform as a Service (PaaS)

Application platform onto which custom applications and services can be deployed. Can be built and deployed more inexpensively, although services need to be supported and managed.

Infrastructure as a Service (IaaS)

Physical infrastructure is abstracted to provide computing, storage, and networking as a service, avoiding the expense and need for dedicated systems.

Simple example:

- IaaS: barebones computer
- PaaS: computer + OS (incl. development environment)
- SaaS: complete solution including application(s)

IaaS, PaaS, SaaS

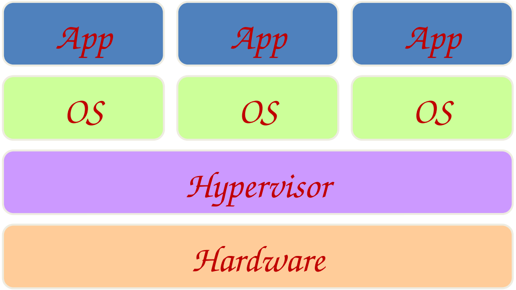
- IaaS: Amazon Web Services (AWS), Microsoft Azure, Google Compute Engine
- PaaS: Google App Engine, Heroku, OpenShift, AWS Elastic Beanstalk
- SaaS: Google Apps, Dropbox, Cisco Webex, Salesforce, Concur, GoToMeeting

Basic Cloud Characteristics

- “No-need-to-know”: interact with underlying infrastructure via API
- Flexibility and elasticity: scale systems up and down (allocate/release resources) based on needs
- Pay as much as used and needed (actual usage vs. service levels)
- Anytime anywhere access

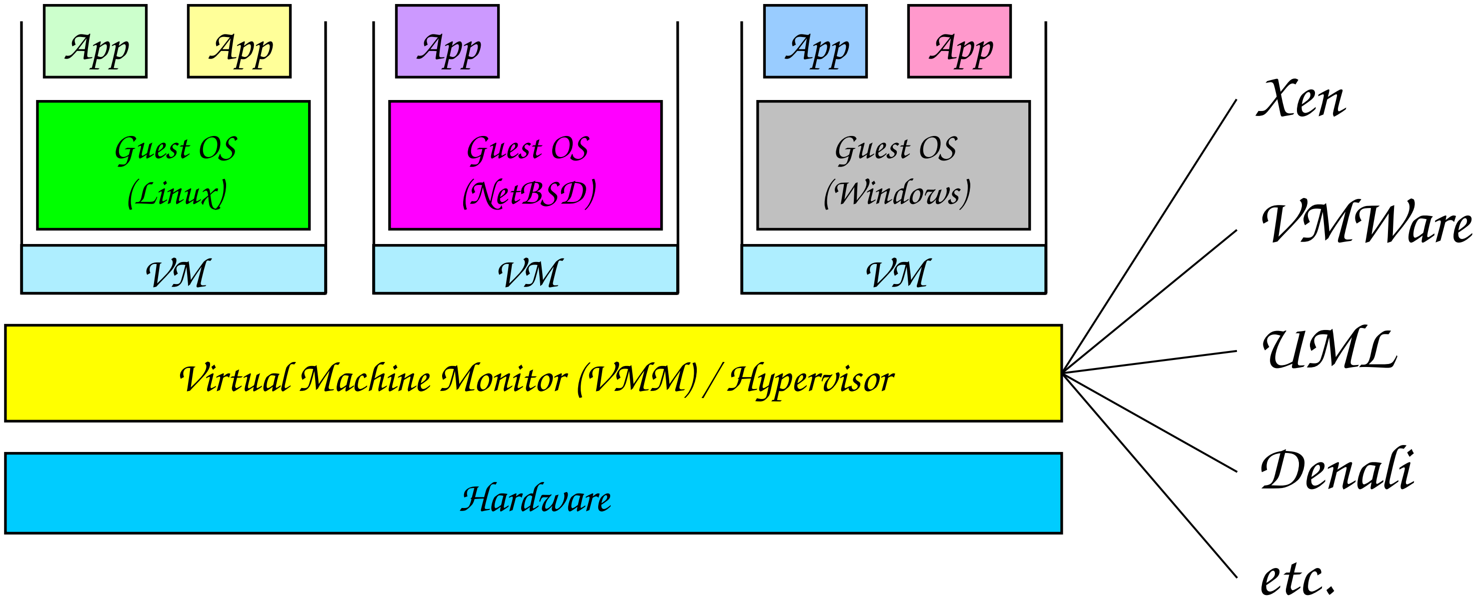
Virtualization

- Virtual workspaces:
  - An abstraction of an execution environment that can be made dynamically available to authorized clients by using well-defined protocols
  - Resource quota (e.g., CPU, memory share)
  - Software configuration (e.g., OS, provided services)
- Implemented on Virtual Machines (VMs):
  - Abstraction of a physical host machine
  - Hypervisor intercepts and emulates instructions from VMs, and allows management of VMs
  - VMWare, Xen, etc.



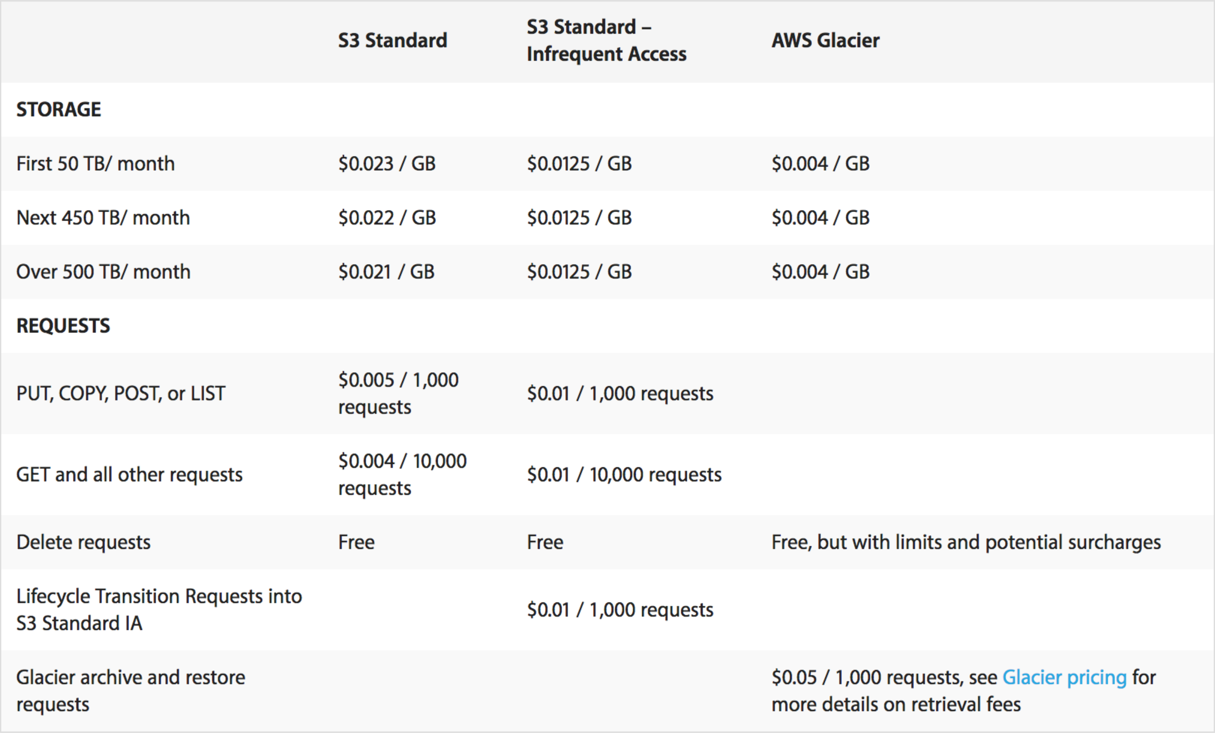
Virtualized Stack

Virtual Machines



Cloud Example: S3

- Amazon Simple Storage Service (S3)
- Unlimited storage
- Pay for what you use



	S3 Standard	S3 Standard – Infrequent Access	AWS Glacier
STORAGE			
First 50 TB/ month	$0.023 / GB	$0.0125 / GB	$0.004 / GB
Next 450 TB/ month	$0.022 / GB	$0.0125 / GB	$0.004 / GB
Over 500 TB/ month	$0.021 / GB	$0.0125 / GB	$0.004 / GB
REQUESTS			
PUT, COPY, POST, or LIST	$0.005 / 1,000 requests	$0.01 / 1,000 requests	
GET and all other requests	$0.004 / 10,000 requests	$0.01 / 10,000 requests	
Delete requests	Free	Free	Free, but with limits and potential surcharges
Lifecycle Transition Requests into S3 Standard IA		$0.01 / 1,000 requests	
Glacier archive and restore requests			$0.05 / 1,000 requests, see Glacier pricing for more details on retrieval fees

Cloud Example: EC2

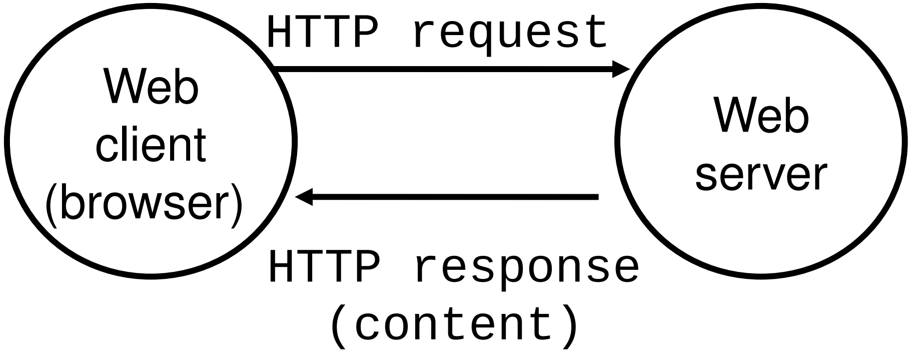
- Amazon Elastic Compute Cloud (EC2)
  - Virtual computing environments (“instances”)
  - Pre-configured templates for instances
  - Launch as many virtual servers as needed (“elastic”)
  - Xen and KVM hypervisor

Do You Use The Cloud?

Cloud for IoT

HyperText Transfer Protocol (HTTP)

- Clients and servers communicate using the **HyperText Transfer Protocol (HTTP)**
  - Client and server establish TCP connection
  - Client requests content
  - Server responds with requested content
  - Client and server close connection (usually)



Web Content

- Web servers return **content** to clients
  - a sequence of bytes with an associated MIME (Multipurpose Internet Mail Extensions) type
- Example MIME types
  - `text/html` HTML document
  - `text/plain` Unformatted text
  - `application/postscript` Postcript document
  - `image/gif` Binary image encoded in GIF format
  - `image/jpeg` Binary image encoded in JPEG format

Static & Dynamic Content

- The content returned in HTTP responses can be either **static** or **dynamic**
  - Static content: content stored in files and retrieved in response to an HTTP request
    - Examples: HTML files, images, audio clips
  - Dynamic content: content produced on-the-fly in response to an HTTP request
    - Example: content produced by a program executed by the server on behalf of the client
- Bottom line: all web content is associated with a **file** that is managed by the server

URLs

- Each file managed by a server has a unique name called a URL (Universal Resource Locator)
- URLs for static content:
  - `http://www.cse.nd.edu:80/index.html`
  - `http://www.cse.nd.edu/index.html`
  - `http://www.cse.nd.edu`
    - Identifies a file called `index.html`, managed by a web server at `www.cse.nd.edu` that is listening on port 80
- URLs for dynamic content:
  - `http://www.cse.nd.edu:8000/cgi-bin/adder?15000&213`
    - Identifies an executable file called `adder`, managed by a web server at `www.cse.nd.edu` that is listening on port 8000, that should be called with two argument strings: `15000` and `213`

Anatomy of an HTTP Transaction

```
unix> telnet www.aol.com 80        Client: open connection to server
Trying 205.188.146.23...           Telnet prints 3 lines to the terminal
Connected to aol.com.
Escape character is '^]'.
GET / HTTP/1.1                     Client: request line
host: www.aol.com                  Client: required HTTP/1.1 HOST header
                                   Client: empty line terminates headers.
HTTP/1.0 200 OK                    Server: response line
MIME-Version: 1.0                  Server: followed by five response headers
Date: Mon, 08 Jan 2001 04:59:42 GMT
Server: NaviServer/2.0 AOLserver/2.3.3
Content-Type: text/html            Server: expect HTML in the response body
Content-Length: 42092              Server: expect 42,092 bytes in the resp body
                                             Server: empty line (“\r\n”) terminates hdrs
<html>                             Server: first HTML line in response body
...                                Server: 766 lines of HTML not shown.
</html>                            Server: last HTML line in response body
Connection closed by foreign host. Server: closes connection
unix>                              Client: closes connection and terminates
```

HTTP Requests

- HTTP request is a *request line*, followed by zero or more *request headers*

- Request line: `<method> <uri> <version>`
  - `<version>` is HTTP version of request (`HTTP/1.0` or `HTTP/1.1`)
  - `<uri>` is typically URL for proxies, URL suffix for servers
  - `<method>` is either `GET`, `POST`, `OPTIONS`, `HEAD`, `PUT`, `DELETE`, or `TRACE`

HTTP Requests

- HTTP methods:
  - `GET`: Retrieve static or dynamic content
    - Arguments for dynamic content are in URI
    - Workhorse method (99% of requests)
  - `POST`: Retrieve dynamic content
    - Arguments for dynamic content are in the request body
  - `OPTIONS`: Get server or file attributes
  - `HEAD`: Like `GET` but no data in response body
  - `PUT`: Write a file to the server
  - `DELETE`: Delete a file on the server
  - `TRACE`: Echo request in response body
    - Useful for debugging

HTTP Responses

- HTTP response is a *response line* followed by zero or more *response headers*
- Response line:
- `<version> <status code> <status msg>`
  - <version> is HTTP version of the response
  - <status code> is numeric status
  - <status msg> is corresponding English text
    - 200 OK Request was handled without error
    - 403 Forbidden Server lacks permission to access file
    - 404 Not found Server couldn’t find the file
- Response headers: `<header name>: <header data>`
  - Provide additional information about response
  - `Content-Type:` MIME type of content in response body
  - `Content-Length:` Length of content in response body

REST

- Representational State Transfer (REST)

- A style of software architecture for distributed hypermedia systems such as the World Wide Web

- A collection of network architecture principles which outline how **resources** are defined and addressed

REST & HTTP

- The motivation for REST was to capture the characteristics of the Web which made the Web successful
  - URI Addressable resources
  - HTTP Protocol
  - Make a Request – Receive Response – Display Response
- Exploits the use of the HTTP protocol beyond HTTP POST and HTTP GET
  - HTTP PUT, HTTP DELETE

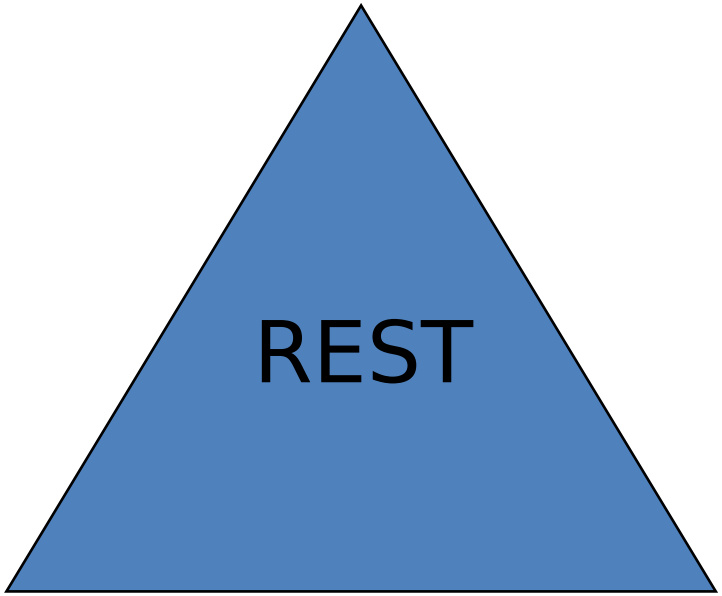
REST

- REST is not a standard
  - is an architectural style

- But it uses several standards:
  - HTTP
  - URL
  - XML/HTML/GIF/JPEG/etc (Resource Representations)
  - text/xml, text/html, image/gif, image/jpeg, etc (Resource Types, MIME Types)

REST Main Concepts

Nouns (Resources)
unconstrained
i.e., http://example.com/employees/12345



Verbs
constrained
i.e., GET

Representations
constrained
i.e., XML

Resources

- The key abstraction of information in REST is a resource
- A resource is a conceptual mapping to a set of entities
  - Any information that can be named can be a resource: a document or image, a temporal service (e.g., “today's weather in Berlin”), a collection of other resources, a non-virtual object (e.g., a person), etc.
- Represented with a global identifier (URI in HTTP)
  - http://www.boeing.com/aircraft/747

Naming Resources

- REST uses URI to identify resources
  - http://localhost/books/
  - http://localhost/books/ISBN-0011
  - http://localhost/books/ISBN-0011/authors

  - http://localhost/classes
  - http://localhost/classes/cs2650
  - http://localhost/classes/cs2650/students

- As you traverse the path from more generic to more specific, you are navigating the data

Verbs

- Represent the actions to be performed on resources

- HTTP GET
- HTTP POST
- HTTP PUT
- HTTP DELETE

HTTP GET

- How clients ask for the information they seek

- Issuing a GET request transfers the data from the server to the client in some representation

- GET http://localhost/books
  - Retrieve all books

- GET http://localhost/books/ISBN-0011021
  - Retrieve book identified with ISBN-0011021

- GET http://localhost/books/ISBN-0011021/authors
  - Retrieve authors for book identified with ISBN-0011021

HTTP PUT & POST

- HTTP POST creates a resource
- HTTP PUT updates a resource

- POST http://localhost/books/
  - Content: {title, authors[], …}
  - Creates a new book with given properties

- PUT http://localhost/books/isbn-111
  - Content: {isbn, title, authors[], …}
  - Updates book identified by isbn-111 with submitted properties

Representations

- How data is represented or returned to the client for presentation.

- Two main formats:

  - JavaScript Object Notation (JSON)

  - XML

- It is common to have multiple representations of the same data

Representations

- XML

```
<COURSE>
    <ID>CS2650</ID>
    <NAME>Distributed Multimedia Software</NAME>
</COURSE>
```

- JSON

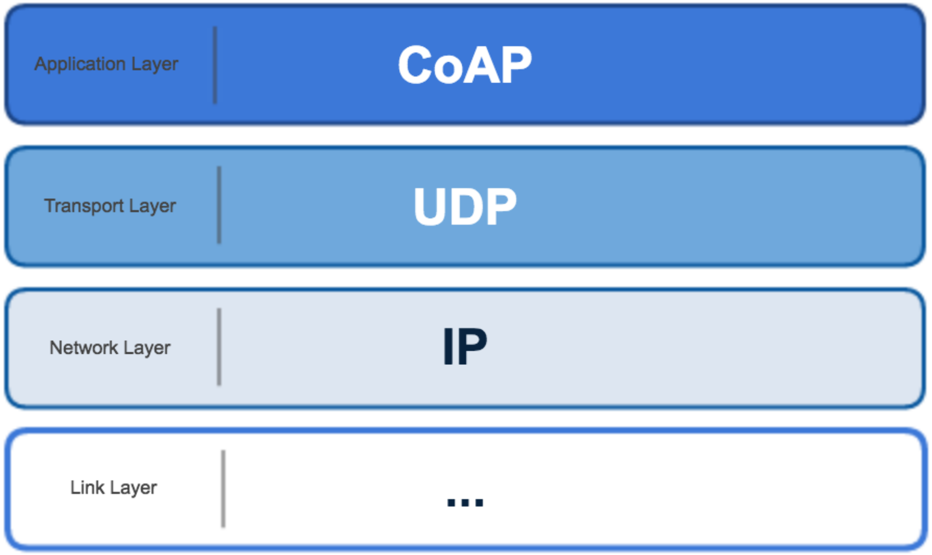
```
{course
    {id: CS2650}
    {name: Distributed Multimedia Software}
}
```

CoAP

- Constrained Application Protocol
  - REST-based web transfer protocol
  - manipulates Web resources using the same methods as HTTP: GET, PUT, POST, and DELETE
  - subset of HTTP functionality re-designed for low power embedded devices such as sensors (for IoT and M2M)

CoAP

- TCP overhead is too high and its flow control is not appropriate for short-lived transactions
- UDP has lower overhead and supports multicast



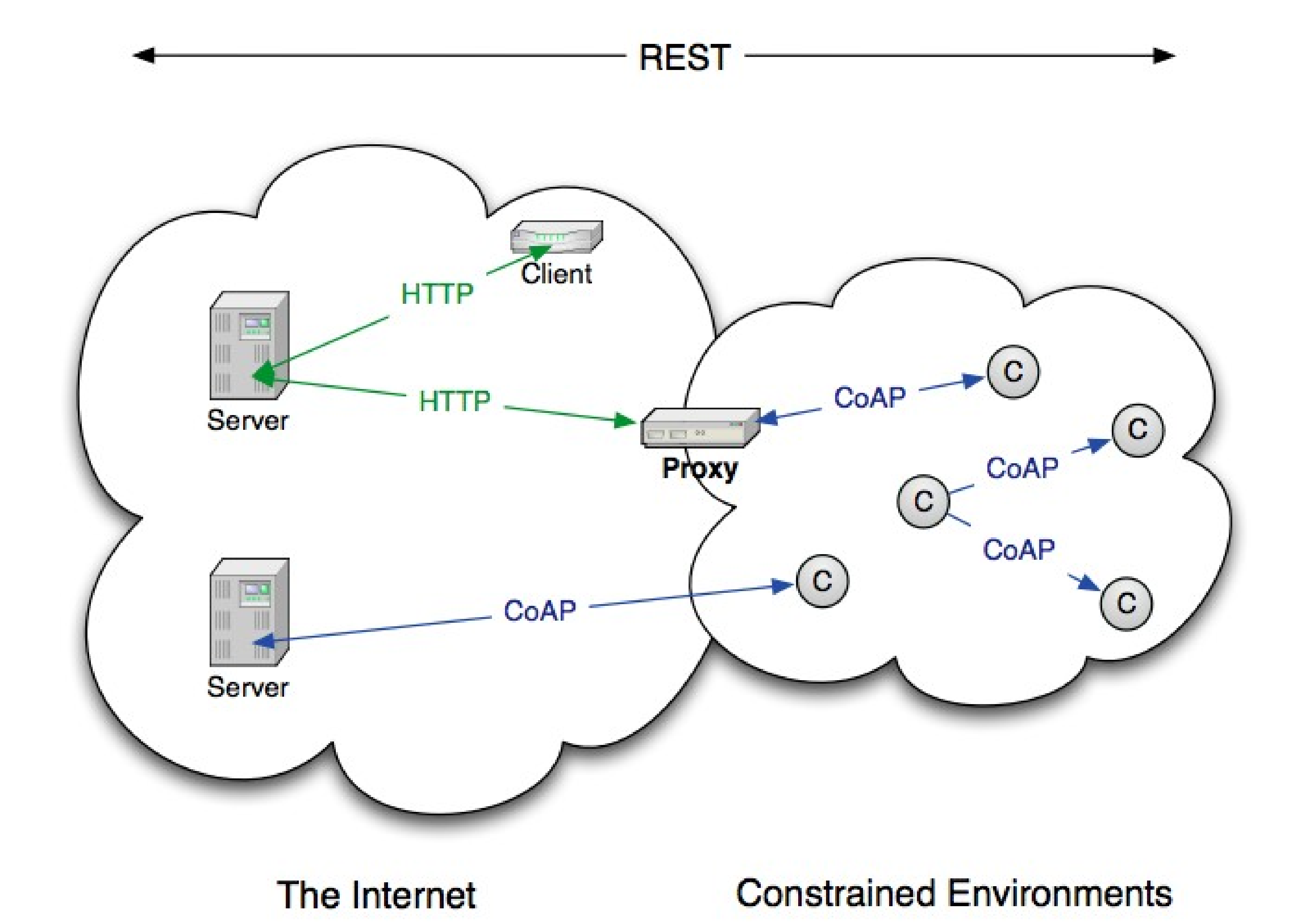
CoAP

- Four message types:
  - **Confirmable** – requires an ACK
  - **Non-confirmable** – no ACK needed
  - **Acknowledgement** – ACKs a Confirmable
  - **Reset** - indicates a Confirmable message has been received but context is missing for processing

CoAP

- CoAP provides reliability without using TCP as transport protocol
- CoAP enables asynchronous communication
  - e.g., when CoAP server receives a request which it cannot handle immediately, it first ACKs the reception of the message and sends back the response in an off-line fashion
- Also supports multicast and congestion control

CoAP


REST
HTTP
Client
Server
HTTP
Proxy
CoAP
C
CoAP
C
C
CoAP
C
Server
CoAP
C
The Internet
Constrained Environments

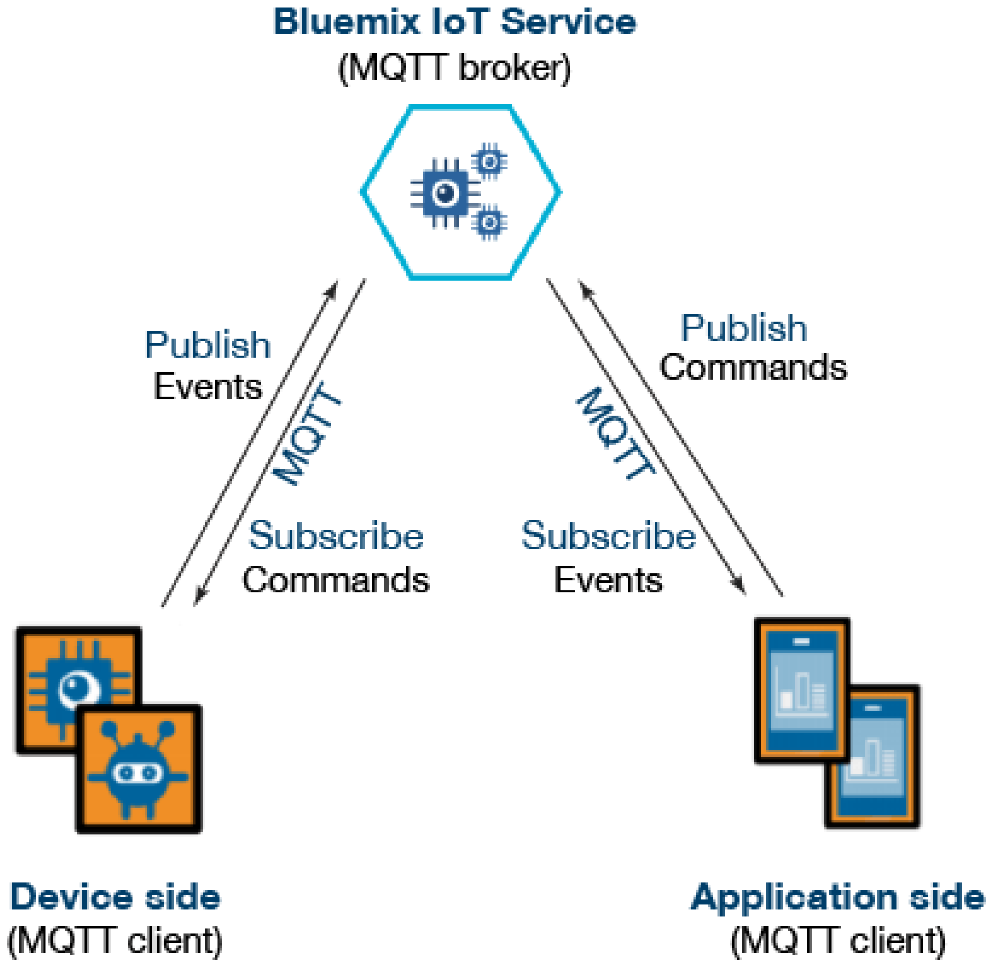
What CoAP Is

- CoAP is
  - A RESTful protocol
  - Both synchronous and asynchronous
  - For constrained devices and networks
  - Specialized for M2M applications
  - Easy to proxy to/from HTTP

MQTT

- Message Queuing Telemetry Transport
- In a nutshell, MQTT consist of three parts:
  - Broker
  - Subscribers
  - Publishers

MQTT


Bluemix IoT Service
(MQTT broker)
Publish
Events
MQTT
Subscribe
Commands
Publish
Commands
MQTT
Subscribe
Events
Device side
(MQTT client)
Application side
(MQTT client)

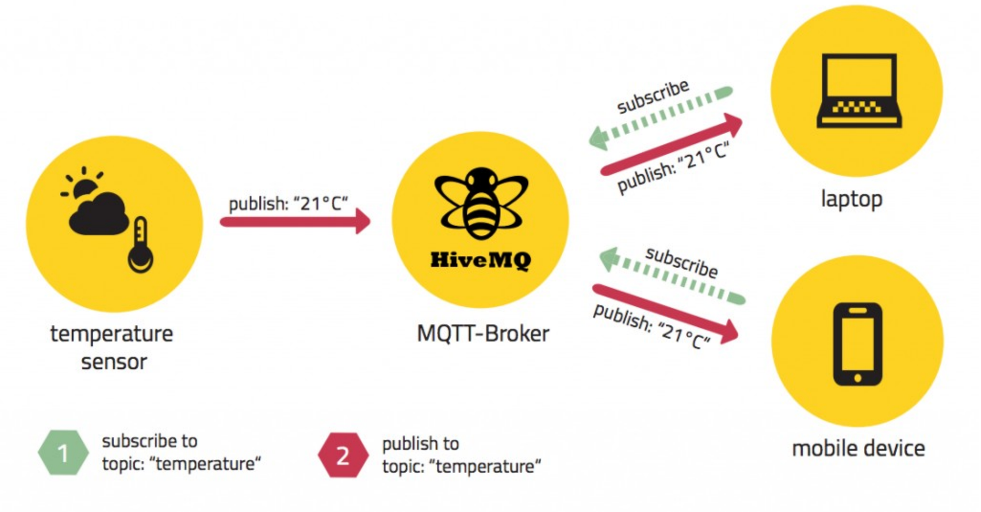
MQTT

- MQTT was invented by Andy Stanford-Clark (IBM) and Arlen Nipper (Arcom, now Cirrus Link) back in 1999, where their use case was to create a protocol for minimal battery loss and minimal bandwidth connecting oil pipelines over satellite connections. They specified the following goals, which the future protocol should have:
  - Simple to implement
  - Provide a Quality of Service Data Delivery
  - Lightweight and Bandwidth Efficient
  - Data Agnostic
  - Continuous Session Awareness

MQTT

- Built for proprietary embedded systems; now shifting to IoT
- You can send anything as a message; up to 256 MB
- Built for unreliable networks
- Enterprise scale implementations down to hobby projects
- Decouples readers and writers
- Message have a topic, quality of service, and retain status associated with them

Publish/Subscribe Concept



Decoupled in space and time: The clients do not need each others IP address and port (space) and they do not need to be running at the same time (time).

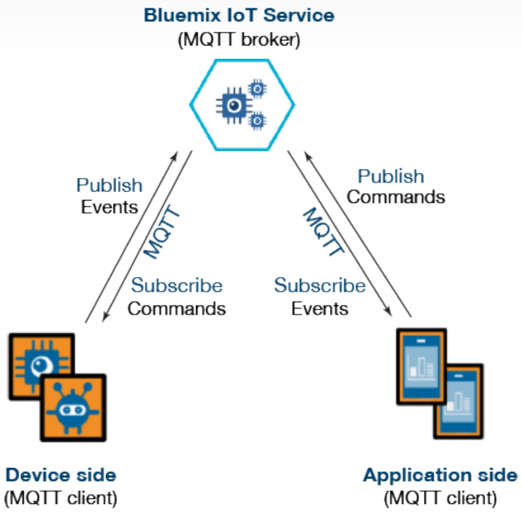
The broker's IP and port must be known by clients

Namespace hierarchy used for topic filtering

It may be the case that a published message is never consumed by any subscriber

MQTT: Example

- Clients connect to a “Broker”
- Clients subscribe to topics e.g.,
  - client.subscribe(‘toggleLight/1’)
  - client.subscribe(‘toggleLight/2’)
  - client.subscribe(‘toggleLight/3’)
- Clients can publish messages to topics:
  - client.publish(‘toggleLight/1’, ‘toggle’);
  - client.publish(‘toggleLight/2’, ‘toggle’);
- All clients receive all messages published to topics they subscribe to
- **Messages can be anything**
  - Text
  - Images
  - etc.

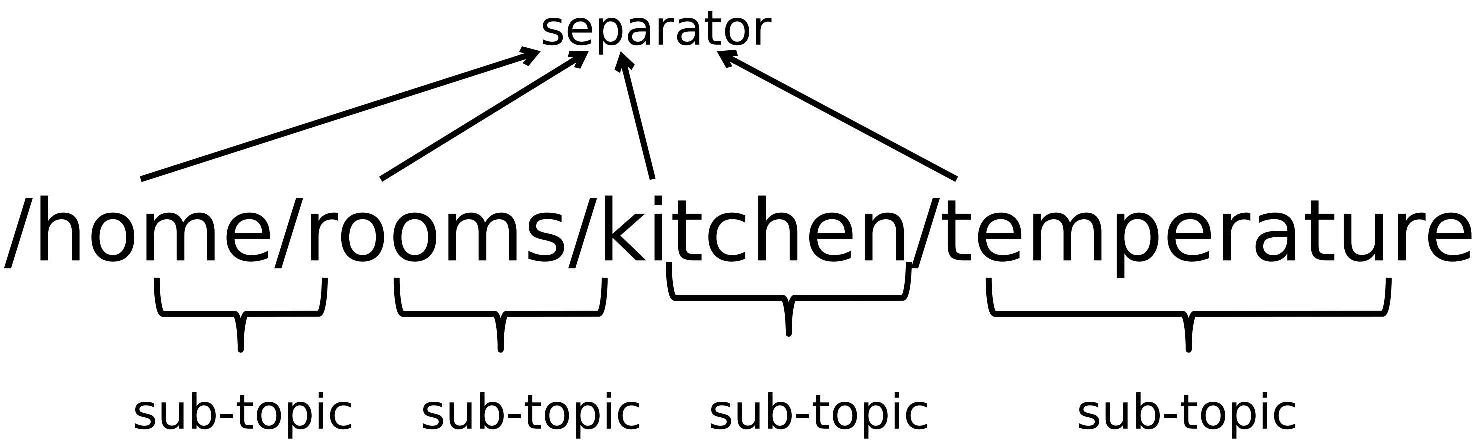


Node.js Example

```
var mqtt = require('mqtt');
var client = mqtt.createClient('<<PortNumber>>', 'm11.cloudmqtt.com', {
    username: '<<UserName>>’,
    password: '<<Password>>'
});
client.on('connect', function () { // When connected
    // subscribe to a topic
    client.subscribe('TEMPERATURE_READING', function () {
        // when a message arrives, do something with it
        client.on('message', function (topic, message, packet) {
            console.log("Received '" + message + "' on '" + topic + "'");
        });
    });
    // publish a message to a topic
    client.publish('SET_TEMPERATURE', '24', function () {
        console.log("Message is published");
    });
});
```

Topics

- Each published data specifies a topic
- Each subscriber subscribed to that topic will receive it
- Topic format:



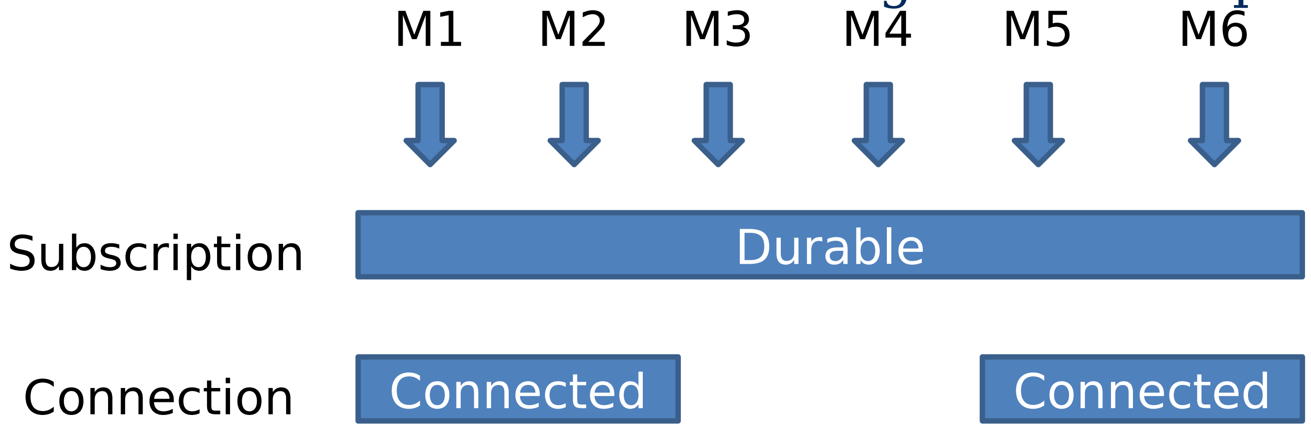
separator

/home/rooms/kitchen/temperature

sub-topic sub-topic sub-topic sub-topic

Durable/Transient Subscriptions

- Subscriptions
  - Durable
    - If the subscriber disconnect messages are buffered at the broker and delivered upon reconnection
  - Non-durable
    - Connection lifetime gives subscription lifetime



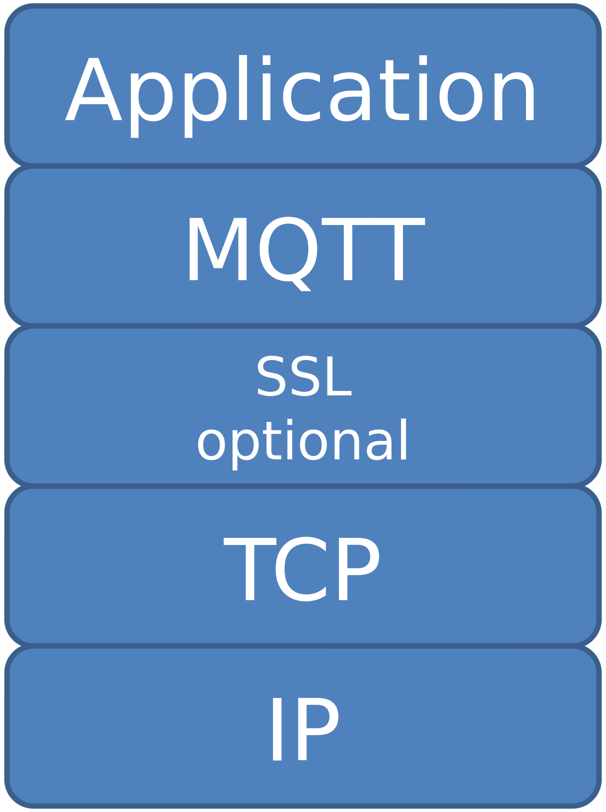
State Retention

- Publications
  - Retained (“persistent” message)
    - The subscriber upon first connection receives the last good publication (i.e., does not have to wait for new publication)
  - One flag set both in the publish packet to the broker and in the published packet to the subscribers
    - Only the most recent persistent message is stored and distributed

Session Aware

- Last Will and Testament (LWT) – topic published upon disconnecting a connection
- Any client can register a LWT
- Anybody subscribing to the LWT topic will know when a certain device (that registered a LWT) disconnected

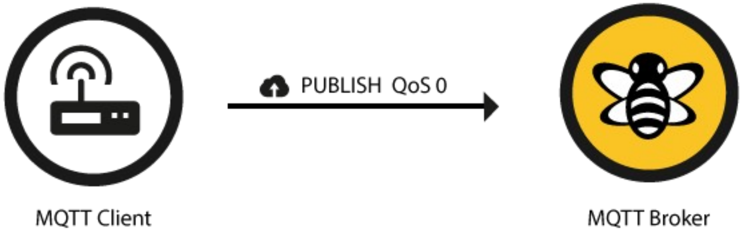
Protocol Stack



TCP/IP Port: 1883
When running over SSL, TCP/IP port 8883
SSL: Secure Socket Layer (encryption)

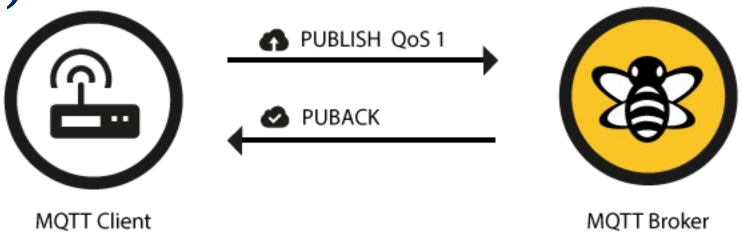
Publishing “QoS” (Reliability)

- 0 – unreliable (aka “at most once”)
  - OK for continuous streams, least overhead (1 message)
  - “Fire and forget”
  - TCP will still provide reliability



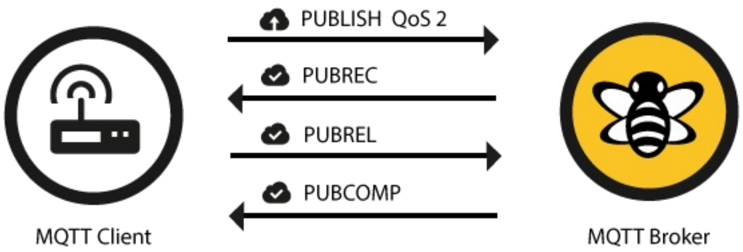
Publishing “QoS” (Reliability)

- 1 – delivery “at least once” (duplicates possible)
  - – Used for alarms – more overhead (2 messages)
  - – Contains message ID (to match with ACKed message)



Publishing “QoS” (Reliability)

- 2 – delivery “exactly once”
  - Utmost reliability is important – most overhead (4 messages) and slowest

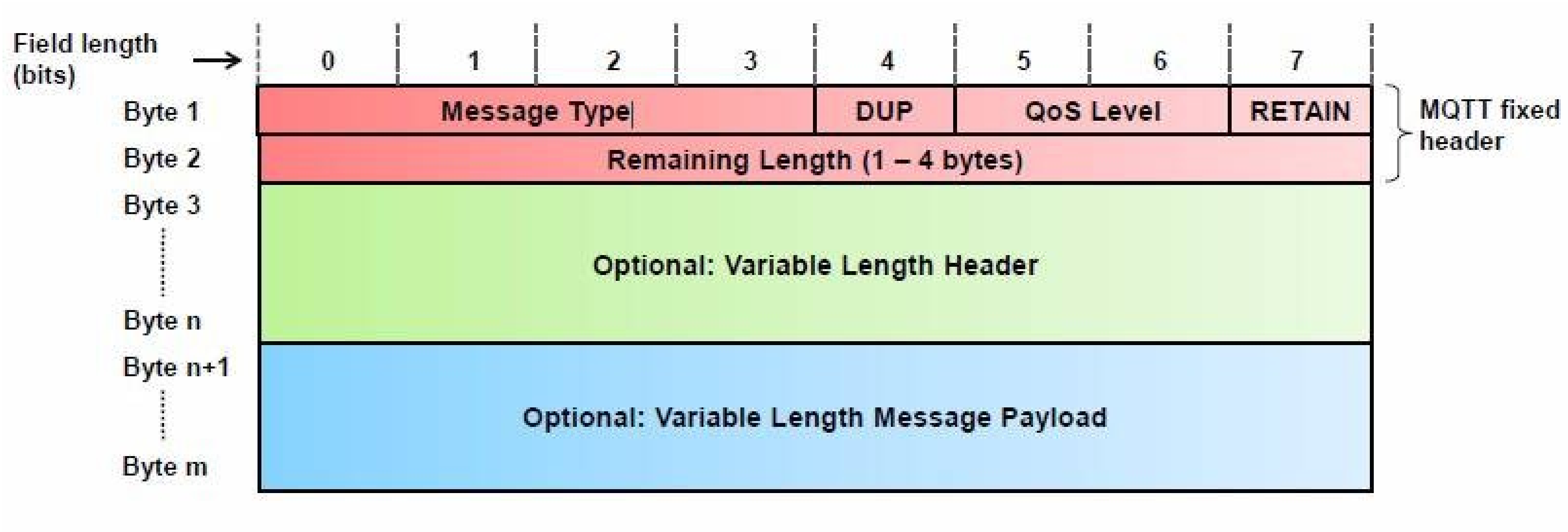


Publishing “QoS” (Reliability)

- Reliability maintained even if the TCP connection breaks (intermittent connections)
- Separate QoS for publishing and for subscribing

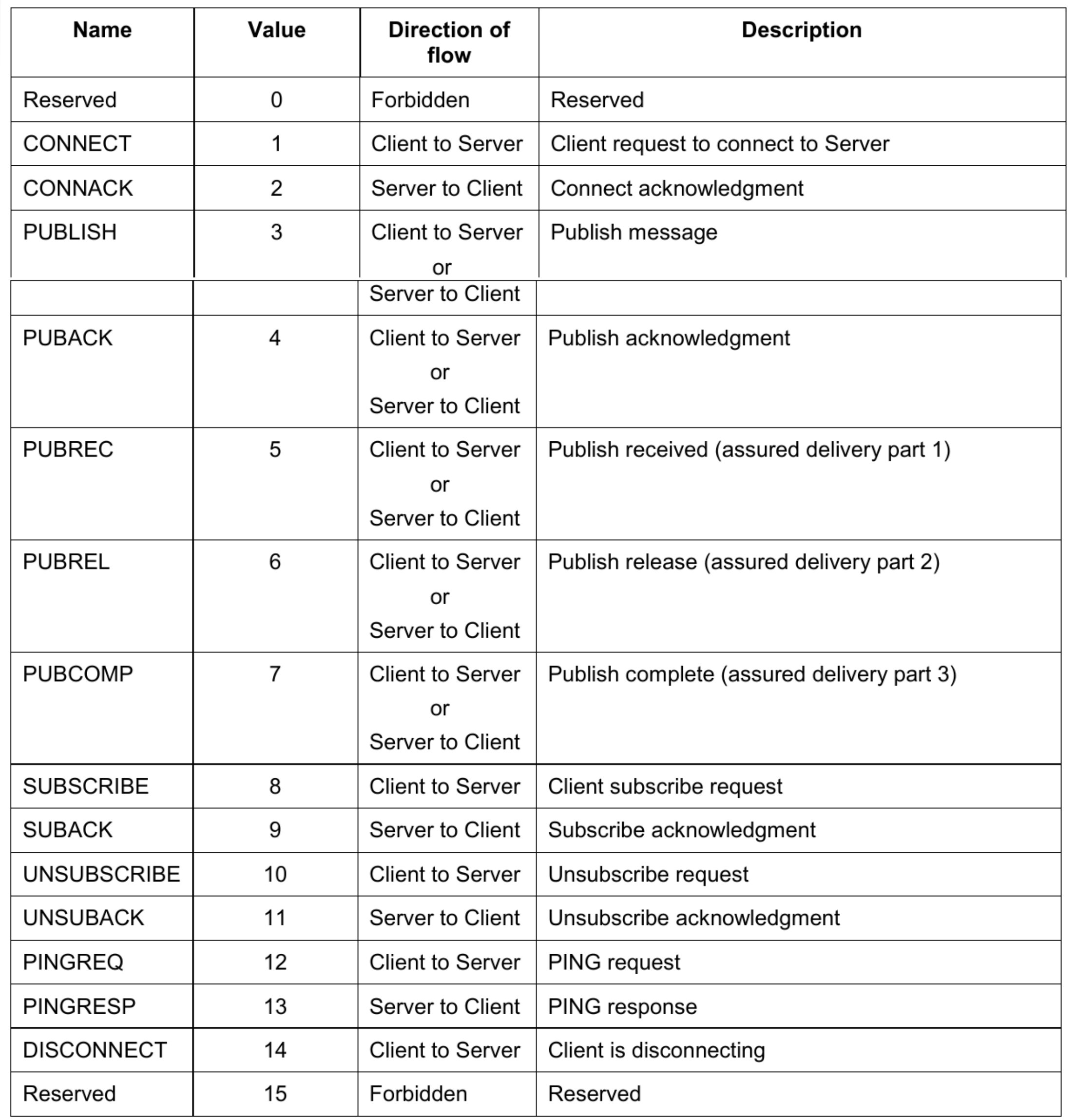
MQTT Message Format

Shortest Message is Two Bytes



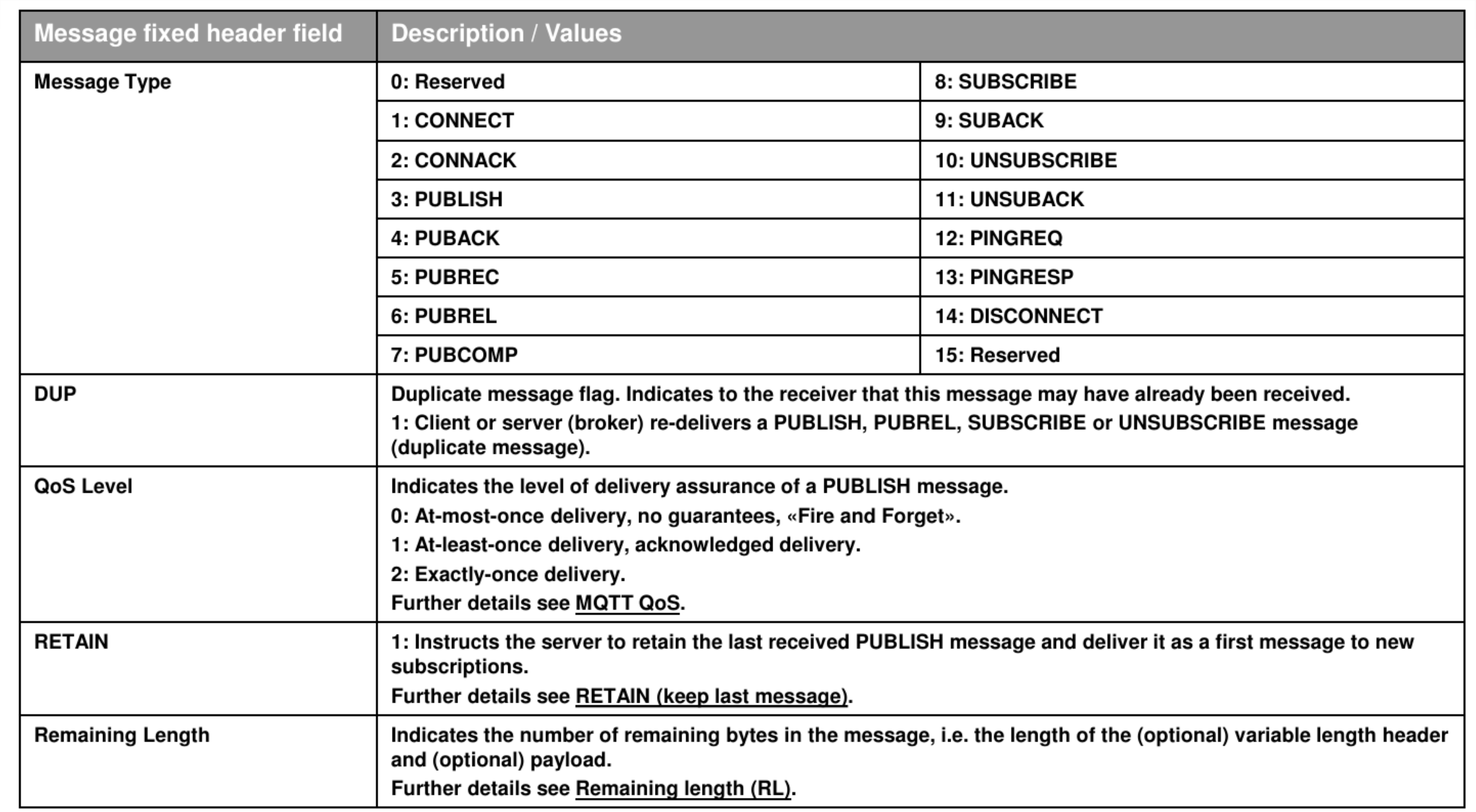
Field length (bits) →	0	1	2	3	4	5	6	7	
Byte 1	Message Type				DUP	QoS Level		RETAIN	MQTT fixed header
Byte 2	Remaining Length (1 – 4 bytes)								
Byte 3 … Byte n	Optional: Variable Length Header								
Byte n+1 … Byte m	Optional: Variable Length Message Payload								

Message Types



Name	Value	Direction of flow	Description
Reserved	0	Forbidden	Reserved
CONNECT	1	Client to Server	Client request to connect to Server
CONNACK	2	Server to Client	Connect acknowledgment
PUBLISH	3	Client to Server or Server to Client	Publish message
PUBACK	4	Client to Server or Server to Client	Publish acknowledgment
PUBREC	5	Client to Server or Server to Client	Publish received (assured delivery part 1)
PUBREL	6	Client to Server or Server to Client	Publish release (assured delivery part 2)
PUBCOMP	7	Client to Server or Server to Client	Publish complete (assured delivery part 3)
SUBSCRIBE	8	Client to Server	Client subscribe request
SUBACK	9	Server to Client	Subscribe acknowledgment
UNSUBSCRIBE	10	Client to Server	Unsubscribe request
UNSUBACK	11	Server to Client	Unsubscribe acknowledgment
PINGREQ	12	Client to Server	PING request
PINGRESP	13	Server to Client	PING response
DISCONNECT	14	Client to Server	Client is disconnecting
Reserved	15	Forbidden	Reserved

Message Types



Message fixed header field	Description / Values	
Message Type	0: Reserved	8: SUBSCRIBE
	1: CONNECT	9: SUBACK
	2: CONNACK	10: UNSUBSCRIBE
	3: PUBLISH	11: UNSUBACK
	4: PUBACK	12: PINGREQ
	5: PUBREC	13: PINGRESP
	6: PUBREL	14: DISCONNECT
	7: PUBCOMP	15: Reserved
DUP	Duplicate message flag. Indicates to the receiver that this message may have already been received. 1: Client or server (broker) re-delivers a PUBLISH, PUBREL, SUBSCRIBE or UNSUBSCRIBE message (duplicate message).	
QoS Level	Indicates the level of delivery assurance of a PUBLISH message. 0: At-most-once delivery, no guarantees, «Fire and Forget». 1: At-least-once delivery, acknowledged delivery. 2: Exactly-once delivery. Further details see MQTT QoS.	
RETAIN	1: Instructs the server to retain the last received PUBLISH message and deliver it as a first message to new subscriptions. Further details see RETAIN (keep last message).	
Remaining Length	Indicates the number of remaining bytes in the message, i.e. the length of the (optional) variable length header and (optional) payload. Further details see Remaining length (RL).	

Comparison CoAP & MQTT

Both used in IoT

- CoAP:
  - one-to-one communication
  - UDP/IP
  - unreliable
  - lightweight and easy to implement
- MQTT:
  - many-to-many communication
  - TCP/IP
  - focus on message delivery; reliable
  - higher overheads (protocol data, processing costs)