Internet of Things

1. Introduction

M.Sc. Computer Science 2024-2025

Viviana Arrigoni

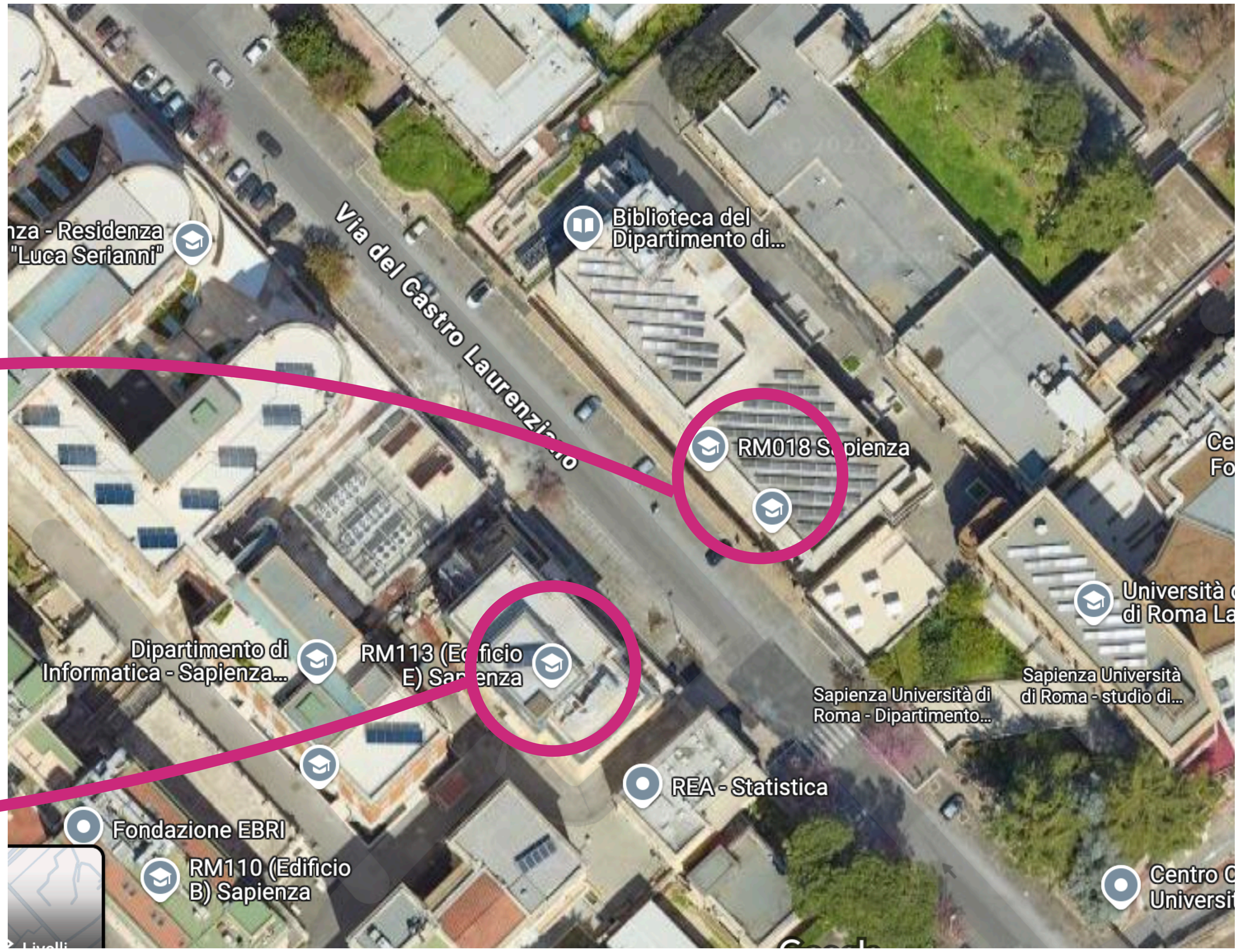
1.1 Useful information

CLASS SCHEDULE

- Monday 5pm-7pm
- Tuesday 10am-1pm
- Room 1L Castro Laurenziano

MY ROOM

- Viale Regina Elena 295
  Building E
  Room 210, second floor



Exam

- Written exam
- Presentation/Project (more details soon)

Summary

- Introduction to IoT
- IoT devices
- Basics of Information Theory
- Radio Frequency Communication
- Communication in IoT
- IoT protocols
- Mobile Networks
- Security in IoT
- Driver technologies

Google Classroom

- Go to https://classroom.google.com using your @studenti.uniroma1.it account.
- Click on the “+” sign in the top right corner
- Insert the code **oxtioba**
- I will share slides and possible notices there
- My email: arrigoni@di.uniroma1.it

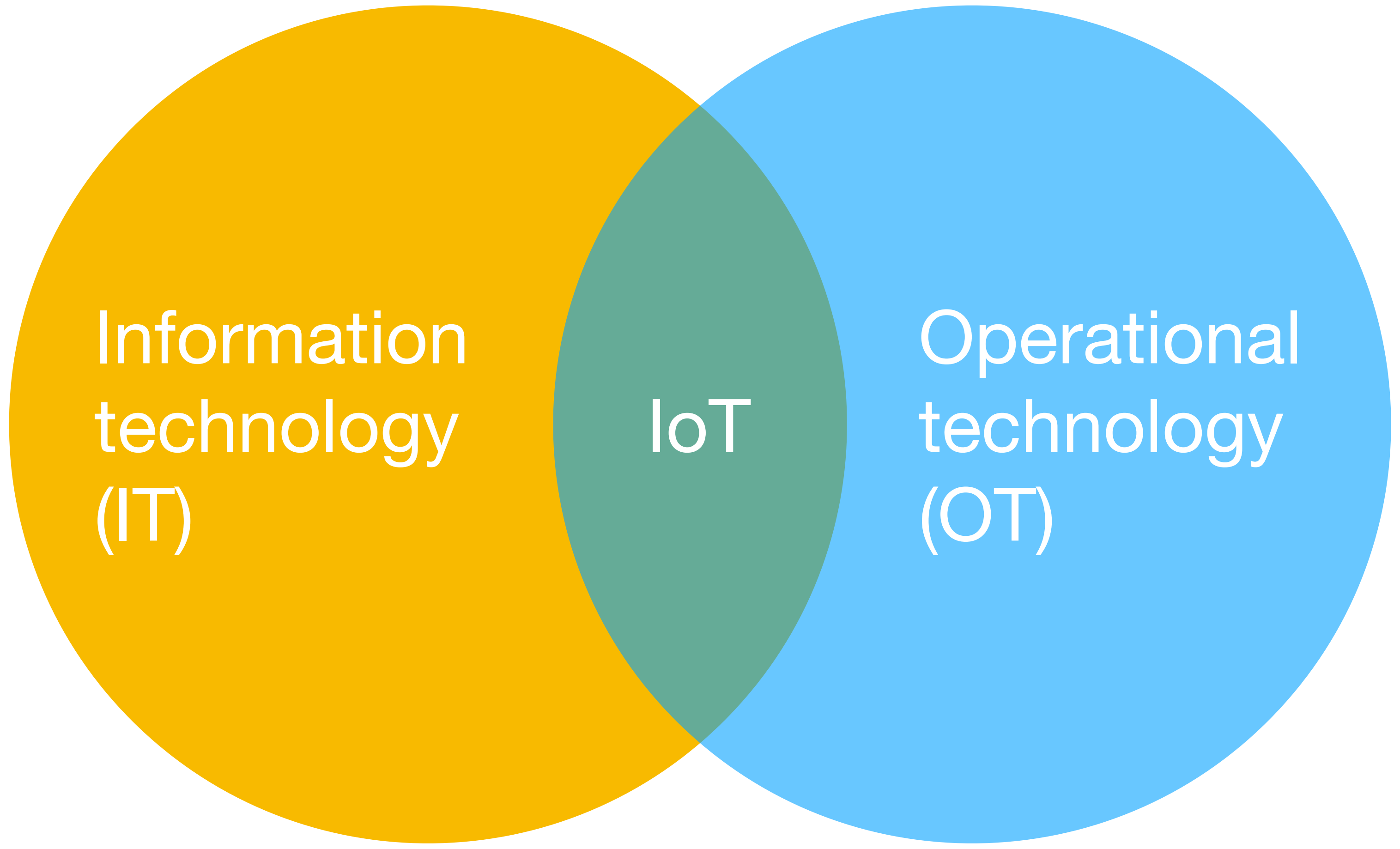
1.2 What is IoT?

- The term IoT was first coined in 1999 by Kevin Ashton in the context of supply chain management, and was redefined during the following years.

IoT = Sensors + Networks + Data + Services

- IoT can be treated as the extension of the contemporary internet services to enclose different objects, which can become part of the IoT when embedded with sensors, actuators, microcontrollers.

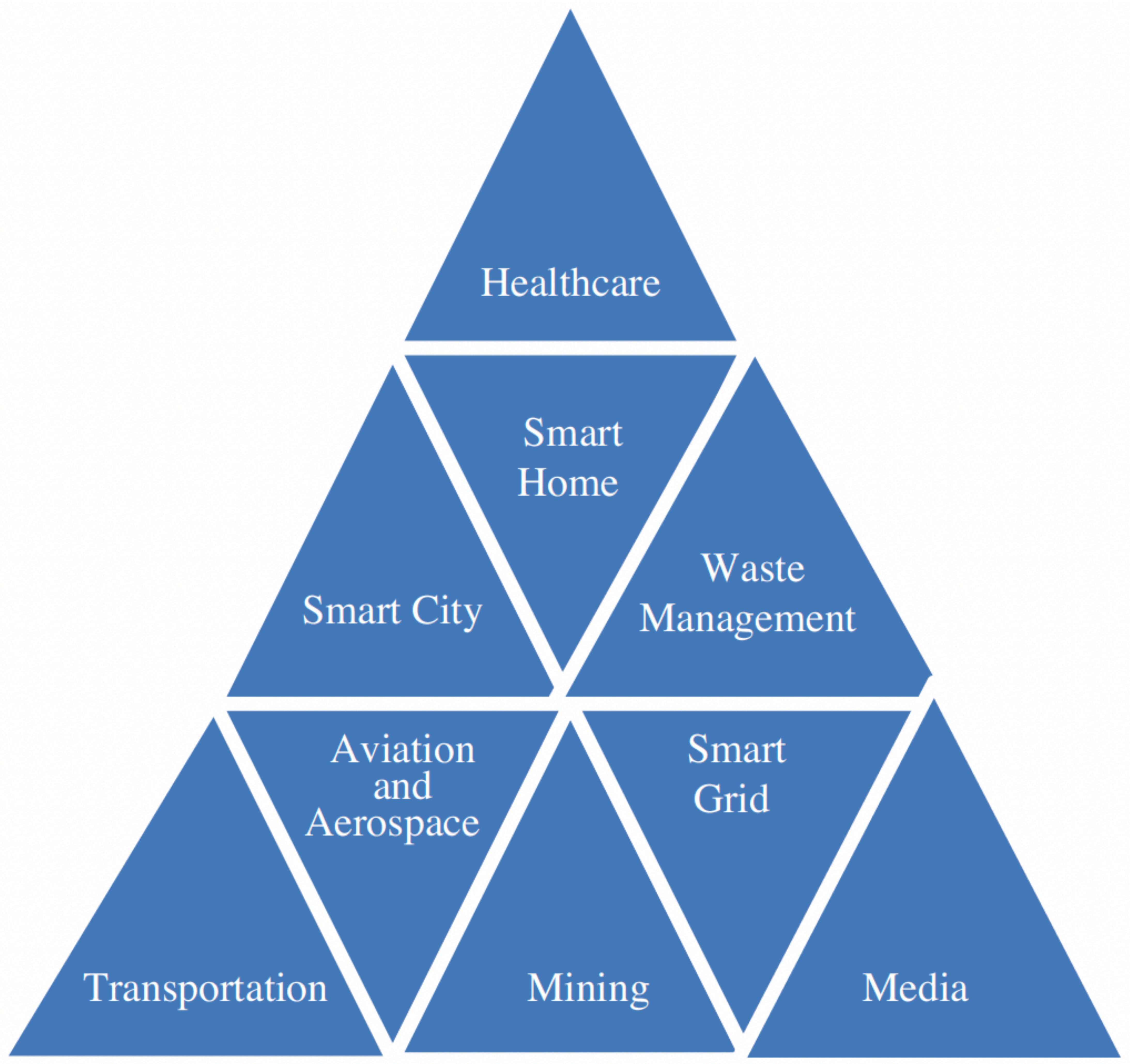
- IoT binds together the IT and OT domains.
  IT consists of the secure connectivity of servers, databases and applications.
  OT is concerned with the industrial work and combines things like sensors and devices connected to the machines or some other equipment. It supervises devices and processes on physical systems (e.g., Industries, roadways, production services etc).



- Internet of things allows all things to communicate with each other.

- The miniaturization and advancements in the field of electronics and computers has made the materialization of IoT in many fields.

- Together with Cloud Computing, IoT represents a pillar of ubiquitous computing.



Smart Objects

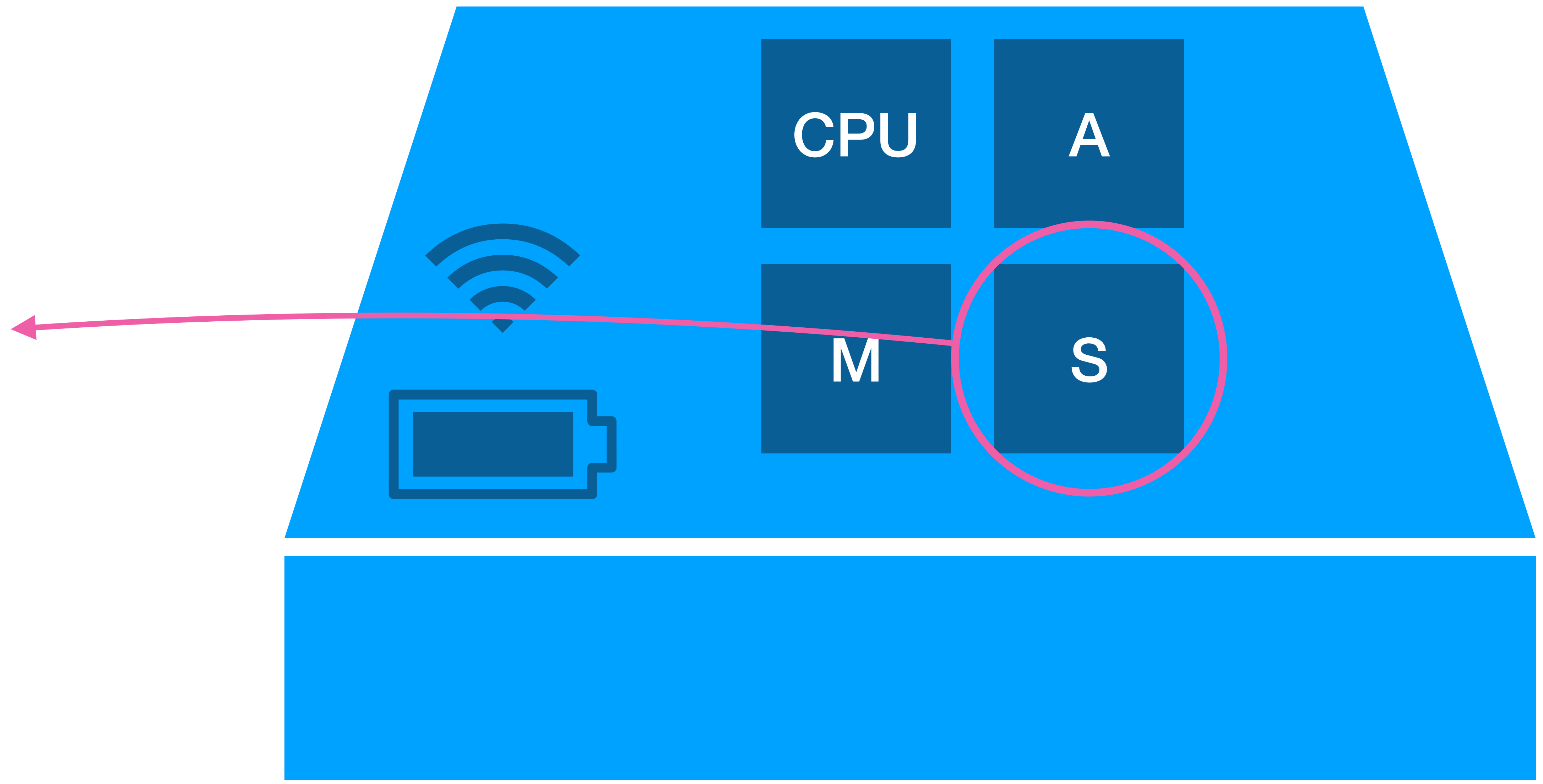
- Like human cells, smart objects represent the building blocks of an IoT system and must have the ability of
    - sensing
    - computing
    - communicating
- IoT revolution: transform an isolated ordinary object into interactive smart object
- Smart objects are made of several components…

Smart objects components: sensors

SENSORS:
Sensors embedded in the device allows the object to

- sensing
- measuring the changes in the environment
- convert the physical quantity into a digital representation

The physical quantity is passed onto some computational unit



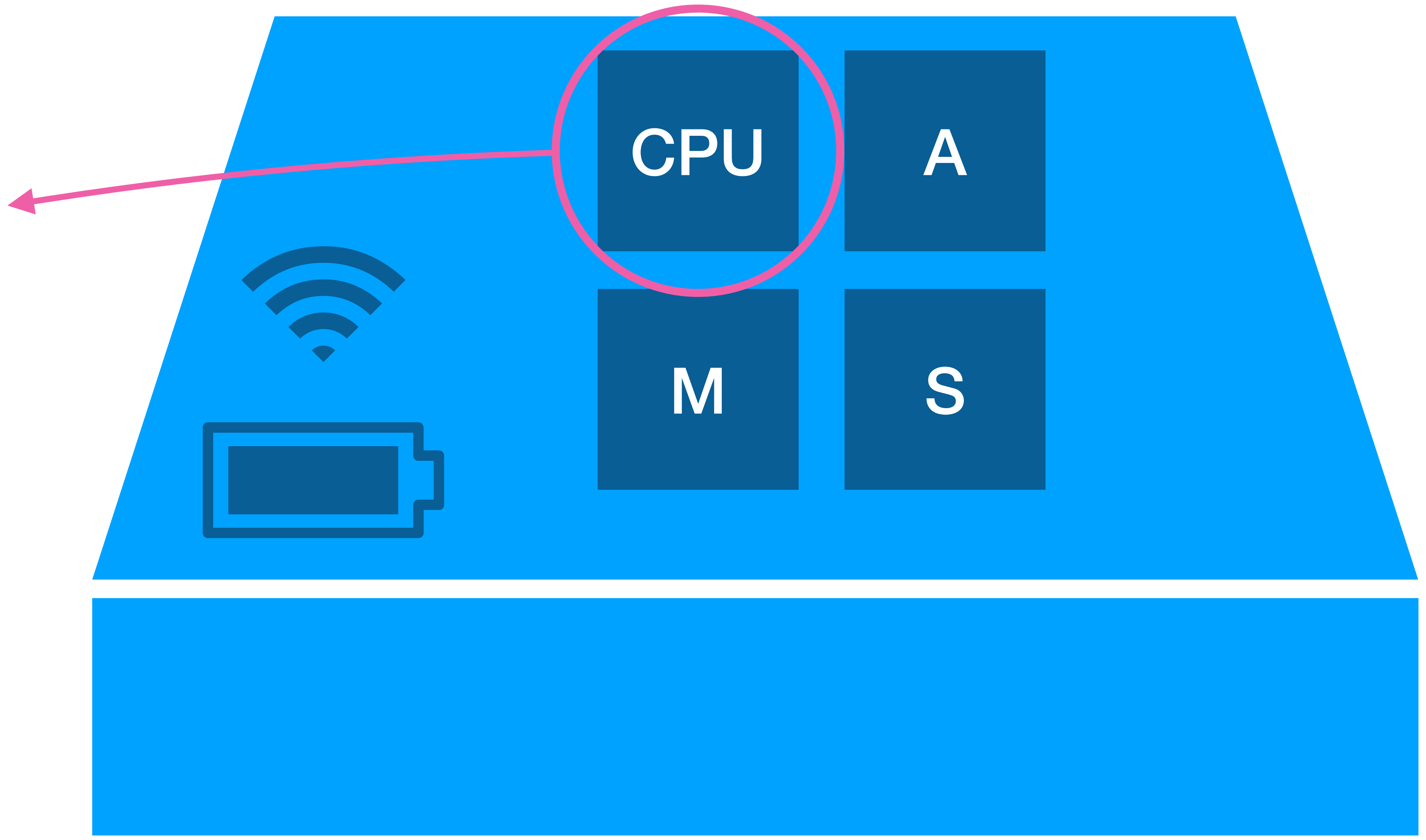
Smart Objects components: processing unit

PROCESSING UNIT:

- Gathers, processes and analyzes the data acquired from the sensors.
- The computations call for control signals that prompt the actuator according to the need.
- Controls communication and power system.

The type of processing unit varies according to the needs and kind of processing to be used by the applications.

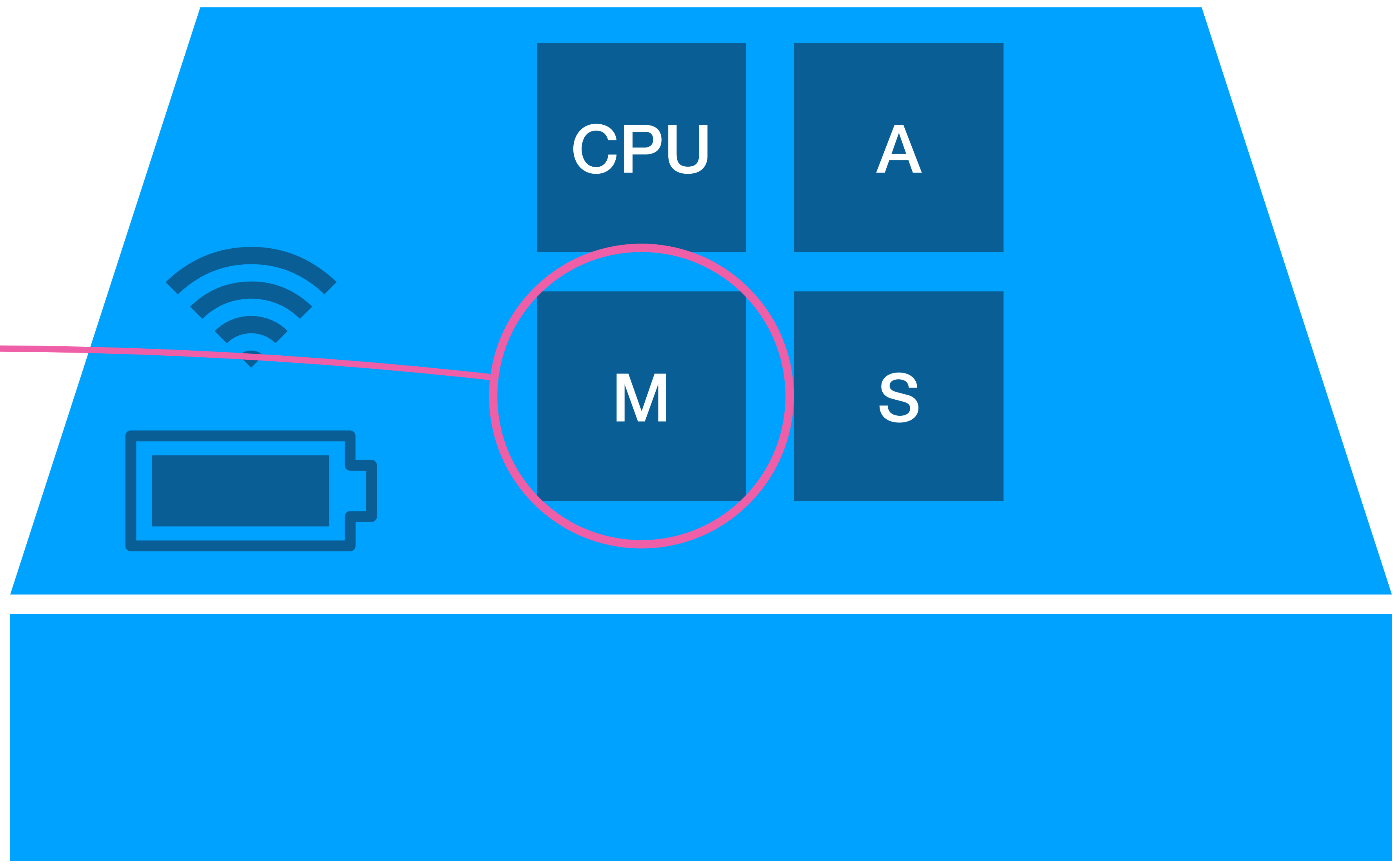
Microcontrollers are widely used technology in smart objects.



Smart Objects components: memory

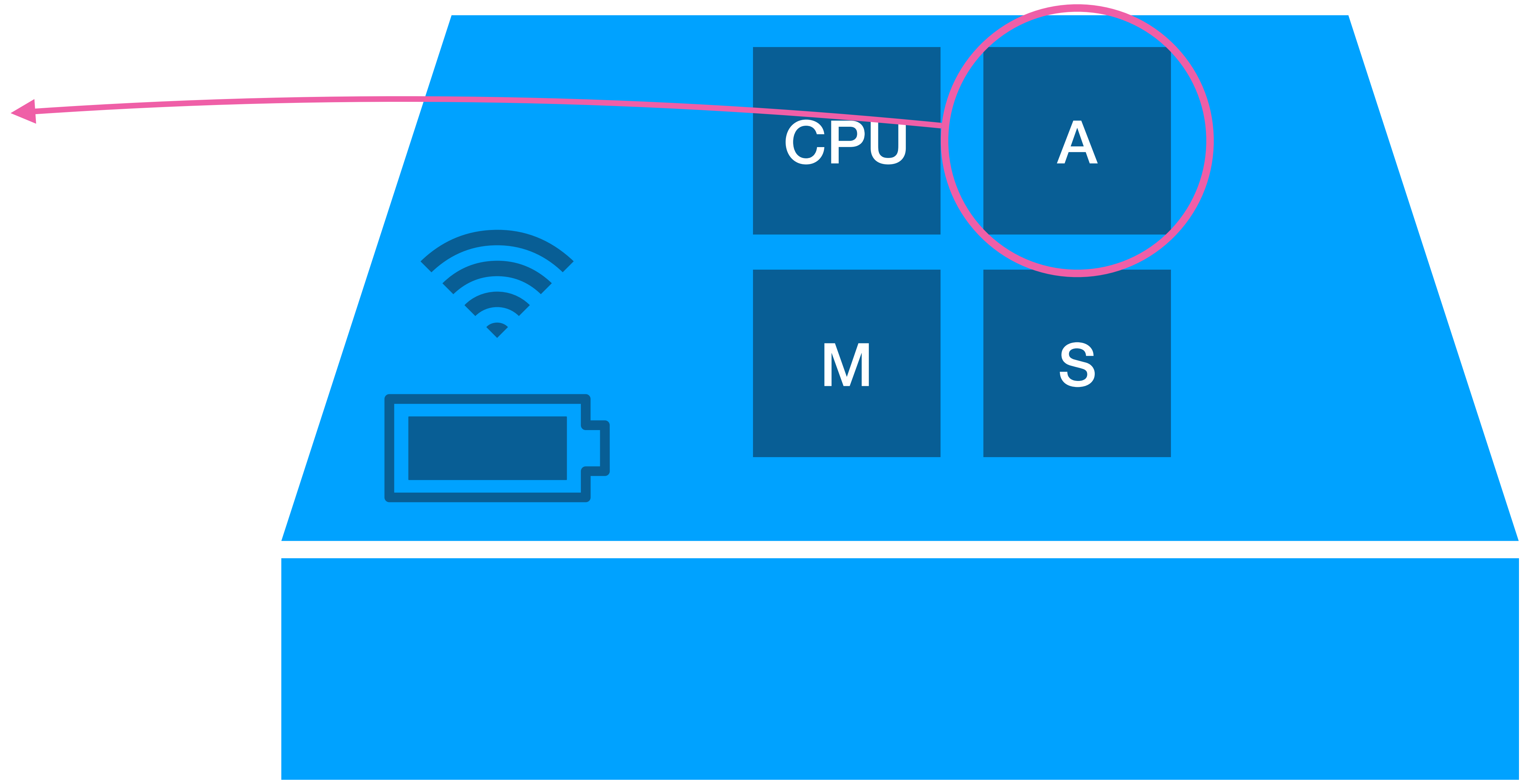
MEMORY:

- Stores key information such as the smart object identifier, physical properties.
- Allows the computation and communication abilities of the device.
- Can store sensed data.
- Varies from few KB to GB.



Smart objects components: actuators

ACTUATORS:
Data collected by the sensors is stored and processed and can in turn trigger the actuators. An actuator receives control signal and produces some response to the physical world



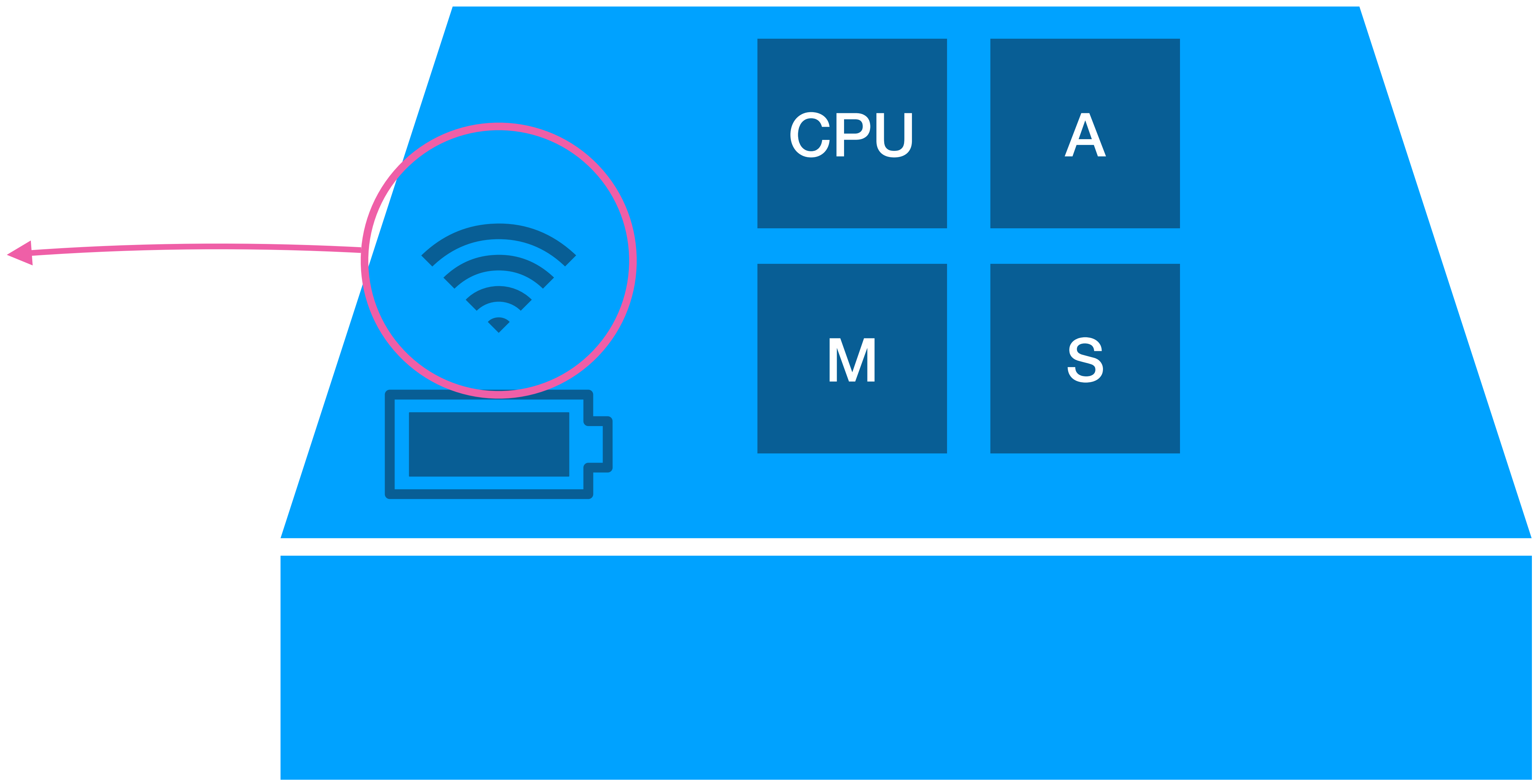
Simple example:

A sensor senses the level of moist in a field. If the level of moist is below a given threshold, we want to open up the water pump and irrigate our field. In this case, the actuator is triggered and turns the pump switch on and off accordingly.

Smart Objects components: communication unit

COMMUNICATION UNIT:

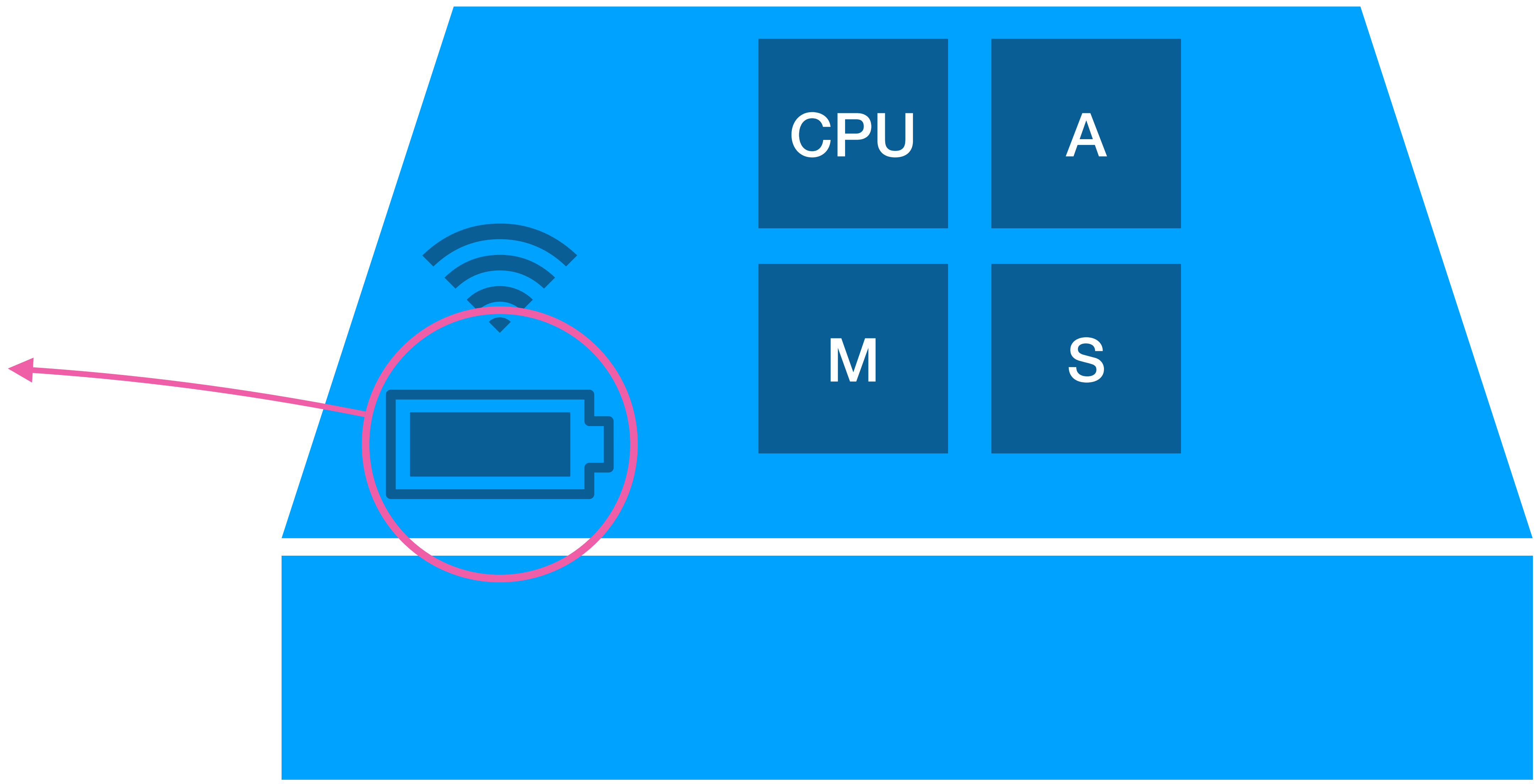
- Allows the smart objects to communicate with other devices for sharing information/data.
- Communication may take place between two or more smart objects or to the outside world through the network.
- The wireless connectivity is preferred more over the wired connectivity (cost, ease of deployment)



Smart Objects components: power source

POWER SOURCE:

- Power sources may be batteries, solar power, wind power, main supply.
- The requirements of power consumption vary greatly according to the scenarios (deployment area, switching between the active and sleep mode, accessibility, the power source being used, criticality of the information etc).



Smart Objects

Notice that not all smart objects are composed of all the components. A smart object could be just a sensor that continuously sends data to a different object equipped with a microprocessor and an actuator.

Desirable features of smart objects are:
- small size
- powerful processing unit
- low power consumption
- good communication capabilities.

1.3 Cool Applications

Smart cities

- A smart city is an urban area that uses digital technology to collect data and to operate/provide services

- Smart cities integrate information and communication technology, and IoT devices to optimize city services and connect to citizens.

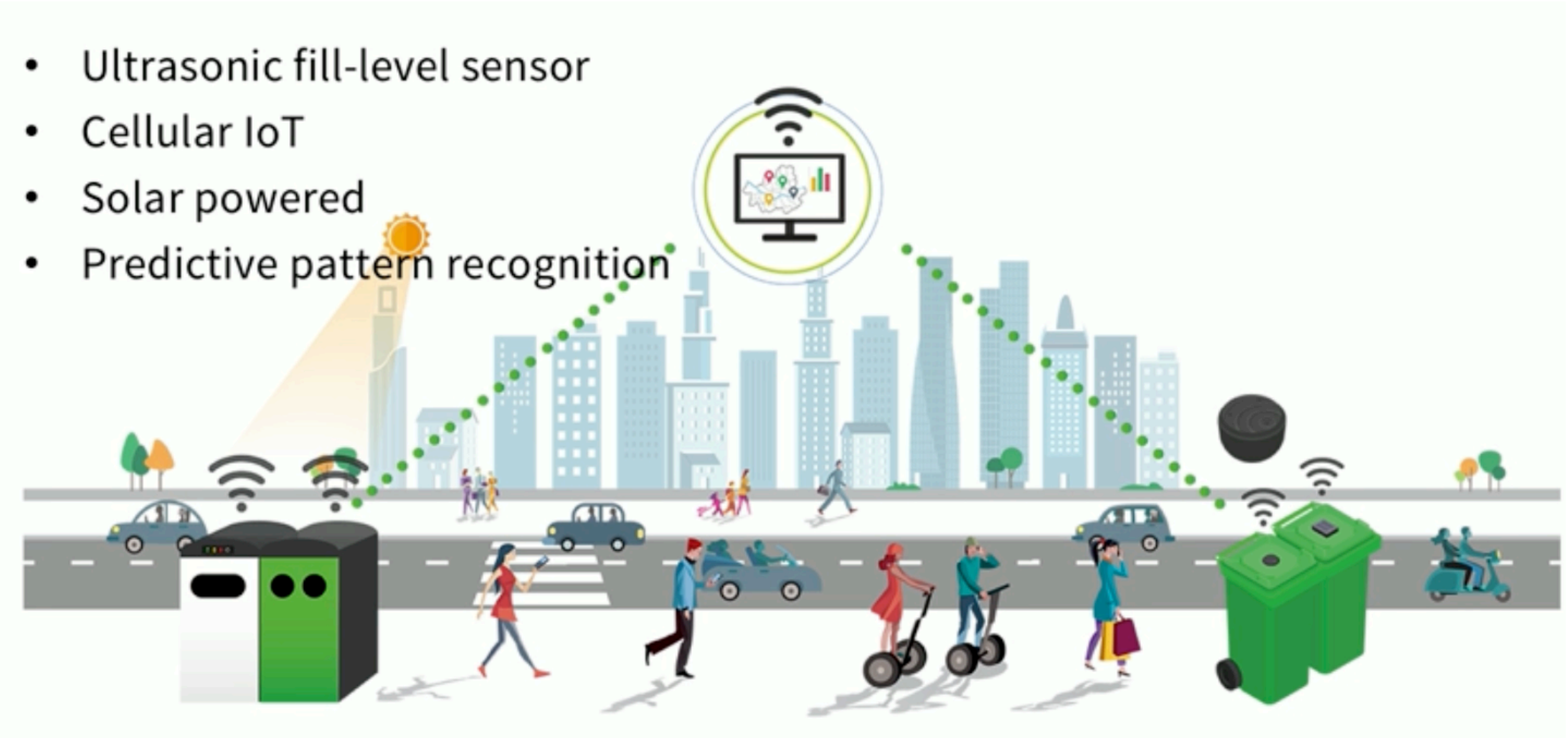
- Applications include traffic and transportation systems, power plants, utilities, urban forestry, water supply networks, waste disposal, criminal investigations, information systems, schools, libraries, hospitals, and other community services.

Smart Waste Management (1)

- Normal trash bins in Dublin airport were collected up to 4 times a day, whether the bins were full or not.

- Cost money, create disturbance to passengers, bad smell, overfull bins.

Smart Waste Management (2)



Smart Waste Management System

- Each trash can is equipped with wireless ultrasonic fill-level sensor (to detect when the trash can is full or even too smelly)
- Uses cellular based wireless technologies to connect to a control centre
- Can be solar powered
- The control center monitors real time trash can fill level and plans the trash collection schedule and the collection routes.

Smart Waste Management (3)

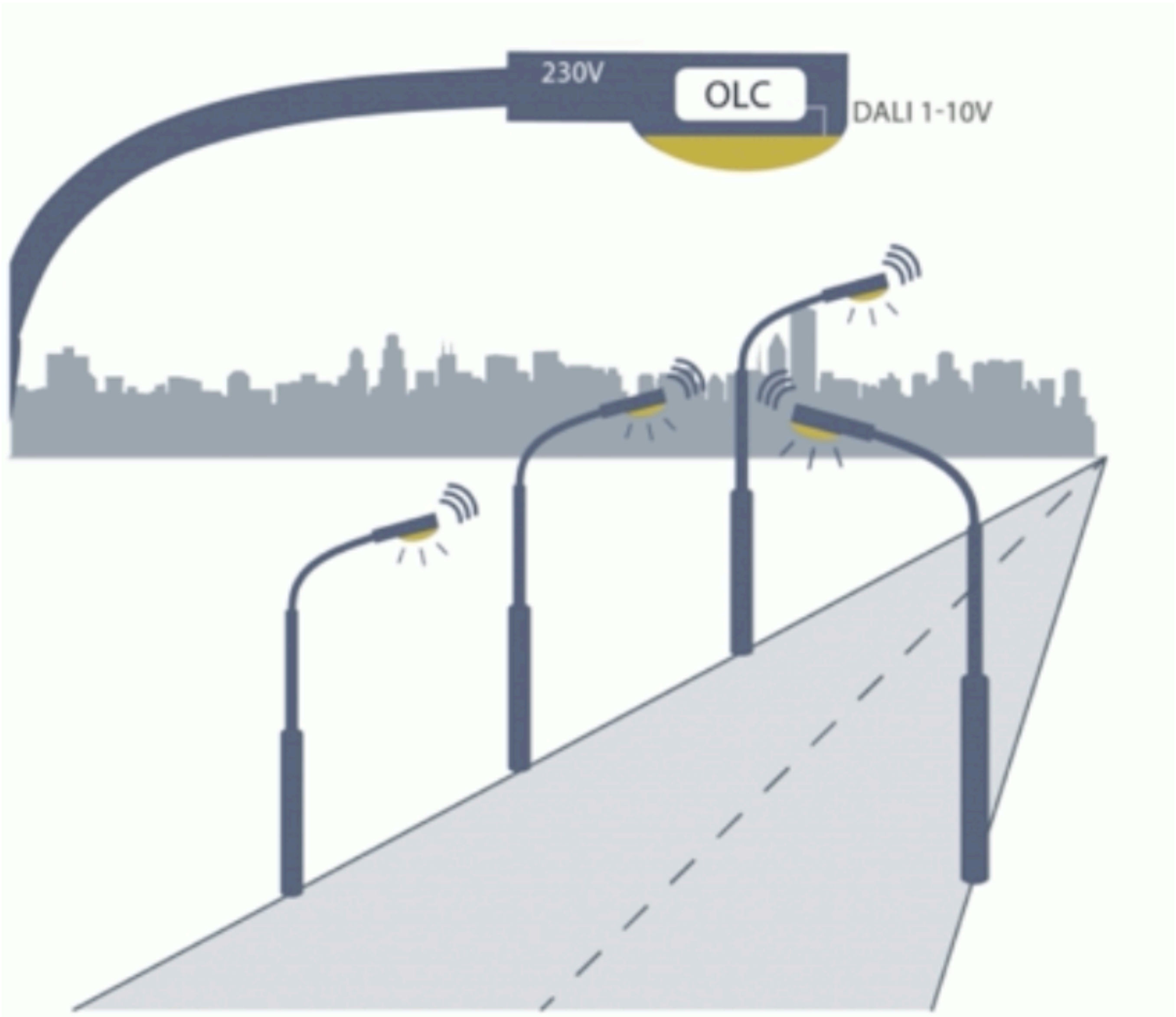
- Go from collecting 840 containers 4 times a day to collecting 80 containers a day
- Increase waste collection efficiency by 90%

Smart Street Lights

- In a smart street light system, street lights adjust their brightness when a car or a pedestrian is approaching
- Light intensity can be adjusted under different weather conditions

- Remote access to street lights
  - No need to employ people full time to drive around the city after dark looking for burnt out streetlights.

Smart Street Lighting System



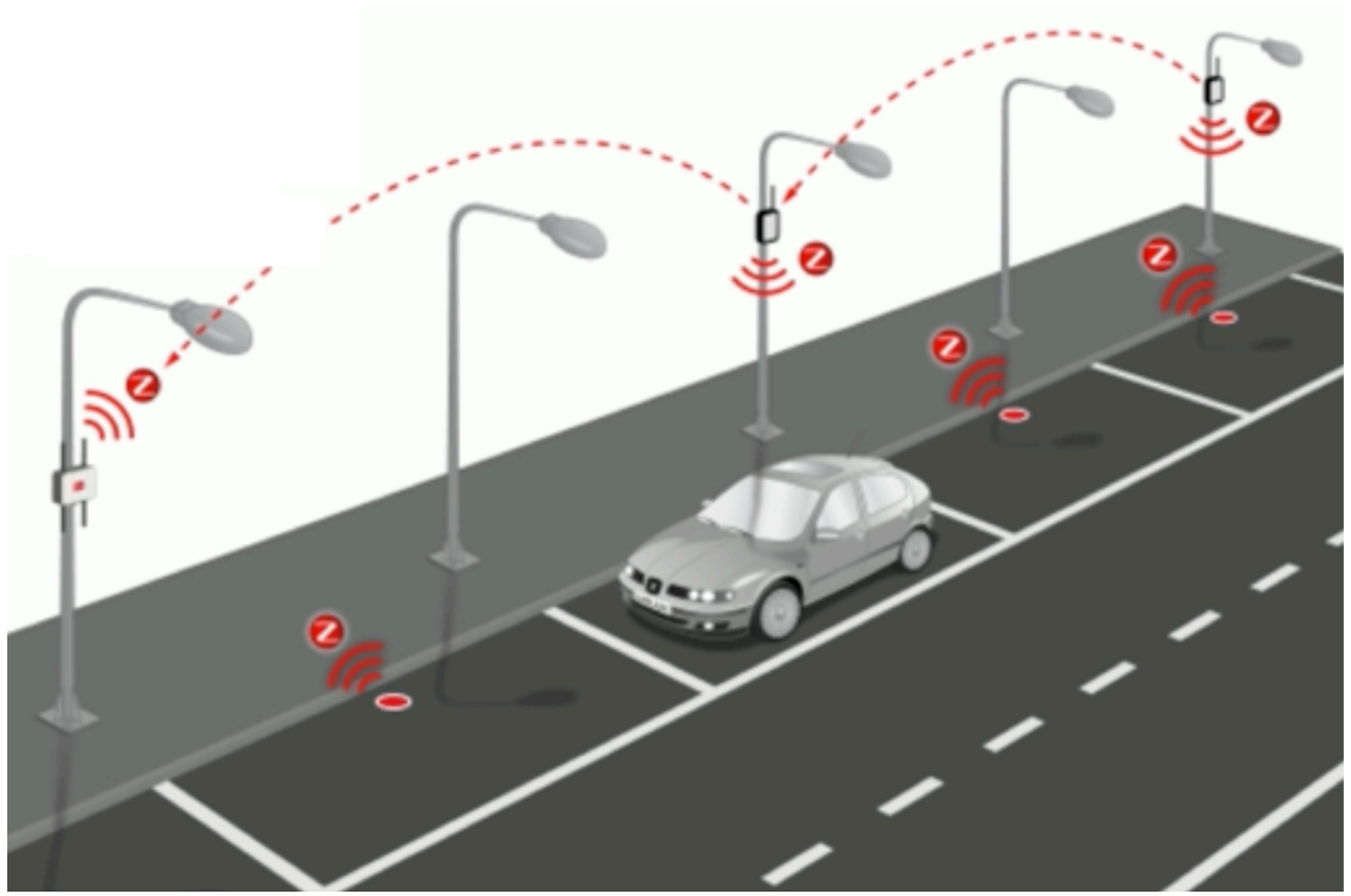
- A smart street lighting system incorporates a cluster of streetlights that can communicate with each other.
- Lights are equipped with lighting and motion sensors triggering some actuators (e.g., if motion is sensed, bright up the light).
- Sensed data is sent to local relay, that manages and transmits the relevant data often by a cellular-based modem to a secure server, that captures the data for further analysis.
- Data can be sent to a central controller and exploited for other smart city systems, e.g., Smart Parking, Traffic and Security Monitoring.

Smart Street Parking (1)

- More than 30% of a city's traffic is caused by drivers searching for a parking spot.
- In NYC, 29% of commuters said that they spent 20 minutes on average looking for a parking spot and 10% spent more than 40 minutes.
- +pollution, traffic congestion.

Smart Street Parking (2)

- Smart Street Parking System:
  - Infrared and magnetic based vehicle detection sensors mounted on the road surface
  - Some wireless protocol (e.g., ZigBee, LoRaWAN) used for connection
  - Mesh networks implemented within street lights, sending data to a central station
  - Apps to direct drivers to empty spaces
  - Dynamic parking prices



Smart Street Parking in Poland

Connected Vehicles

Autonomous vehicles

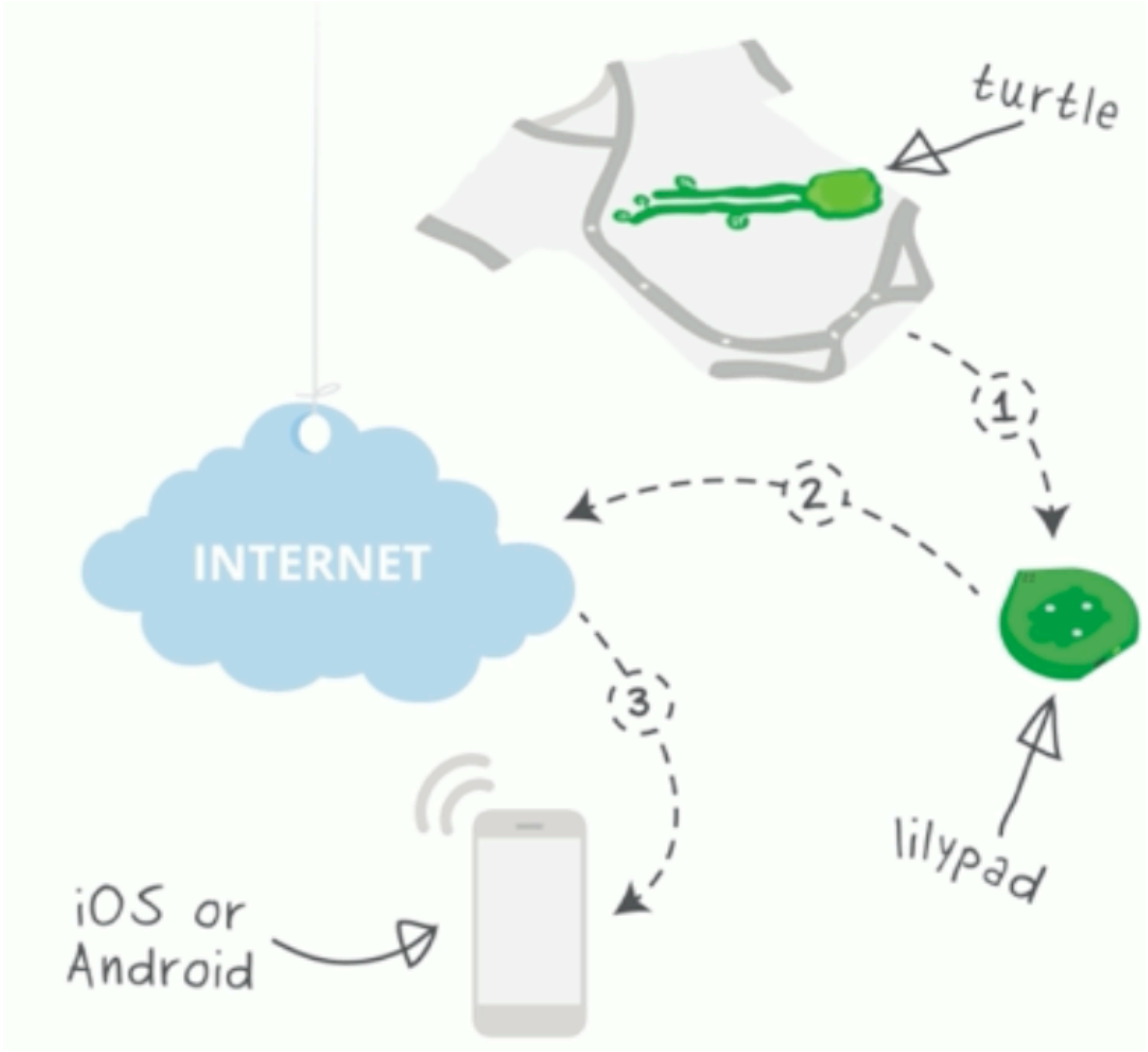
- Vehicles are equipped with many sensors to sense the surroundings
- Vehicles can share information with other vehicles and with the surroundings (V2X, vehicle-to-X communication, where X = other vehicles, infrastructures, roads, etc)
- Issues:
  - Sensor limitation and failures
  - Software bugs and AI errors
  - Infrastructure not compatible with the vehicle’s system
  - Ethical issues: interaction with human drivers and pedestrians

Wikipedia
The Free Encyclopedia

Smart city initiatives have been criticized as driven by corporations,[19][20] poorly adapted to residents' needs,[21][22] as largely unsuccessful,[*citation needed*] and as a move toward totalitarian surveillance.[23]

Healthcare - baby monitoring

- Activity tracking:
  - Body Position
  - Breathing
  - Oxygen level
  - Skin temp
  - Wake/sleep pattern
  - ECG

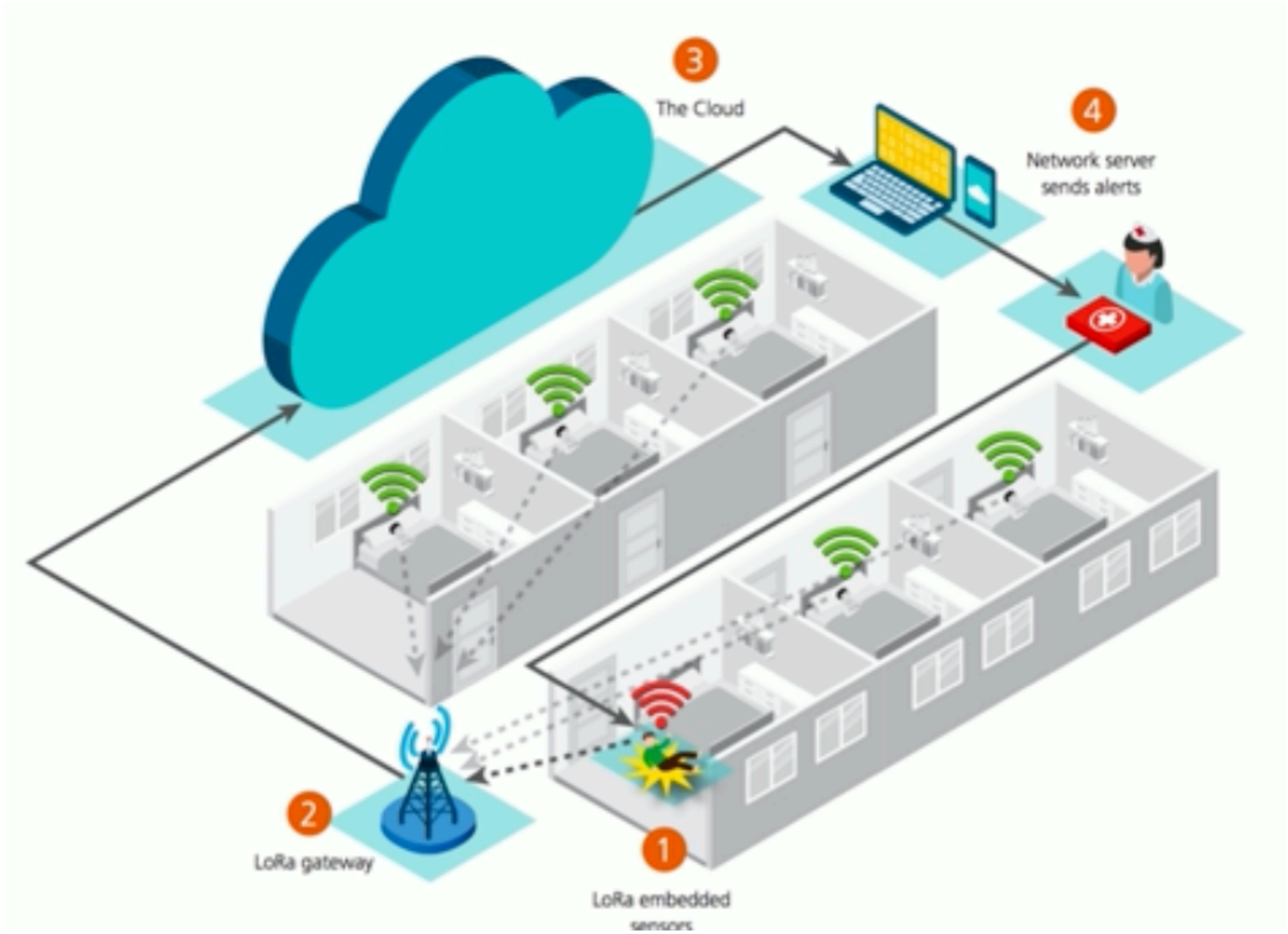


- The turtle sends information about the baby's breathing, body position, sleep pattern, skin temp to the lilypad via BLE
- The board uses WiFi to send data to the cloud
- Parents receive real-time insights about their baby on their smartphone.

Healthcare - fall detection

- Every 11 seconds, an older adult is treated in the emergency room for a fall; every 19 minutes, an older adult dies from a fall.
- Falls are the leading cause of fatal injury and the most common cause of nonfatal trauma-related hospital admissions among older adults.
- In 2013, the total cost of fall injuries was $34 billion.

Fall detection in a senior home



1. Fall/movement data collected by sensors embedded with LoRa technology
2. Data from all sensors is sent to a LoRa gateway
3. Gateway sends information to the cloud where data is analysed by an application to detect what is a fall and what is normal
4. Application server sends reports and alert to a computer or mobile device.

Disease treatment and progression monitoring

Continuously monitoring of people with certain diseases can provide gradual data which can be crucial for assessing the state of the disease or the effectiveness of a therapy.

Example - Parkinson’s disease.

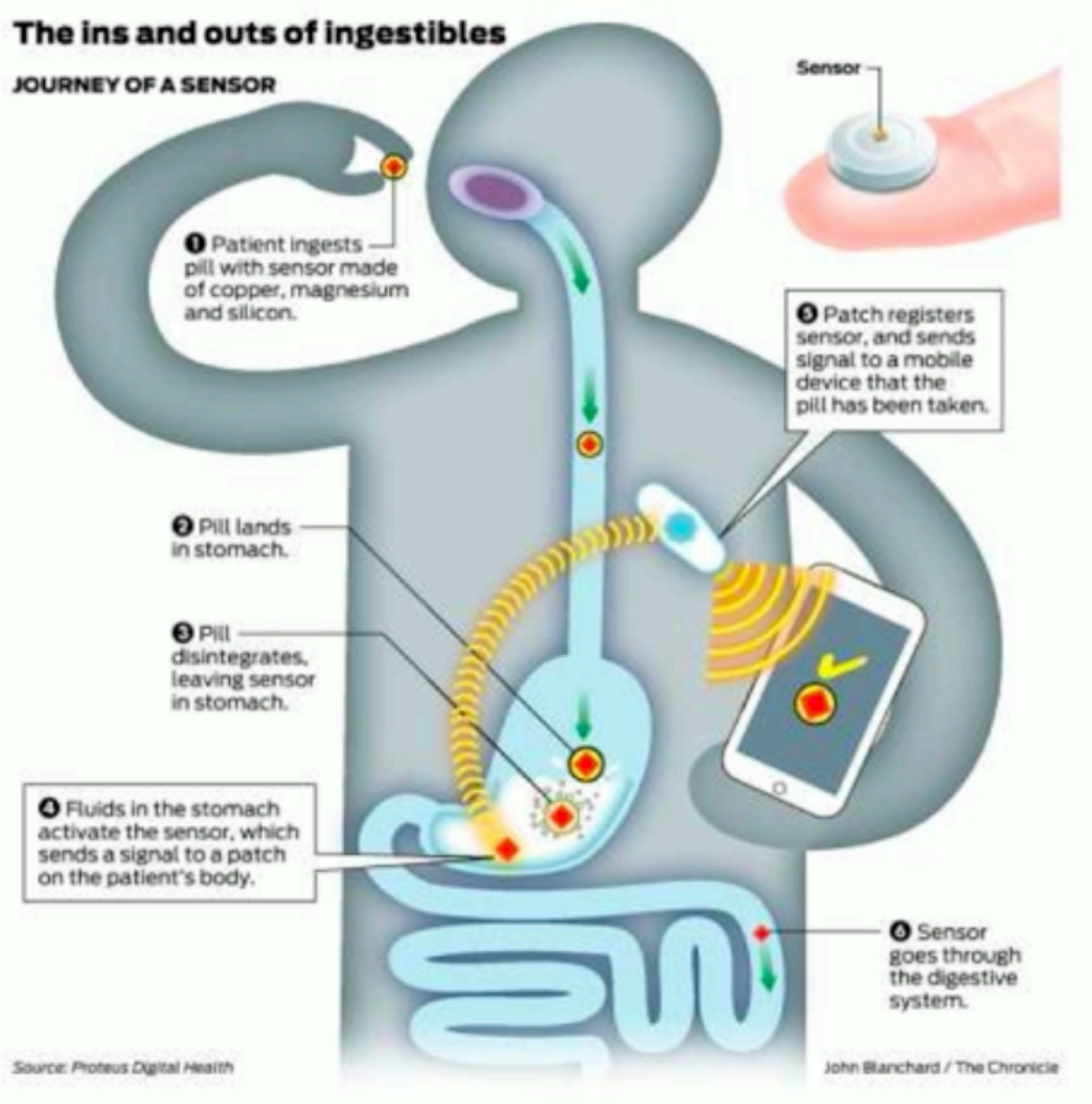
- motion and audio sensors to detect changes in how a patient moves and speaks.

- Intel and Micheal J. Fox Foundation for Parkinson’s Research, Pfizer and IBM are collaborating on this idea.

Enhance adherence in healthcare

- In the US, the 84% of healthcare spending in on patients with chronic conditions, and more than 50% of prescribed medications are not taken as directed.
- Reasons why people are not able to take their medication:
    - They may forget
    - They may not be convinced of the medication's effectiveness or be unsure that it is working
    - They may fear side effects or have difficulty taking the medication
    - Rising cost of medications

enhance adherence - ingestible sensors



Agriculture - precision agriculture

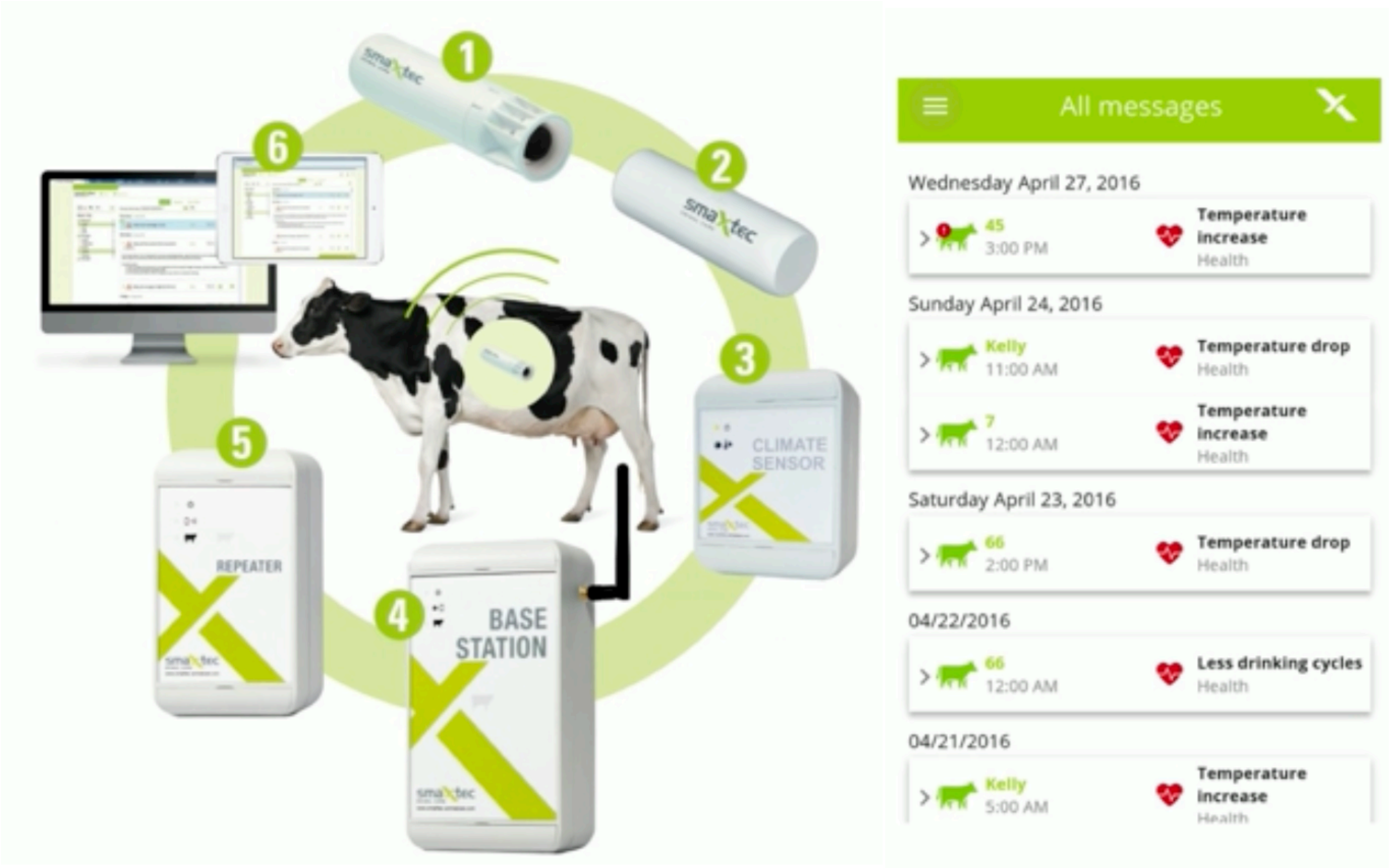
- Precision Agriculture is a farming management concept based on observing, measuring and responding to inter and intra-field variability in crops.

- In the past, precision agriculture technology was implemented by big agribusiness due to high costs. IoT have made precision agriculture affordable for many farmers.

- Farmers can make decisions based on detailed information about water, climate changes, soil quality etc.

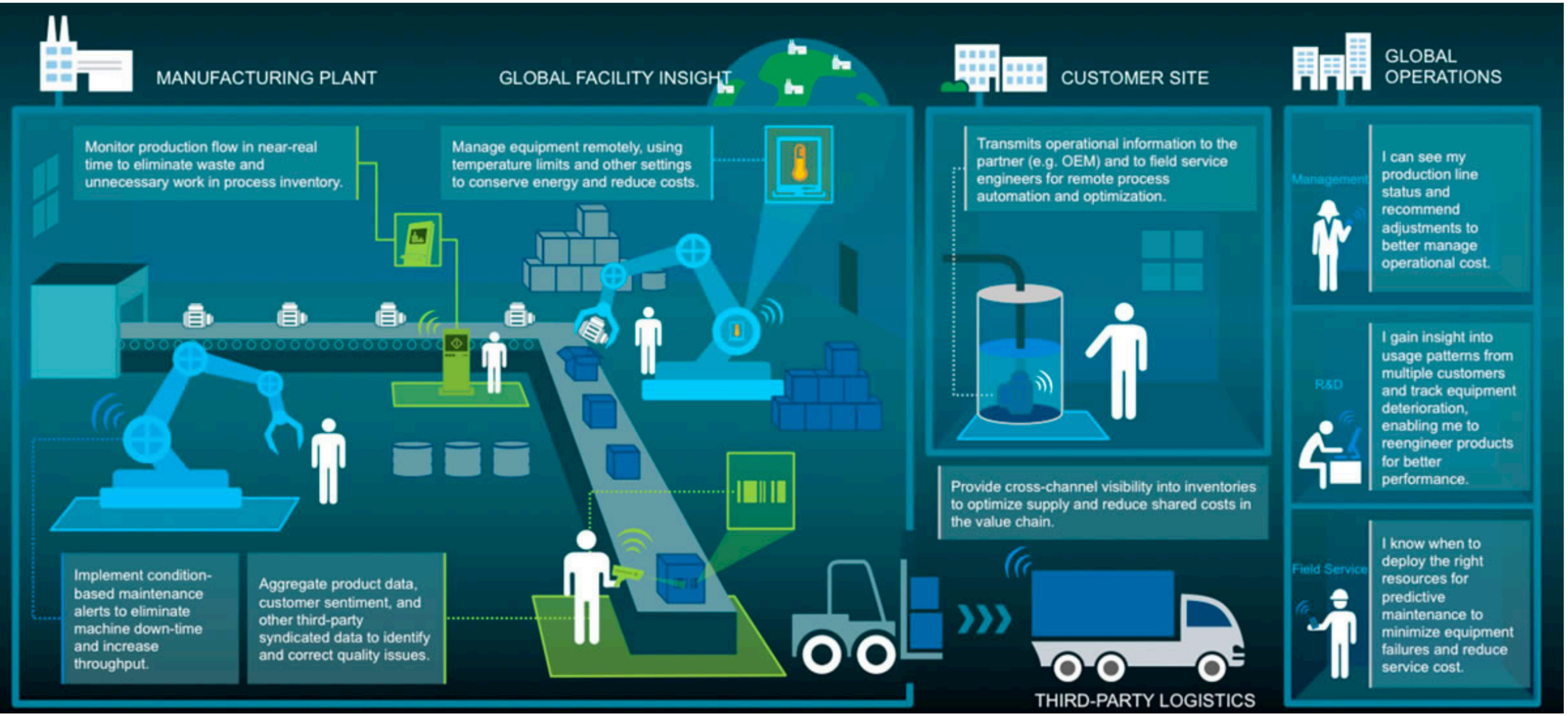
AG TECH: 100+ TECHNOLOGY COMPANIES CHANGING THE FARM

Livestock



- It is difficult to detect in advance diseases of animals.
- IoT device implanted in a cow continuously records PH and temperature and sends data to a base station.
- The base station can also integrate the received data with other information such as outside temperature, humidity level, air pressure.

Smart Manufacturing



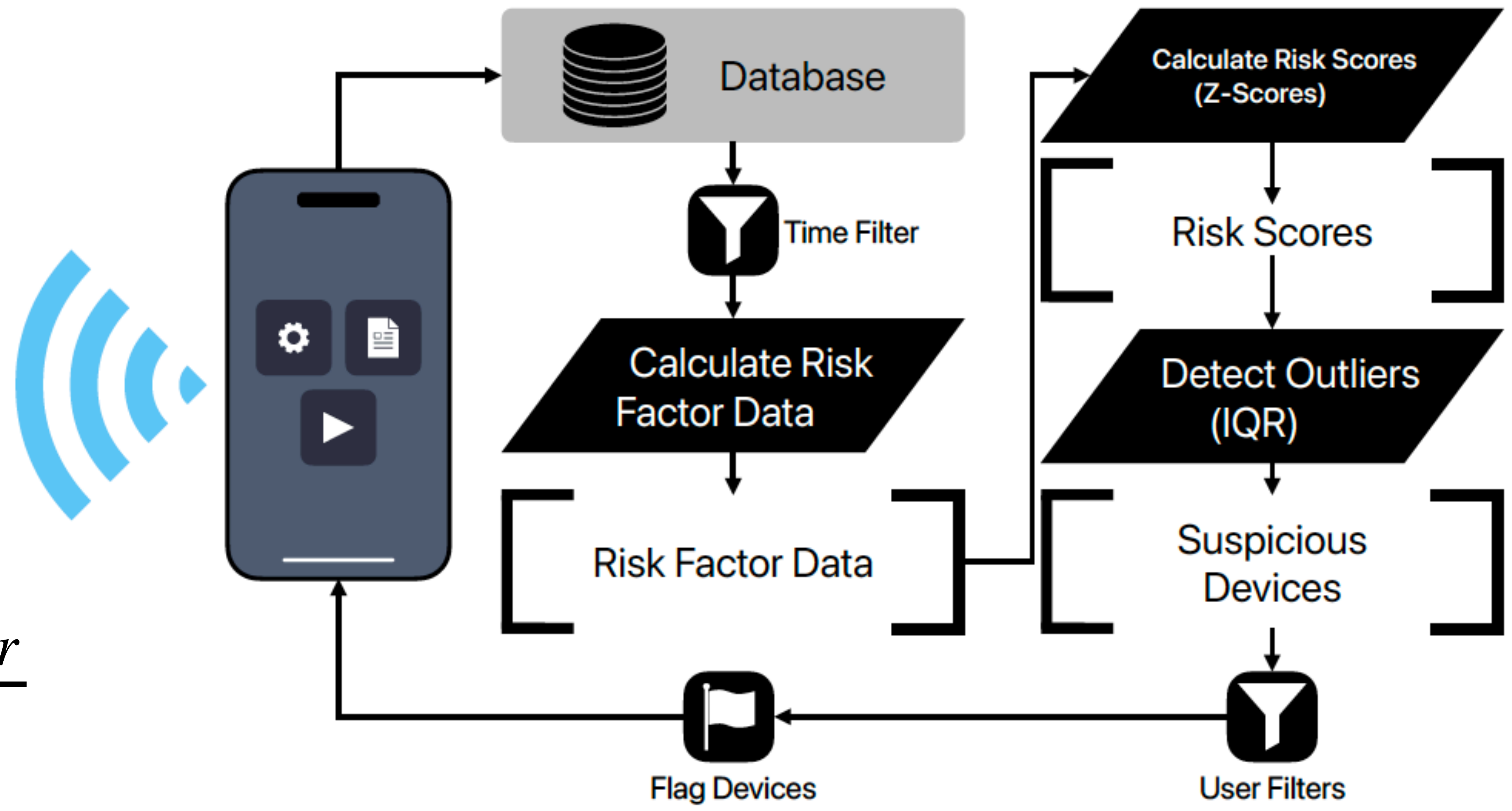
- Smart manufacturing is the use of IoT devices to improve efficiency and productivity of manufacturing operations.
  - Typically, it involves retrofitting sensors to existing manufacturing equipment
  - New manufacturing equipment often comes with IoT sensors pre-installed.
- Smart manufacturing is the first largest vertical IoT market, twice as large as the second one, transportation

Smart Label

https://www.youtube.com/watch?v=awT87YbV-J4&ab_channel=Labels%26Labeling

Identifying suspicious demo trackers

- BL(u)E CRAB, a framework for tracker detection.
  - Scan for Bluetooth Low Energy (BLE) devices in the vicinity of a user device (such as AirTag, SmartTag, and Tile)
  - Record time, location and signal strength.
  - Information is stored in a database and periodically retrieved
  - Compute risk factor data:
    - Time with user
    - Incidence
    - Distance travelled
    - Area count
    - Device proximity
  - Compute Z-score for each risk factor r, i.e., $z_r = \dfrac{x_r - \mu_r}{\sigma_r}$
  - Detect outliers, performs user filtering
  - Send alert



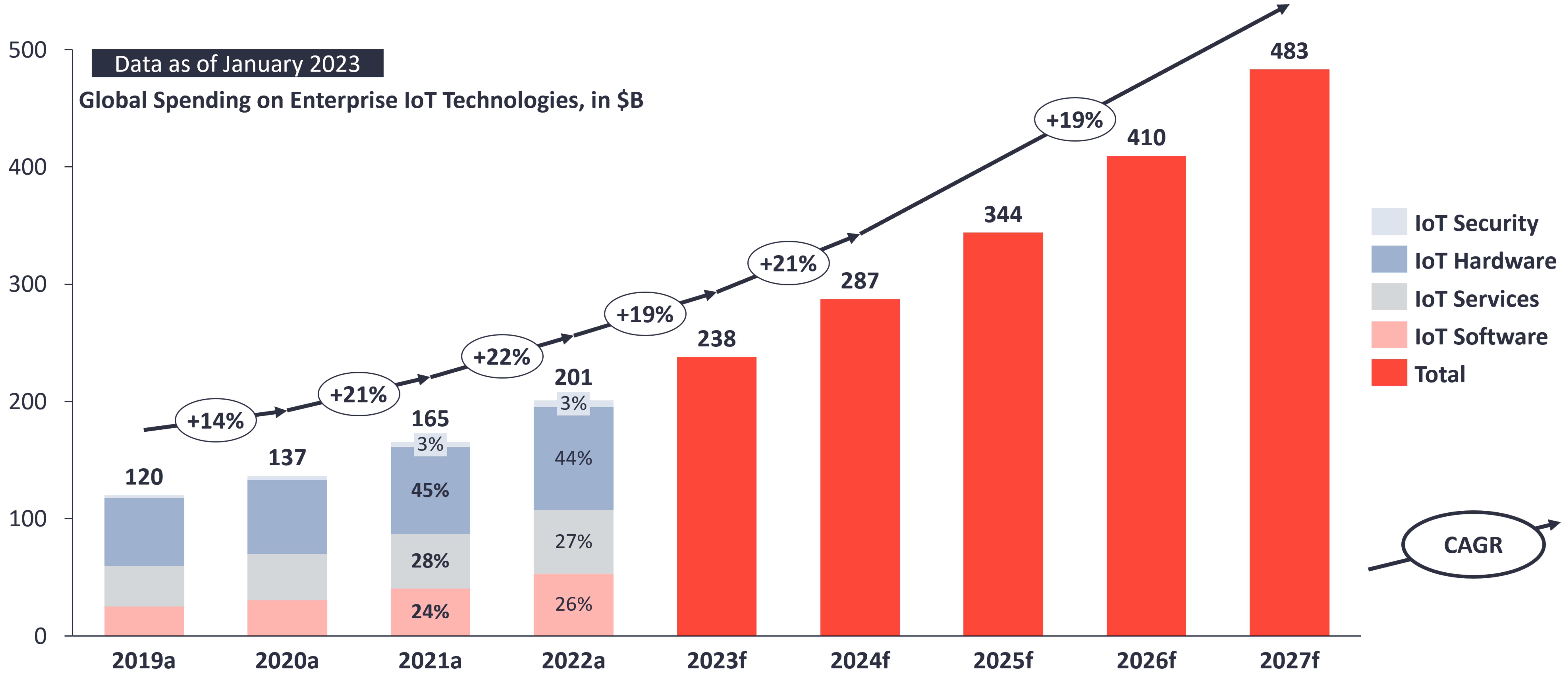
1.4 Facts, features and challenges

IOT ANALYTICS

February 2023

Your Global IoT Market Research Partner

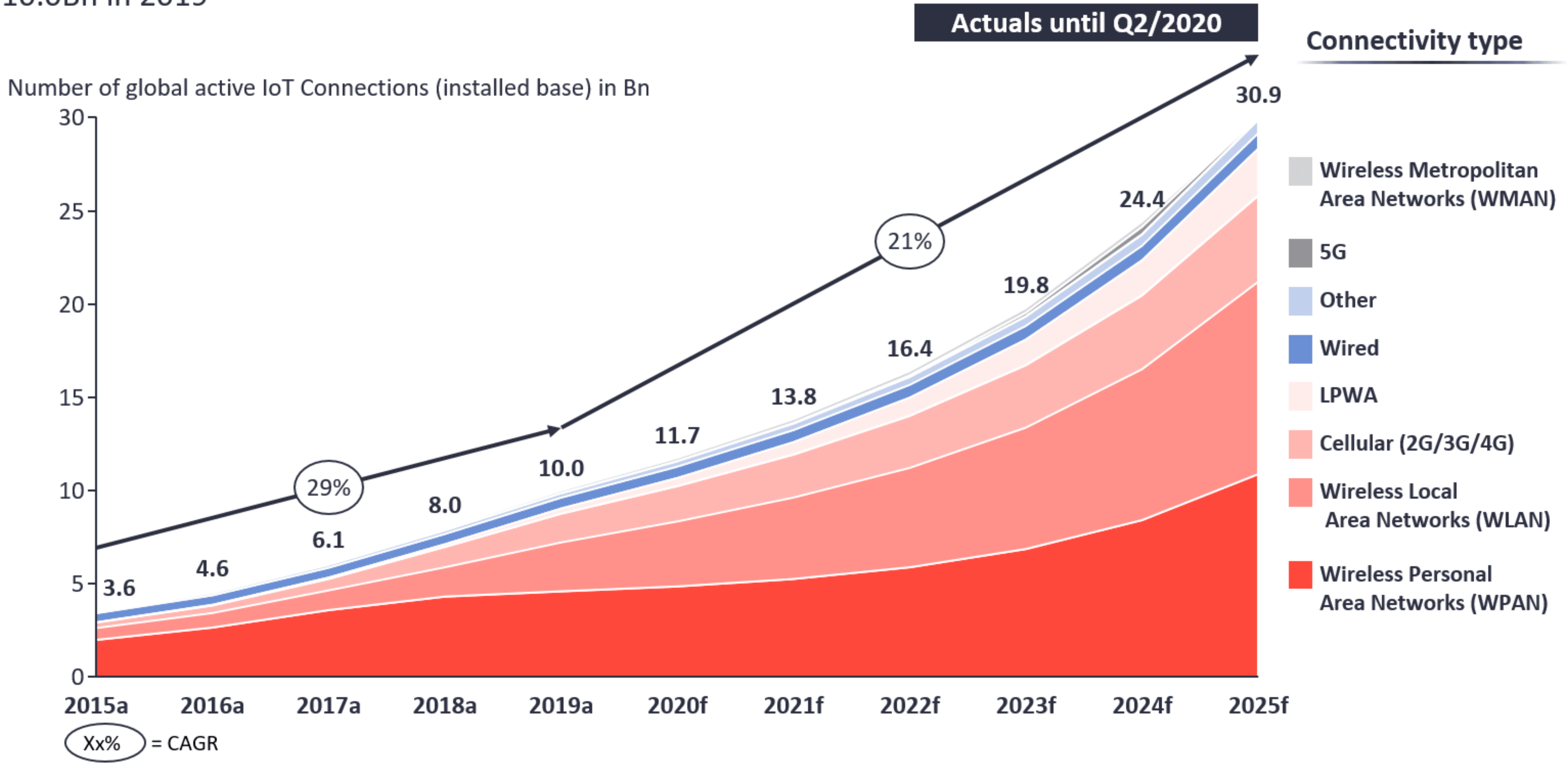
Enterprise IoT market 2019–2027



Note: IoT Analytics defines IoT as a network of internet-enabled physical objects. Objects that become internet-enabled (IoT devices) typically interact via embedded systems, some form of network communication, or a combination of edge and cloud computing. The data from IoT-connected devices is often used to create novel end-user applications. Connected personal computers, tablets, and smartphones are not considered IoT, although these may be part of the solution setup. Devices connected via extremely simple connectivity methods, such as radio frequency identification or quick response codes, are not considered IoT devices. a: Actuals, f: Forecast
Source: IoT Analytics Research 2023. We welcome republishing of images but ask for source citation with a link to the original post or company website.

Global Number of Connected IoT Devices

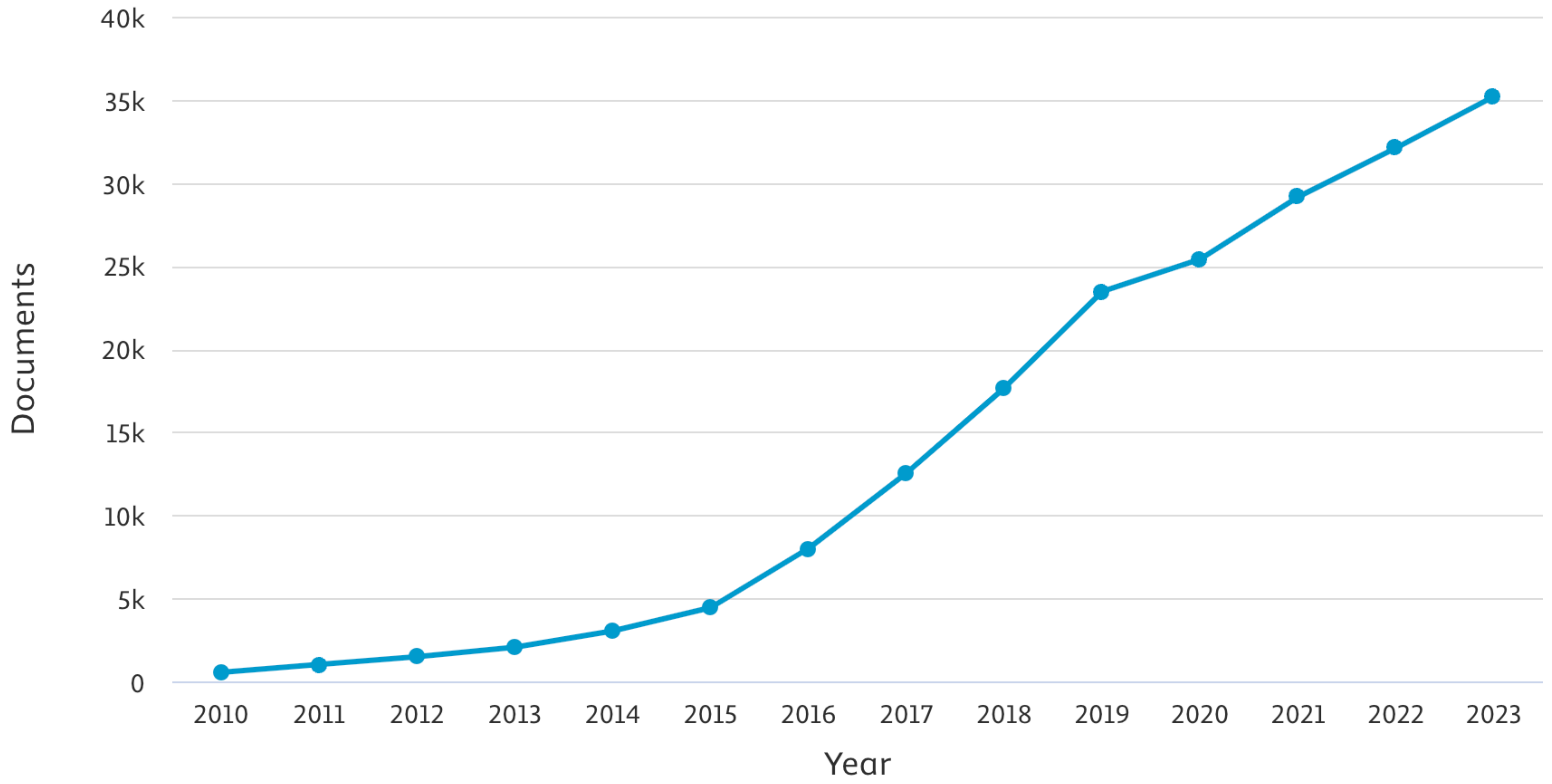
10.0Bn in 2019



Note: IoT Connections do not include any computers, laptops, fixed phones, cellphones or tablets. Counted are active nodes/devices or gateways that concentrate the end-sensors, not every sensor/actuator. Simple one-directional communications technology not considered (e.g., RFID, NFC). Wired includes Ethernet and Fieldbuses (e.g., connected industrial PLCs or I/O modules); Cellular includes 2G, 3G, 4G; LPWAN includes unlicensed and licensed low-power networks; WPAN includes Bluetooth, Zigbee, Z-Wave or similar; WLAN includes Wi-fi and related protocols; WMAN includes non-short range mesh, such as Wi-SUN; Other includes satellite and unclassified proprietary networks with any range.

Source(s): IoT Analytics - Cellular IoT & LPWA Connectivity Market Tracker 2010-25

Number of research papers with “IoT” or “Internet of Things” in title/abstract/keywords



13.6 ZETTABYTES

Data generated
by IoT devices
in 2019 alone

127

the number of new IoT
devices connected to
the web per second

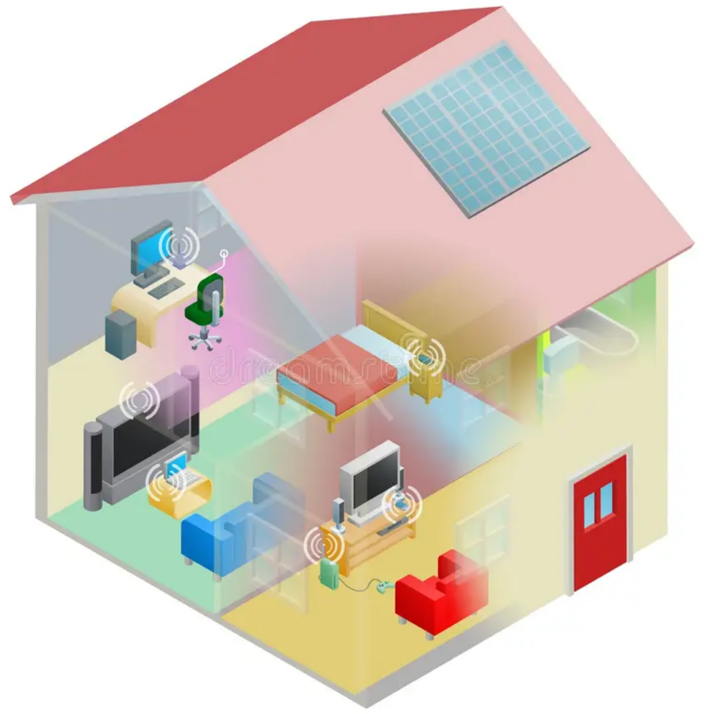
*1ZB = 10^{12} GB

Internet(s) of Things

- IoT systems can be very different from one another.

Industrial Automation
Thousands/person
controlled environment
high reliability
industrial requirements

WirelessHART



Home Area Networks
hundreds/person
uncontrolled environment
convenience
consumer requirements

ZigBee

Personal Area Networks
tens/person
personal environment
instrumentation
fashion vs. Function

Bluetooth

Internet(s) of Things

- IoT systems can be very different from one another.

Huge spectrum of applications, application requirements, technologies, protocols, hardware, software, programming languages

Industrial Aut
Thousands/pe
controlled environment
high reliability
industrial requirements

WirelessHART

uncontrolled environment
convenience
consumer requirements

ZigBee

Area Networks
on
personal environment
instrumentation
fashion vs. Function

Bluetooth

MGC Architecture

- Despite all the differences, all IoT systems have a similar architecture

eMbedded devices

6LowPAN
ZigBee
Wave
Bluetooth
WiFi
Wireless

Gateways

3G/4G
Ethernet
TCP/IP

Cloud

WHY TODAY?

- Microcontrollers and tiny wireless devices were developed more than 25 years ago, but things started to change some time after that.

- Three game changers:

ARM cortex M series (2004)

Bluetooth Low Energy (2006)

6LoWPAN (2007)

ARM cortex M series

- Ultra low power 32-bit processor
- 8-96kB RAM
- 64-512 KB code flash (amount of code they can store)
- What really made the difference was that, in sleep mode, the microcontroller would use less than 500 µA (now we can do microcontrollers with ~1µA).
    - Decreased power consumption was a key driver for IoT development

Bluetooth Low Energy (BLE)

- First released in 2006, supported by many chips but not by mobiles or computers.
- If well configured, could send 30 byte once per second.
  - Temperature sensor reporting temperature at 1 hertz can last for a year with a coin cell battery.
- Apple rolled out iBeacon (positioning system for indoor environments), which used BLE, and was therefore supported by all apple devices.
  - Almost immediately Android followed.

Thanks to BLE, IoT devices (embedded systems) can bridge directly to mobile devices and therefore to the internet, changing drastically the networking landscape

6LoWPAN

- Stands for IPv6 over Low-Power Wireless Personal Area Networks.
- Making small devices access the internet is tricky:
  - Internet packets are designed for large scale systems.
  - 6LoWPAN is a standard for IPv6 over low-power link layers.
    - Defines how IP packet headers are compressed.
    - Independent of any Mac or routing layer (allowing interoperability between networks and software flexibility).

Why today?

- Because we can now build very inexpensively energy-efficient microcontrollers, allowing to deploy thousands of small devices in IoT systems.

- Because we now have protocols for connecting small devices together which are very energy efficient.

- Because we have new Internet standards to compress internet packets.

Key characteristics of IoT systems (1)

- **Heterogeneity**
  - Very different devices involved, with different scopes, capabilities, characteristics and communication protocols
- **Massive deployment**
  - Billions of devices connected with each other and through the Internet will likely surpass the capabilities of the current Internet.
    Challenges:
    - design of networking and storage architectures for smart devices
    - efficient data communication protocols
- **Inter-connectivity**
  - Devices are connected with each other and to the Internet.
  - Local connectivity (e.g., swarm of drones)
- **Communication in close proximity**
  - New communication protocols with respect to traditional Internet
- **Ultra-reliable and low latency communication**
  - Industrial process automation and transportation systems

Key characteristics of IoT systems (2)

- **Low-power and low-cost communication**
  - Most IoT devices are small, battery powered and with very reduced resources.
- **Self-organizing and self-healing characteristics**
  - Minimize maintenance, especially when thousands of smart devices are used and in emergency scenarios.
- **Dynamic changes in the network**
  - To spare power, many IoT devices alternate sleep and wake modes.
  - Some devices are mobile, changing the topology of the network dynamically.
- **Safety**
  - IoT systems are subject to many different kinds of attacks.
  - Some IoT systems carry very sensitive data.
- **Intelligence**
  - IoT systems are programmed in an efficient way to make wise decisions based on processed data.

Challenges in IoT (1)

- **Security and Privacy Concerns**
  - IoT devices are vulnerable to hacking, data breaches, and unauthorized access.
- **Data Overload and Management**
  - IoT generates massive amounts of data, requiring efficient storage, processing and analysis.
- **Interoperability and Standardisation**
  - Lack of common standards can hinder the integration of devices from different manufacturers.
- **Scalability**
  - Scaling IoT networks while maintaining performance, security and efficiency is difficult.
- **Energy Efficiency and Battery Life**
  - Many IoT devices rely on battery power, and frequent replacements are impractical.

Challenges in IoT (2)

- **Cost and Return On Investment (ROI)**
  - High deployment and maintenance costs can deter adoption, especially for smaller organizations.
- **Latency and Reliability**
  - Critical IoT applications like healthcare or autonomous vehicles demand low-latency, reliable connections.
- **Ethical and Legal Issues**
  - Collecting and analyzing personal data raises questions about consent, surveillance, and data ownership.
- **Environmental Impact**
  - Disposal of IoT devices and batteries contributes to e-waste.
- **Challenges related to specific Operational Technology applications**

Bibliography

- https://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=9060970
- Stanford, Introduction to IoT
- Milenkovic, Milan. Internet of Things: Concepts and System Design. Springer Nature, 2020.
- BL(u)E CRAB (will appear at PerCom2025). Demo video: https://www.youtube.com/watch?v=J9vjPuSkJyU&ab_channel=DylanConklin