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UNIVERSITY OF OXFORD

Lecture 1: *"Things of the Internet"*

(With grateful thanks to Andrew Markham)

WIRED BACKCHANNEL BUSINESS CULTURE GEAR IDEAS SCIENCE SECURITY SIGN IN

MATT SIMON SCIENCE JUN 5, 2019 12:00 PM

Inside the Amazon Warehouse Where Humans and Machines Become One

In an Amazon sorting center, a swarm of robots works alongside humans. Here's what that says about Amazon—and the future of work.

Introduction

- **Lecturer**
  - Nhat (Nick) Pham. (nhat.pham@cs.ox.ac.uk)
- **Course website**
  - https://www.nhatpham.info/teaching/aims-iot-2023
  - (Linked to Canvas)
  - Please check it regular for updates!
- **Teaching Assistants**
  - Lab 1: Minh Tran. (minh.tran@ndcn.ox.ac.uk)
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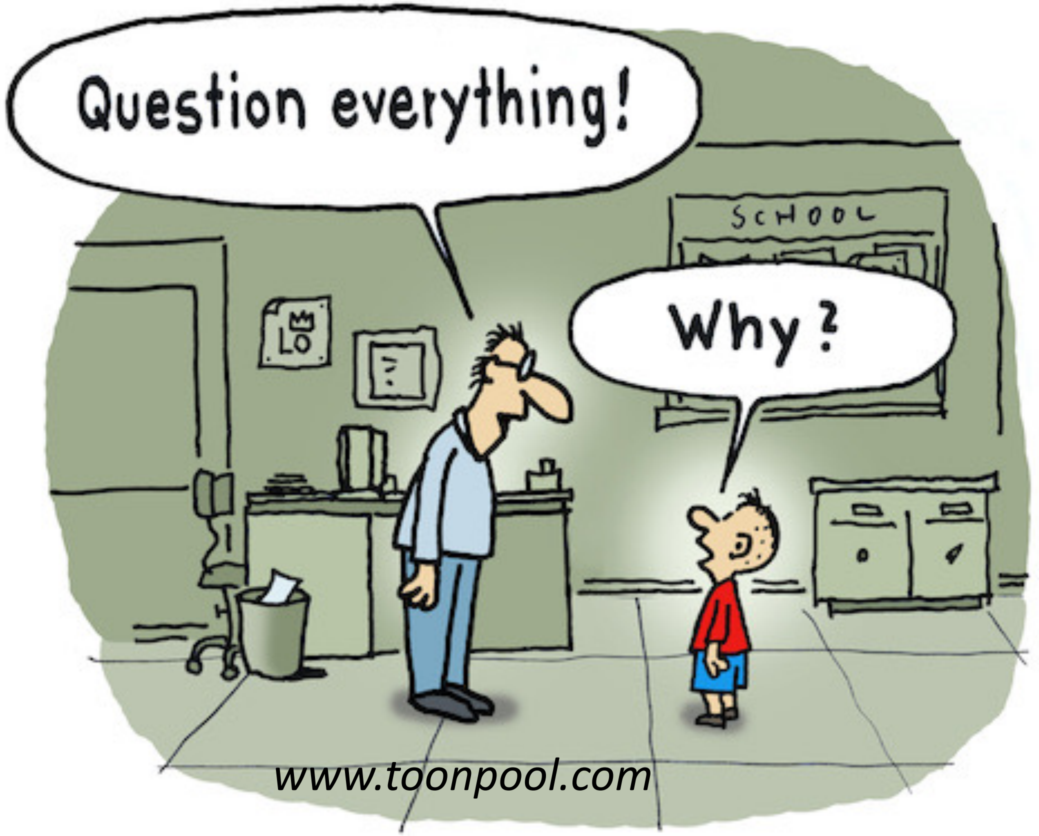
  - Lab 3: Tien Ly. (kim.ly@st-hughs.ox.ac.uk)
- **Lab assessments.**
  - Please send your completed (individually) lab results (PDF) to my email by Monday.

Introduction



www.toonpool.com

What is the IoT?

www.vecteezy.com

What will we cover in this module?

Origins

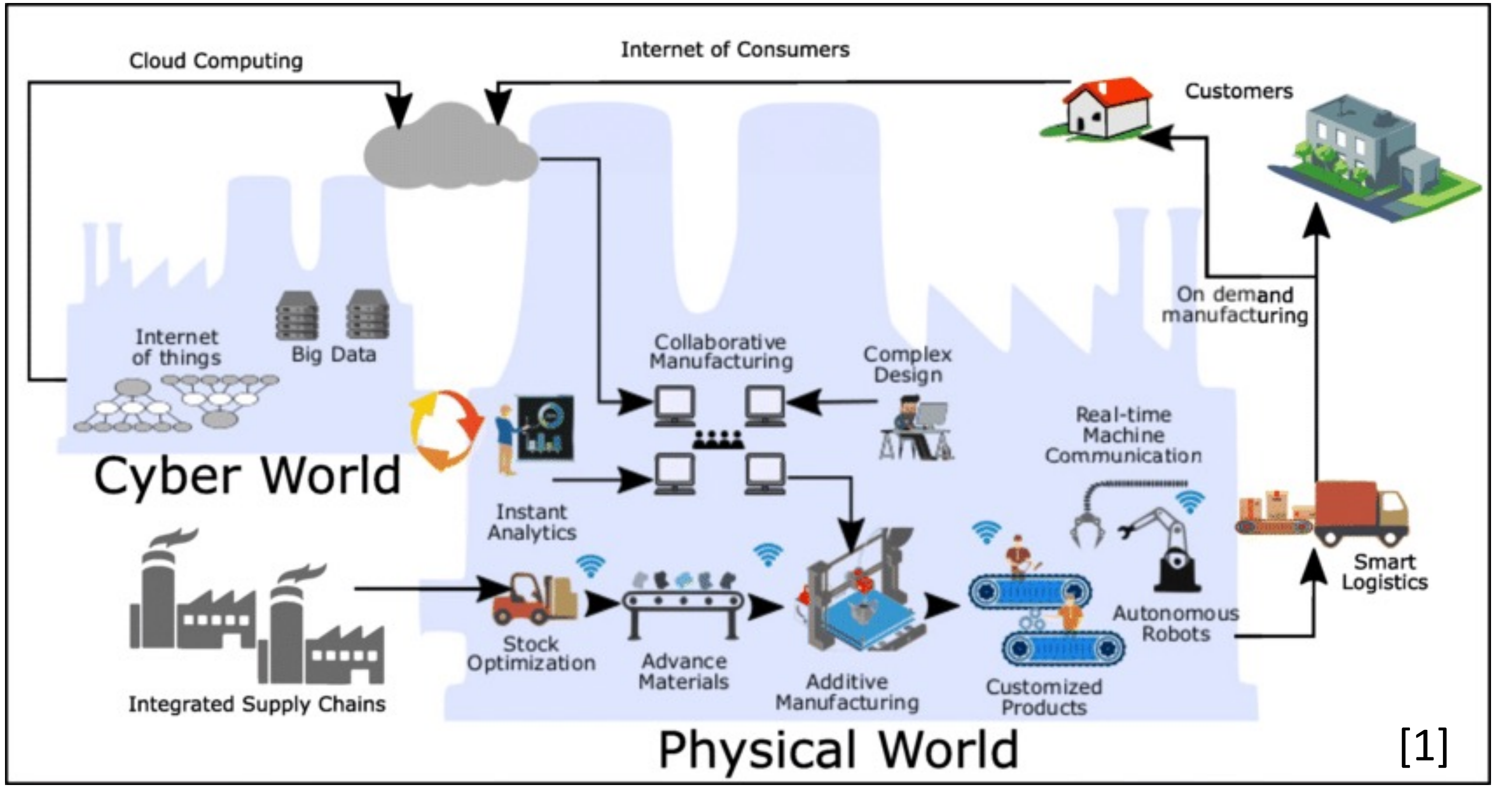
- The *Internet of Things* (IoT) - ubiquitous sensors connecting the physical world to the Internet
- Coined by UK scientist Kevin Ashton in 1999
- An umbrella term that means everything from embedded sensing through to data analytics

Smart...Everything?

- ❑ Smart Home
- ❑ Smart City
- ❑ Smart Factory
- ❑ Smart Body
- ❑ Smart Farm
- ❑ Smart Grid
- ❑ Smart *

Is it just a marketing exercise?

- ❑ Cyber-Physical Systems
- ❑ Industry 4.0
- ❑ M2M (machine-to-machine)
- ❑ V2V (vehicle-to-vehicle)
- ❑ V2X (vehicle-to-anything)
- ❑ Wireless Sensor Networks



[1]

Can we define the IoT?

- It is not particularly easy
- IEEE has an 86-page document which tries to do just this[1]

[1] https://iot.ieee.org/definition.html

An IoT Definition

A world where physical objects are seamlessly integrated into the information network, and where the physical objects can become active participants in business processes.[2]

[2]Weber et al. 2010

Another IoT Definition

System where the Internet is connected to the physical world via ubiquitous sensors.[3]

[3]Oasis 2014

Another IoT Definition

The Internet of Things represents a vision in which the Internet extends into the real world embracing everyday objects. Physical items are no longer disconnected from the virtual world, but can be controlled remotely and can act as physical access points to Internet services. An Internet of Things makes computing truly ubiquitous.[4]

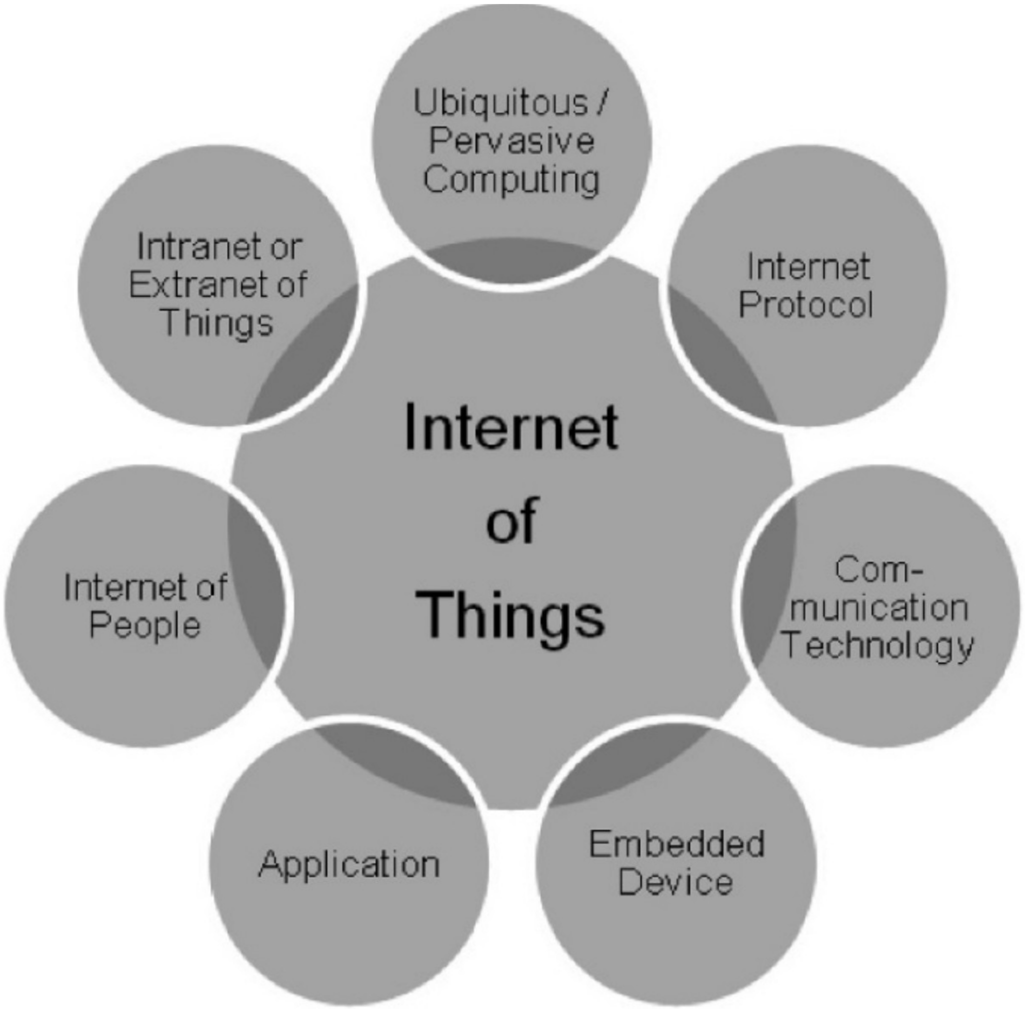
[4] Mattern et al. 2010

Another IoT Definition

The expression Internet of Things is wider than a single concept or technology. It is rather a new paradigm that involves a wide set of technologies, applications and visions.[5]

[5] Giusto et al. 2010

IoT Intersections[6]



[6]Architecting the IoT, Uckelmann et al. 2011

Key ingredients of the IoT

- Perception/Sensing
- Computation
- Communication
- Actuation
- Localisation
- Integration

What then is a thing?

In the vision of IoT, things are very various such as computers, sensors, people, actuators, refrigerators, TVs, vehicles, mobile phones, clothes, food, medicines, books, etc. These things are classified as three scopes: people, machine (for example, sensor, actuator, etc.) and information (for example, clothes, food, medicine, books, etc.)[8]

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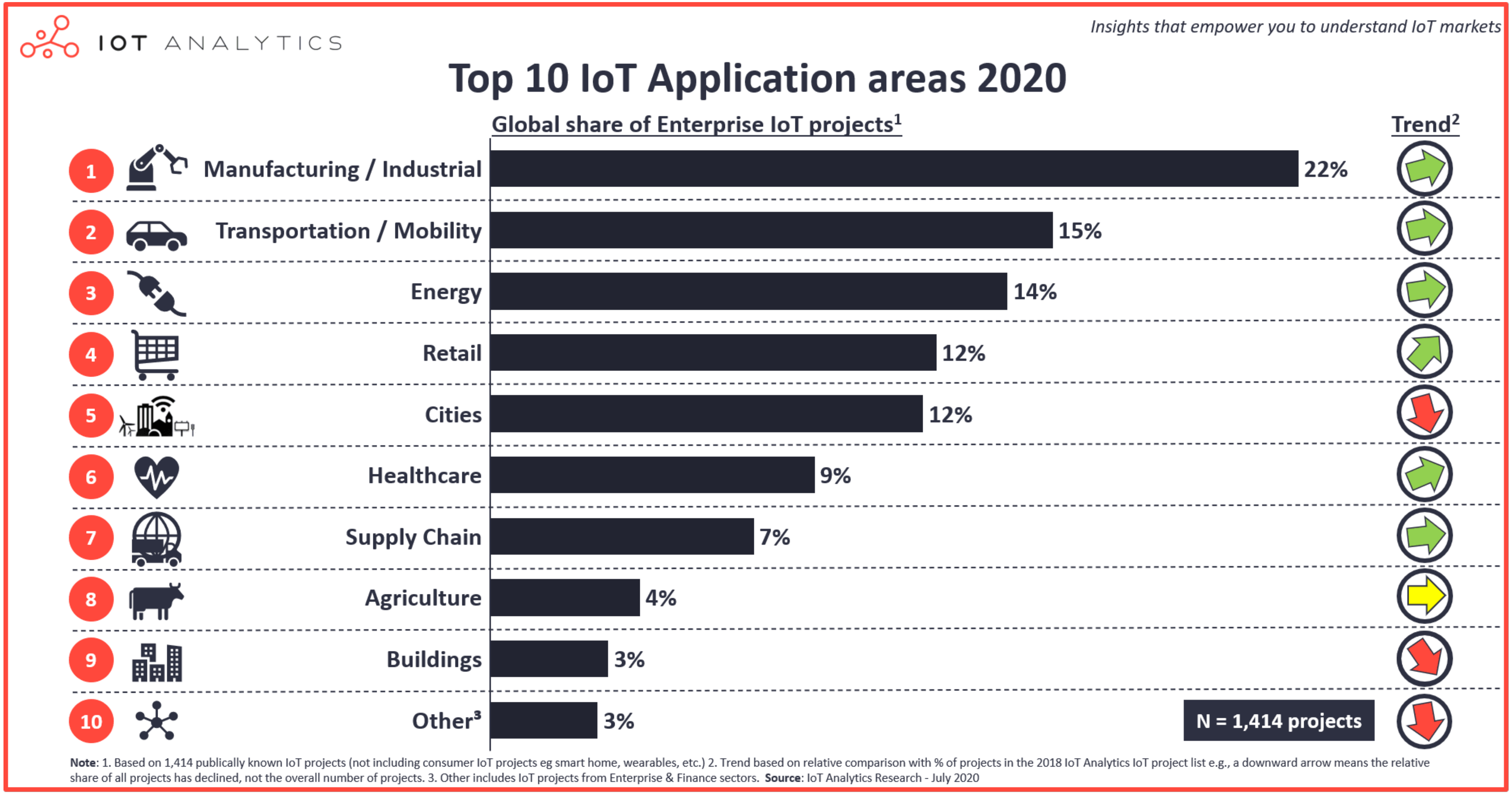
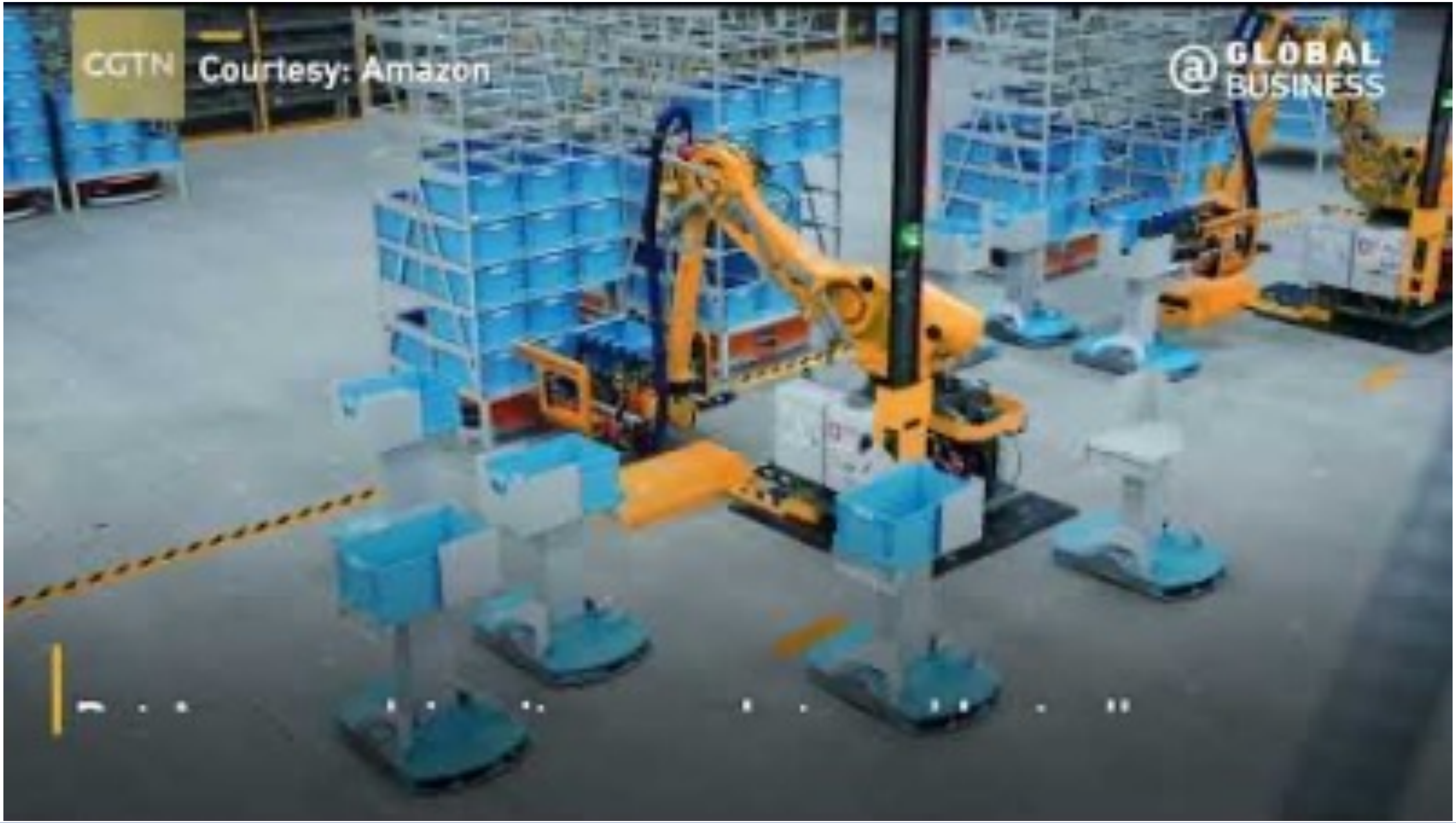
[8]IETF

IoT Share[11]



[11] IoT Analytics report

Amazon robotic warehouse



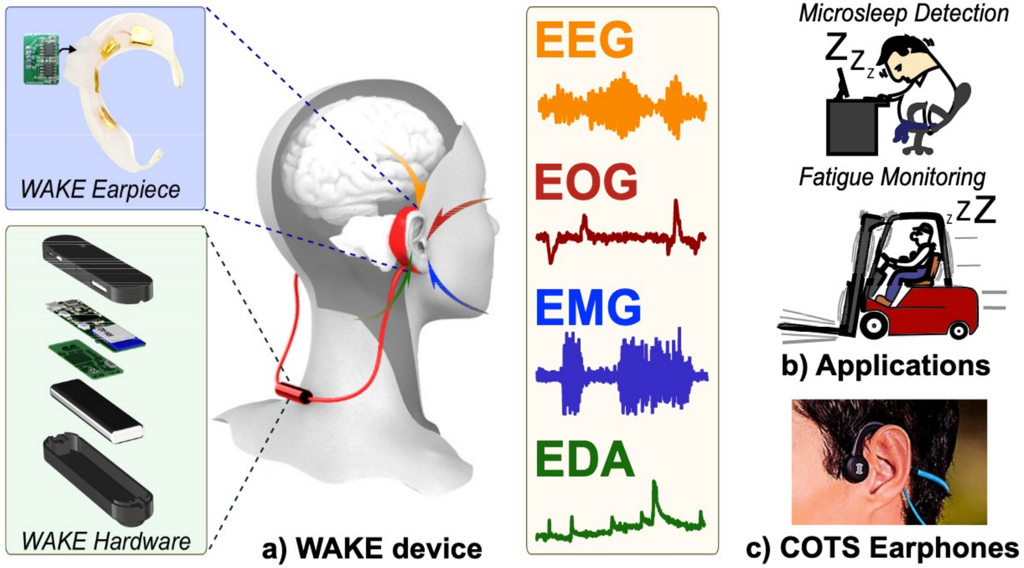
Home automation

Smart buses


electric-hybrid technology
Kidlington 2A
Evans Lane › Grovelands
electric-hybrid technology
353
R3 OXF

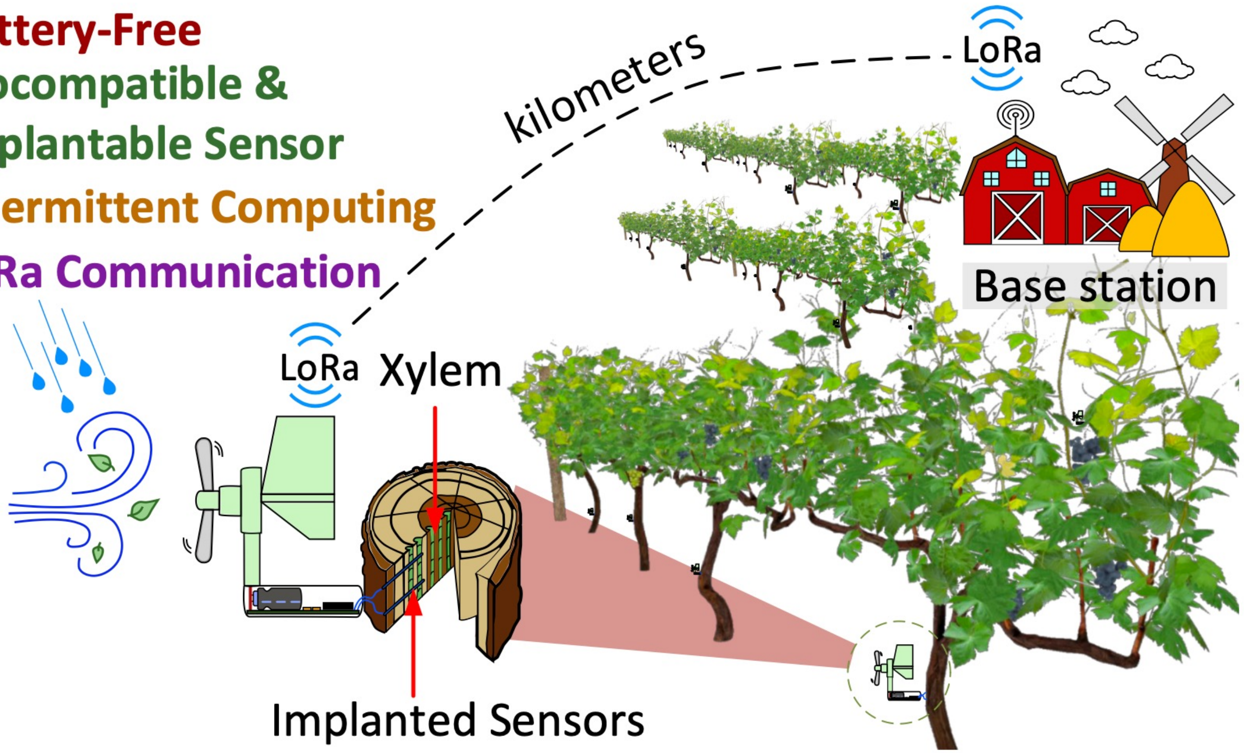
Autonomous vehicles

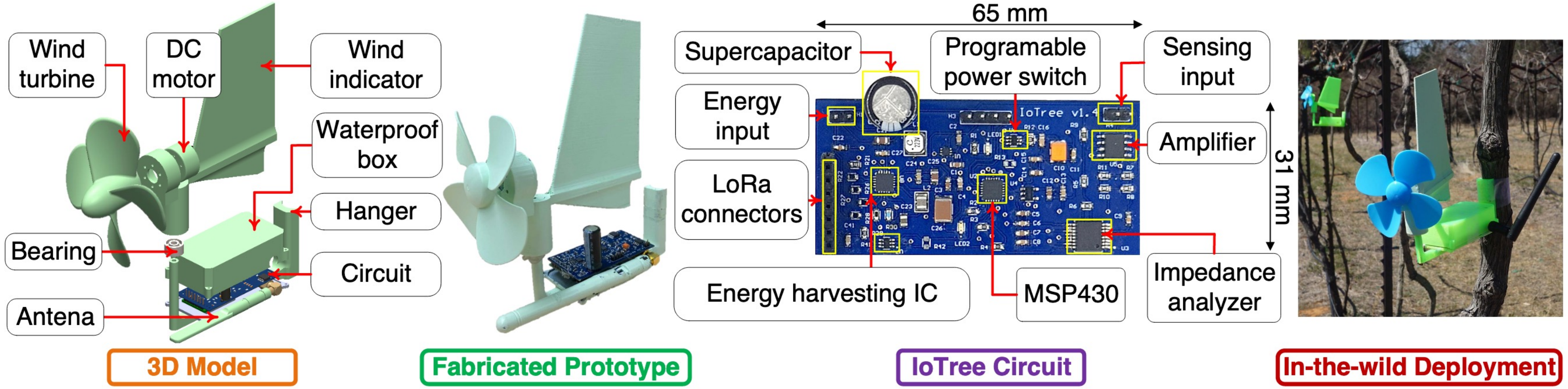
Smart wearables



Smart agriculture

Battery-Free
Biocompatible &
Implantable Sensor
Intermittent Computing
LoRa Communication





Dang, Tuan, et al. "ioTree: a battery-free wearable system with biocompatible sensors for continuous tree health monitoring." *Proceedings of the 28th Annual International Conference on Mobile Computing And Networking*. 2022.

Broad course organization

Yes:

- Anatomy of things
- Localization
- Routing and Networking
- ROS
- Navigation and Positioning
- Wearable Computing
- On-chip intelligence

No:

- Physical layer and the realities of electromagnetic propagation
- Medium Access
- Information Processing
- Securing the IoT
- Vendor-specific solutions and architecture
- The broader internet and the cloud: instead, we focus on the things themselves

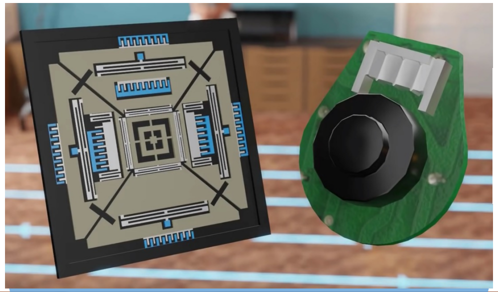
Anatomy of a Thing

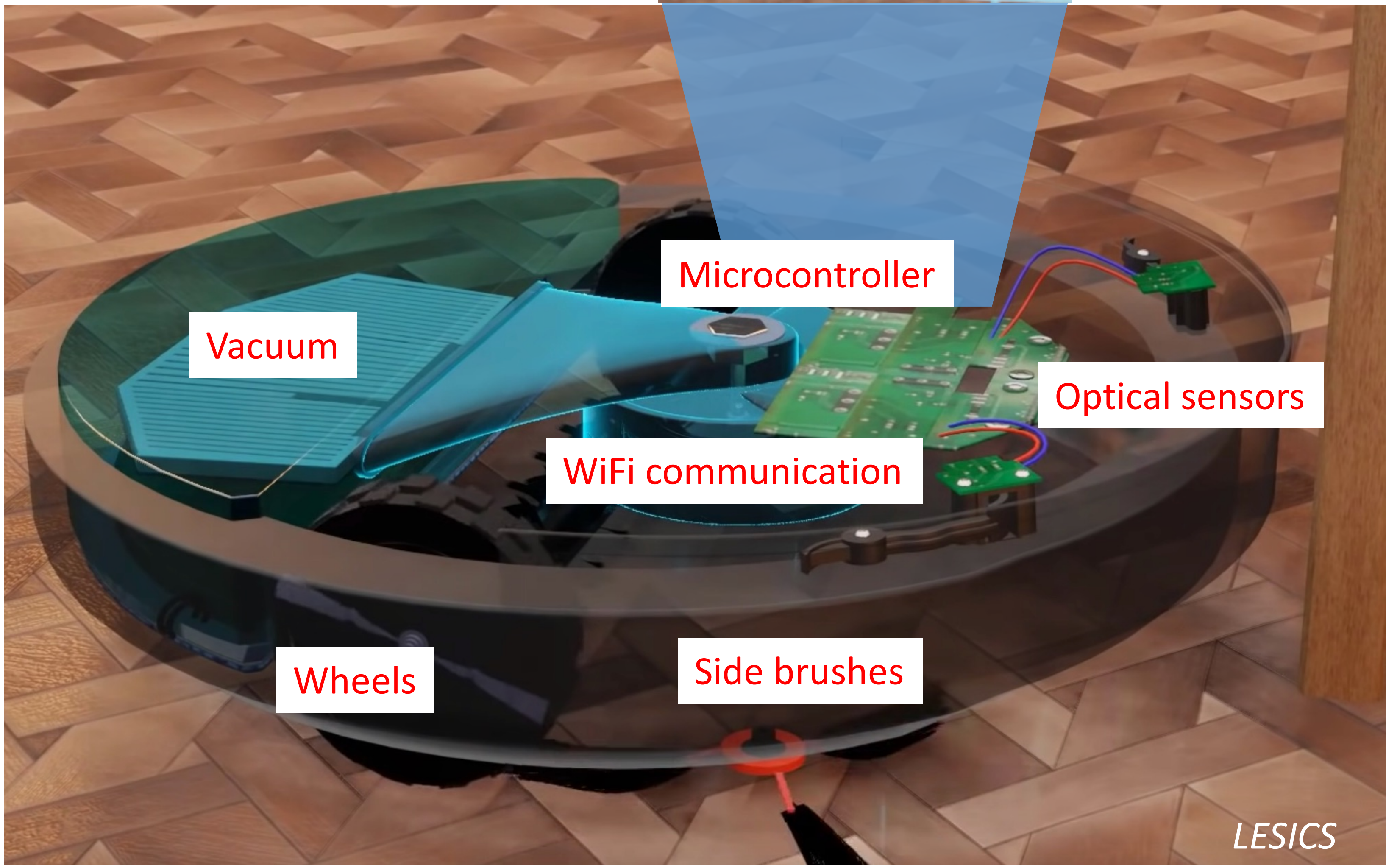
Overview

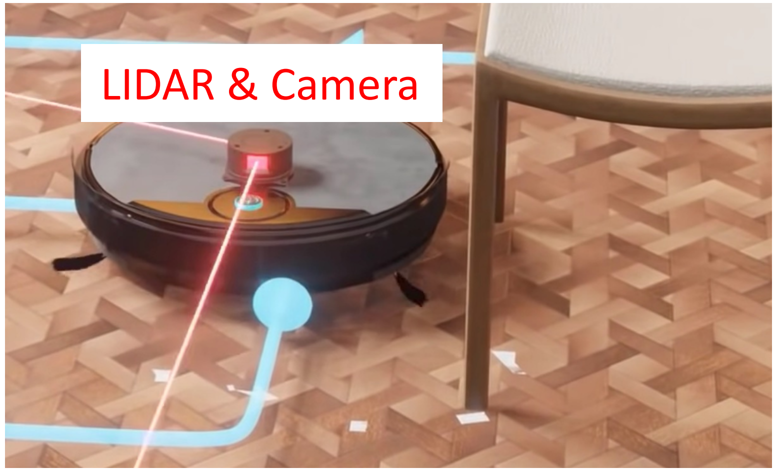
- ❑ What makes up a thing?
- ❑ How does it process information?
- ❑ Where does it get power from?

Things

- Things combine:
  - Computation
  - Communication
  - Sensing
  - Actuation
- Examples
  - Vacuum robots.







Anatomy of a Thing

Computation

Highly heterogeneous

- Available computational power varies widely
- Strongest correlation is with availability of energy

High-end

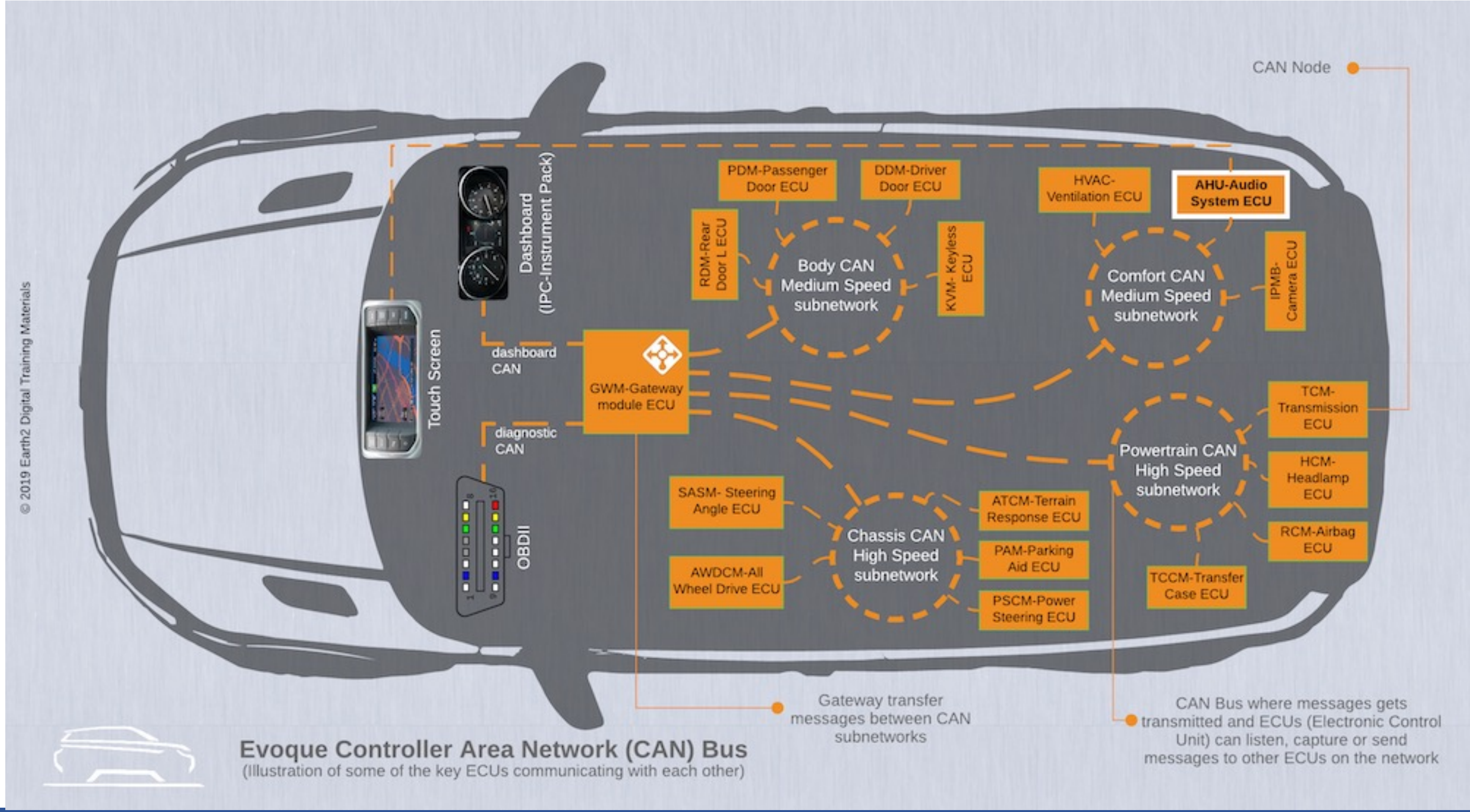
- Single-board computer (in the PC sense)
- Raspberry Pi/Beaglebone or equivalent
- Typical power consumption in the order of a few Watts
- Run Linux or similar operating systems
- ‘Consumer’ IoT e.g. Amazon Echo

High-end: RPi Zero W

- ❑ 1GHz, single-core CPU
- ❑ 512Mb RAM
- ❑ WiFi/Bluetooth
- ❑ 1.1 W power consumption
- ❑ £10

Mid-range

- More towards an ‘embedded’ platform
- Typical power consumption in hundreds of mW
- Run ucLinux, freeRTOS or similar
- Industrial motor-control, HVAC systems



Mid-range: iMX6-SOM

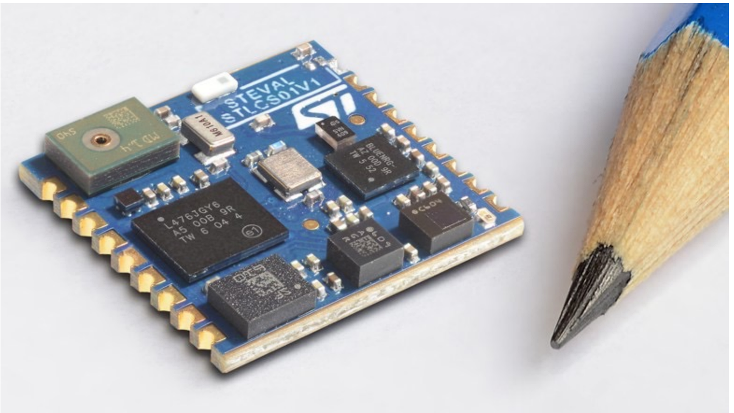
31

- 500 MHz, single-core ARM-Cortex A7 CPU
- 256 Mb DDRAM
- 250 mW power consumption
- £18

Low-end

- Battery-powered end devices
- Emphasis on highly optimized design
- Typical power consumption in few mW
- Embedded RTOS
- Fitness monitors etc.

Low-end: STM SensorTile



- 80 MHz, single-core ARM-Cortex M4 CPU
- 192 kb RAM
- 1 Mbyte Flash
- 30 mW power consumption, 1uW in sleep mode
- BLE
- £25

Nano-end

- Battery-powered end devices
- System-on-module
- Typical power consumption in few mW
- Embedded RTOS
- Smoke alarms, HVAC sensors etc.

siemens.com

Nano-end: Silicon Labs MGM

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- ❑ 40 MHz, single core ARM-Cortex M4 CPU
- ❑ 32 kB RAM
- ❑ 128 kB Flash
- ❑ 802.15.4 (Zigbee) Transceiver
- ❑ £7

Pico-end

- Battery-less, powered by RF backscatter
- Mainly used for identification (e.g. RFID)
- Some devices integrate sensors e.g. temperature
- Highly optimized for extremely low cost

www.pepperl-fuchs.com

Pico-end: RFID EPC GEN2

- ❑ 10 m read distance
- ❑ 64 bytes of programmable memory
- ❑ £0.05 unit cost

Operating Systems for the IoT

- The choice of operating systems depends on the computational power and available energy
- Embedded Linux is a good fit for mains-powered devices
- For resource-constrained devices, alternative RTOSes are needed:
  - FreeRTOS
  - ARM mbed OS
  - ContikiOS
  - RIOT

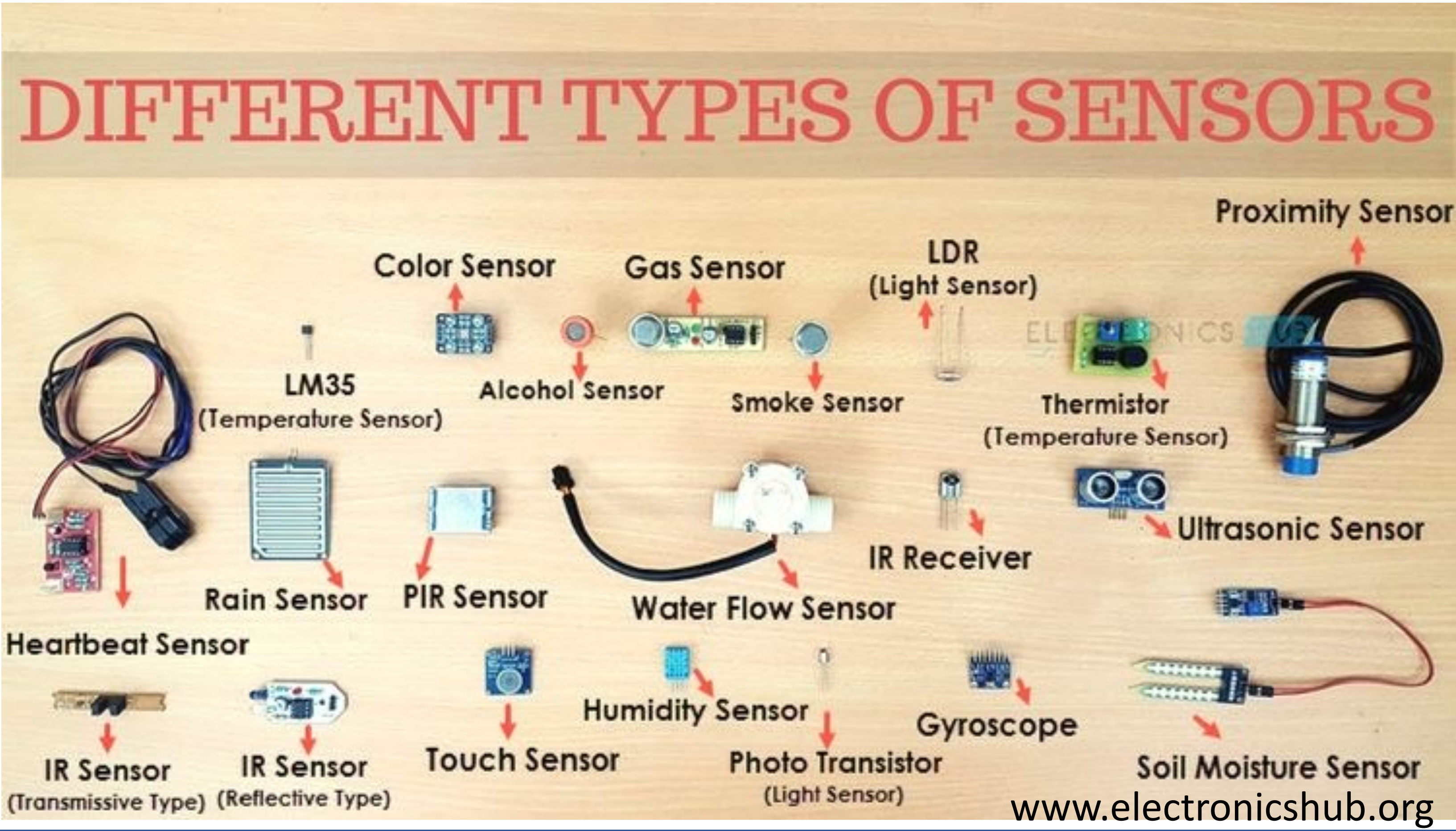
Linux™ freeRTOS RIOT

Anatomy of a Thing

Sensors and Actuators

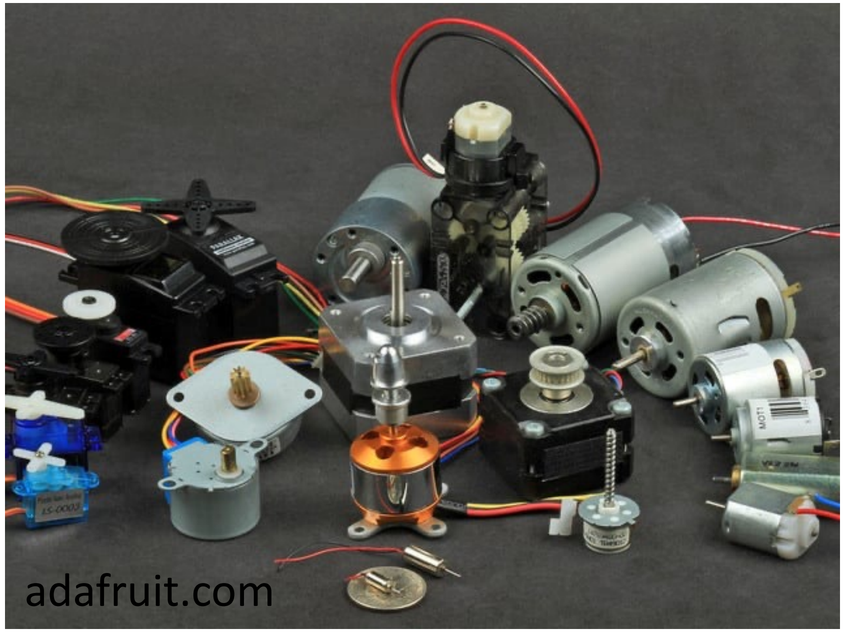
Sensors

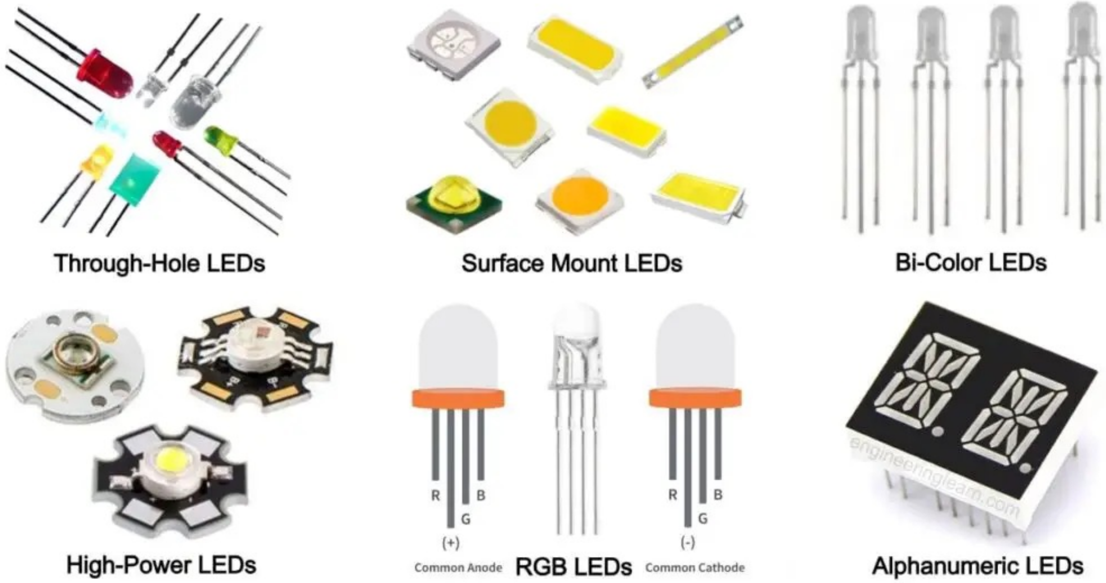
- Sensors convert real-world parameters to digital quantities
- Interfaces (e.g., screens and buttons) do both
- Huge variety of sensors:
  - Temperature
  - Light
  - Sound
  - Pressure
  - Acceleration
  - etc. etc. etc.



Actuators

- ❑ Components that affect physical changes in the real world
- ❑ Many types:
  - Motors
  - Lasers
  - LEDs
  - Display Screens
  - etc.





engineeringlearn.com

Key parameters

- Sampling rate, e.g. 100 Hz
- Resolution, e.g. 10 bit
- Power consumption, e.g. 1~mW
- Size, e.g. 6 mm x 4 mm
- Cost

Example Sensor: MEMS microphone

- Digital output
- 700μA when active
- 96 kHz maximum sampling rate
- 136 dB SPL maximum level

Anatomy of a Thing

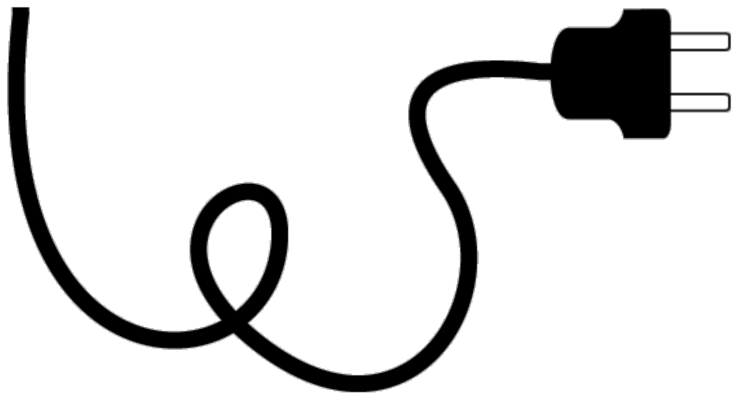
Power

Energy

- ❑ To perform any meaningful operation, energy is required
- ❑ A pervasive IoT requires ubiquitous power
- ❑ Energy is one of the key limitations that constrain the widespread deployment

Wires

- If possible, get mains power
- Perpetual computing without any of the fuss
- A significant limitation on where devices can be placed



Batteries

- Most common approach is to use a chemical battery
- *Primary* battery has a high energy density, but cannot be recharged
- *Secondary* batteries can be charged, but where does that energy come from?

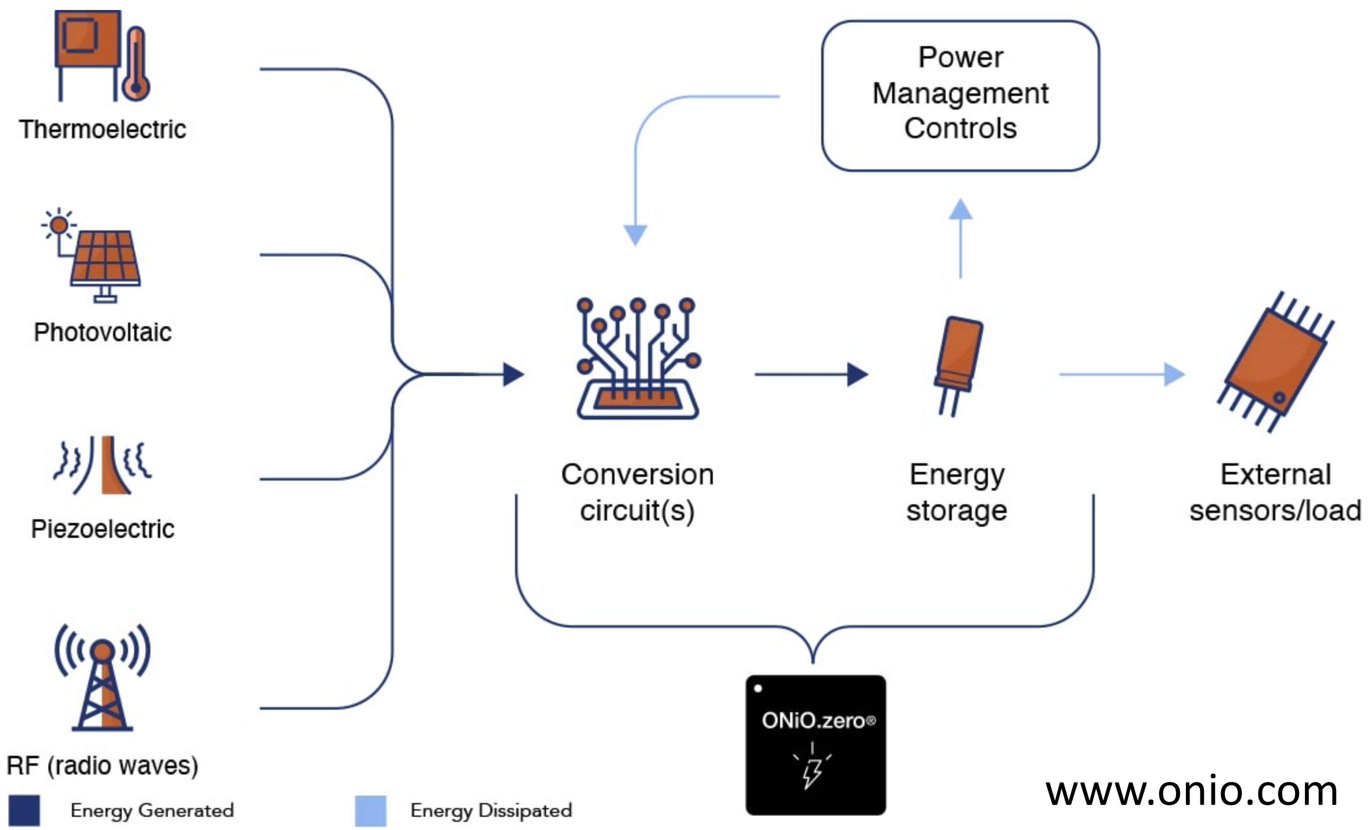
components101.com

Batteryless

- ❑ In reality, many deployments are uncontrolled
- ❑ Costs of running wires to each sensor are not feasible
- ❑ Maintenance costs of changing batteries not sustainable
- ❑ Environmental impact of (incorrectly) disposed chemical batteries is immense

Ambient harvesting

- ❑ Extract energy from ambient surroundings
- ❑ Availability may be highly variable
- ❑ Buffer energy in small battery or super-capacitor
- ❑ Theoretical perpetual operation

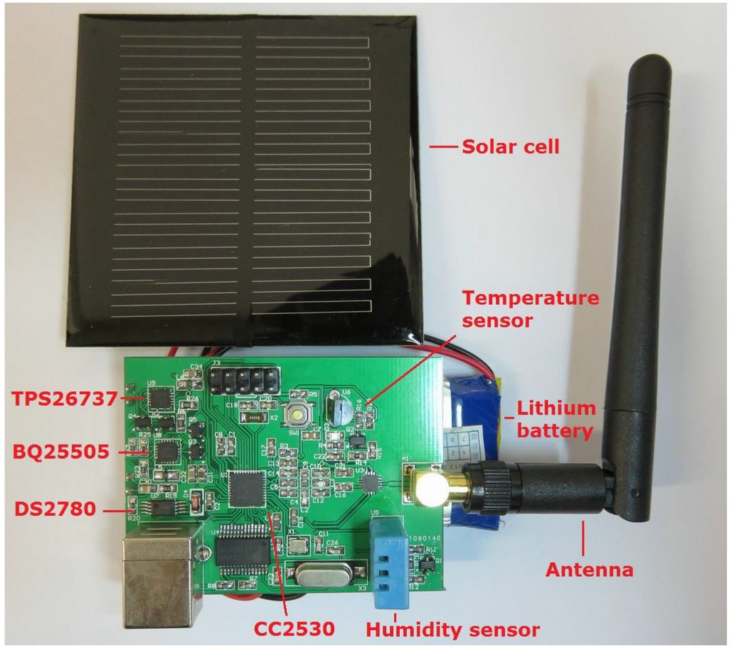


www.onio.com

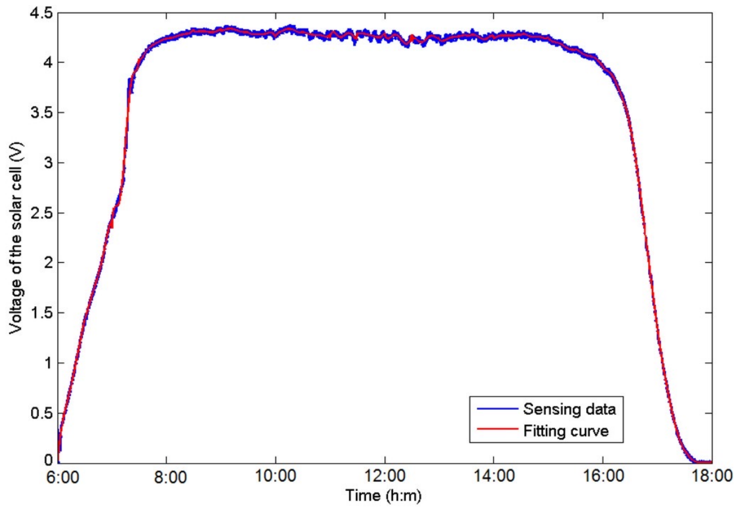
Solar

- Photo-voltaic cells convert radiant solar energy to electrical current
- 1000W/m^2 outside
- Inside is much more challenging
- Seasonal and diurnal variations
- Significant levels of harvestable energy (watts)

Solar



(a) Sensor Node



(b) Forecasting

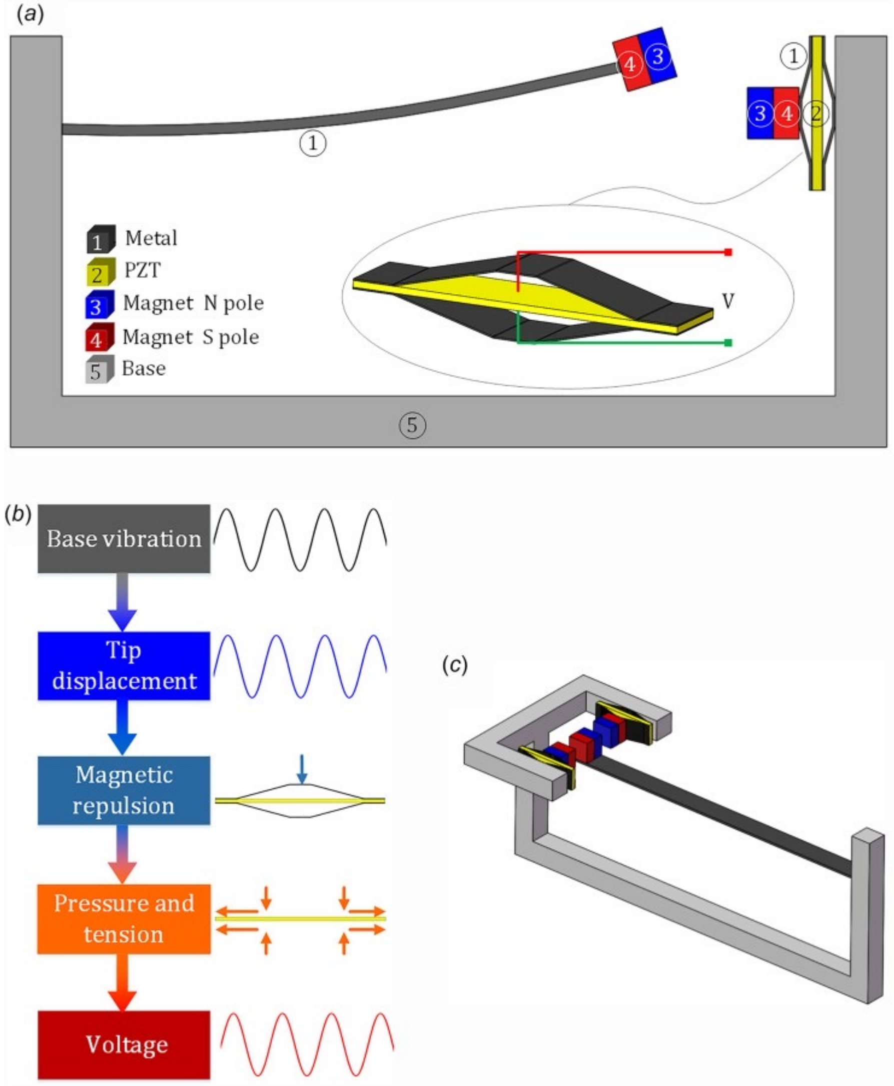
Figure 1: Predictive solar energy harvesting[1]

[1]Tengyue Zou et al. “Energy-efficient control with harvesting predictions for solar-powered wireless sensor networks”. In: *Sensors* 16.1 (2016), p. 53.

Vibration

- ❑ Use resonant masses to extract energy from vibrations/impacts
- ❑ Regular vibrations: e.g. air-conditioning duct
- ❑ Irregular vibrations e.g. train or road bridge
- ❑ Harvestable energy is small (milliwatts)

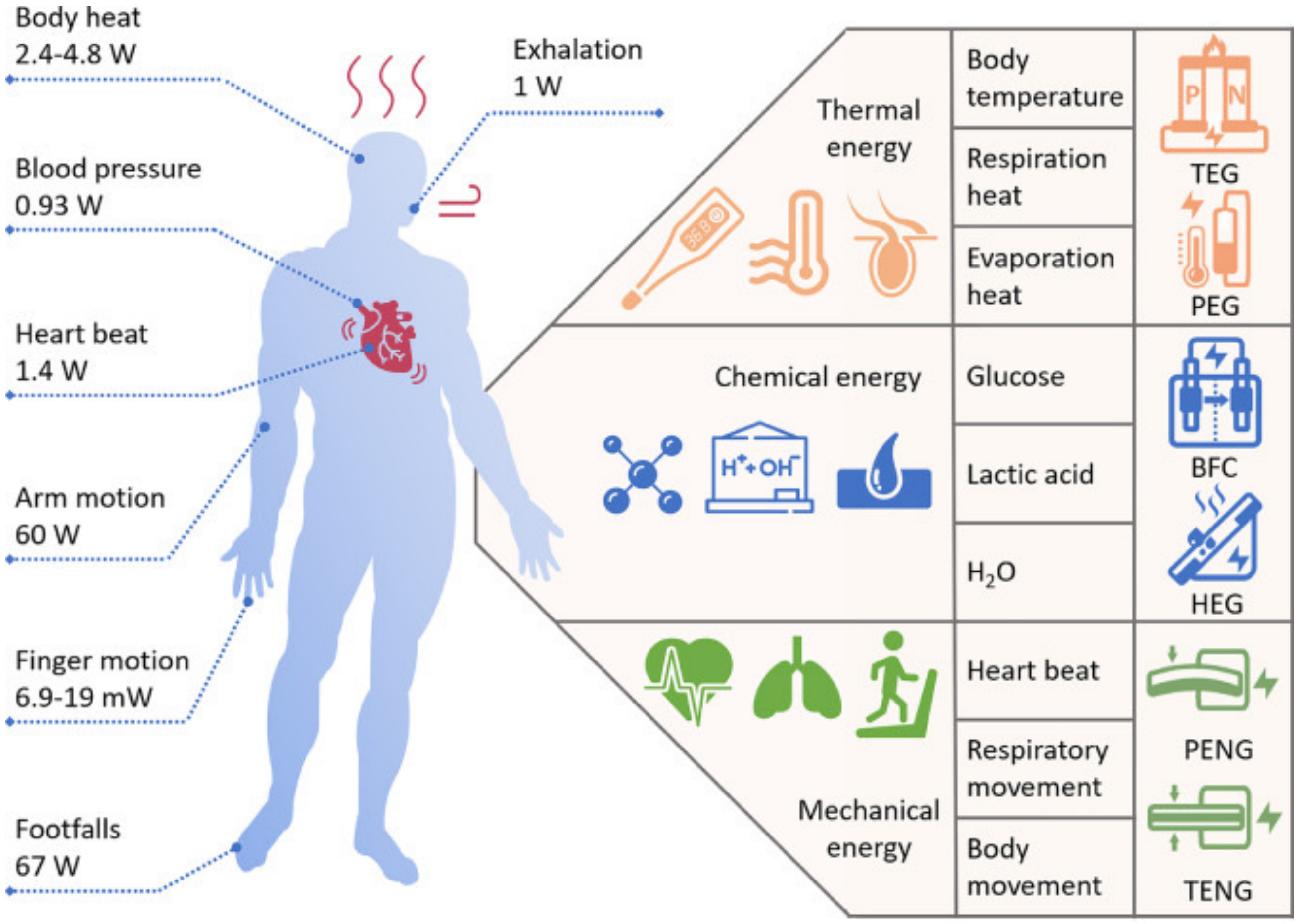
Vibration harvesting[2]



[2]Hong-Xiang Zou et al. “A compressive-mode wideband vibration energy harvester using a combination of bistable and flextensional mechanisms”. In: *Journal of Applied*

Thermal

- Exploit thermal gradient e.g. between person and surroundings
- Harvestable energy is very small (microwatts)
- Can be boosted using thermal reservoirs to buffer thermal energy



Radio: Rectennas

- Harvest energy from radio broadcasts e.g. WiFi/TV broadcasts
- Amounts of power are relatively small, but enough to power a low-power sensor node
- Well suited to indoor and industrial applications
- Challenge is tuning antenna to signals of opportunity

RFID Harvesting[3]

[3]http://www.getfreevolt.com/

Radio: RFID

- Canonical example of battery-less, passive tags
- Extremely low-cost (<5p)
- Only powered up when in range of a transmitter
- Simultaneous communication and power transfer
- e.g. UHF-GEN2

Comparison[4]

Energy source	Classification	Power density	Weakness	Strength
Solar power	Radiant energy	100 mW/cm^3	Require exposure to light, low efficiency for indoor devices	Can use without limit
RF waves	Radiant energy	0.02 $\mu W/cm^2$ at 5 km	Low efficiency for indoor	Limitless use
RF energy	Radiant energy	40 $\mu W/cm^2$ at 10 m	Low efficiency for out of line of sight	Limitless use
Body heat	Thermal energy	60 $\mu W/cm^2$ at 5 °C	Available only for high temperature difference	Easy to build using thermocouple
External heat	Thermal energy	135 $\mu W/cm^2$ at 10 °C	Available only for high temperature difference	Easy to build using thermocouple
Body motion	Mechanical energy	800 $\mu W/cm^3$	Dependent on motion	High power density, not limited on interior and exterior
Blood flow	Mechanical energy	0.93 W at 100 mmHg	Energy conversion efficiency is low	High power density, not limited on interior and exterior
Air flow	Mechanical energy	177 $\mu W/cm^3$	Low efficiency for indoor	High power density
Vibration	Mechanical ENERGY	4 $\mu W/cm^3$	Has to exist at surrounding	High power density, not limited on interior and exterior
Piezoelectric	Mechanical energy	50 $\mu J/N$	Has to exist at surrounding	High power density, not limited on interior and exterior

[4]ASM Zahid Kausar et al. “Energizing wireless sensor networks by energy harvesting systems: Scopes, challenges and approaches”. In: *Renewable and Sustainable Energy Reviews* 38 (2014), pp. 973–989.

Software implications

- An assumption we make in conventional computing is perpetual power
- But how do we modify these paradigms in the face of intermittent energy?
- Transiently powered computation requires different primitives.

Energy-aware operating systems

- As power can be removed at any time, operations need to be atomic and rollback-able
- State (a checkpoint) is stored in non-volatile memory
- However, this costs energy, so a tradeoff needs to be made as to how often this is done

Example: HarvOS

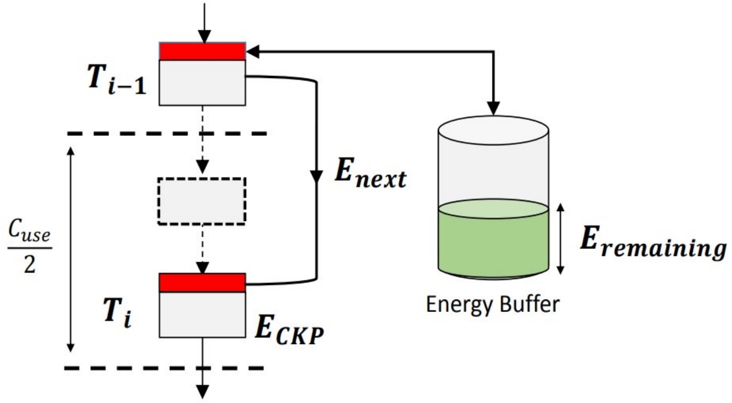


Figure 3: Decision logic to take a checkpoint. *At the T_{i-1}-th trigger call, the system checks if sufficient energy remains to reach the next trigger call at T_i and to checkpoint at T_i. If so, the execution continues. If not, a checkpoint takes place at T_{i-1}.*

- HarvOS is an OS for transiently powered computation[5]
- It heuristically decides how many cycles to run before checkpointing. When power is restored, the system carries on from the last checkpoint

[5]Naveed Anwar Bhatti and Luca Mottola. "HarvOS: Efficient code instrumentation for transiently-powered embedded sensing". In: *Proceedings of the 16th ACM/IEEE International Conference on Information Processing in Sensor Networks*. ACM. 2017, pp. 209–219.

Summary

- No such thing as a "thing" in the Internet of Things
- All things are different
- Vast heterogeneity in terms of:
  - Connectivity (e.g. WiFi vs LoRA)
  - CPU (e.g. ARM A9 vs M0+)
  - Power (e.g. mains vs battery)
  - Cost (e.g. £100 vs £0.05)

Further Reading

Pouya Kamalinejad et al. “Wireless energy harvesting for the Internet of Things”. In: *IEEE Communications Magazine* 53.6 (2015), pp. 102–108

Oliver Hahm et al. “Operating systems for low-end devices in the internet of things: a survey”. In: *IEEE Internet of Things Journal* 3.5 (2016), pp. 720–734

Tolga Soyata, Lucian Copeland, and Wendi Heinzelman. “RF energy harvesting for embedded systems: A survey of tradeoffs and methodology”. In: *IEEE Circuits and Systems Magazine* 16.1 (2016), pp. 22–57