DTU

Networked Embedded Systems

Week 1: Introduction to Networked Embedded Systems

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Embedded Systems

- What is an Embedded System?

Embedded Systems

- A computer in a device whose principal mission is not computation

- A special-purpose computing system
  - Has a dedicated function within a larger system or product
  - Typically measures and controls physical operations

- As opposed to general-purpose computers
  - Laptops, Desktops, Servers

- Embedded systems are everywhere
  - In 2009, it was estimated that more than 98% of produced processors are used in embedded systems
  - Examples: washing machines, microwave ovens, calculators, digital watches, cruise missiles, GPS receivers, heart monitors, laser printers, engine controllers, digital cameras, traffic lights, remote controls, bread machines, fax machines, pagers, cash registers, treadmills, gas pumps, credit/debit card readers, thermostats, pacemakers

Image source: Wikipedia

Washing Machine as an Embedded System

- What are the different computer-controlled functions of a washing machine?

Image source: Wikipedia

Washing Machine as an Embedded System

- Input/Output
  - User selects programme, temperature, rinsing speed, duration, etc
  - User preferences are captured via buttons, switches, touch screens
  - Status of washing cycle, errors are shown in a screen or using LEDs
- Control functions (sensing and actuation)
  - Control valves for getting water in and out of tank
  - Control heater for heating the water in the correct temperature
  - Control power that goes to the rotation motor to get the right RPM
- Safety functions (errors and warnings)
  - Check the door is closed before the programme can start
  - Check the weight of the cloths
  - Check that the right amount of water is in before it starts heating it
- Time keeping
  - Keep the time passed between washing stages
  - Delayed start functionality

Image source: Wikipedia

Connecting the Digital to the Physical World

- Embedded Systems are close to the physical world
  - They employ sensors to measure/perceive the physical world
  - They employ actuators to alter/manipulate the physical world

- Sensors
  - Cameras, microphones, thermometers, humidity sensors, pressure sensors, light sensors, radars, lidars, motion sensors

- Actuators and other output devices
  - Screens, speakers, electric motors, fluid motors, switches, valves, heaters, vibration motors, lights

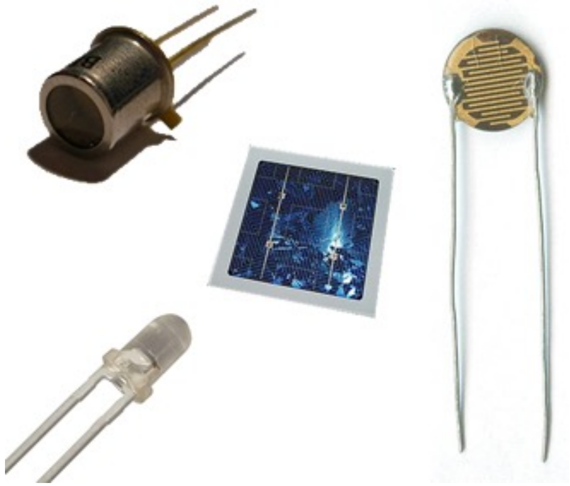
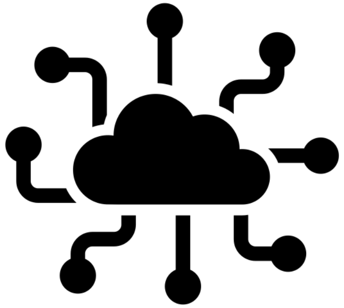


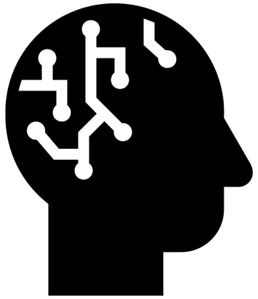
Image source: Wikipedia

Two big trends in Embedded Systems

- **Connectivity**
  - Embedded Systems send/receive data to/from other Embedded Systems or larger systems



- **Intelligence**
  - Embedded Systems provide/consume data as part of Artificial Intelligence (AI) frameworks that extract knowledge and perform reasoning

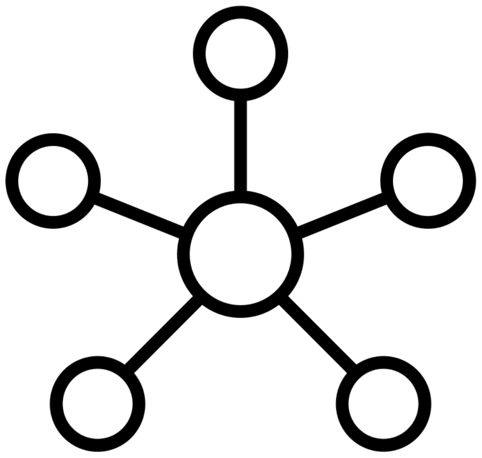


Networked Embedded Systems

- Originally, Embedded Systems operated in isolation as part of a single machine or system
  - E.g. a thermostat inside a boiler measures the temperature and controls the power that goes to heater to reach the desired temperature

- Networked Embedded Systems
  - A group of embedded systems connected over a network and cooperate towards one goal or application
  - Also known as Distributed Embedded Systems

- The first Networked Embedded Systems were connected over wired networks



CAN Bus

- A wired networking solution designed for vehicles
- Originally developed by Bosch starting in 1983
- Officially, released in 1986
- Mercedes-Benz first introduced in the production vehicles in 1991
- Standardised by ISO in 1993

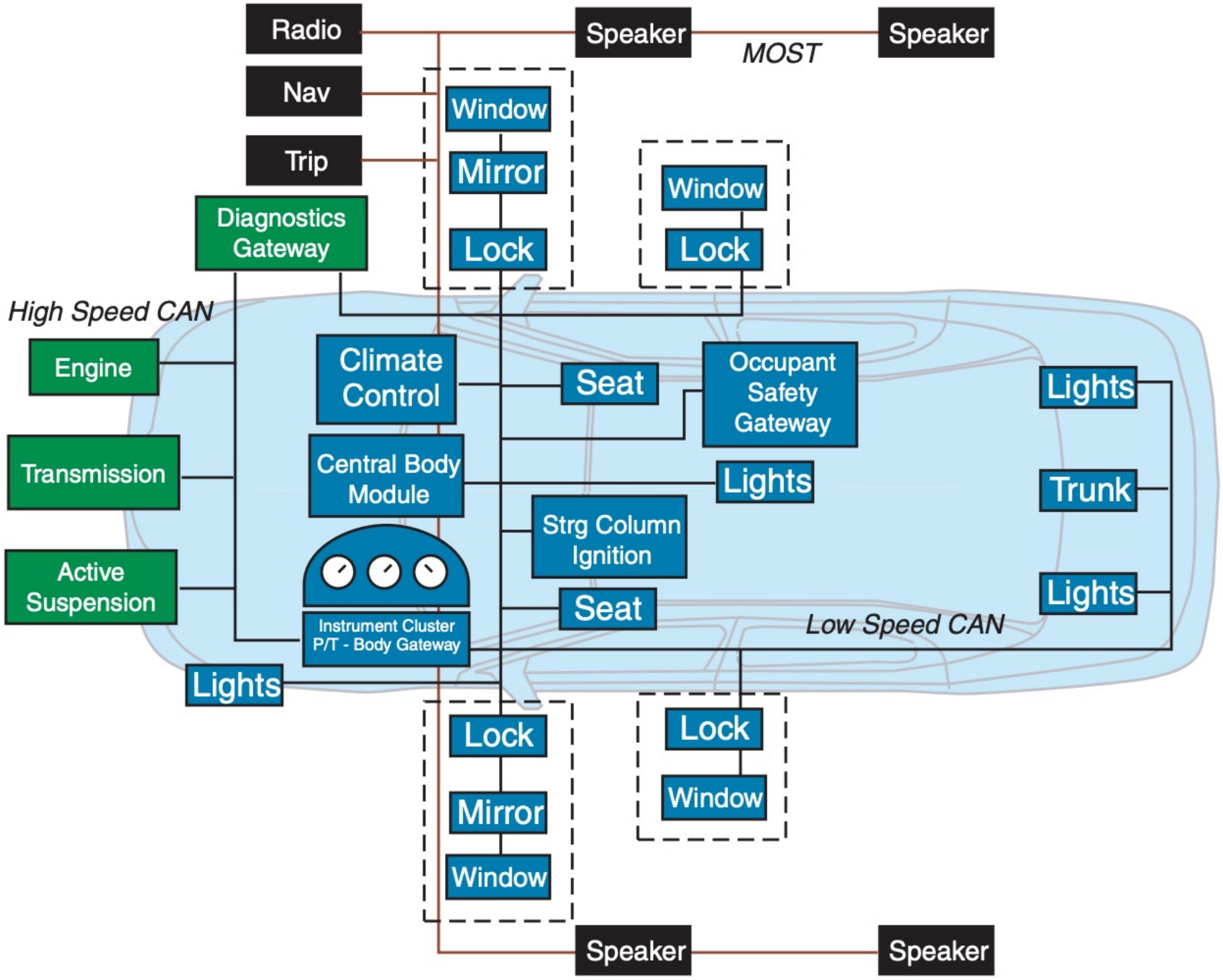
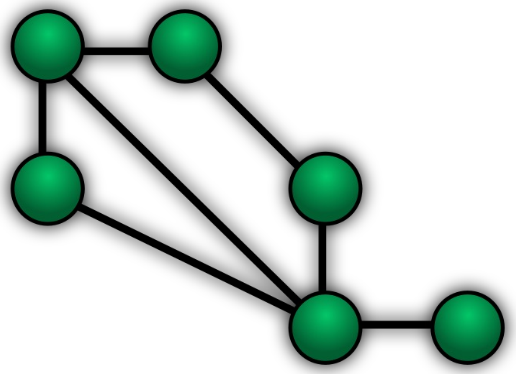


Image source: https://www.eecs.umich.edu/courses/eecs461/doc/CAN_notes.pdf

From Wired to Wireless Embedded Systems

- Wireless Networks are flexible and not require an infrastructure
  - An apartment can have a wires embedded in the walls when built/renovated
  - But wireless networking makes it easier when this infrastructure does not exist

- Wireless Networks provide an easy way to extend the area of coverage
  - From star networks to multi-hop networks
- Wireless Networks enable mobility
  - E.g., wearable embedded systems, portable embedded systems
- Wireless Embedded Systems form:
  - Wireless Sensor Networks
  - Wireless Sensor and Actuator Networks



Mesh

Image source: Wikipedia

Wireless Embedded Systems in Agriculture

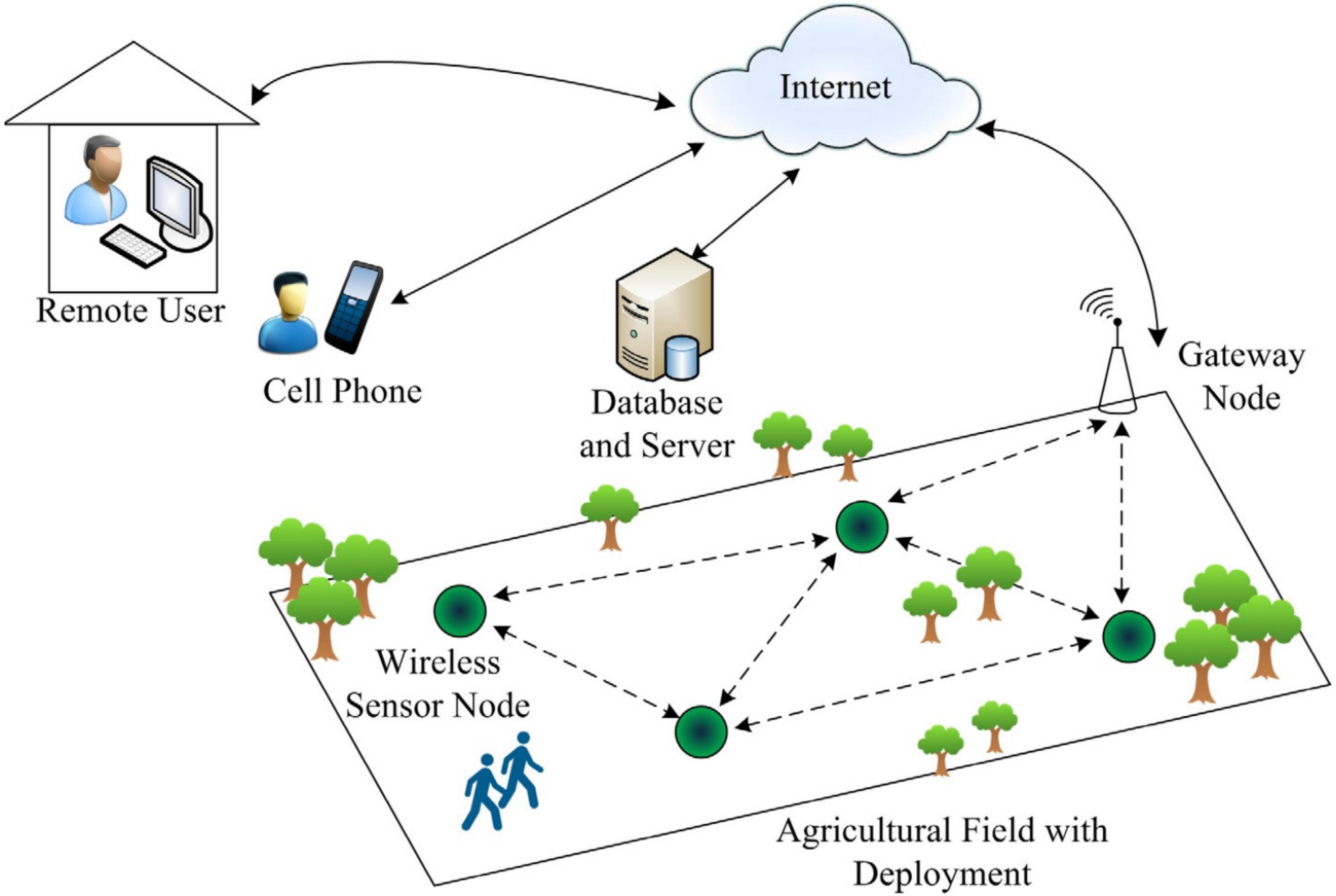


Image source: https://doi.org/10.1016/j.compag.2015.08.011

The Internet of Things

- The Internet of Things connects isolated networks of Embedded Systems in a “global” network

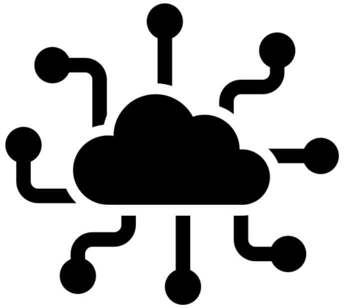
- Several application domains:
  - Smart Cities, transportation networks, logistics
  - Environmental monitoring, wildlife monitoring
  - Disaster response, earthquakes, wildfires
  - Industrial networks, manufacturing, factories
  - Agriculture, maritime
  - Energy management, smart grid
  - Health systems, personal health, fitness
  - Consumer electronics, entertainment
  - Building automation, smart homes
  - Military

Image source: Wikipedia

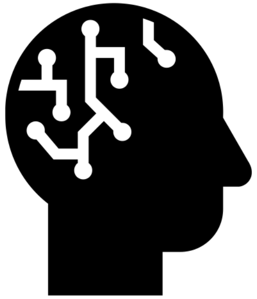
The Connectivity Trend

- Embedded Systems experience an increasing trend for connectivity and collaboration

- From isolated Embedded Systems…
  - To networks of Embedded Systems within the same machine…
  - To Networked Embedded Systems forming wired networks…
  - To Wireless Embedded Systems covering wider areas…
  - To the potentially global and beyond (e.g. satellites) connectivity of the Internet of Things



Intelligent Embedded Systems



- Artificial Intelligence
  - The process of finding patterns and extracting knowledge out of raw data
  - Using the data/knowledge to perform reasoning, decision making, planning, etc
- Cognitive Systems
  - Systems that imitate the human brain

  "Cognition encompasses all aspects of intellectual functions and processes such as: perception, attention, thought, intelligence, the formation of knowledge, memory and working memory, judgment and evaluation, reasoning and computation, problem solving and decision making, comprehension and production of language." Wikipedia
- Autonomous Systems
  - Systems that operate with little or no human intervention

Control Systems

- Regulate a variable using sensing, actuation and a control algorithm
- The classic Embedded System application
- Involves perception (sensing) and decision making (actuation)

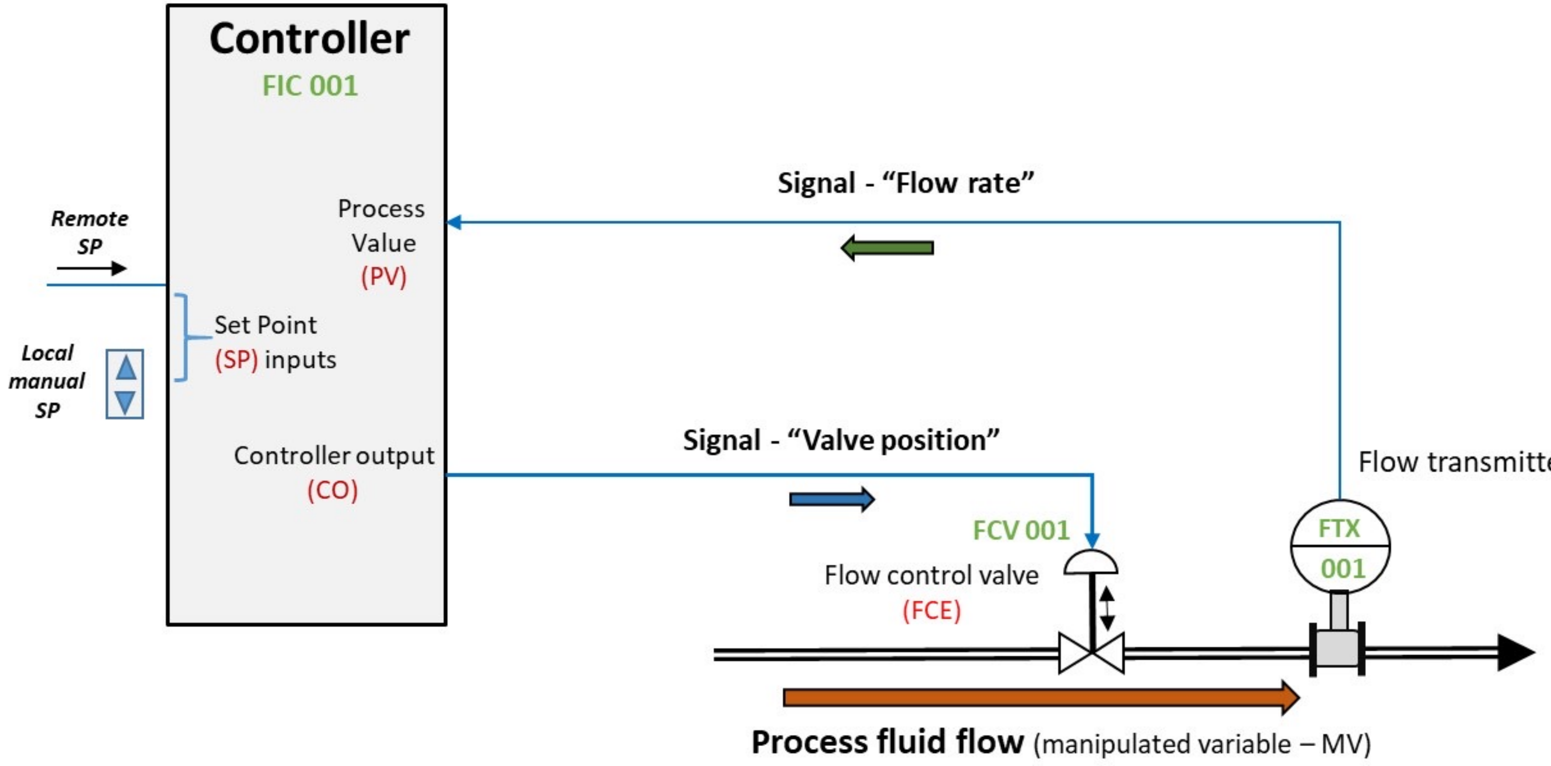
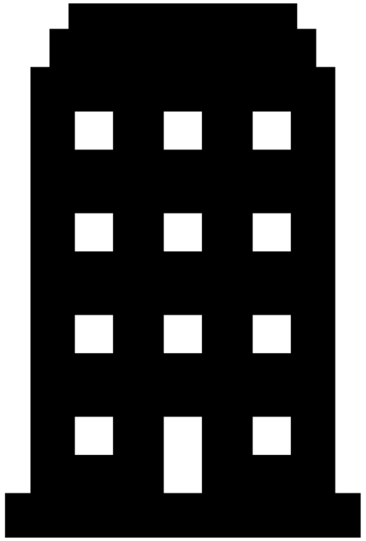


Image source: Wikipedia

Rule-Based Machine Intelligence

- Deductive Reasoning
  - Derive conclusions from rules and axioms
  - E.g. “All humans are mortal”, “Alice is human”, therefore “Alice is mortal”
- Can be formulated as “if-then” statements
  - E.g. ”if X is human, then X is mortal”
- Intelligence and Automation in Networked Embedded Systems
  - E.g. Building Automation:
    - If “motion sensor inside room detects movement” AND
    - “time is between 9 am and 5 pm” AND
    - “room temperature is lower than 19 degrees” THEN
    - “turn on room heating”



Data-Driven Machine Intelligence

- Inductive Reasoning
  - Derive models from observations
  - E.g. “All swans we have seen are white”, therefore “All swans are white”, therefore “I predict that an unknown swan we haven’t seen is also white”
- In relatively “simple” problems, we can hand-craft models out of observations that have high predictive power
  - E.g. We can use Newton's Law’s to predict the exact location of a planet in the future
- In more “complex” problems, we instruct machines to find a model that explains the input data and use it to predict future data
  - Machine Learning

Deep (Artificial) Neural Networks

- Very good at constructing complex models with high predictive power based on observations
- Require a lot of computing power
- Require a lot of observations (input data)
- Enabled by advances in Cloud Computing and Big Data
- In this context, Networked Embedded Systems play the role of (big) data generators

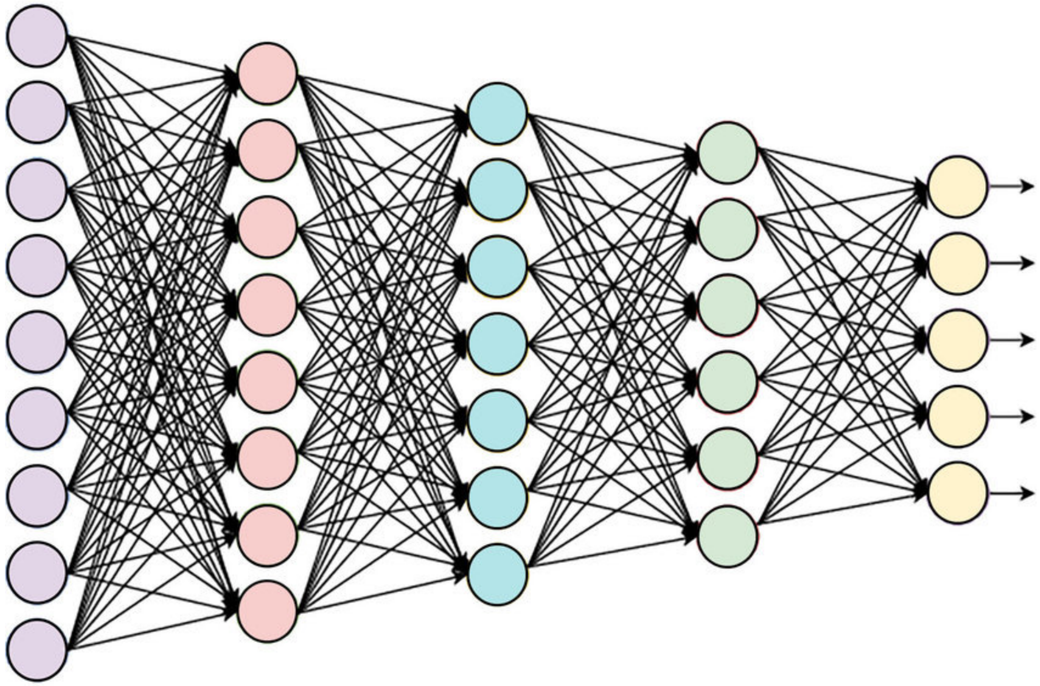


Image source: http://dx.doi.org/10.1109/ACCESS.2020.3009819

Cloud-based IoT Systems

- Advantages
  - Lots of computing power
  - Lots of storage
  - Possible to train really accurate but very resource-consuming deep learning models
- Disadvantages
  - High cost to transfer, store, process lots of data
  - Latency may be prohibiting for delay-sensitive use cases
  - Dependency to infrastructure (no coverage zones)
  - Privacy (potentially sensitive data goes to third parties)

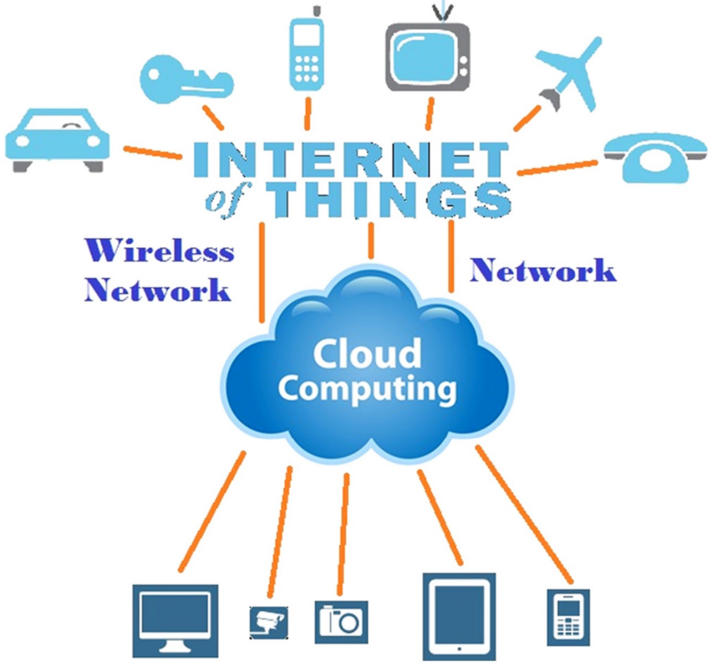


Image source: https://doi.org/10.1016/j.future.2016.11.031

Cloud-Fog-Edge Continuum

- Computing and AI is distributed in a cloud-fog-edge continuum as needed by the applications
- Embedded AI
  - AI comes to Embedded Systems (inference, training)
  - Embedded System become more autonomous (sensing, knowledge extraction, planning, decision making)
- Local Fog Servers are employed when more computing power or data fusion is needed
  - Privately-owned or offered as a service
- Cloud Data Centres used for really demanding tasks (e.g. training NLP models)

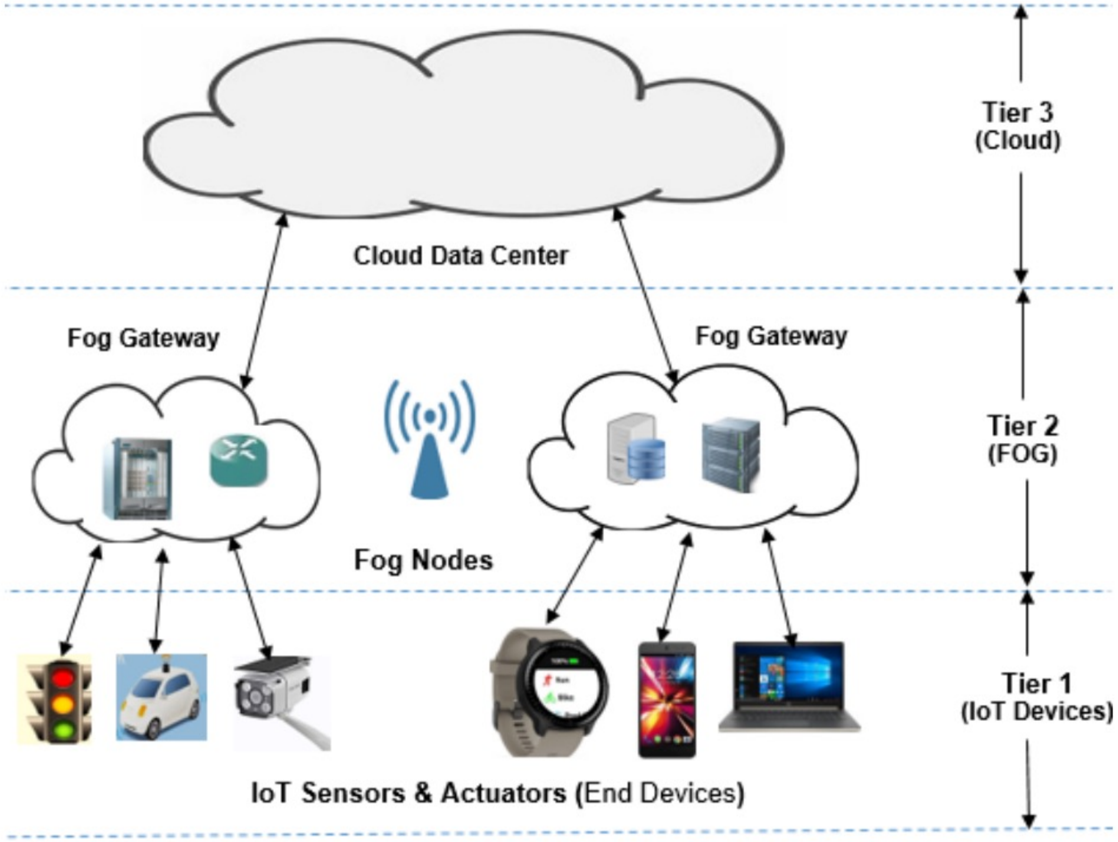
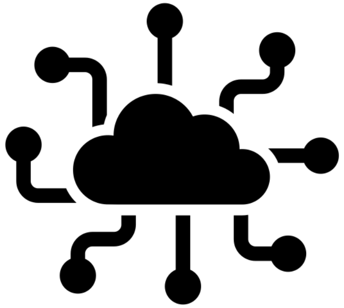


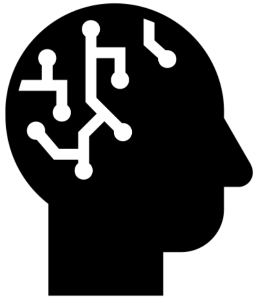
Image source: https://doi.org/10.1109/ACCESS.2020.3032388

Two big trends in Embedded Systems

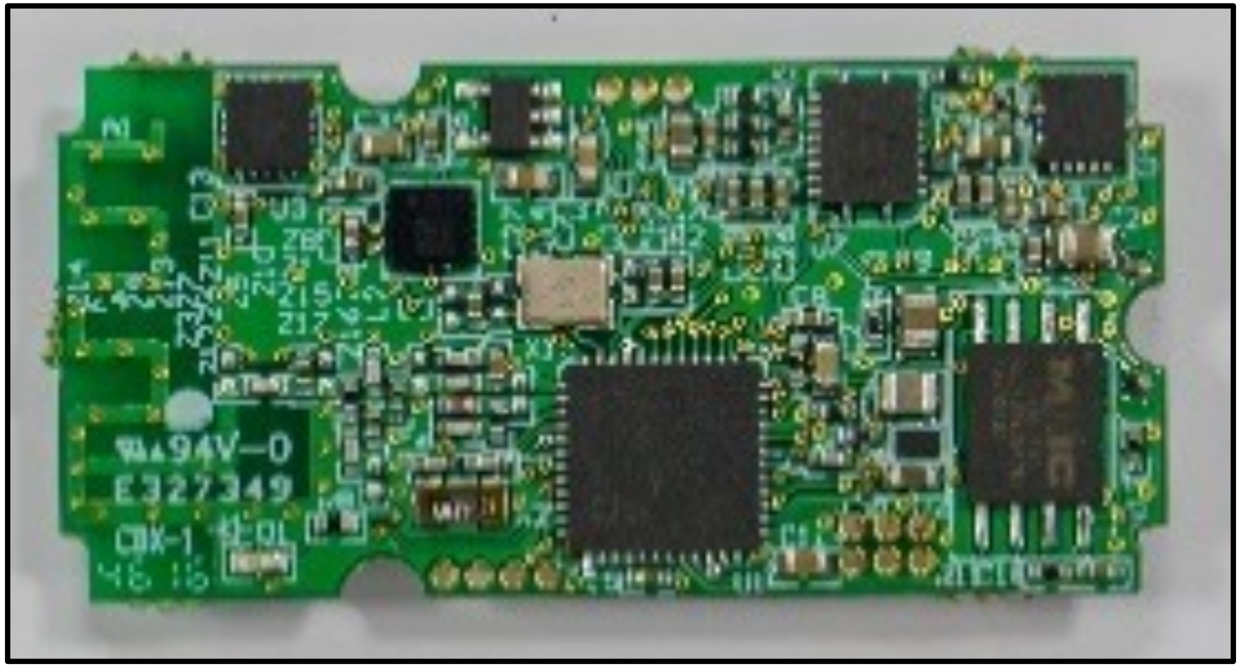
- **Connectivity**
  - Embedded Systems are getting connected, forming larger and wider (potentially global) collaboration networks



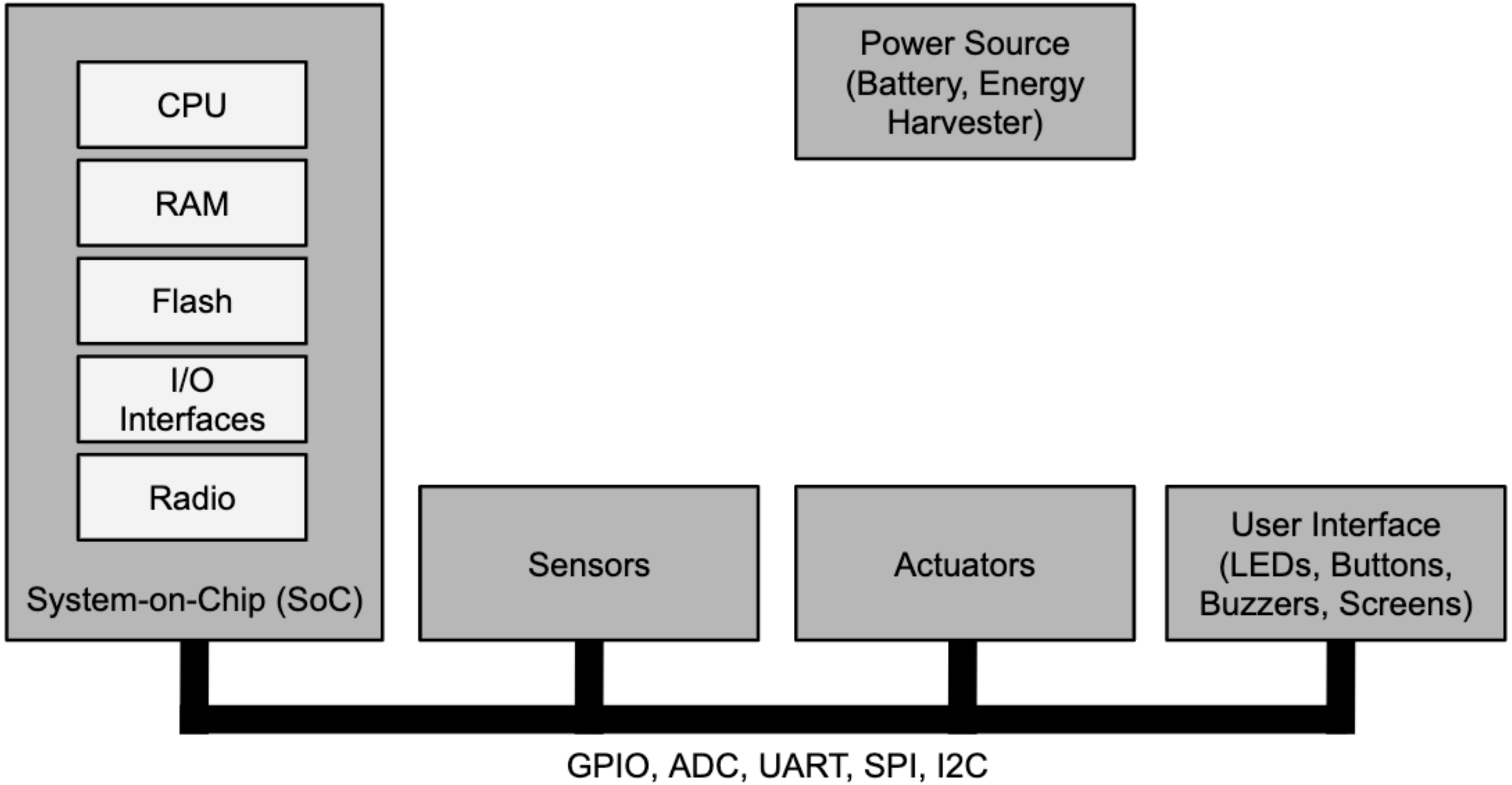
- **Intelligence**
  - Embedded Systems are becoming more intelligent, processing data locally, capable of embedded AI, and autonomous decision making



What are the main components of an Embedded System?



Anatomy of an Embedded System



Microcontrollers (MCU) and Systems-on-Chip (SoC)

- Small computer in a chip
  - Processor (CPU)
  - RAM
  - Input/Output Peripherals

- System-on-Chip (SoC)
  - MCU (processor, RAM, I/O)
  - Non-volatile storage (flash memory)
  - Network interfaces (wireless radio)
  - Other processing units (GPU, DSP, accelerators)
  - Integrated Sensors

Image source: Wikipedia

Example SoC

- CC2650 by Texas Instruments
  - ARM-based CPU
  - Memory (RAM, Cache, ROM, Flash)
  - Wireless Module with its dedicated CPU/RAM
  - Sensor Controller
  - Various controllers for interfaces
  - Various timers
  - Crypto module
  - Integrated temperature sensor
  - Integrated battery monitor
  - Direct Memory Access (DMA)

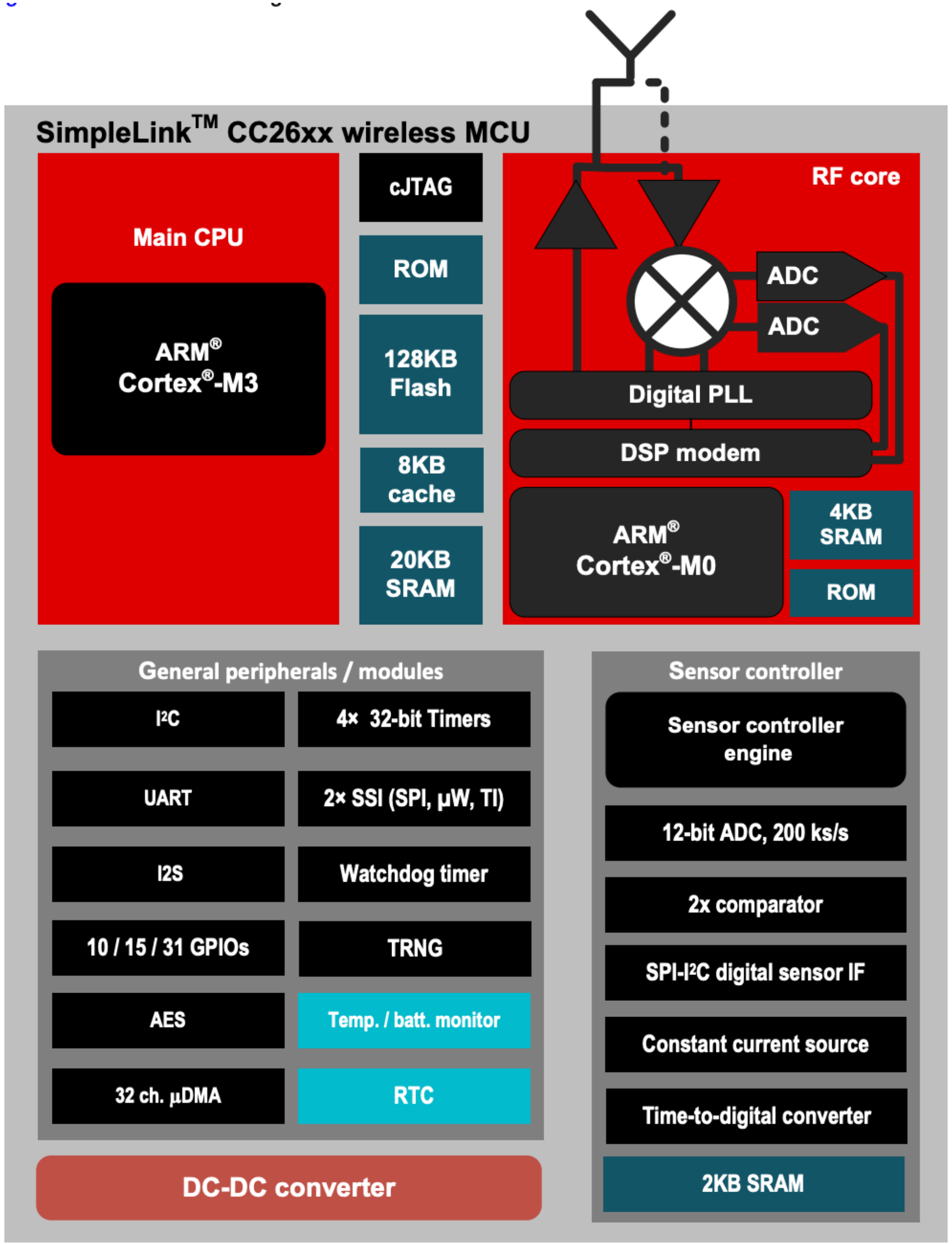


Image source: CC2650 Datasheet by Texas Instruments

Processors

- 8-bit, 16-bit, 32-bit, 64-bit architectures
- Popular architectures/vendors
  - AVR (Atmel)
  - PIC (Microchip)
  - MSP (Texas Instruments)
  - STM (ST Microelectronics)
- ARM (licenses CPUs to chip vendors)
  - ARM Cortex-A series (generic applications)
  - ARM Cortex-R series (real-time)
  - ARM Cortex-M series (embedded, low-power)

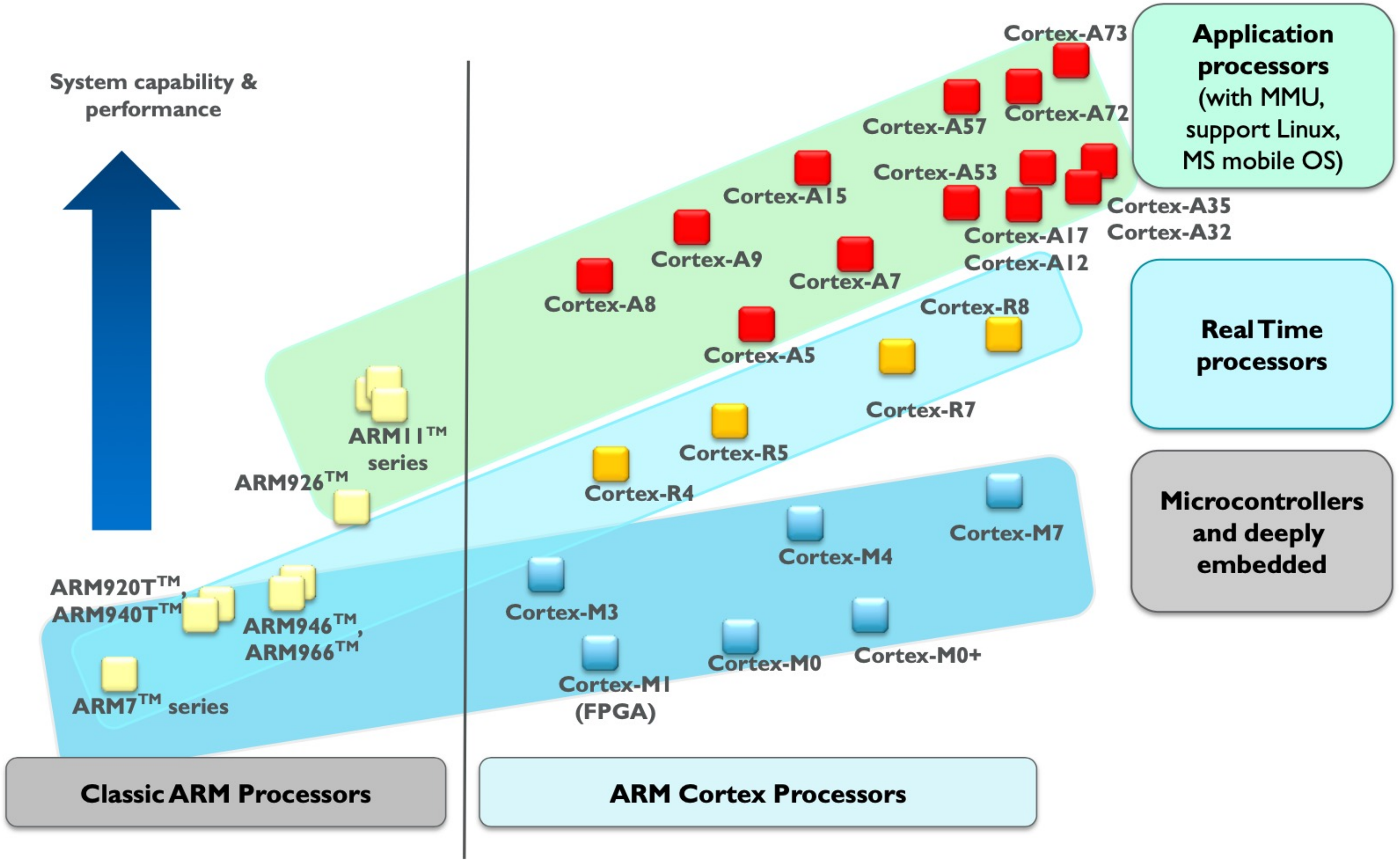


Image source: Cortex-M for Beginners by ARM

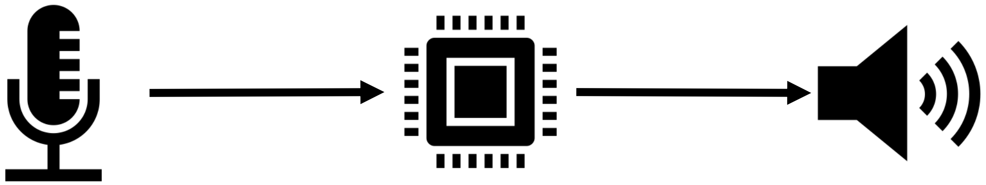
Transducers: Sensors and Actuators

- Sensors/Actuators are transducers that convert a signal from one form of energy to another

- Input Transducers convert a physical quantity into an electrical signal
  - Sensors (e.g. accelerometer, thermometer, microphone, cameras)

- Output Transducers convert an electrical signal into a physical quantity
  - Actuators and other output devices (e.g. motors, heaters, speakers, LEDs)

- Types of Transducers
  - Electromechanical
  - Electromagnetic
  - Electrochemical
  - Electroacoustic
  - Electro-optical
  - Thermoelectric



Sensors

- Analogue Sensors
  - Produce an electrical signal that correlates with a physical phenomenon
  - To be processed by a digital system, we need an Analogue-to-Digital Converter (ADC)
- Digital Sensors
  - Analogue sensors packed in a chip with an ADC and a controller

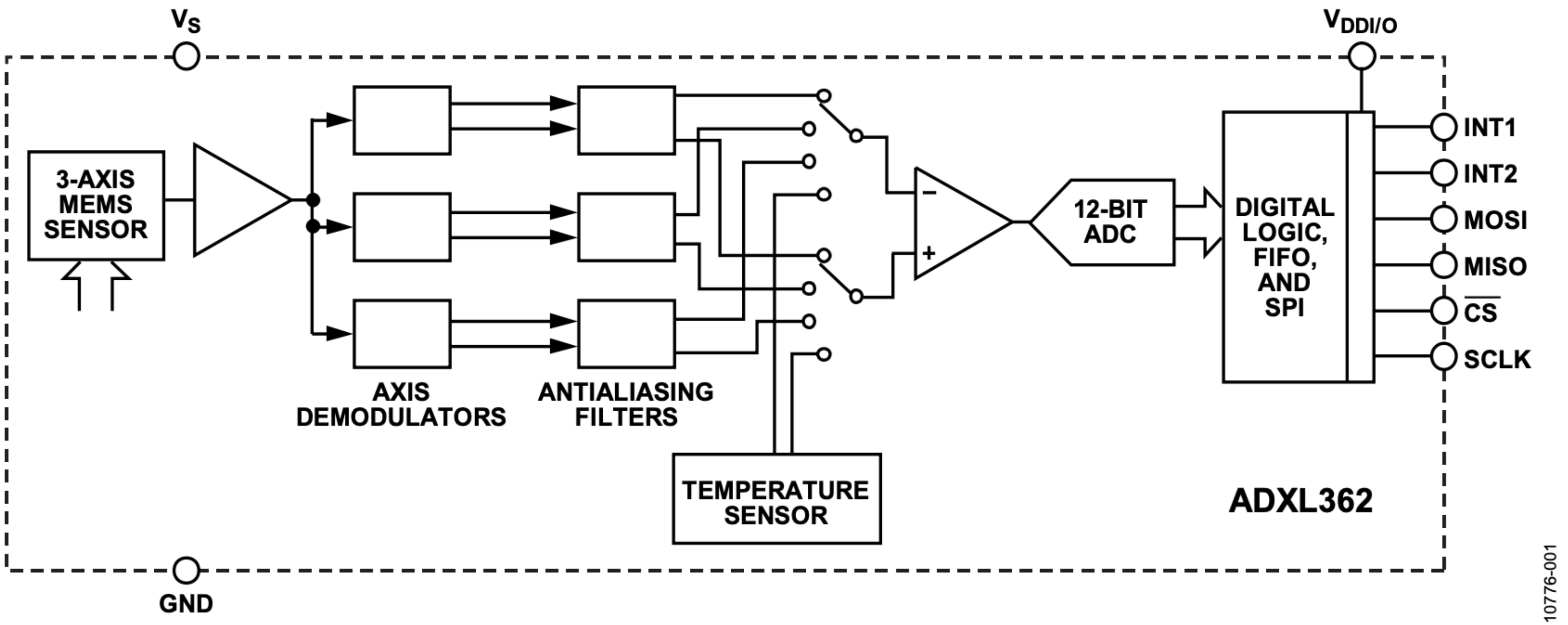


Image source: ADXL362 Datasheet by Analog Devices

Types of Sensors

- Electromechanical
  - Accelerometer, gyroscope, flow meters, air pressure
- Electromagnetic
  - Magnetometer, contact sensors, RADAR
- Electrochemical
  - pH, gas sensors, chemical detection
- Electroacoustic
  - Microphone, ultrasound, piezoelectric sensors
- Electro-optical
  - Camera, infrared camera, light sensor, PIR, LIDAR, heart rate (PPG)
- Thermoelectric
  - Temperature sensor, body temperature

Actuators/Output Devices

- Actuators/Output Devices
  - Control/manipulate an physical quantity with an electric signal
  - To be controlled by a digital system, we need a Switch, Digital-to-Analogue Converter (DAC), Signal Generator or Modulator

- Controller Chips
  - Implement a command interface to control the physical output

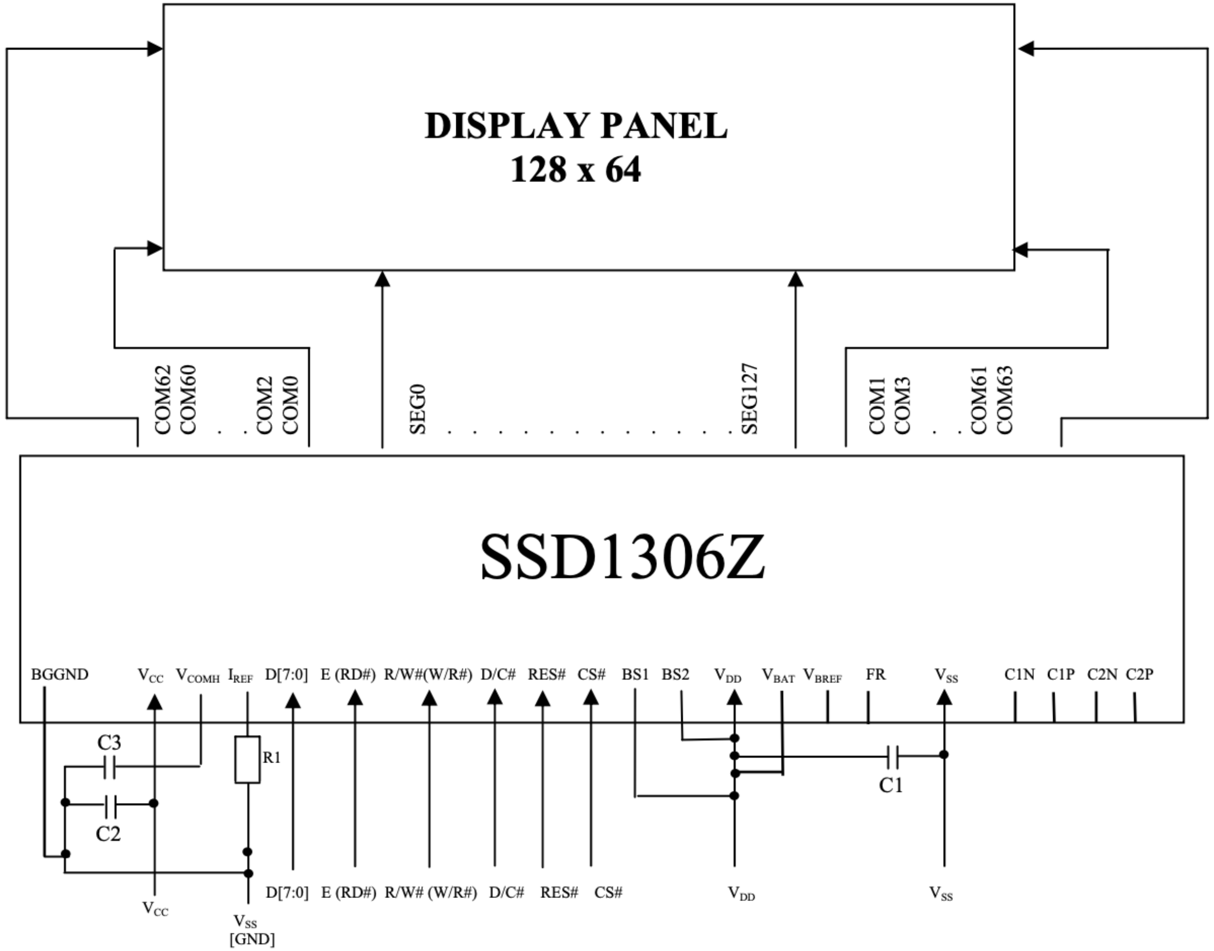


Image source: SSD1306 Datasheet by Solomon Systech

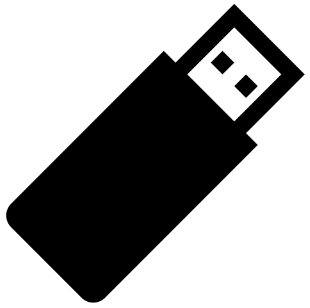
Types of Actuators/Output Devices

- Electromechanical
  - Motors, valves, vibration motor
- Electroacoustic
  - Loudspeaker
- Electro-optical
  - Screen, LEDs
- Thermoelectric
  - Heater

Other Input/Output Components

- External Storage
  - Flash memory chips
  - SD cards

- Connectors/Interfaces
  - Jacks, pin headers, sockets
  - Antenna connectors, printed antennas
  - Jumpers, solder bridges
  - Etc



Power Management

- Embedded Systems are typically powered by DC sources
  - Batteries or via the mains through rectification
  - Power source is typically noisy and imperfect
- Voltage Regulators
  - Automatically maintain constant output voltage
  - Linear Voltage Regulator (linear voltage adjustment, dissipate power)
  - Switching Regulators (rapid on/off switching, more efficient)
- Voltage Converters (DC-to-DC converter)
  - Converts a source from one voltage to another
  - Components may require to be powered at different voltage levels
  - Step-down Converter (Buck Converter): output voltage is lower than the input voltage
  - Step-up Converter (Boost Converter): output voltage is higher than the input voltage

Power Management

- Battery Charging
  - Battery Charger (e.g. via USB)
  - Inductive Wireless Power Receiver (e.g. Qi)

- Energy Harvesting
  - Solar Power Manager
  - RF Power Manager
  - Etc

The main components of an Embedded System