Embedded Computer Systems and Applications

Lecture 1

Hardware, Software and Applications

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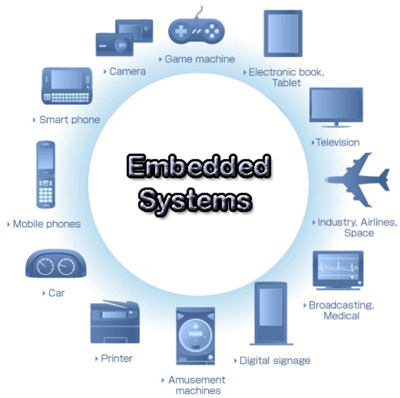
Contents

- What are embedded systems?
  - Past, present and future
  - Technology trends and limitations
- What will be used in this class?
  - Course ware: lecture slides, technical manuals, etc.
  - Hardware: Raspberry Pi 4B and sense hat
  - Software: Raspberry Pi OS (Linux) and Python
- What are the assignments?
  - Essentially at-home lab exercises
- What is your semester project?
  - Propose your own.
  - Presentations for the draft and eventually for the final product.

Section I

WHAT ARE EMBEDDED SYSTEMS



Embedded Systems

- Embedded system is an electronic, electrical or mechanical system with computer at its center.
  - The first: Apollo Guidance Computer 1965.
  - Robots, driverless cars, home appliances, telecommunication, IoT (internet-of-things), etc.
- Often for specific applications, not general purpose.
- Mostly for real-time applications.
- Less “open”; i.e. fewer or no option to expand, modify or adapt to new configuration.
- May use generic platform or costumed designs.

A Brief History of Embedded Systems

- Random Logic: Claude Shannon 1937.
- Microprocessor /Microcontroller: Intel 4004 1971.
- Personal computers:
  - Micral N with Intel 8080 in 1971.
  - Apple I with MOS 6502 in 1976.
- System-on-Chip: due to Moore’s Law
  - One PCB => One VLSI IC
- Intellectual Property Cores: around 1990’s
- FPGA: Xilinx XC2064 1985.
- VHDL: VHSIC project, IEEE 1076-1987.
- Embedded Operating systems

Confusing Terminology

Terminology	Perspective	Meanings
Embedded Systems	System organization	Electronic, electrical or mechanical system with computer at its center. Not general purpose. Mostly for real-time applications.
Embedded OS	Special OS	OS optimized (simplified) for embedded systems specific needs.
Micro-controller	Processor design	A simple CPU for simple controlling of I/Os.
Internet-of-things	Distributed system org.	A vast network of embedded systems and/or micro-controller systems. Everything is connected.
Cyber-physical syst.	Applications	Emphasis on the human-machine, or machine-real-world interfaces and their applications.
System-on-Chip	IC manufacturing	A complete computer system on a single IC chip.

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Technology Trends and Limitations

- Moore's Law dictates the technology trends for the past five decades.
  - Semiconductor road map publish annually by Semiconductor Industry Association actually enforce the continuation of Moore's Law.
  - As of 2020, the smallest dimension is 5nm in commercial production of IC. Samsung has announced their 3nm production to be commercially available in 2021.
  - The number of devices on a single chip enables the system-on-chip, and soft-core IPs.
- There is a limitation to how much performance can be improved with increasing number of processors (cores): Amdahl's Law.
- The limitation may also come from power/heat.

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Moore's Law

- The number of transistors on a single IC increases exponentially, i.e. double every (1, 1.2, 2, ..) years
  - Physical property: transistors can be scaled down.
  - Manufacturing: IC chip dimensional can grow larger.
  - SIA (Semiconductor Industry Association): annually release its roadmap to ensure Moore's Law may continue.
- The current limitations are:
  - Multi-core and/or Parallel computing have diminishing return (Amdahl's Law). When adding more processors or more computers to a system does not significantly increase its computational power.
  - Heat due to huge power consumption is a major concern.
    - Data center: spend more on cooling than computing.
    - IC chip: forced cooling for high-end chips.

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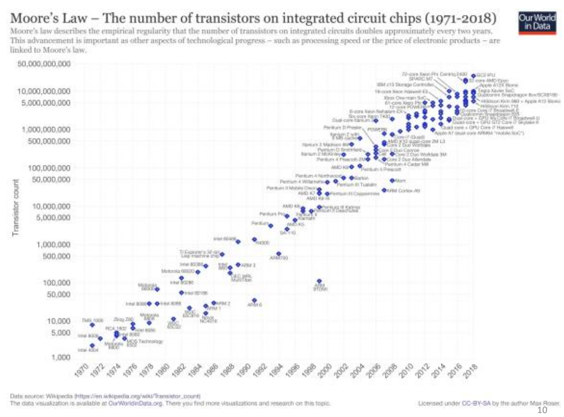

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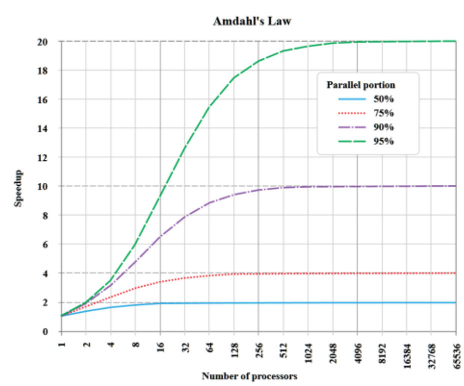

Amdahl's Law

- The speedup factor of a computer system with more than one processor, i.e. multi-core or parallel computing, is limited by the serial part of the program being executed.
  - Speedup is not proportional to the number of processors, e.g. quad-core CPU is not 4-time faster than a single-core CPU.
  - Speedup is limited by the program not the number of processors.
  - Any parallel program has a serial part that can only be executed on a single processor.

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Power Consumption of Digital Electronics

- Typical CMOS circuits:
  Power = Pdyn + Psc + Pleak
- Pdyn = power consumed due to circuit activities
  Pdyn = C V^2 f
  - C : total capacitance
  - V : supply voltage
  - F : circuit frequency
- Psc = power consumed due to short-circuit, when switching from one state to another state a logic gate may have momentary short circuit.
- Pleak = Power loss due to leakage.

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Reducing Power (Heat)

- Voltage reduction – dual-voltage CPUs, dynamic voltage scaling, etc.
- Frequency reduction – underclocking, dynamic frequency scaling, etc.
- Capacitance reduction – increasingly integrated circuits that replace PCB traces between two chips with relatively lower-capacitance on-chip metal interconnect between two sections of a single integrated chip; low-k dielectric, etc.
- Techniques such as clock gating and globally asynchronous locally synchronous, which can be thought of as reducing the capacitance switched on each clock tick, or can be thought of as locally reducing the clock frequency in some sections of the chip
- Various techniques to reduce the switching activity
- Layering heat-conduction zones within the CPU framework

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System-on-Chip

- System-on-Chip (SoC) puts the entire system on a single IC chip. Usually a fully equipped computer system including memory and I/O.
- It's a natural progression of integration:
  - Loose transistors → integrated circuit (IC)
  - MSI → LSI → VLSI
  - As ICs become larger and more complex, number of ICs on a mother is reduced
  - Put (almost) the entire motherboard on an IC (SoC)
- Applications:
  - Embedded systems
  - Mobile computing
  - Personal computers

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Outlooks of SoC

- Moore's Law may continue for a while, however the growth rate will slow down significantly.
- Improvements in parallel programming so far has continue to provide speedup for multi-core (CPU) architecture.
- Heat due to the power consumption is still an issue. However, many solutions have been in placed in many commercial chips.
- The SoC has been a norm for the IC industry. The industry is thus separated into IC fabrication companies, Chip designers, and IP cores venders.

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Semiconductor IP Cores

- Advent of soft IP cores
  - A complete system involves many diverse components such as CPU, memory, I/O devices, etc. It is too complex for one single company to handle them all.
  - There are companies (venders) who sell IP cores (design only) and thus make SoC or SoPC feasible.
  - The design of SoPC is thus about using these IP cores to built a complete computer system.

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Hard vs. Soft IP Cores

- Hard IP cores: the design (circuit) has been realized in the lowest level and is not allowed to altered by the user. Usually a hard IP core may come in the form of an encrypted IC layout. User will then integrated it with the other components on the chip.
- Soft IP cores: the design is described in a hardware description language, VHDL, Verilog HDL, etc., and the user will integrate it with the hardware description of the other components of the system. The manufacturing of the real hardware is by the users.

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ARM Processor

- **ARM**, previously **Advanced RISC Machine**, originally **Acorn RISC Machine**, is a family of reduced instruction set computing (RISC) architectures for computer processors, configured for various environments.
- ARM Holdings develops the architecture and licenses it to other companies, who design their own products.
- ARM processor is actually a soft IP core. However, Intel implemented it on the FPGA and thus the hard processor not soft processor.

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Embedded Systems Applications

- Embedded systems are commonly found in consumer, industrial, automotive, home appliances, medical, telecommunication, commercial and military applications.
- Cyber-Physical Systems
- Internet-of-Things
- Driverless cars

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Cyber-Physical Systems

- A **cyber-physical system** (**CPS**) is a mechanism that is controlled or monitored by computer-based algorithms, tightly integrated with the Internet and its users.
- A recent and important branch of embedded systems.
- Unlike more traditional embedded systems, a full-fledged CPS is typically designed as a network of interacting elements with physical input and output instead of as standalone devices.
- Closely tied to concepts of robotics and sensor networks with computational intelligence.

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Internet-of-Things

- Mass number of smart devices connected/communicated via a network
  - Most devices (things) are embedded system having the capabilities to collect data to transmit over the network or receive command to act.
  - Each device has an unique identifier (UID).
  - Network bandwidth must be sufficient.
  - Wireless network is more popular than wired one.
- Applications:
  - Home
  - Military
  - Healthcare
  - Manufacturing

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Driverless Cars

- SAE (Society of Automotive Engineers) classifications:
  - Level 0: (no automation) issue warning and may momentarily intervene
  - Level 1: (hands on; driver assistance) adaptive cruise control, parking assistance, etc.
  - Level 2: (hands off; partial automation) system drives the car with driver monitoring the operation.
  - Level 3: (eyes off; conditional automation) driver can leave the system to drive most of the time.
  - Level 4: (mind off; high automation) no driver attention is ever required. Driver may still regain control in special cases.
  - Level 5: (steering wheel optional; full automation) absolutely no driver intervention, and thus no more steering wheel.
- Tesla Autopilot → SAE level 2

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Embedded Operating Systems

- Simple embedded systems usually do not need an operating system.
- Modern embedded systems, especially cyber-physical systems, require an embedded operating system to handle the multi-tasking, and network management. In some applications, human interface via touch screen display is very important.
- Embedded operating systems are often real-time and reconfigurable.
- Embedded operating systems are optimized for specific embedded systems, e.g. Android vs. Linux

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Future of Embedded Systems (I)

- The SoCs for embedded systems will see the integration of more co-processors, accelerator, special devices, etc. rather than just adding more CPU (cores).
- Micro-kernel operating system as opposite to the macro-kernel Linux system is more suitable for embedded systems.
- Each application is unique. However, common architectures/organizations of embedded systems are still possible.

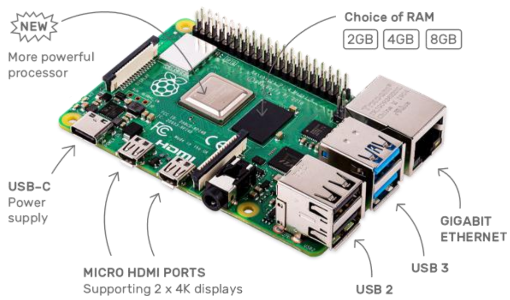
Future of Embedded Systems (II)

- Wireless networks:
  - Higher bandwidth and faster response time
  - More power efficient
- Embedded system will not just collect data and upload them to the server or the cloud, but will pre-process or process data locally.
- Security of embedded systems are increasingly important especially for those in military, industrial and public-safety related applications.
  - Virus protection
  - Data encryption
  - Hardware Trojan or hardware related attacks prevention.

Section II

WHAT WILL BE USED IN THIS CLASS?

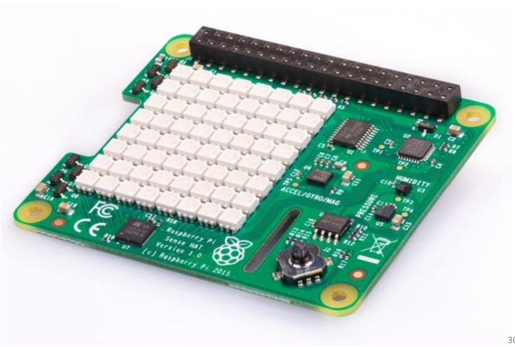
Raspberry Pi 4B



Raspberry Pi 4B

- **Processor: Broadcom BCM2711, quad-core Cortex-A72 (ARM v8)** 64-bit SoC @ 1.5GHz
- **Memory: 2GB, 4GB or 8GB LPDDR4** (depending on model)
- **Connectivity: 2.4 GHz and 5.0 GHz IEEE 802.11b/g/n/ac wireless** LAN, Bluetooth 5.0, BLE
  - Gigabit Ethernet
  - 2 × USB 3.0 ports
  - 2 × USB 2.0 ports.
- **GPIO:** Standard 40-pin GPIO header
- **Video & sound:**
  - 2 × micro HDMI ports (up to 4Kp60 supported)
  - 2-lane MIPI DSI display port
  - 2-lane MIPI CSI camera port
  - 4-pole stereo audio and composite video port
- **SD card support:** Micro SD card slot for loading operating system and data storage

Raspberry Pi Sense Hat



Raspberry Pi Sense Hat

- The Sense HAT is an add-on board for Raspberry Pi, made especially for the Astro Pi mission – it launched to the International Space Station in December 2015 – and is now available to buy.
- The Sense HAT has an 8×8 RGB LED matrix, a five-button joystick and includes the following sensors:
  - Gyroscope
  - Accelerometer
  - Magnetometer
  - Temperature
  - Barometric pressure
  - Humidity
- A Python library providing easy access to everything on the board.

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Raspberry Pi OS

Formerly known as Raspbian

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Raspberry Pi OS

- **Raspberry Pi OS** (formerly **Raspbian**) is a Debian-based operating system for Raspberry Pi. Since 2015 it has been officially provided by the Raspberry Pi Foundation as the primary operating system for the family of Raspberry Pi single-board computers.
  - The original Raspbian OS was created by Mike Thompson and Peter Green as an independent project.
  - The initial build was completed in June 2012.
- Raspberry Pi OS is highly optimized for the Raspberry Pi lines of compact Single Board Computers with ARM CPUs.
  - Modified LXDE as its desktop environment
  - The Openbox stacking window manager
  - The distribution is shipped with:
    - algebra program Wolfram Mathematica
    - a version of Minecraft called Minecraft Pi
    - a lightweight version of Chromium
    - Python

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Section III

WHAT ARE THE ASSIGNMENTS?

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Assignments/Labs

- Assignments are essentially at-home lab exercises.
  - Four lab assignments (9/21, 9/28, 10/5, 10/12) to familiar with the Raspberry Pi and sense hat.
    - Getting started
    - Sense Hat Pong
    - Web server
    - Neural network
  - Mid-term assignment (10/26; after the proposal draft presentation). This will be similar in scope and difficulty like the regular lab assignments but with severe time constraint (complete in one day).

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Section IV

WHAT IS YOUR SEMESTER PROJECT?

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Project guidelines

- Try to use only the existing hardware and software already available.
- The project must use at least one sensor input; the more the merrier.
- The project should have the network component so the embedded system can communicate with other computer systems. This may be for uploading data, establish machine interaction, provide remote control, etc.
- Human to machine interaction may be optional but encourage.
- Project does not have to be totally novel! Repeating exiting designs but with a new twist is always a good idea to learn.

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Project Proposal Draft

- Week 7 (10/26): presentation of the project draft
  - Goals
    - What will be achieved?
    - Where is the design be used?
    - Why is the project “important” or “interesting”?
  - Milestones
    - How are the works divided into five weeks?
    - What are the “checkpoints” at the end of each week?
  - Resources
    - What exactly will be needed to complete the project; including all hardware and software?
    - Any extra hardware or software not currently available?

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Final Project Presentation

- Week 13 (12/7): presentation and demonstration of the project final.
  - Each person will have about 10 minutes to give a final presentation and to demonstrate the project design.
  - A written final project report.
  - The software source codes.
  - Presentation slides

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