SoC 101

a.k.a., "Everything you wanted to know about a computer but were afraid to ask"

Prof. Adam Teman

EnICS Labs, Bar-Ilan University

21 March 2023

EnICS
Emerging Nanoscaled
Integrated Circuits and Systems Labs

The Alexander Kofkin
Faculty of Engineering
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Lecture 1: Introduction

Prof. Adam Teman

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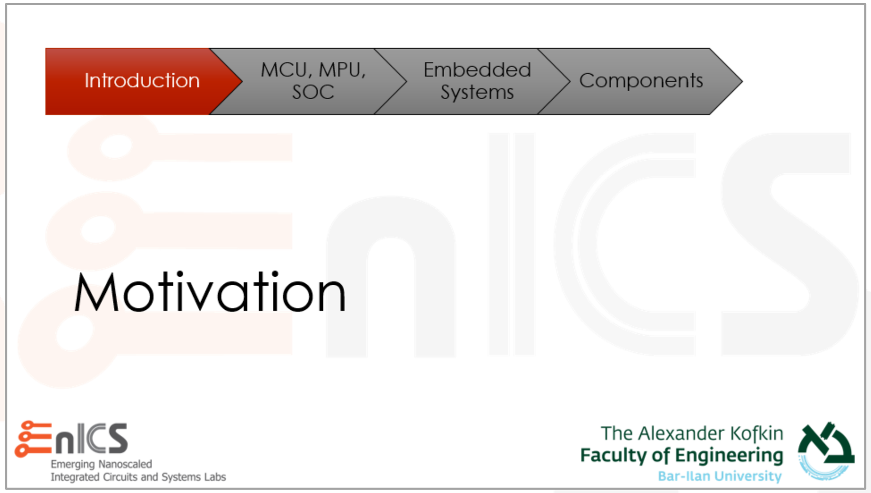
Outline


Introduction | MCU, MPU, SOC | Embedded Systems | Components

Motivation

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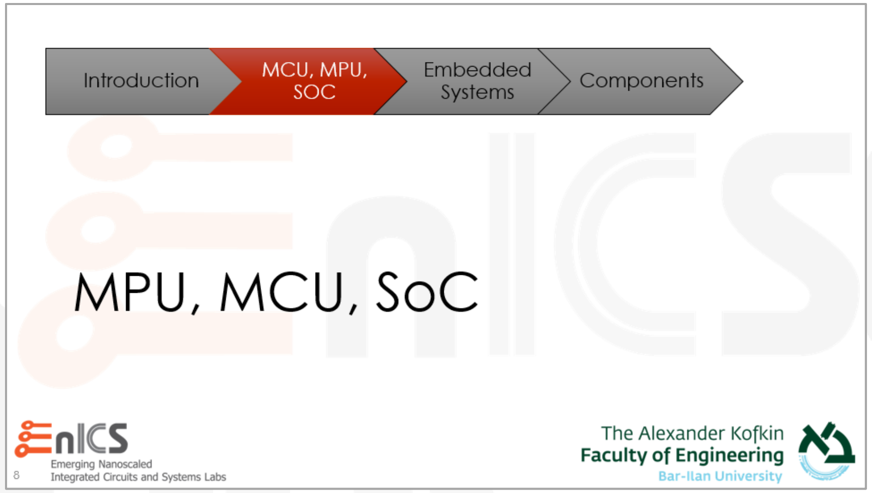
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MPU, MCU, SoC

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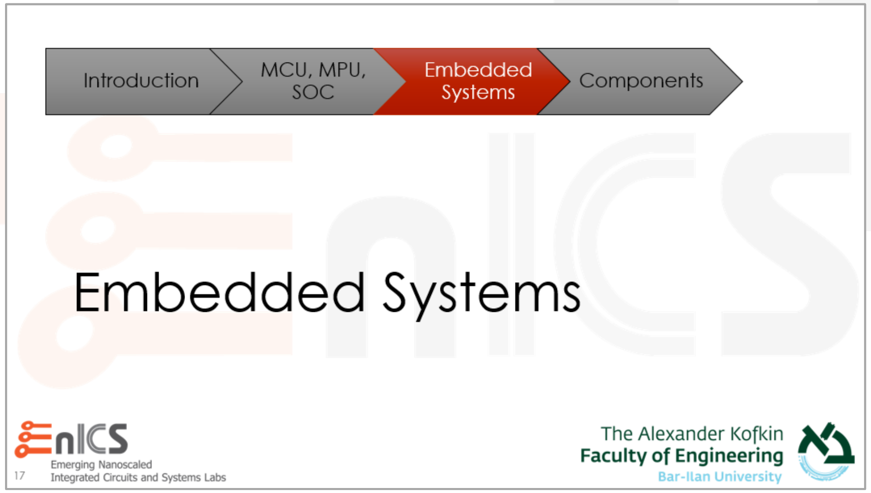
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Embedded Systems

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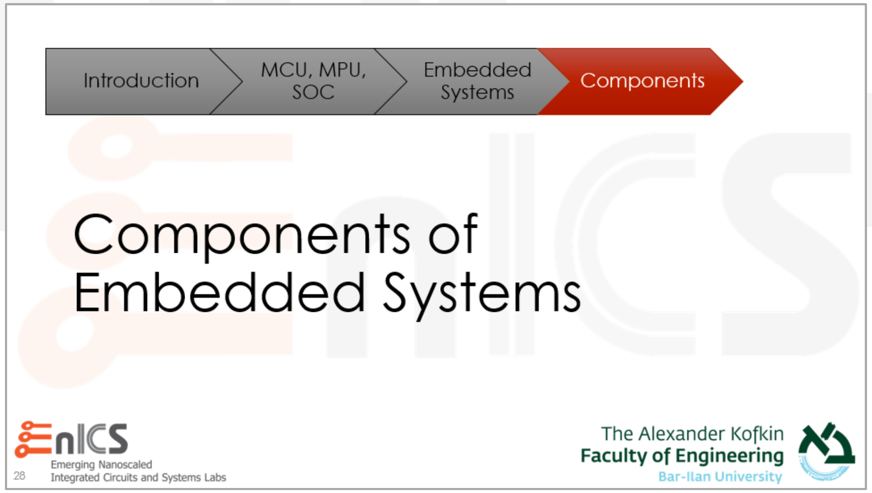
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Components of Embedded Systems

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Introduction | MCU, MPU, SOC | Embedded Systems | Components

Motivation

Course Motivation

- **How many of you understand this recent news item?**

- Qualcomm Snapdrago
  - CPU ... Cortex-X3

...264, ... etc.

...SP with AI Engine

...-bit up to 3200MHz,

...EVC), VP9, VP8

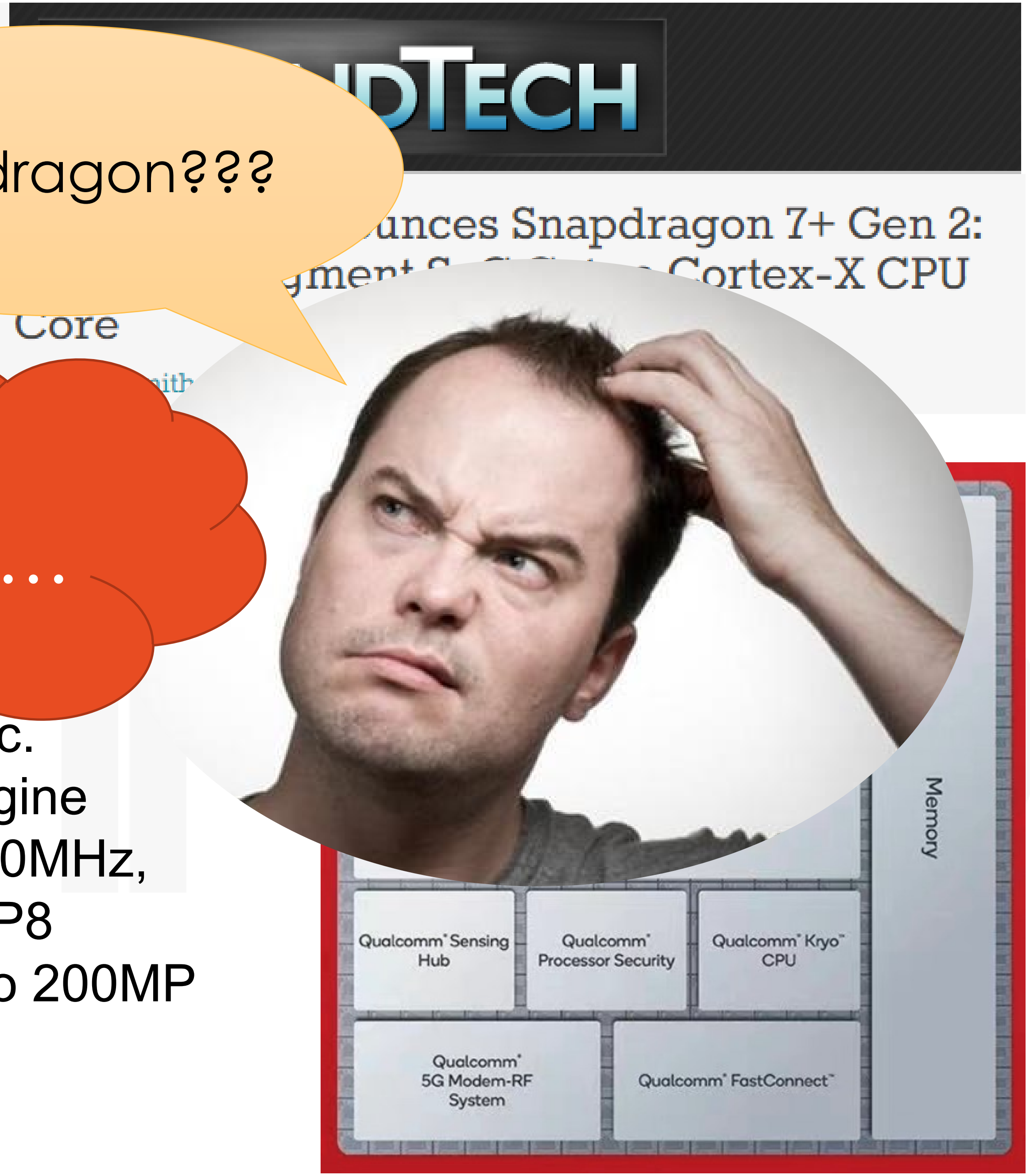
...ectra ISP up to 200MP

...G Dual Sim

...C 4nm

Snapdragon???

I thought so…



...unces Snapdragon 7+ Gen 2: ...gment S... Cortex-X CPU Core

...ith

Motivation

- **Welcome to Hardware Engineering.**
- To get you started on your graduate studies, let me introduce you to a wonderful invention…

The Computer!

- Don’t you think it’s about time you know what’s inside?

Course Objective

- **To tell you a little more than “just common knowledge” about computers, in general, and embedded systems, in particular, including:**
  - Basic Terminology
  - Components
  - Systems (on a chip)
  - Software
  - Methodology
- **Who is this class for?**
  - Actually, it’s for any engineer.
  - But specifically, when I finished my EE/CE studies (BSc, MSc, PhD), I realized I never learned this stuff.
  - And, unfortunately, I can say the same about most graduates I meet today.

Introduction | MCU, MPU, SOC | Embedded Systems | Components

MPU, MCU, SoC

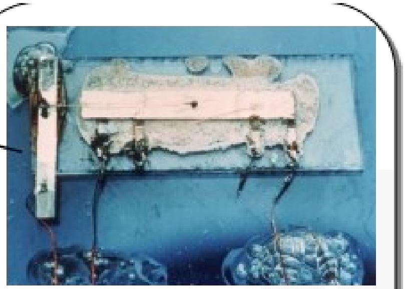
Our good old friend Moore

- **$1.2*10^{21}$ (1.2 sextillion)**
  - The number of transistors in 2014!
  - Transistors > grains of rice harvested in 2004
  - 10^6 times estimated number of ants on earth

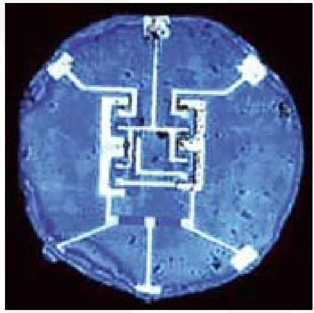
PHOTO: tipspr.com

From

1 Transistor
3 Resistors
1 Capacitor



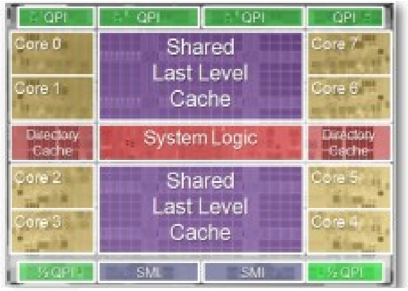
Germanium IC
Jack Kilby
Texas Instruments



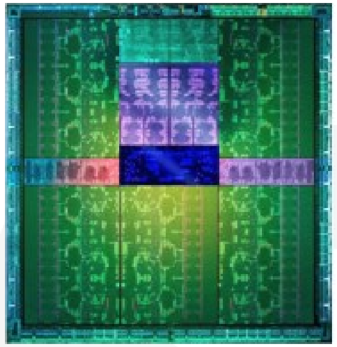
Silicon IC
Robert Noyce
Fairchild Semiconductor

circa 1958

To



Intel Poulson (8-core microprocessor)
3.1 Billion transistors
(32 nm)



NVIDIA GK110 Kepler
(Graphics processor with 2880 “cores”)
7.1 Billion transistors
(28 nm)

circa 2013

A 3,000,000,000 fold increase in 55 years

Source: Raghunathan, ECE 695R

What do we do with all the transistors?

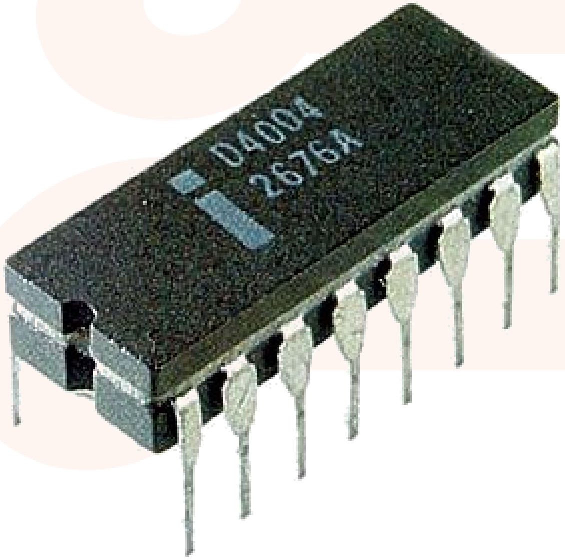
- **Scaling option #1 (component-driven scaling)**
  - Microprocessors, GPUs
    - Pre-2005: Deeper pipelines, more complex logic for instruction-level parallelism, more cache
    - 2005- : More cores, more cache
  - Memory chips
    - Easy – just keep increasing capacity
- **Scaling option #2 (system-driven scaling)**
  - Integrate more and more system functions onto a chip

Source: Raghunathan, ECE 695R

98 % of “computing” systems are embedded

MPU, MCU, SoC

- **Microprocessor (MPU)**
  - A computer processor where the data processing lo on a single integrated circuit.



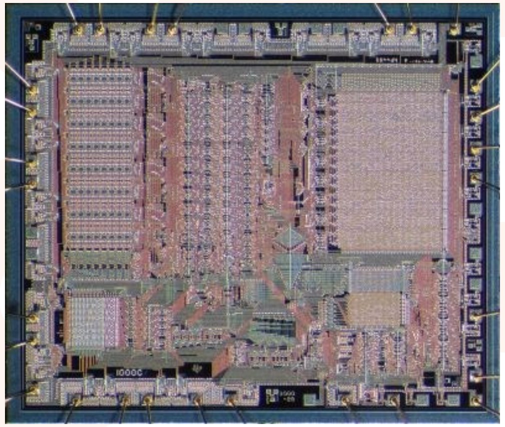
4-bit Intel 4004
First monolithic microprocessor

Bellmac 32
First 32-bit microprocessor

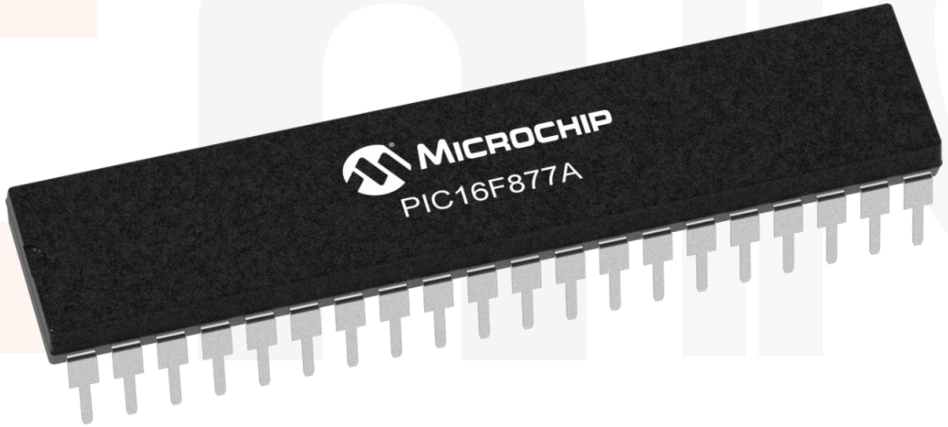
AMD Opteron
First 64-bit x86 microprocessor

MPU, MCU, SoC (2)

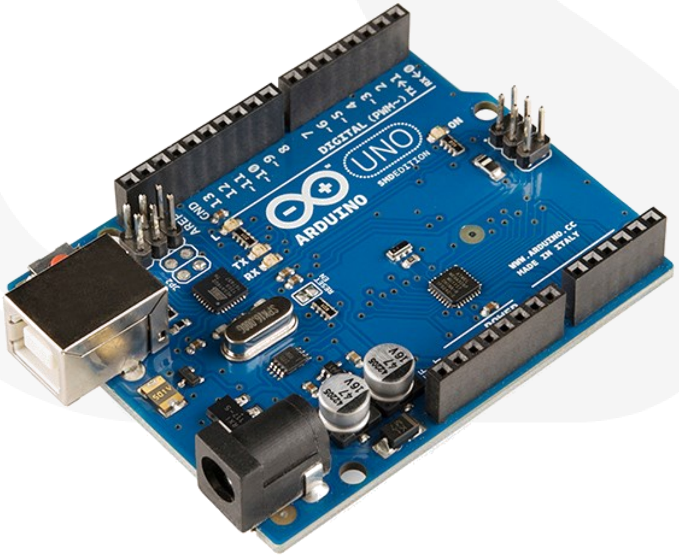
- **Microcontroller (MCU)**
  - A microcontroller is a small computer on a single integrated circuit chip.
  - A microcontroller contains one or more CPUs along with memory and programmable input/output peripherals.



TI TMS-1000
First high-volume microcontroller



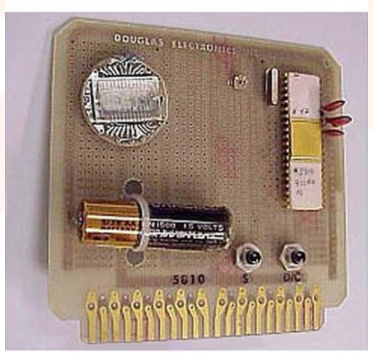
PIC Microcontroller
Over 12B parts sold (2013)



ATmega328P
The chip at the heart of the Arduino Uno

MPU, MCU, SoC (3)

- **System on a chip (SoC)**
  - A system on a chip is an integrated circuit that integrates all or most components of a computer or other electronic system.
  - An SoC integrates an MCU, MPU or perhaps several processor cores with peripherals like a GPU, Wi-Fi and cellular network radio modems, and/or one or more coprocessors – all on a single substrate or microchip.
  - An SoC can be seen as integrating an MCU with more advanced peripherals.



Intel 5810 Watch
First SoC (1974)

AMD286ZX/LX
First Largescale SoC

Apple M1
First Apple Silicon Mac

From Microprocessor to Microcontroller

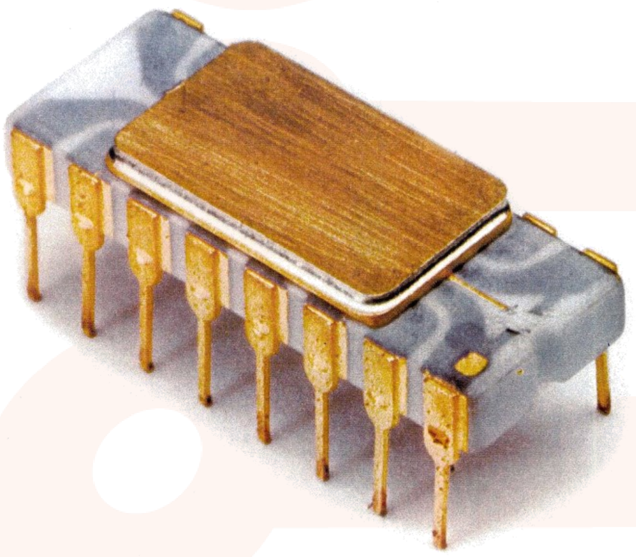
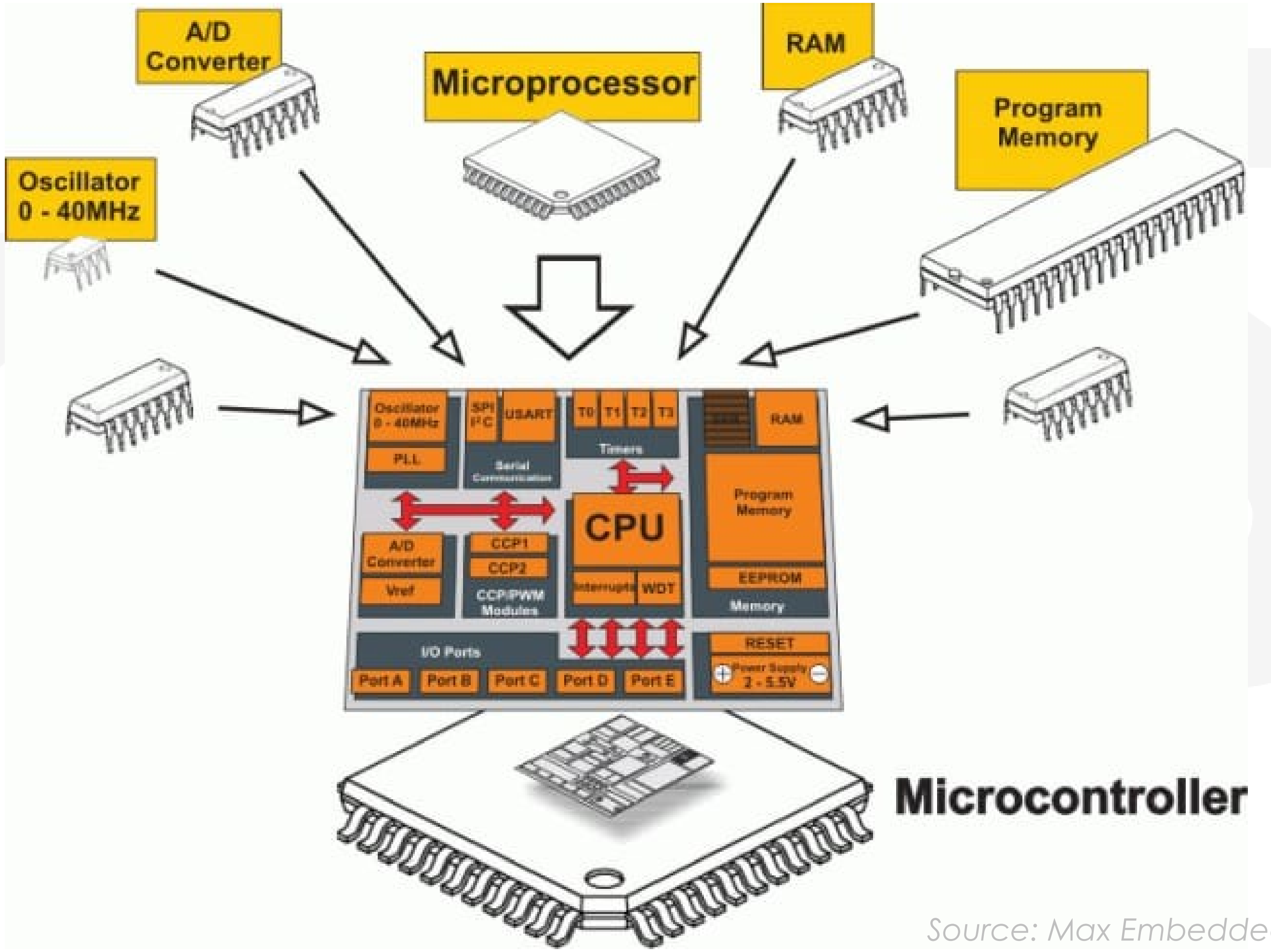
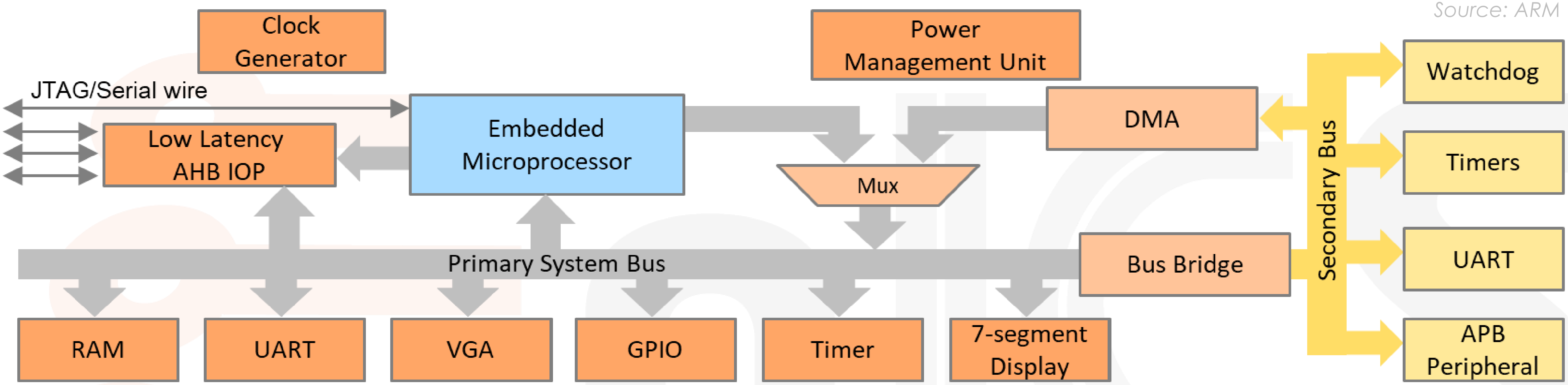


Photo: Intel

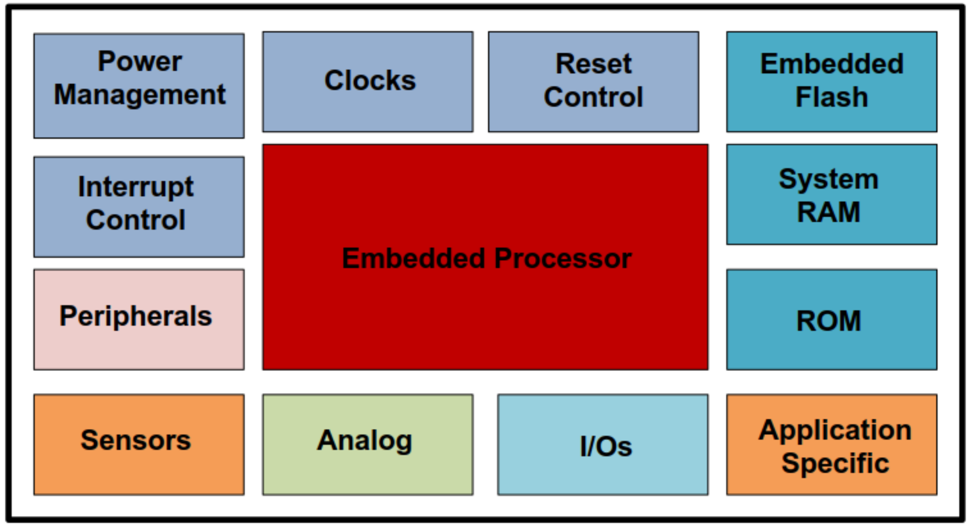


Source: Max Embedded

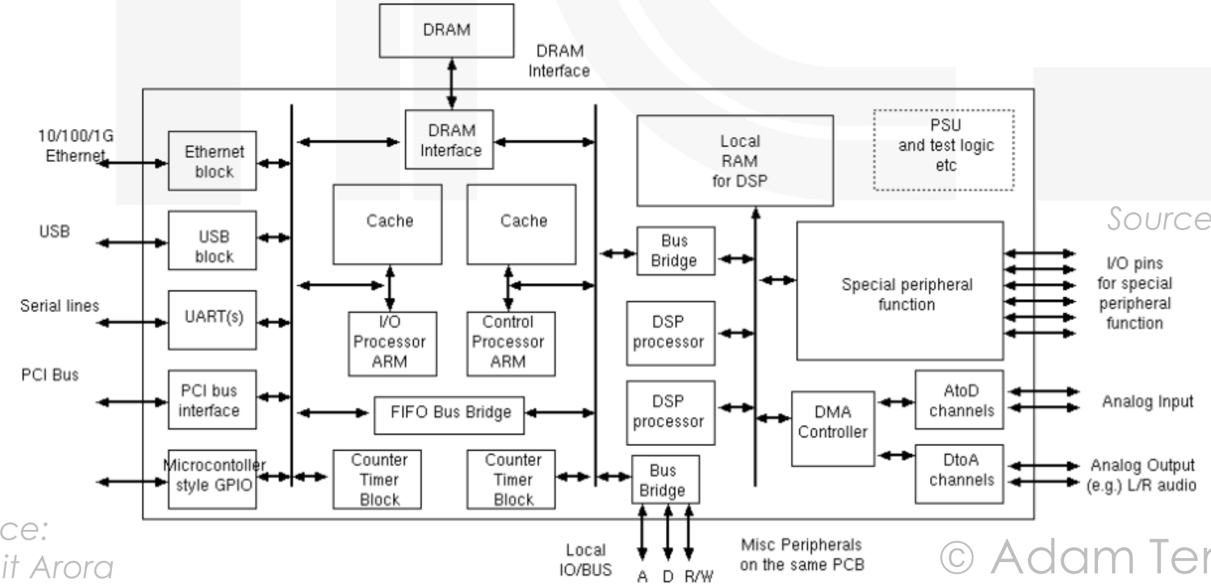
To System-on-Chip



Source: ARM



Source: Mohit Arora



Source: Greaves, U. Cambridge

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CPU vs. MCU vs. SoC

- **CPU:**
  - Is a single processor core
  - Used for general purposes
  - It needs to be supported with memories and IOs

- **MCU:**
  - Typically has a single processor core.
  - Has memory blocks, basic IOs, and other basic peripherals
  - Mainly used for basic control purposes, e.g., embedded applications

- **SoC:**
  - Single or multiple processors
  - Larger memory blocks, a variety of IOs, and other peripherals
  - Integrated with more powerful blocks, e.g., GPU, DSP
  - Capable of running OSs
  - Mainly used for advanced applications (e.g., smartphones, tablets).

SoC Advantages

- Higher Performance
- Power Efficiency
- Lower Cost
- Lighter Footprint
- Higher Reliability

SoC Limitations

- Application Specific
- Less Flexibility
- Complexity

Embedded Systems

Embedded Systems

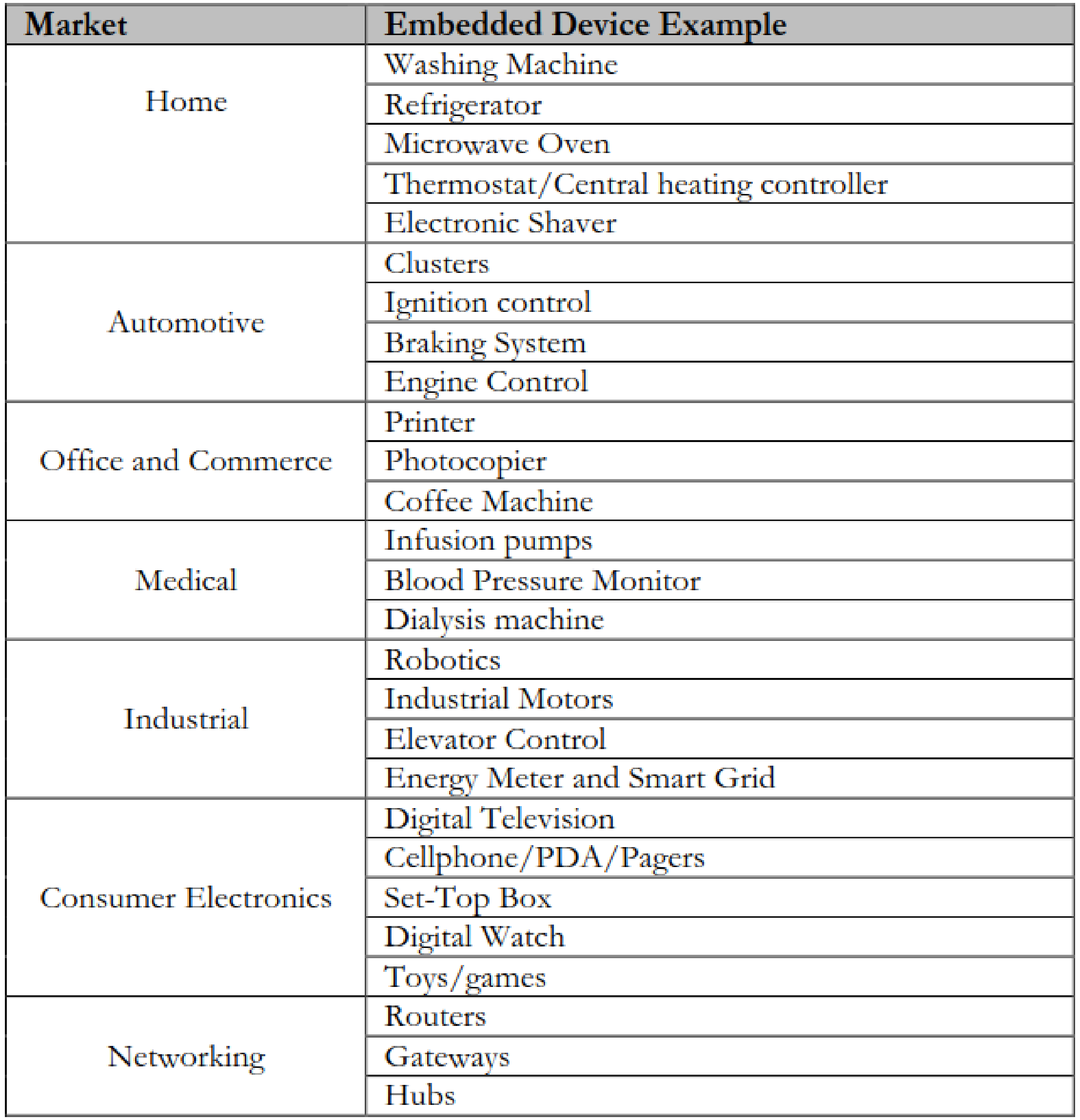
- **An embedded system is combination of computer hardware and software that is specifically designed for a particular function.**
  - "*Loosely defined, it is any device that includes a programmable computer but is not itself intended to be a general purpose computer*" by W. Wolf
  - "*An embedded computer system includes a microcomputer with mechanical, chemical and electrical devices attached to it, programmed for a specific dedicated purpose, and packaged as a complete system*" by J. Valvano
  - "*Embedded Systems are the electronic systems that contain a microprocessor or a microcontroller, but we do not think of them as computers– the computer is hidden or embedded in the system*." by T. Morton
- **A cyber-physical system is one that combines physical devices, known as the plant, with computers that control the plant.**
  - The embedded computer is the cyber-part of the cyber-physical system.

Embedded Systems (2)

- **An embedded system is designed to handle a particular task.**
  - e.g, washing machines, electronic shavers, Digital TV, digital cameras, air-conditioning etc.
- **However, some embedded devices may perform variety of functions.**
  - such as a Smartphone, Digital TV etc.
- **The main loop of an embedded system:**

```
while(1) {
    Embedded Program
}
```

* The program never executes a return; *there is no place to return to.*



Market	Embedded Device Example
Home	Washing Machine
	Refrigerator
	Microwave Oven
	Thermostat/Central heating controller
	Electronic Shaver
Automotive	Clusters
	Ignition control
	Braking System
	Engine Control
Office and Commerce	Printer
	Photocopier
	Coffee Machine
Medical	Infusion pumps
	Blood Pressure Monitor
	Dialysis machine
Industrial	Robotics
	Industrial Motors
	Elevator Control
	Energy Meter and Smart Grid
Consumer Electronics	Digital Television
	Cellphone/PDA/Pagers
	Set-Top Box
	Digital Watch
	Toys/games
Networking	Routers
	Gateways
	Hubs

Source: Mohit Arora

General vs. Embedded Computer System

- **General Computer System**
  - Microprocessor
  - Large Primary Memory (RAM, ROM, Cache)
  - Large Secondary Memory (HDD, SSD, DVD)
  - Operating System (OS)
  - General purpose user interfaces and application software.

- **Embedded Computer System**
  - Hardware that includes the core and necessary I/O for a specific function.
  - Embeds main application software into embedded Flash.
  - Embeds a real time operating system (RTOS) which supervises the application software tasks running on the hardware.

Embedded System Characteristics

- **Limited hardware and software functionality**
  - Limited performance, reduced power consumption, memory, hardware functionality
  - Limited real-time operating system (RTOS) or even no OS (“Bare Metal”) and scaled-down applications
- **Custom designed for a dedicated function**
  - Primarily designed for one specific function
- **High quality and reliability**
  - Some embedded devices are highly reliable and can work for long operation hours without failure
- **Sophisticated functionality**
  - Some embedded systems require running complex algorithms and providing a fancy User interface

PHOTO: Evan-Amos

PHOTO: myrhythmdevice.org

PHOTO: techspot.com

Embedded System Characteristics (2)

- **Low Latency and real time operation**
  - Many embedded computing systems have to perform in real time – if the data isn't ready by a certain deadline, the system breaks.
  - Some functions require low latency for quality of service

PHOTO: electrek

- **Multirate support**
  - Several real-time activities may be going on at the same time.
  - They may simultaneously control some operations that run at slow rates and others that run at high rates (e.g., audio vs. video)

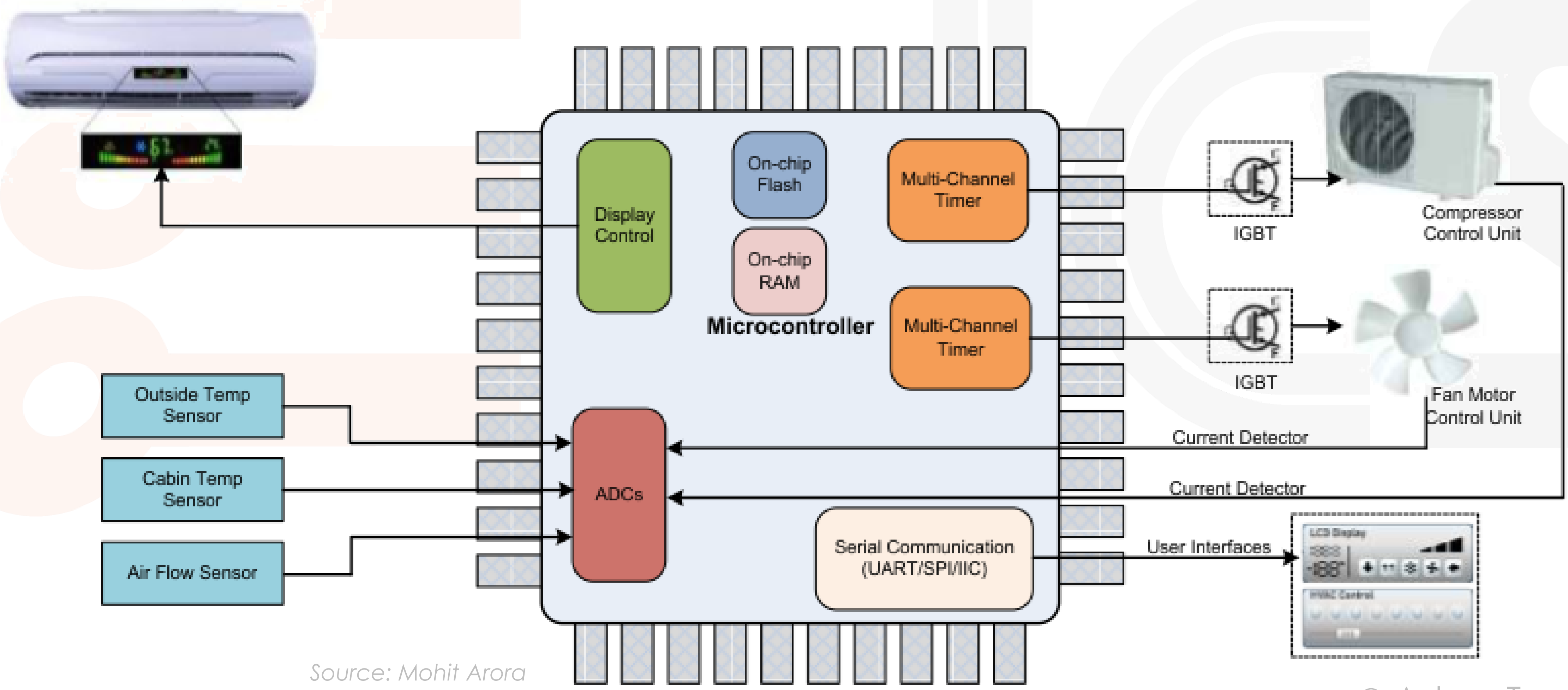
PHOTO: Roku

- **System Costs**
  - Low manufacturing cost
  - Low power and energy budgets

PHOTO: MacRumors

Embedded System Example #1

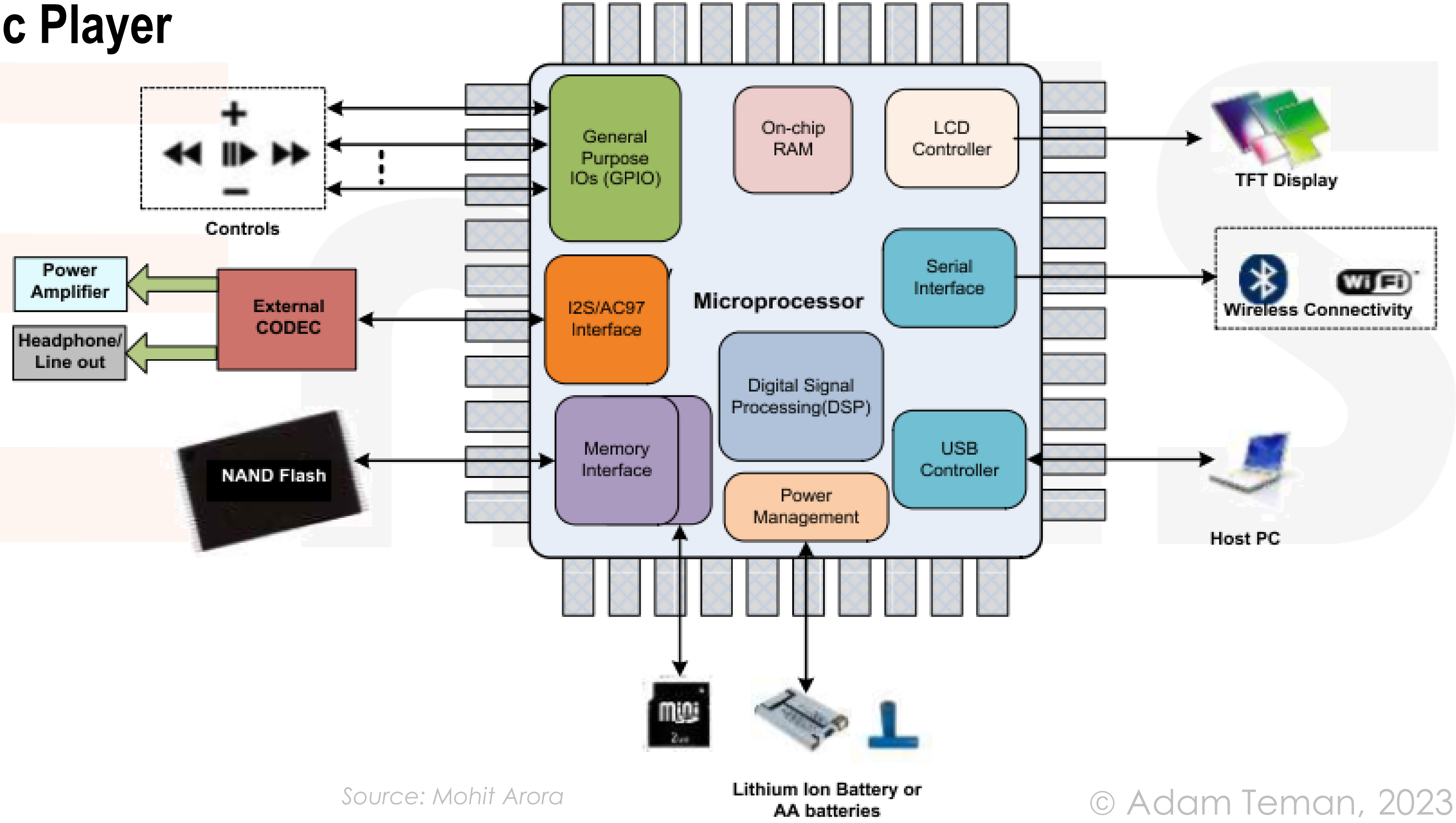
- **Air Conditioning System**



Source: Mohit Arora

Embedded System Example #2

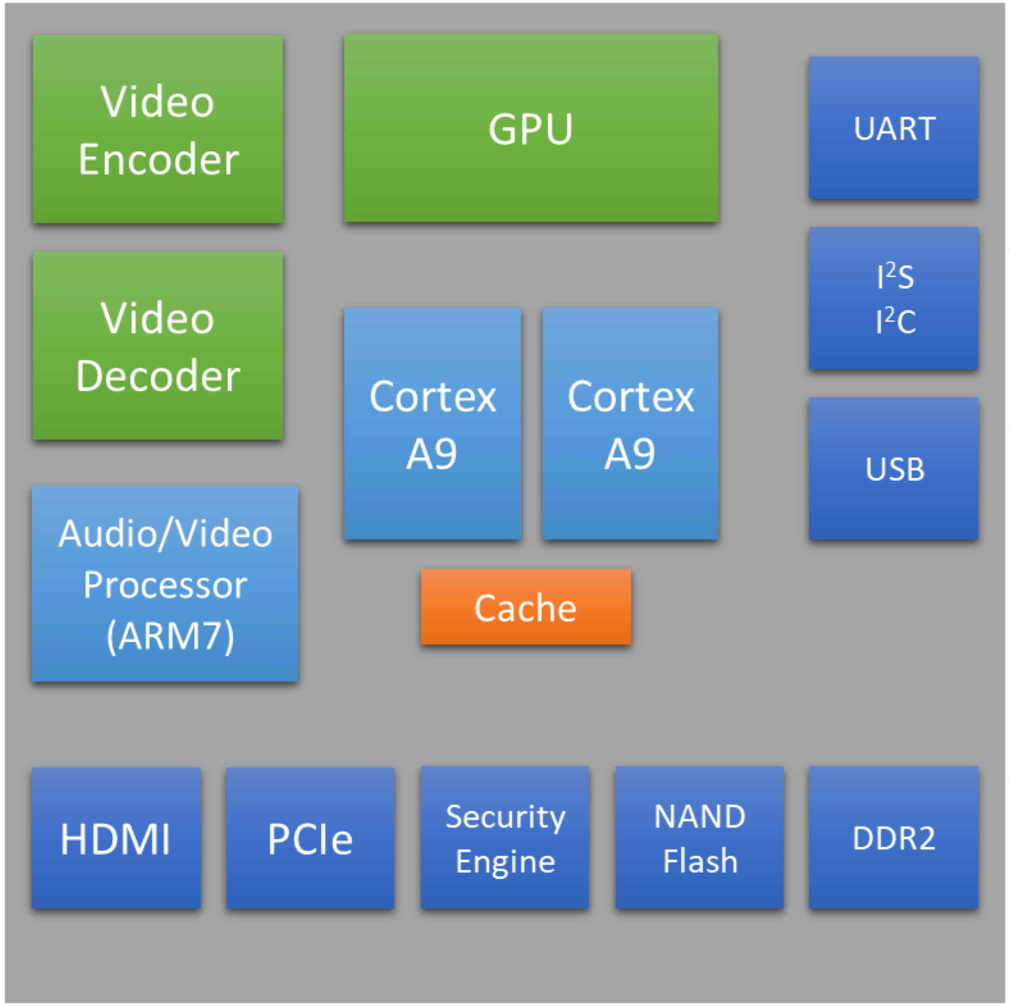
- **Portable Music Player**



Source: Mohit Arora

SoC Example: NVIDIA Tegra 2

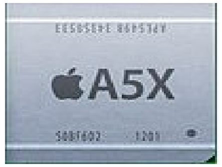
Designer	NVIDIA
Year	2010
Processor	Arm Cortex-A9 (dual-core)
Frequency	Up to 1.2 GHz
Memory	1 GB 667 MHz LP-DDR2
Graphics	ULP GeForce
Process	40 nm
Package	12 × 12 mm (package on package)
Used in tablets	Acer Iconia Tab A500 Asus Eee Pad Transformer Motorola Xoom Motorola Xoom Family Edition Samsung Galaxy Tab 10.1 Toshiba Thrive



Source: ARM

SoC Example: Apple SoC Families

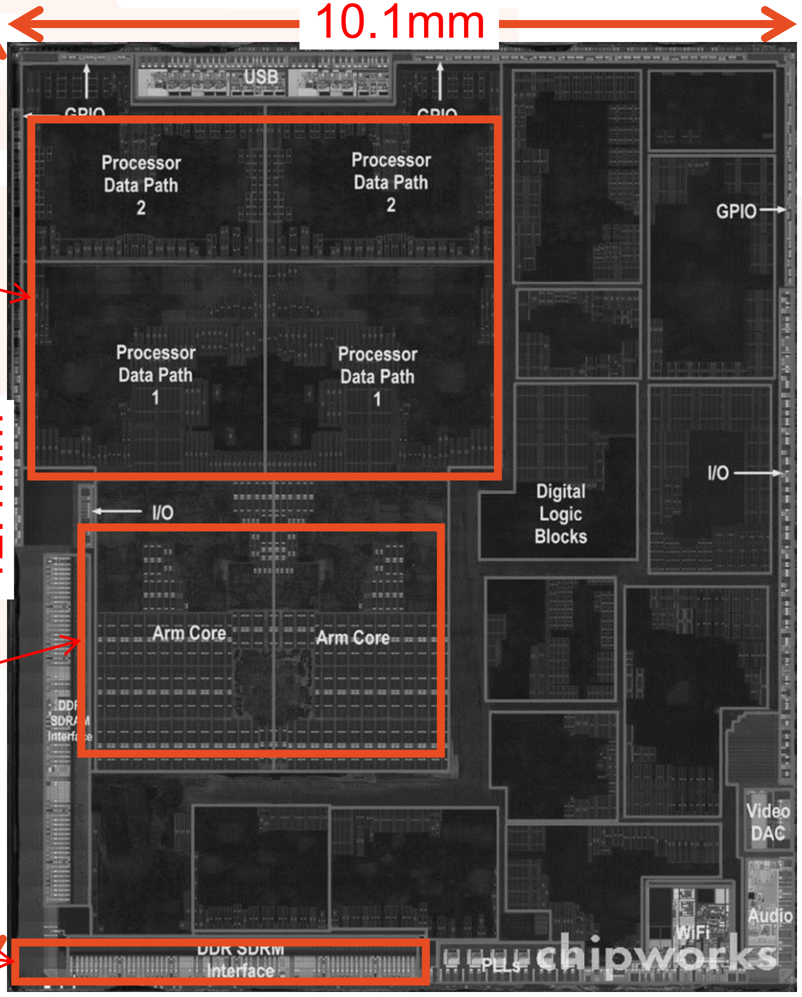
SoC	Model No.	CPU	CPU ISA	Technology	Die size	Date	Devices
N/A	APL0098	Arm11	Armv6	90 nm	N/A	6/2007	iPhone iPod Touch (1st gen.)
A4	APL0398	Arm Cortex-A8	Armv7	45 nm	53.29 mm^2	3/2010	iPad, iPhone 4, Apple TV (2nd gen.)
A5	APL0498	Arm Cortex-A9	Armv7	45 nm	122.6 mm^2	3/2011	iPad 2, iPhone 4S
	APL2498	Arm Cortex-A9	Armv7	32 nm	71.1 mm^2	3/2012	Apple TV (3rd gen.)
	APL7498	Arm Cortex-A9	Armv7	32 nm	37.8 mm^2	3/2013	Apple TV 3
A5X	APL5498	Arm Cortex-A9	Armv7	45 nm	162.94 mm^2	3/2012	iPad (3rd gen.)
A6	APL0598	Swift	Armv7s	32 nm	96.71 mm^2	9/2012	iPhone 5
A6X	APL5598	Swift	Armv7s	32 nm	123 mm^2	10/2012	iPad (4th gen.)
A7 (64-bit)	APL0698	Cyclone	Armv8-A	28 nm	102 mm^2	9/2013	iPhone 5S, iPad mini (2nd gen.)
	APL5698	Cyclone	Armv8-A	28 nm	102 mm^2	10/2013	iPad Air



Source: ARM

SoC in Embedded System

- **Let’s look inside an Apple iPad 2:**

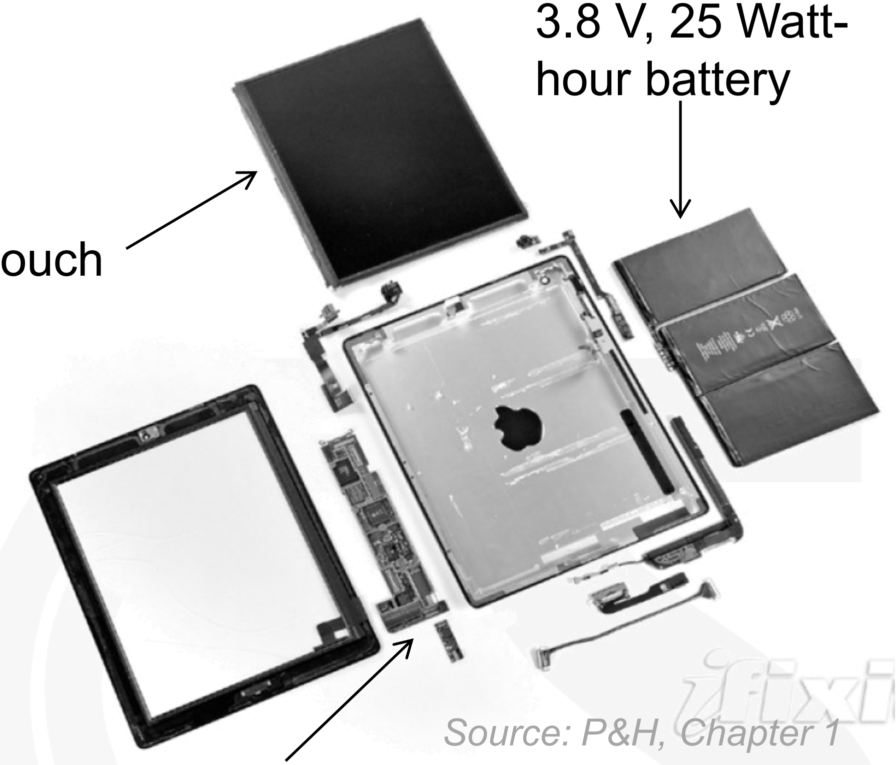


4X GPU Datapath

2X ARM Core @1GHz

DDR Interface

45nm Apple A5 SoC

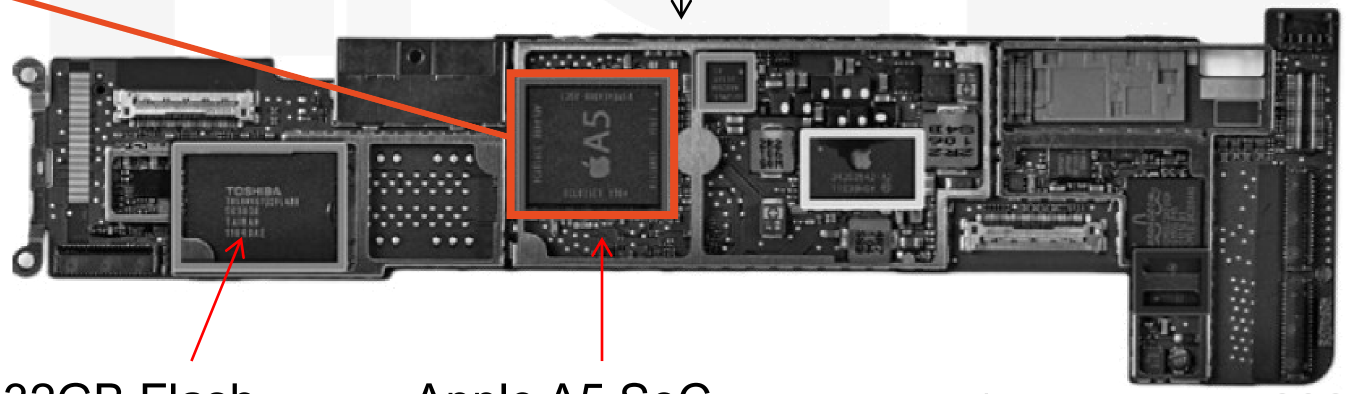


3.8 V, 25 Watt-hour battery

Capacitive multitouch LCD screen

Computer board

Source: P&H, Chapter 1



32GB Flash

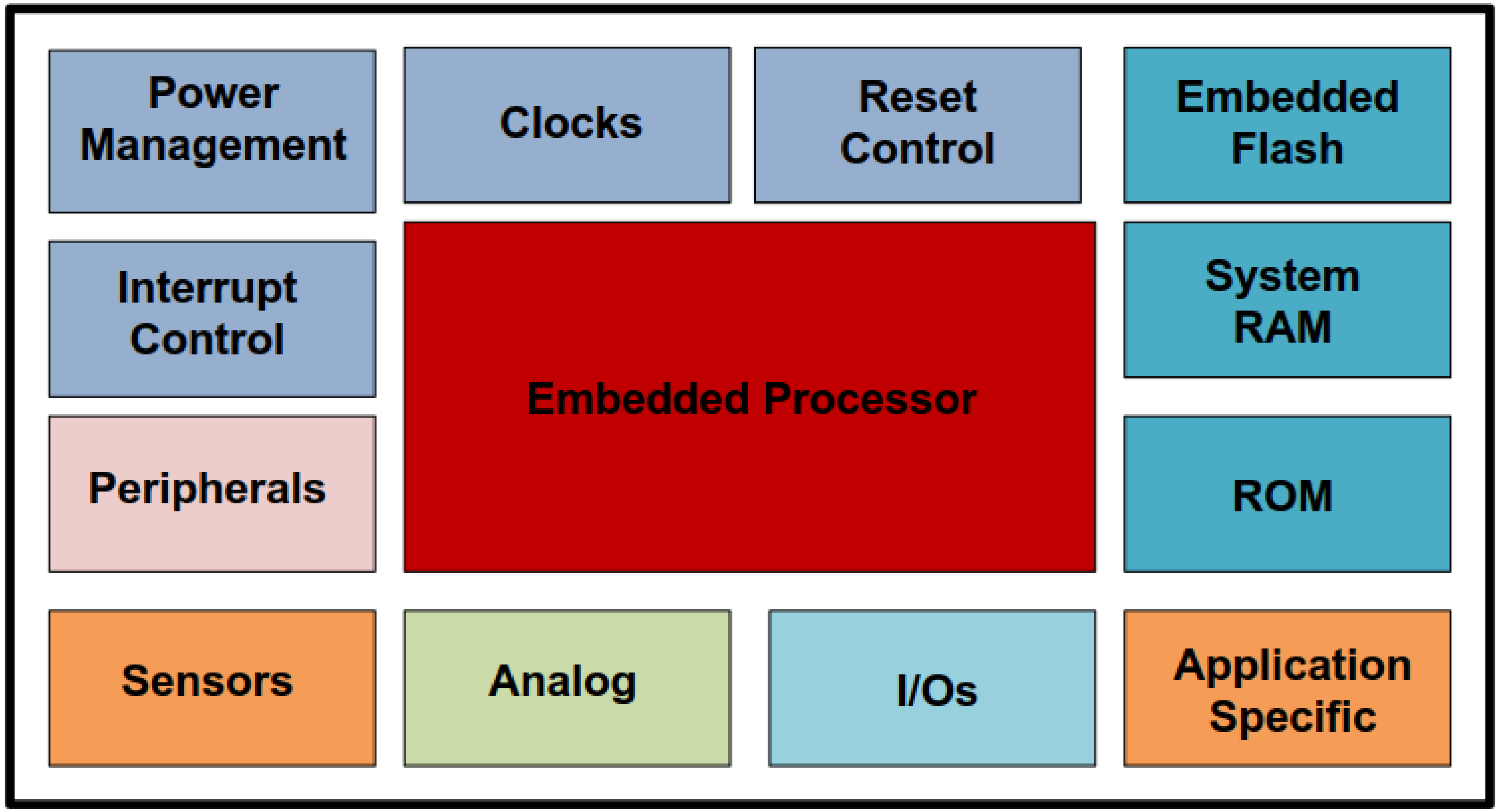
Apple A5 SoC

Introduction | MCU, MPU, SOC | Embedded Systems | Components

Components of Embedded Systems

A Typical Embedded SoC

- Embedded Processor
- Embedded Memory
- Peripherals and I/Os
- Timers and Watchdog
- Power Management
- Sensors and Analog
- Interrupt Controller
- Clocking and Reset
- Additional Application Specific



Power Management

Clocks

Reset Control

Embedded Flash

Interrupt Control

Embedded Processor

System RAM

Peripherals

ROM

Sensors

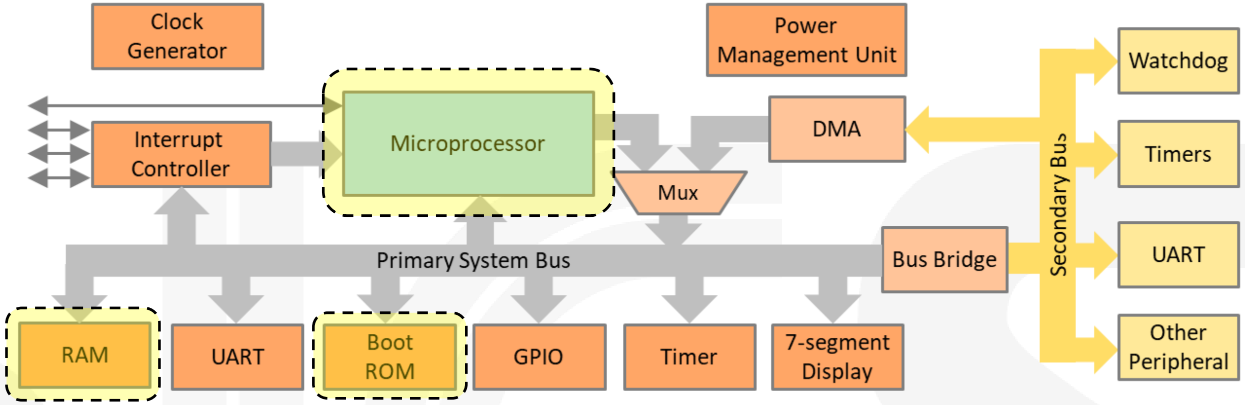
Analog

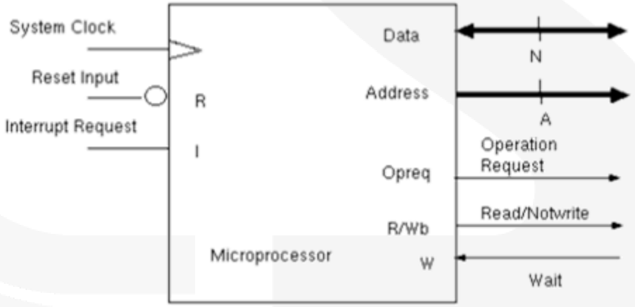
I/Os

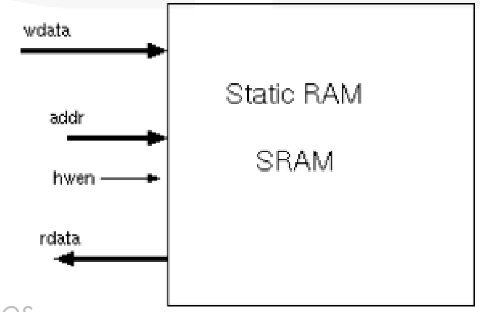
Application Specific

Components of Embedded Hardware

- **Embedded Processor**
  - Optimized for general purpose use
  - Lower functionality and performance than desktop processor
  - Runs software (RTOS)
  - Master of bus transactions
- **Embedded Memory**
  - Low access time and high density
  - ROM as primary bootloader (preprogrammed)
  - RAM (volatile) to store transient input or output data
  - Usually no secondary storage (HDD)
  - Code size is important!





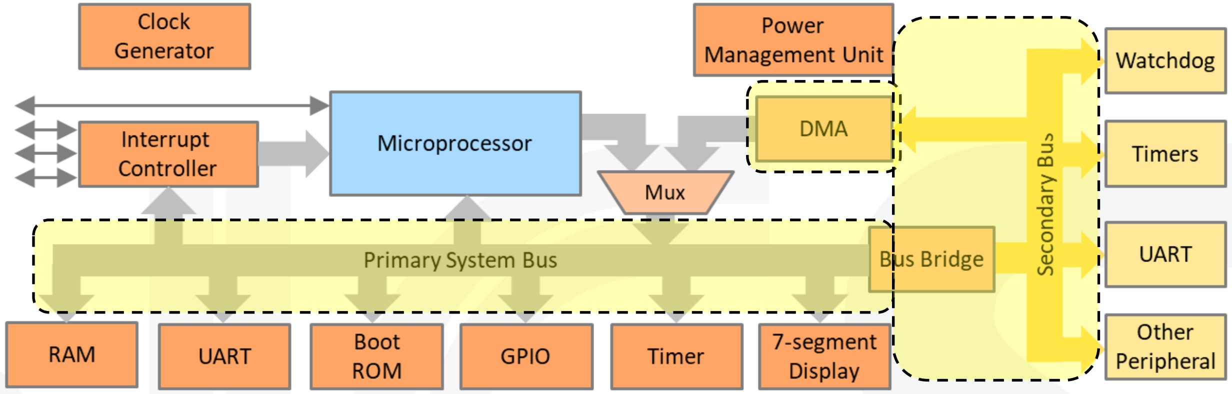


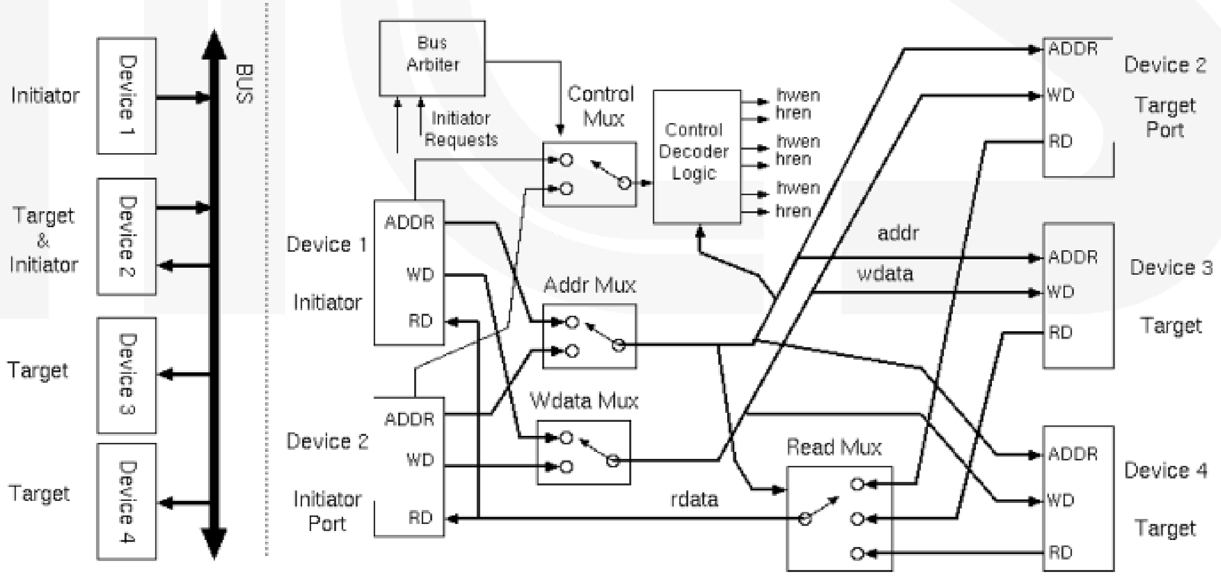
Source: Greaves, U. Cambridge

Components of Embedded Hardware (2)

- **Communication Buses**
  - Multiple Masters/Slaves
  - Multiplexing address/data
  - Arbitration
  - High Speed/Low Speed/Bridge

- **DMA Controller**
  - Offload memory access from CPU by becoming a bus master
  - Allows continuing CPU operation during long bus transfers

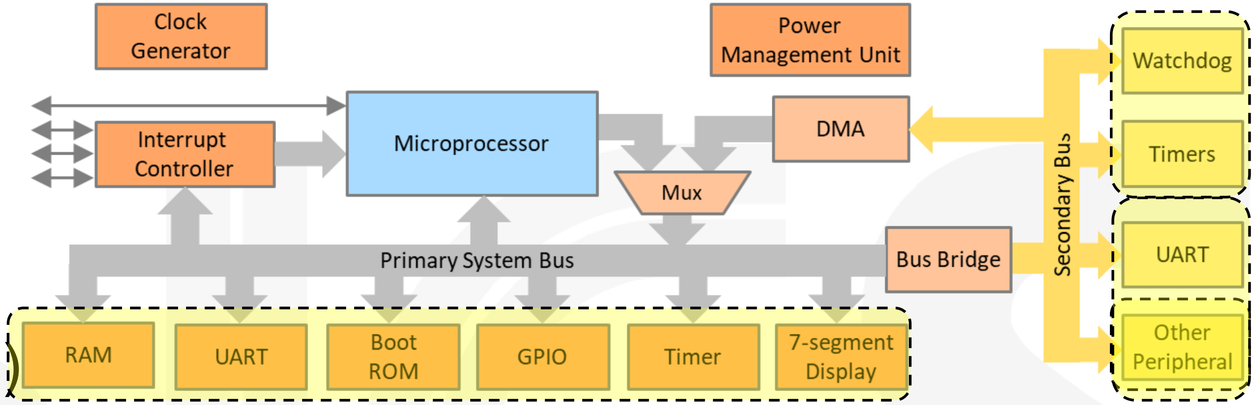


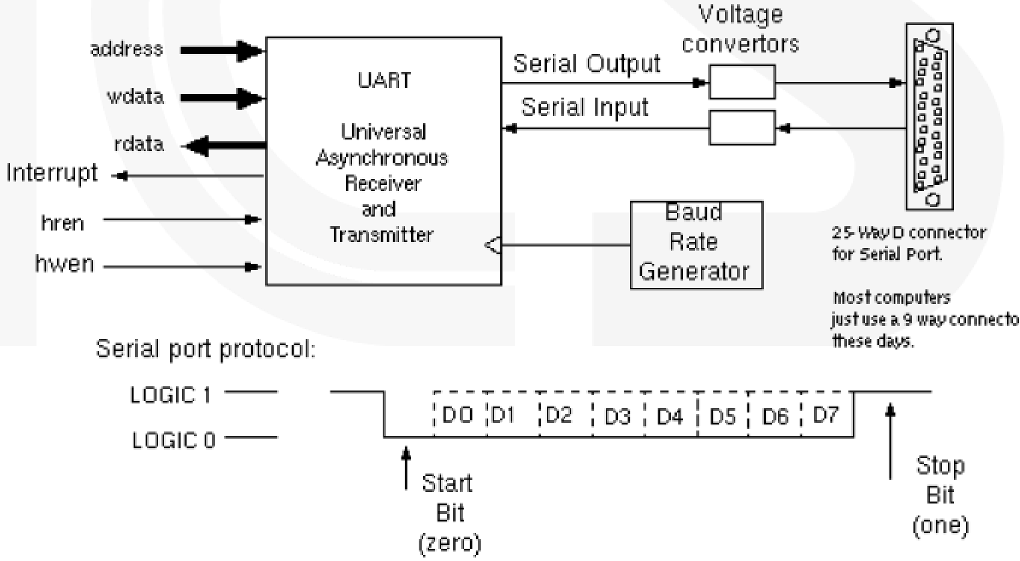


Source: Greaves, U. Cambridge

Components of Embedded Hardware (3)

- **Peripherals and I/Os**
  - Peripherals are I/O devices connected to the serial and parallel ports.
  - Communicates through common interface protocols (e.g., UART, SPI, I2C)
  - General Purpose Input/Output Pins
- **Timers and Watchdog**
  - Various timers for counts internal clock pulses or external events
  - Interrupts the processor on a certain count value
  - “Watchdog Timer” is used to detect and recover from code runaway or other malfunctions
- **Sensors and Analog**
  - e.g., temperature sensor, Digital to Analog converter, Analog to Digital Converter, Operational Amplifiers

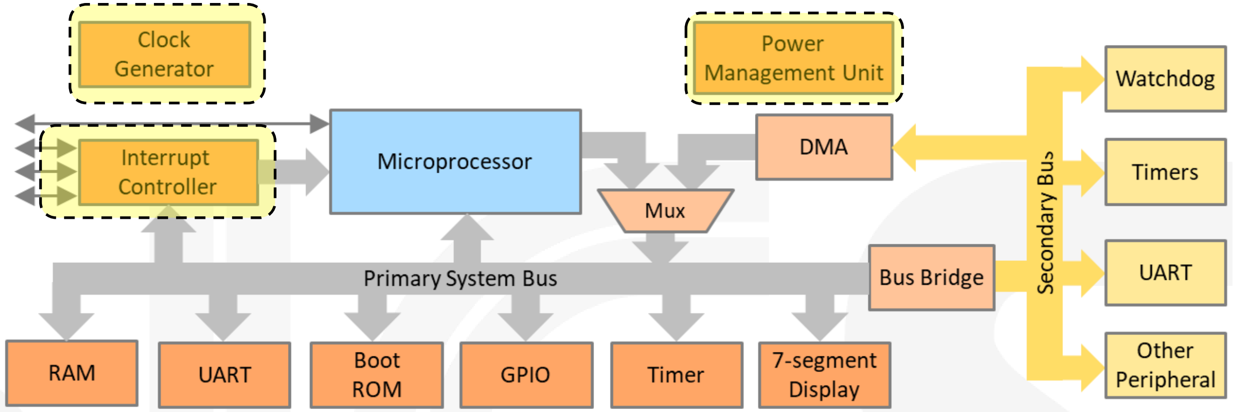


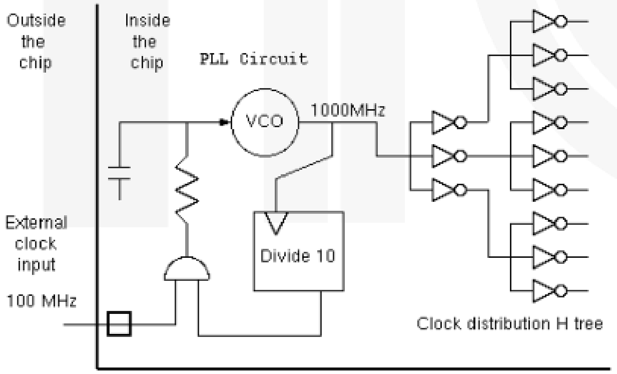


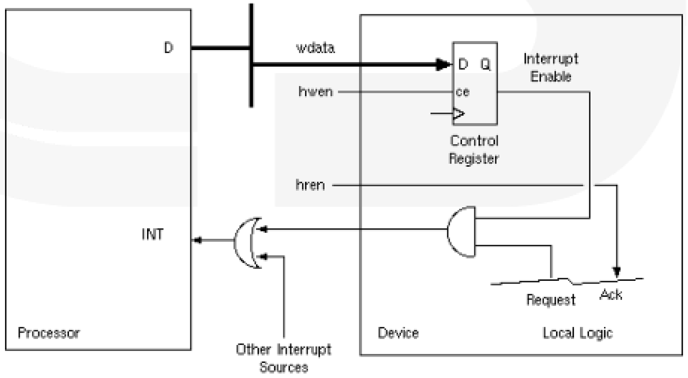
Source: Greaves, U. Cambridge

Components of Embedded Hardware (4)

- **Interrupt Controller**
  - Real Time operation requires interrupt support
  - Low latency and fast response to an interrupt event.
- **Clocking and Reset**
  - External crystal reference
  - Internal phase-locked loop (PLL)
  - Power-on-Reset (POR) circuitry
- **Power Management:**
  - Power supply
  - Support variety of power modes
  - Always-on peripherals (e.g., RTC)







Source: Greaves, U. Cambridge

Application Software and RTOS

- **Features of embedded software:**
  - Program code resides in embedded Flash or ROM. (no secondary storage)
  - Storage space for variables is allocated in the RAM.
  - Programs should execute continuously (do not call “exit” function)
  - Should be capable of handling all possible exceptional conditions.
- **RTOS (real-time operating system)**
  - Scheduler that manages the execution of multiple tasks
  - Should schedule tasks and interrupt service routines such that they are completed within their deadlines
  - Sets the rules during execution of application processes to enable finishing of a process within the assigned time interval and with assigned priority.
  - Provides semaphores to prevent multiple tasks from simultaneously writing into shared memory.

Summary

- **Today, we discussed the definition of different categories of computing hardware:**
  - Microprocessors
  - Microcontrollers
  - System on a Chip
  - General Purpose Computers
  - Embedded Systems
- **And we took a brief look at the components of an embedded computing system.**

- **From here on, we will go deeper into these components and how they communicate and work together.**

Main References

- Arora, "Embedded System Design - Introduction to SoC System Architecture," Learning Bytes Publishing 2016
- Chakravarthi, "A Practical Approach to VLSI System on Chip (SoC) Design," Springer 2020
- Wolf, "Computer as Components - Principles of Embedded Computing System Design," Elsevier 2012
- Anand Raghunathan, Purdue ECE 695R: System-on-Chip Design
  - https://nanohub.org/courses/ECE695R/o1a
- David Greaves, Cambridge: SoC Design and Modeling
- Patterson, Hennessy "Computer Organization and Design – The RISC-V Edition"
- ARM University "Introduction to SoC Design Education Kit"