Embedded Systems

1 - Introduction

What will you learn?

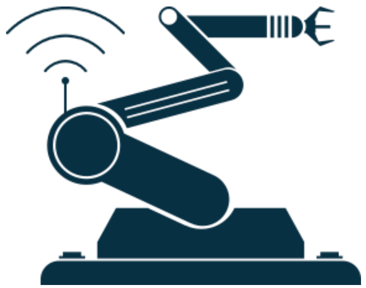
- Theoretical foundations and principles of the analysis and design of embedded systems.
- Practical aspects of embedded system design, mainly software design *(or hardware design?)* .

Embedded Systems - Impact

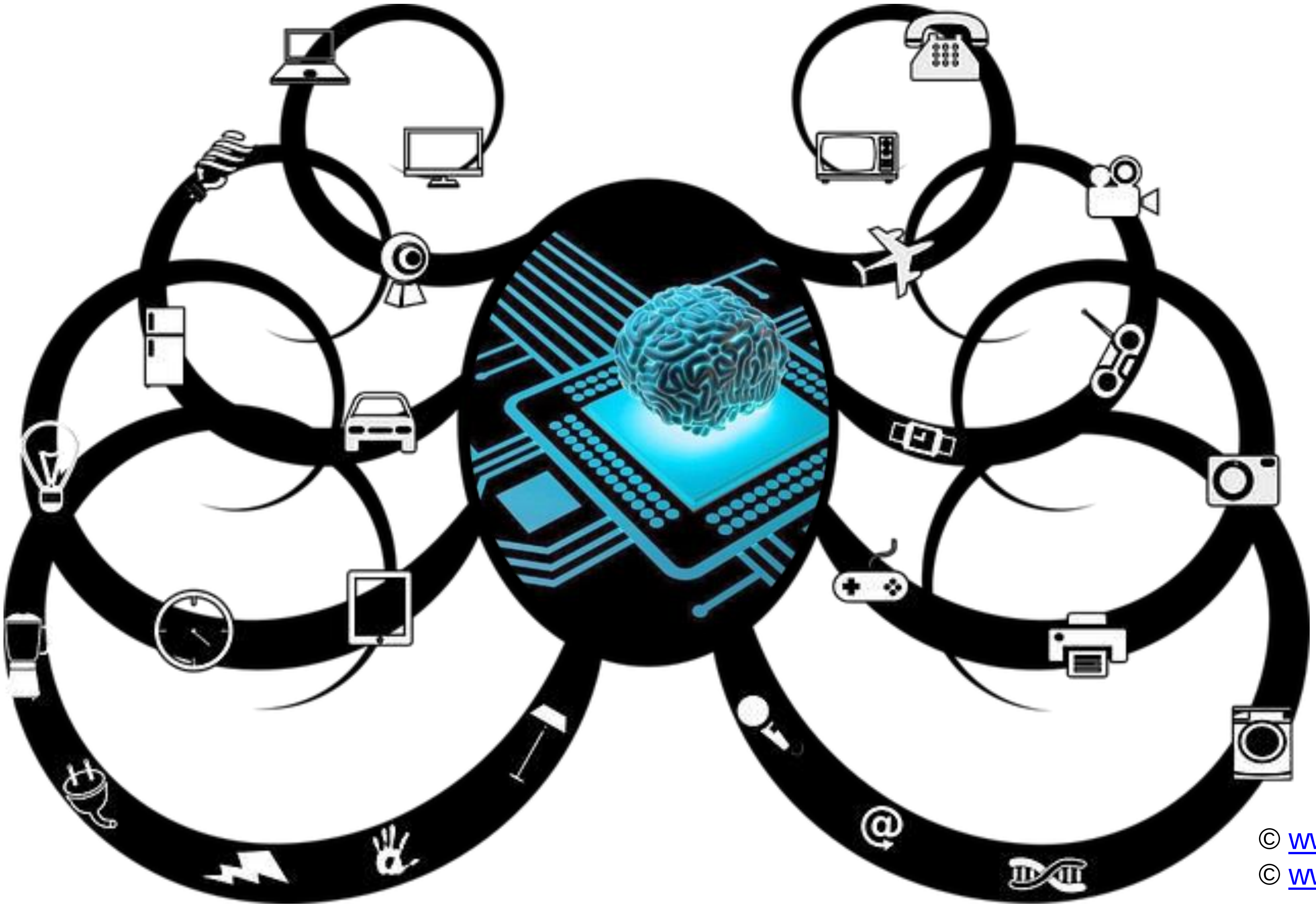
Embedded Systems

Embedded systems (ES) = **information processing systems embedded into a larger product**

Examples:



Often, the main reason for buying is not information processing



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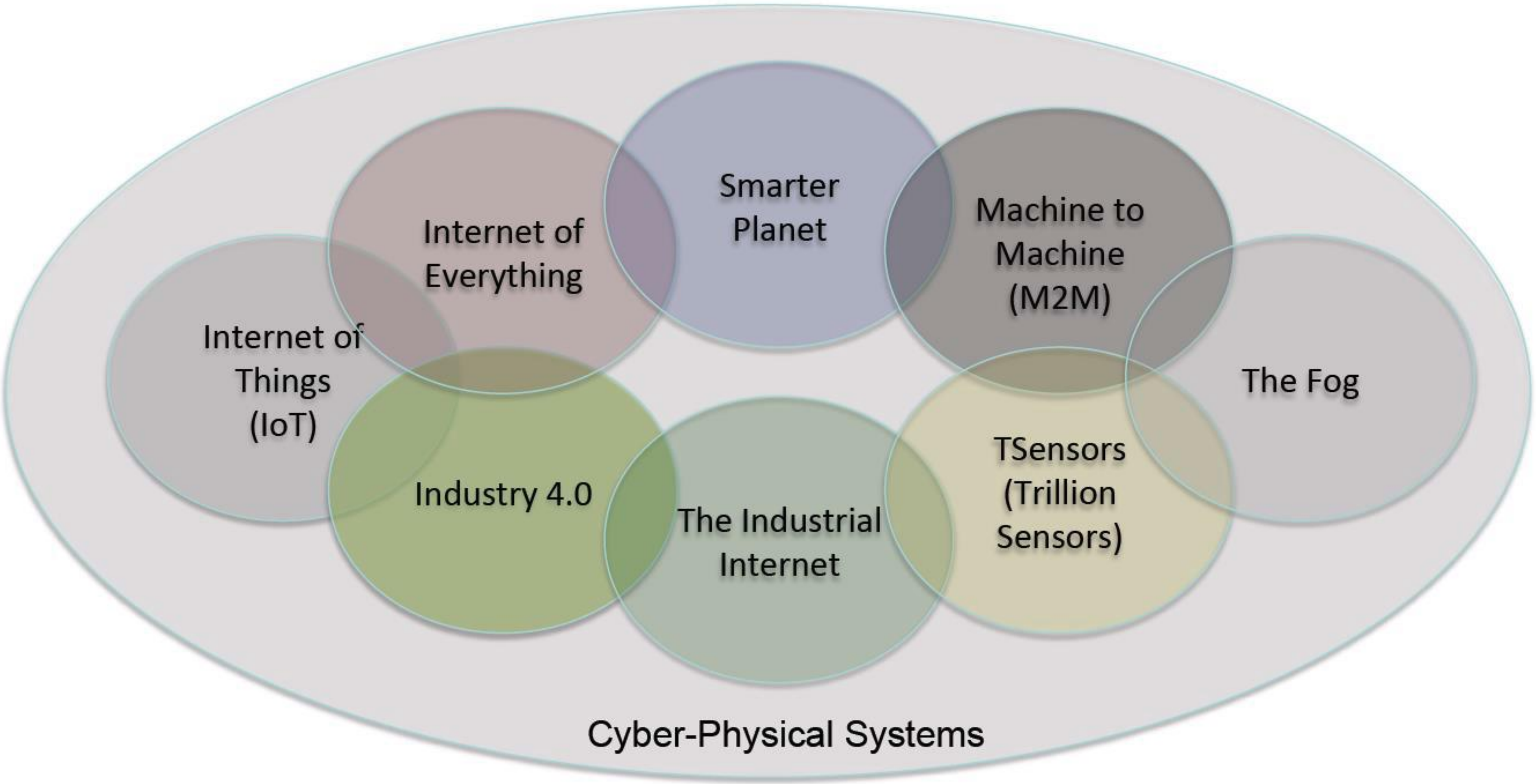
Many Names – Similar Meanings



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Embedded Systems are an essential component

Twelve potentially economically disruptive technologies

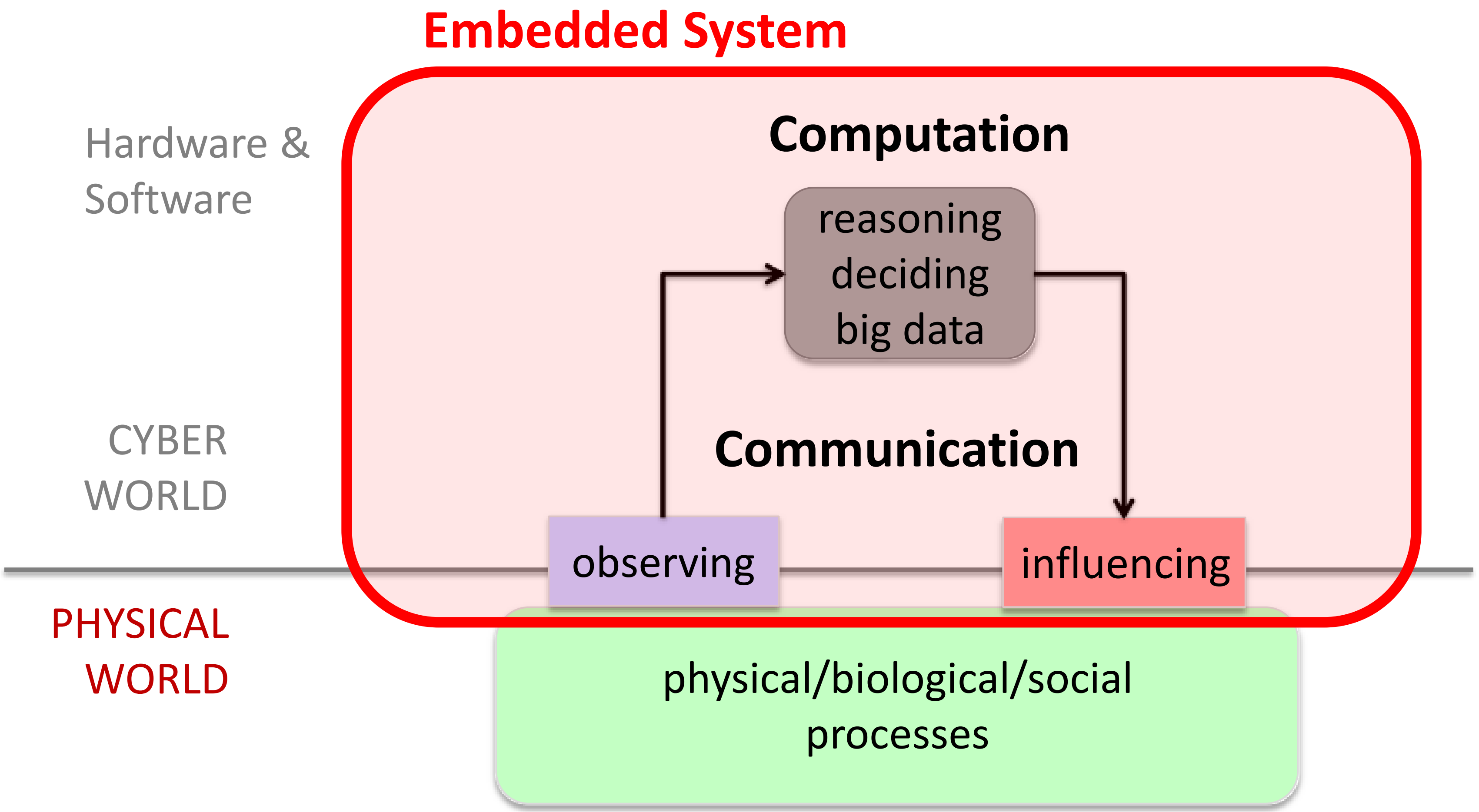
Mobile Internet	Increasingly inexpensive and capable mobile computing devices and Internet connectivity
Automation of knowledge work	Intelligent software systems that can perform knowledge work tasks involving unstructured commands and subtle judgments
The Internet of Things	Networks of low-cost sensors and actuators for data collection, monitoring, decision making, and process optimization
Cloud technology	Use of computer hardware and software resources delivered over a network or the Internet, often as a service
Advanced robotics	Increasingly capable robots with enhanced senses, dexterity, and intelligence used to automate tasks or augment humans
Autonomous and near-autonomous vehicles	Vehicles that can navigate and operate with reduced or no human intervention

...

Next-generation genomics	Fast, low-cost gene sequencing, advanced big data analytics, and synthetic biology ("writing" DNA)
Energy storage	Devices or systems that store energy for later use, including batteries
3D printing	Additive manufacturing techniques to create objects by printing layers of material based on digital models
Advanced materials	Materials designed to have superior characteristics (e.g., strength, weight, conductivity) or functionality
Advanced oil and gas exploration and recovery	Exploration and recovery techniques that make extraction of unconventional oil and gas economical
Renewable energy	Generation of electricity from renewable sources with reduced harmful climate impact

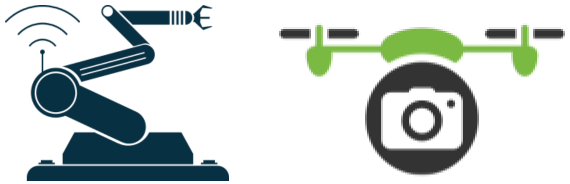
Manyika, James, et al. *Disruptive technologies: Advances that will transform life, business, and the global economy*. Vol. 180. San Francisco, CA: McKinsey Global Institute, 2013.

Embedded System



Use feedback to influence the dynamics of the physical world by taking smart decisions in the cyber world

Reactivity & Timing



Embedded systems are often reactive:

- Reactive systems must react to stimuli from the system environment :

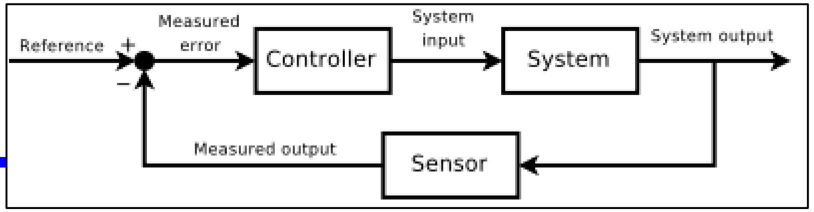
> *"A reactive system is one which is in continual interaction with is environment and executes at a pace determined by that environment" [Bergé, 1995]*

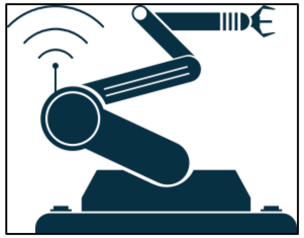
Embedded systems often must meet *real-time constraints:*

- For hard real-time systems, right answers arriving too late are wrong. All other time-constraints are called soft.

> *"A real-time constraint is called hard, if not meeting that constraint could result in a catastrophe" [Kopetz, 1997].*

Predictability & Dependability





CPS = cyber-physical system

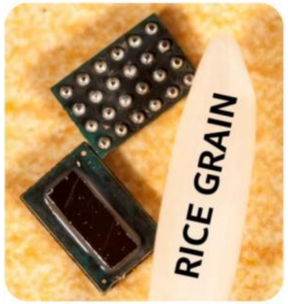
“It is essential to *predict* how a CPS is going to behave under any circumstances […] *before* it is deployed.”[Maj14]

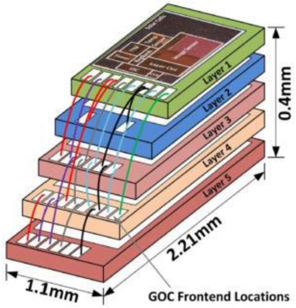
“CPS must *operate dependably*, safely, securely, efficiently and in real-time.”[Raj10]

[Maj14] R. Majumdar & B. Brandenburg (2014). Foundations of Cyber-Physical Systems.
[Raj10] R. Rajkumar et al. (2010). Cyber-Physical Systems: The Next Computing Revolution.

Efficiency & Specialization

- Embedded systems must be *efficient:*
  - *Energy* efficient
  - *Code-size* and *data memory* efficient
  - *Run-time* efficient
  - *Weight* efficient
  - *Cost* efficient





Embedded Systems are often *specialized* towards a certain application or application domain:

- Knowledge about the expected behavior and the system environment at design time is exploited to *minimize resource usage* and to *maximize predictability and reliability*.

Comparison

Embedded Systems:

- Few applications that are known at design-time.
- Not programmable by end user.
- Fixed run-time requirements (additional computing power often not useful).
- Typical criteria:
  - cost
  - power consumption
  - size and weight
  - dependability
  - worst-case speed

General Purpose Computing

- Broad class of applications.
- Programmable by end user.
- Faster is better.
- Typical criteria:
  - cost
  - power consumption
  - average speed

Overview

Software

1. Introduction to Embedded Systems
2. Software Development
3. Hardware-Software Interface
4. Programming Paradigms
5. Embedded Operating Systems
6. Real-time Scheduling
7. Shared Resources
8. Hardware Components
9. Power and Energy
10. Architecture Synthesis

Hardware

Hardware-Software

Components and Requirements by Example

Components and Requirements by Example
- Hardware System Architecture -

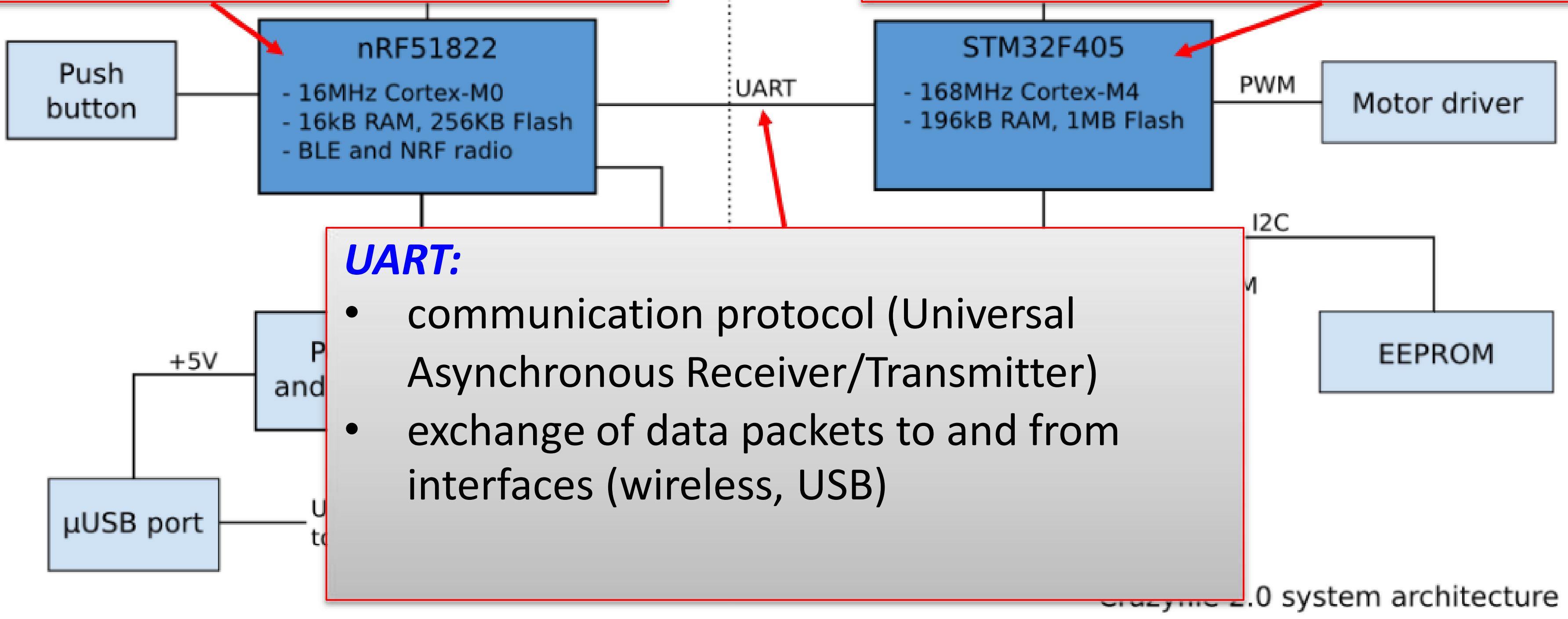
High-Level Block Diagram View

low power CPU

- enabling power to the rest of the system
- battery charging and voltage measurement
- wireless radio (boot and operate)
- detect and check expansion boards

higher performance CPU

- sensor reading and motor control
- flight control
- telemetry (including the battery voltage)
- additional user development
- USB connection



UART:

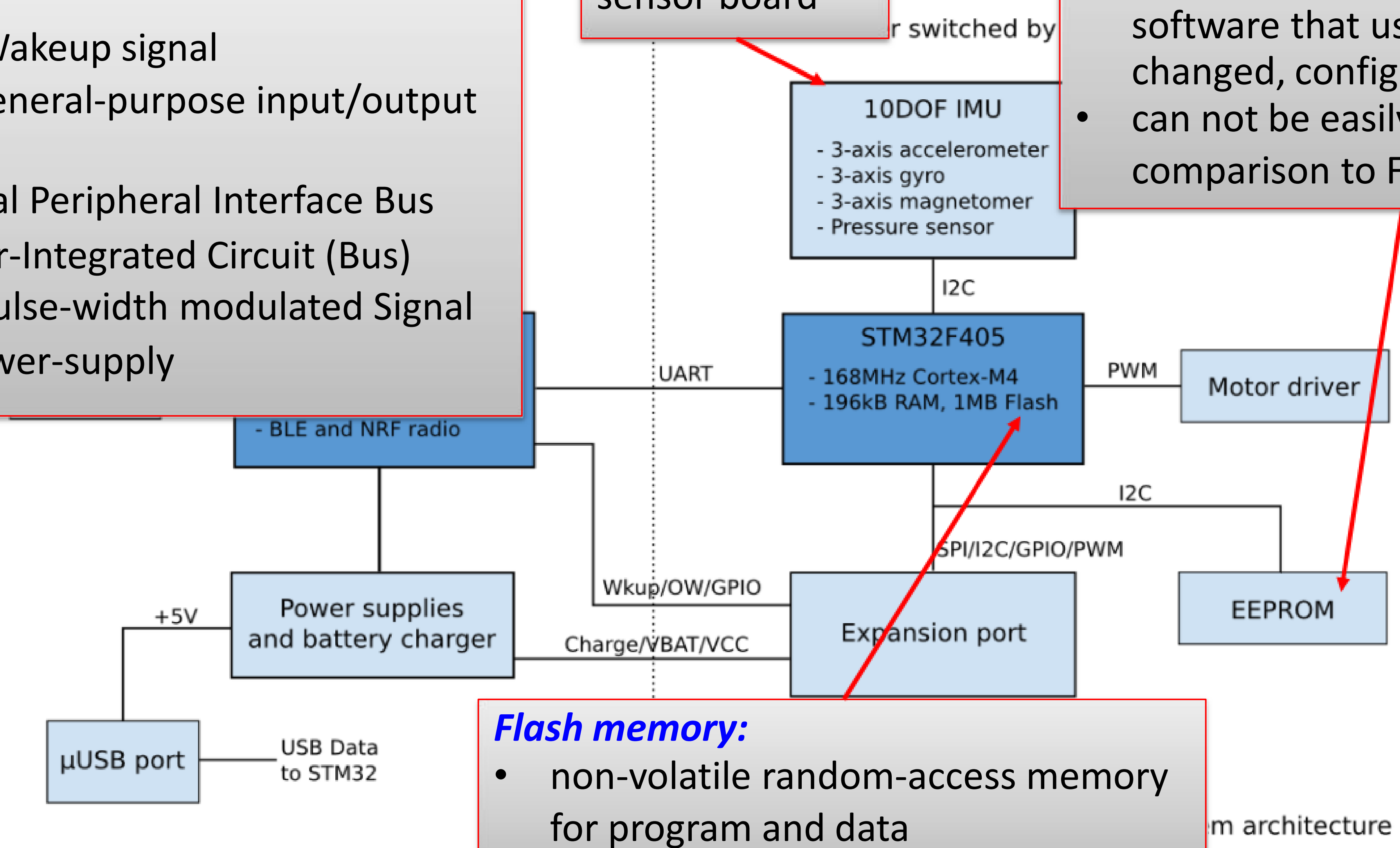
- communication protocol (Universal Asynchronous Receiver/Transmitter)
- exchange of data packets to and from interfaces (wireless, USB)

High-Level Block Diagram View

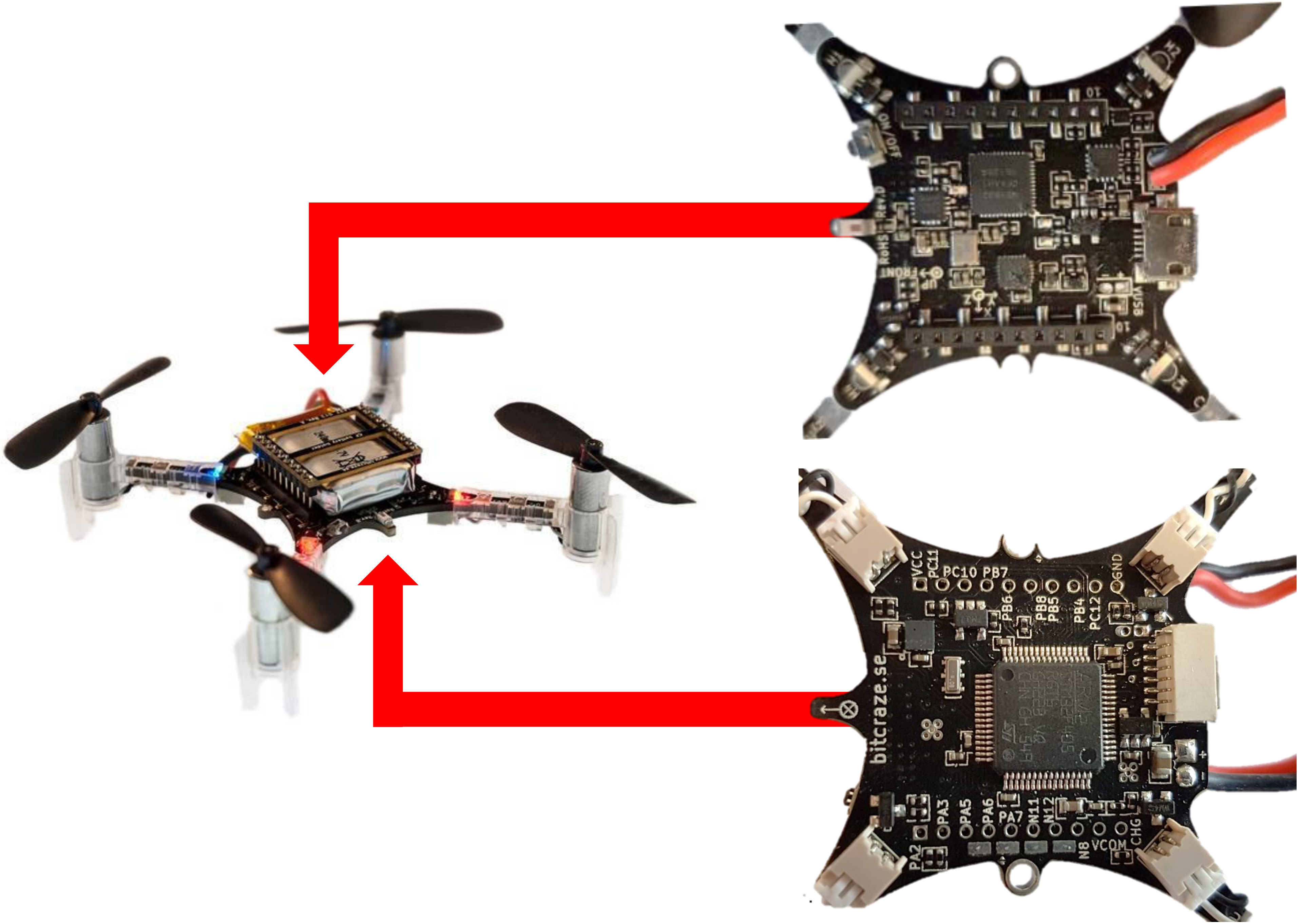
Acronyms:
- Wkup: Wakeup signal
- GPIO: General-purpose input/output signal
- SPI: Serial Peripheral Interface Bus
- I2C: Inter-Integrated Circuit (Bus)
- PWM: Pulse-width modulated Signal
- VCC: power-supply

sensor board

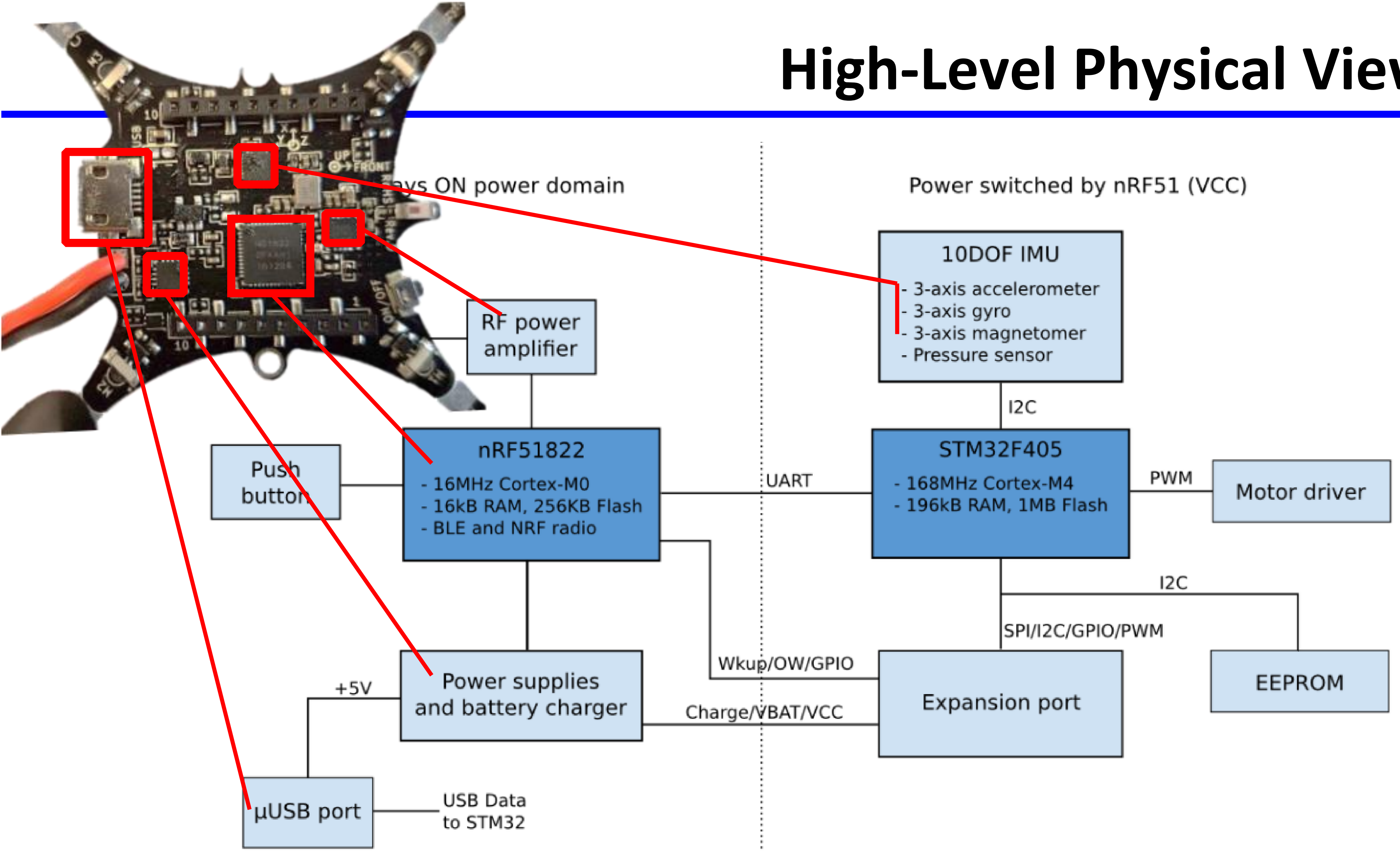
EEPROM:
- electrically erasable programmable read-only memory
- used for firmware (part of data and software that usually is not changed, configuration data)
- can not be easily overwritten in comparison to Flash



Flash memory:
- non-volatile random-access memory for program and data

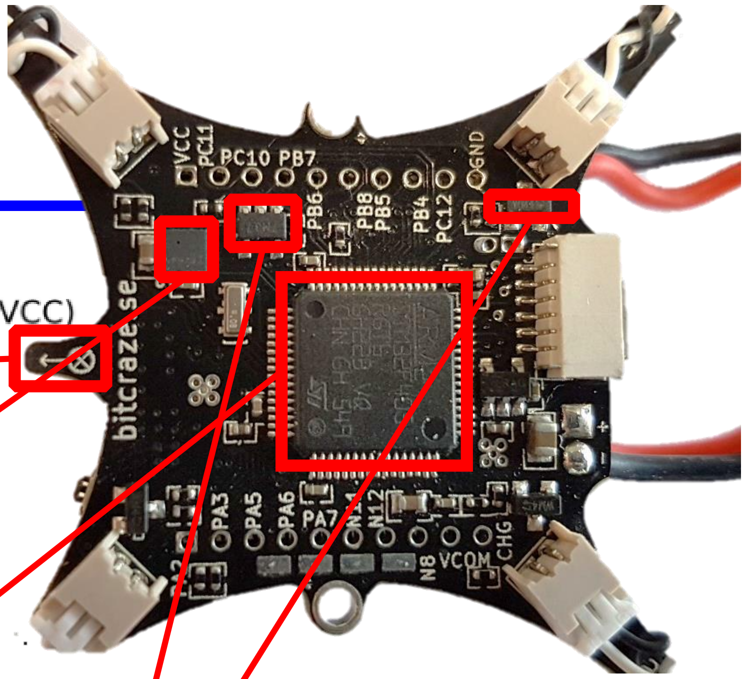

bitcraze.se
VCC
PC11
PC10 PB7
PB6
PB8
PB5
PB4
PC12
GND
PA2
PA3
PA5
PA6
PA7
VCOM
CHG
Rev.D
RoHS
UP FRONT
VUSB

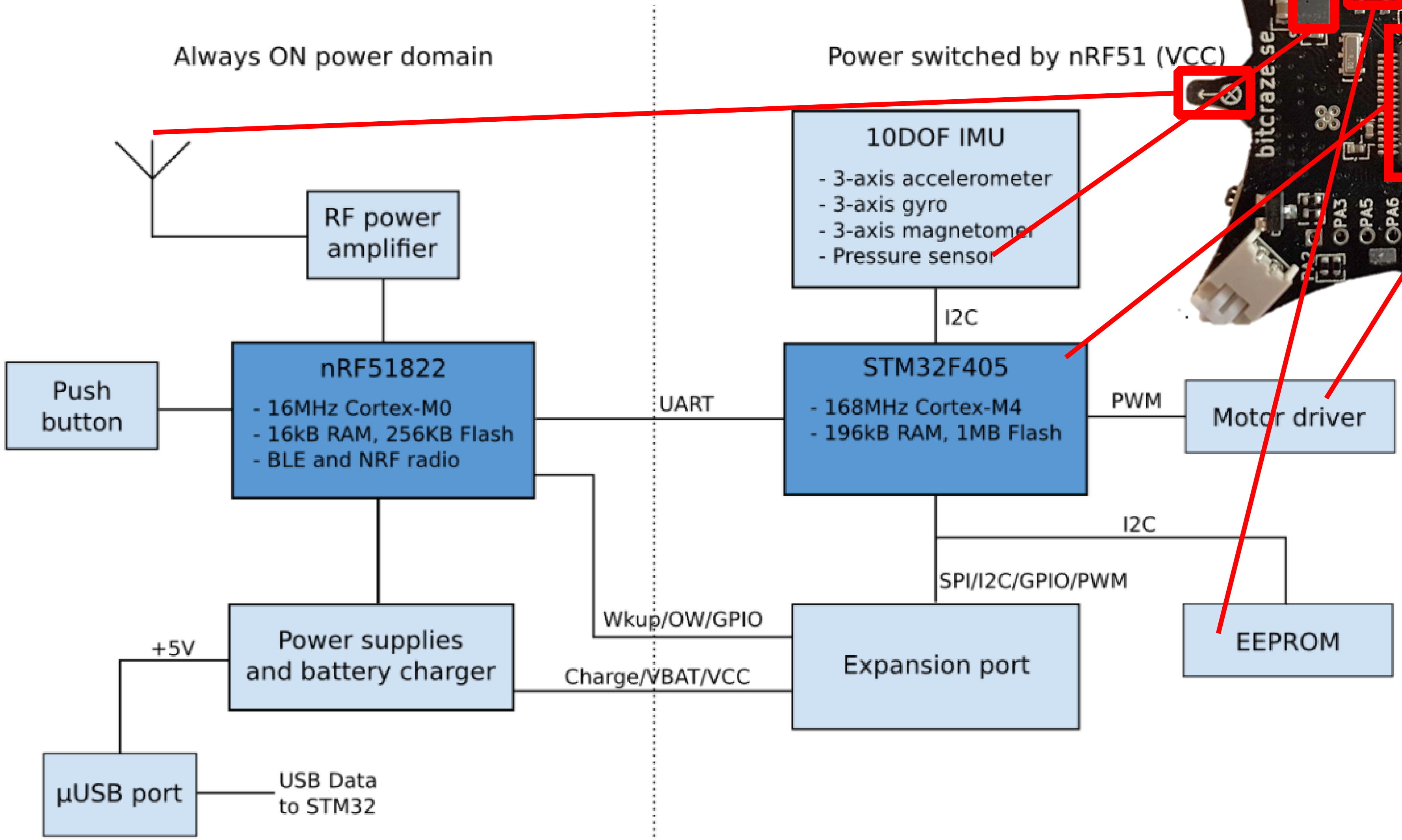
High-Level Physical View



Crazyflie 2.0 system architecture

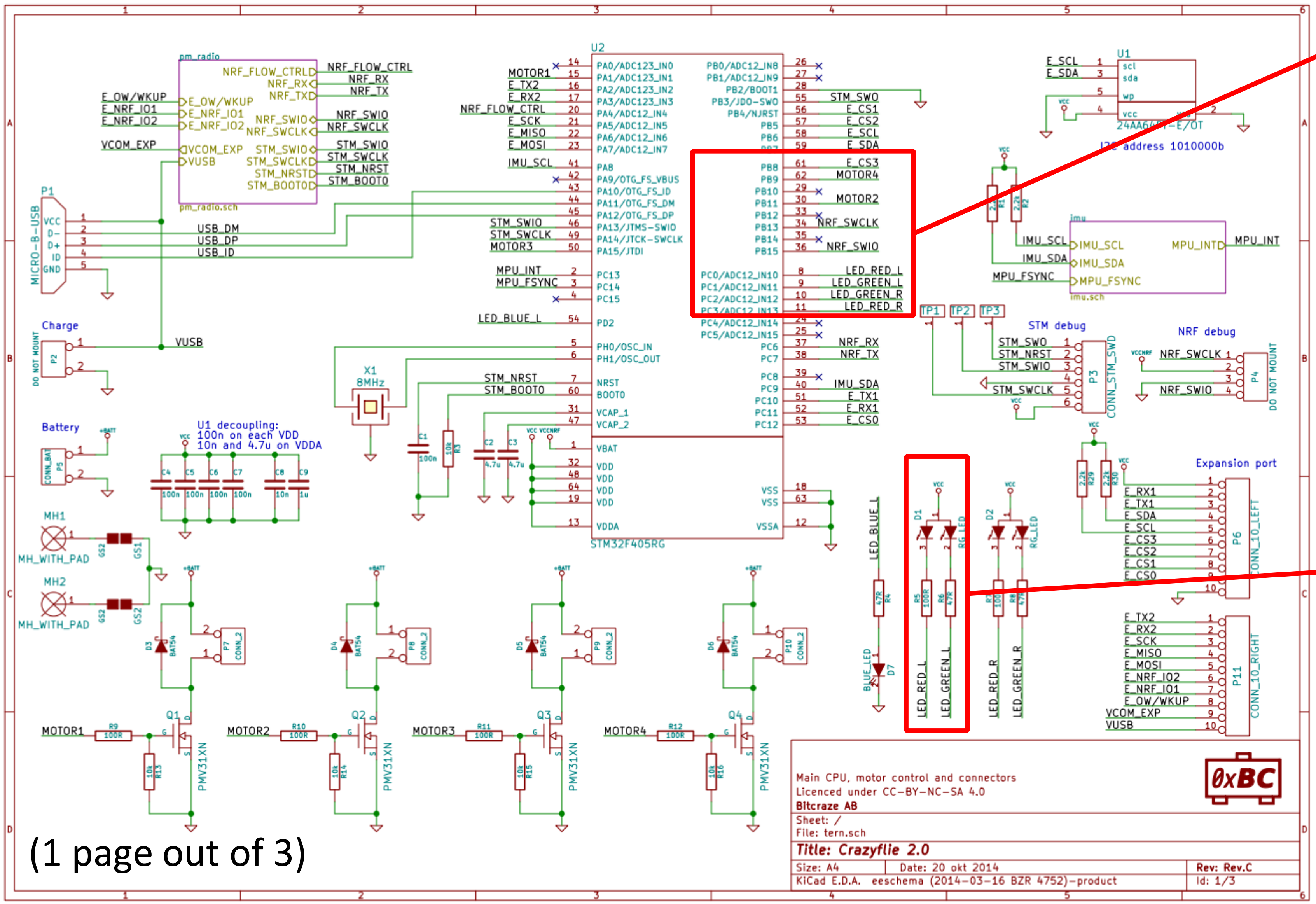
High-Level Physical View





Crazyflie 2.0 system architecture

Low-Level Schematic Diagram View



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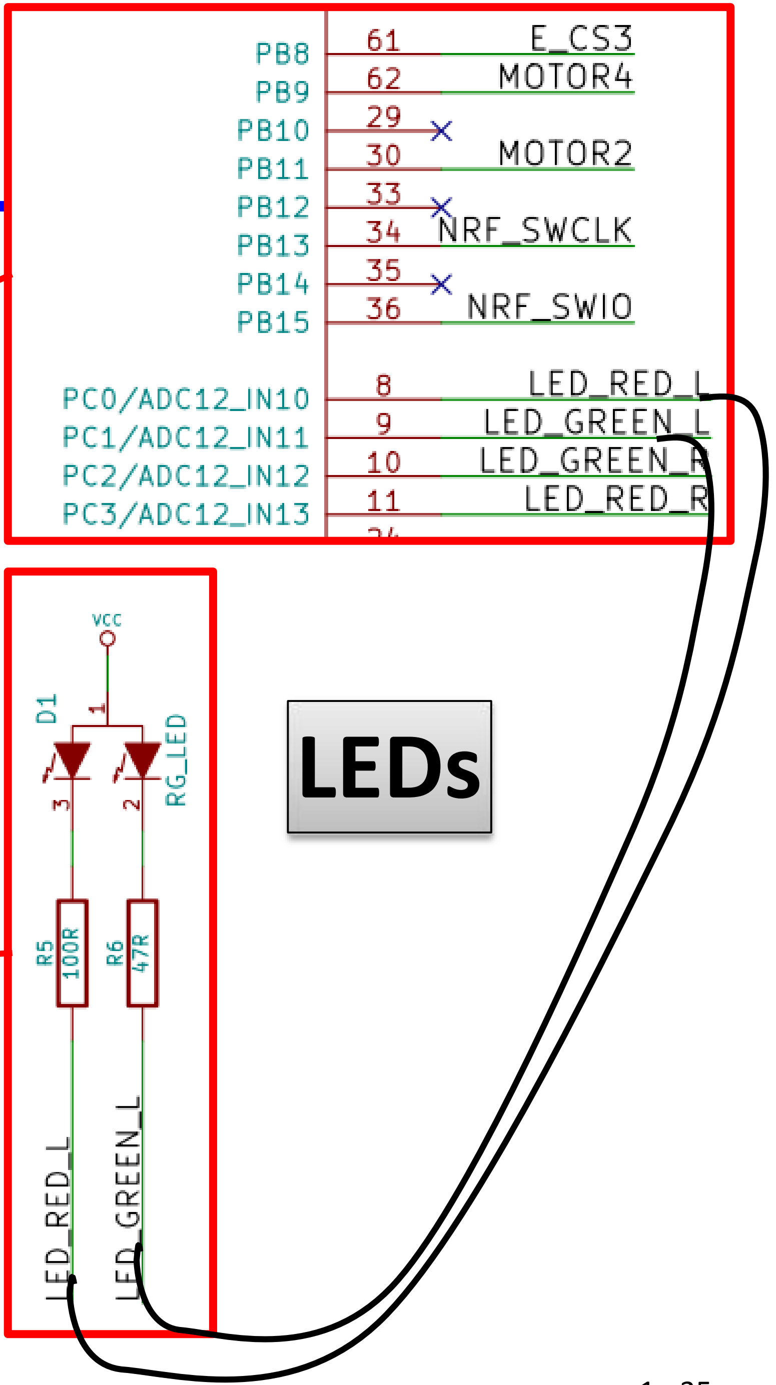
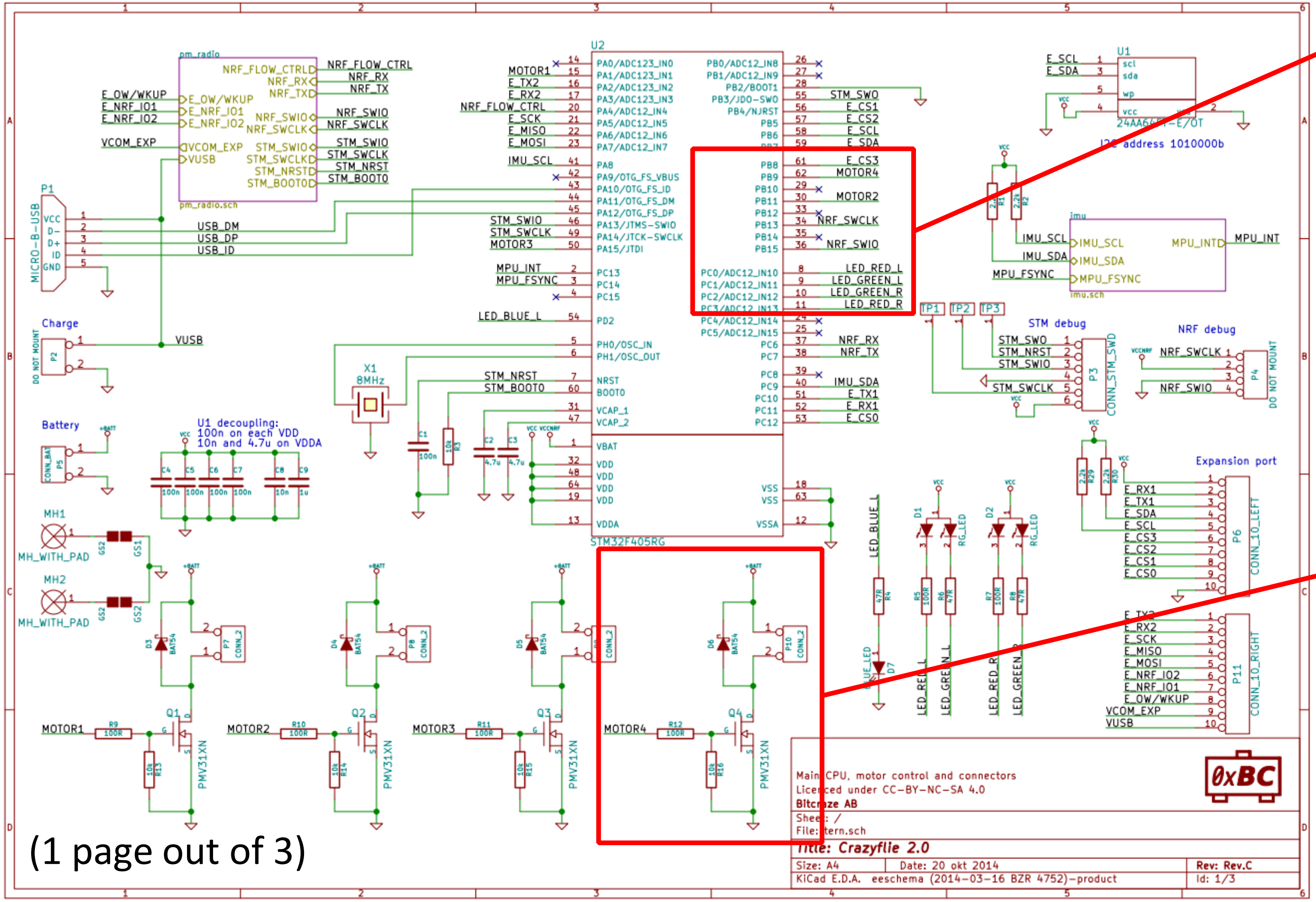


Low-Level Schematic Diagram View



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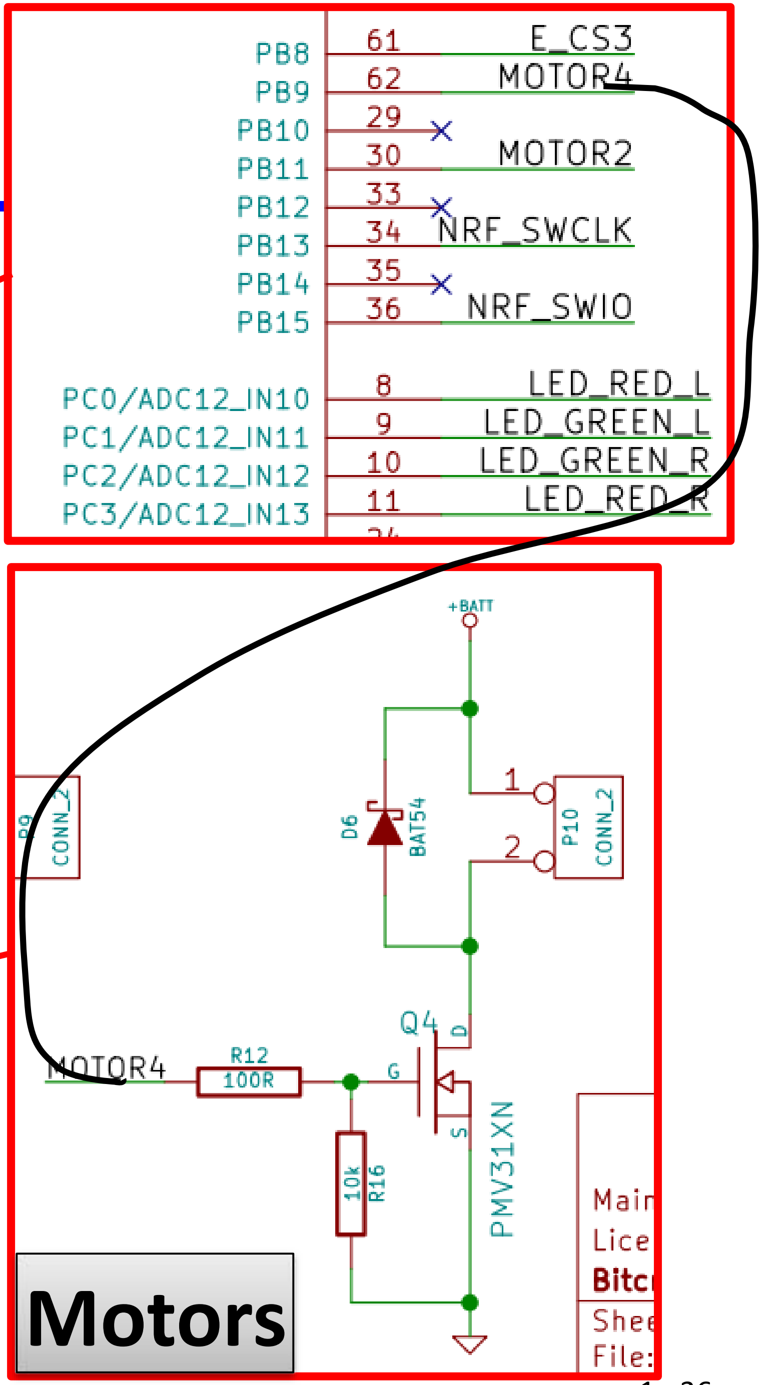
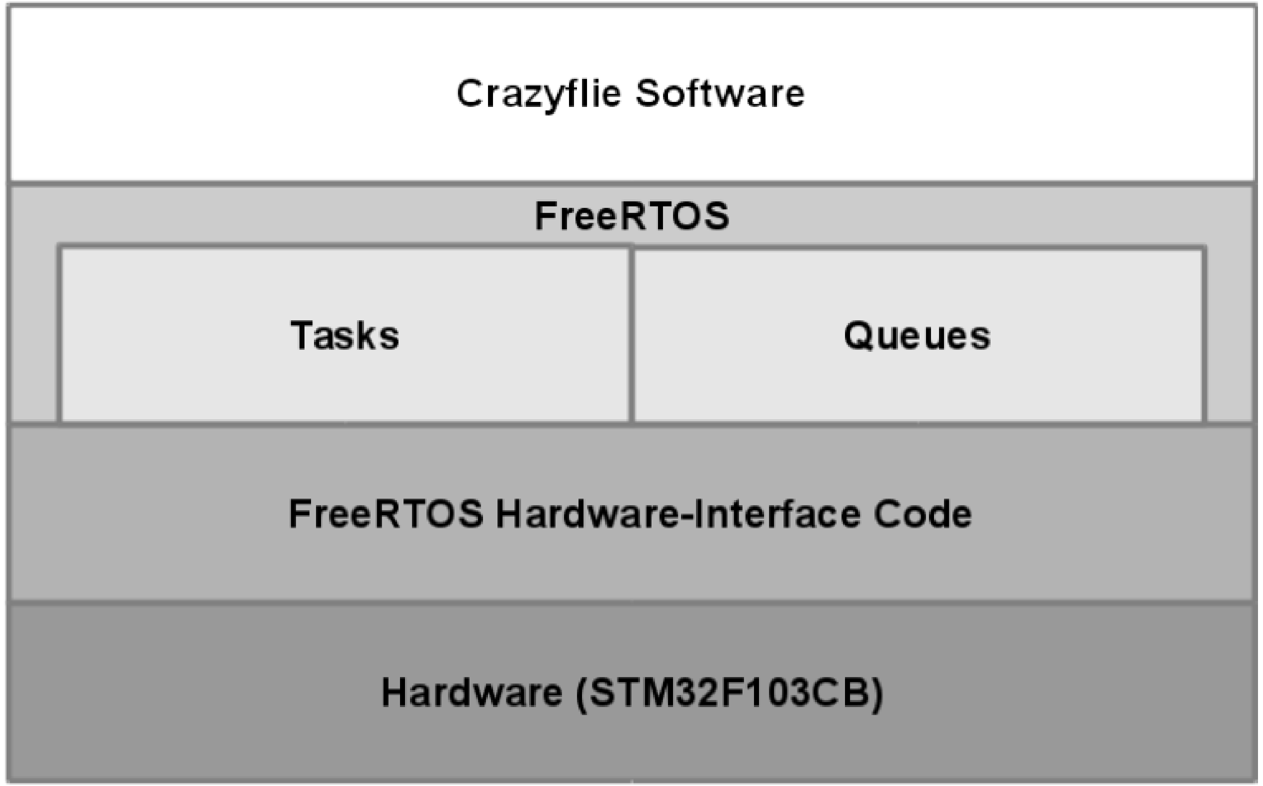


High-Level Software View

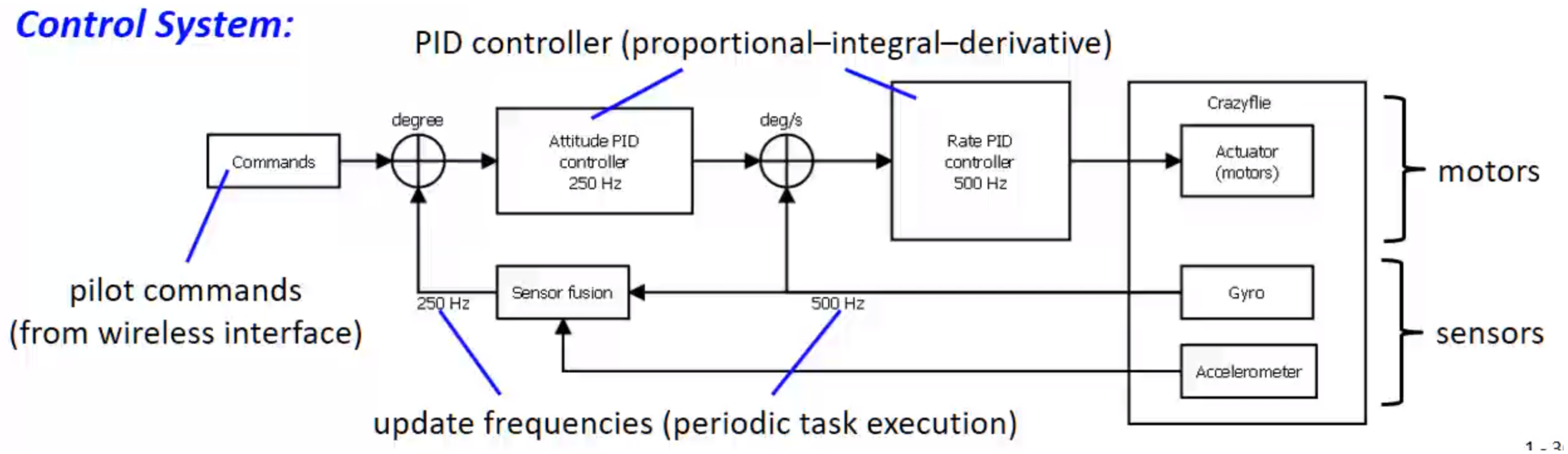
- The software is built on top of a *real-time operating system*.
- We will use FreeRTOS operating system



High-Level Software View

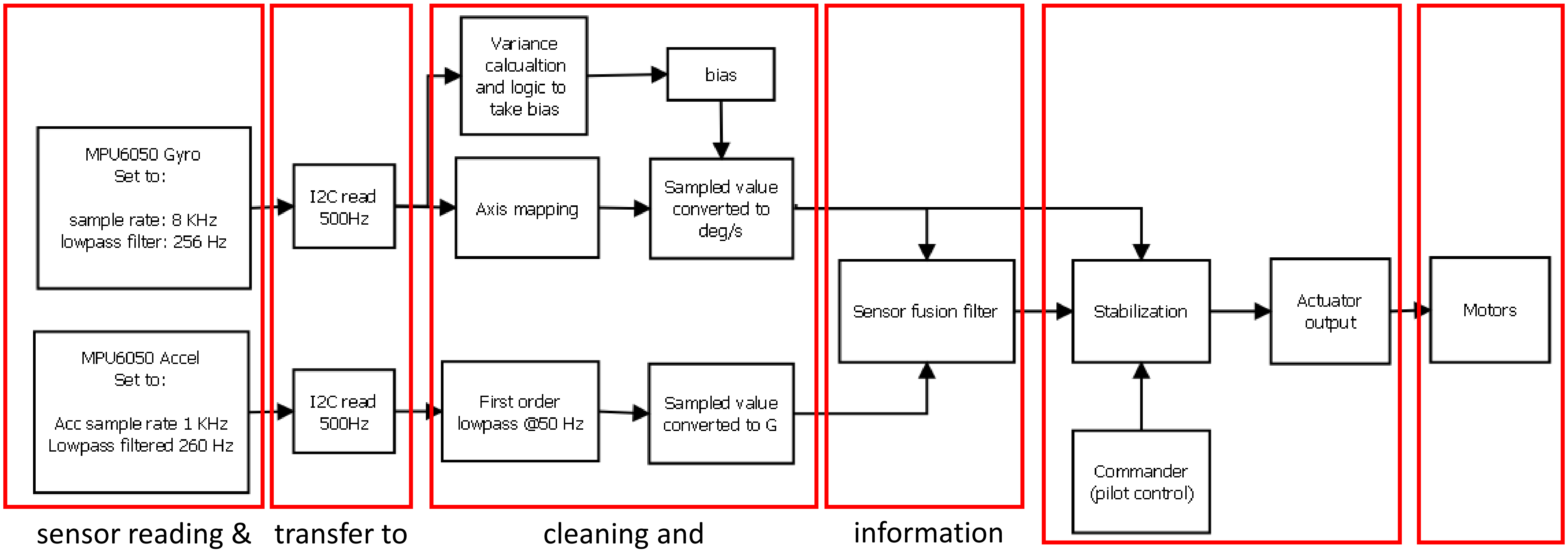
The *software architecture* supports

- *real-time tasks* for motor control (gathering sensor values and pilot commands, sensor fusion, automatic control, driving motors using PWM (pulse width modulation, …) but also
- *non-real-time tasks* (maintenance and test, handling external events, pilot commands, …).



High-Level Software View

Block diagram of the stabilization system:



sensor reading & analog-digital conversion on sensor component

transfer to processor

cleaning and preprocessing

information extraction from sensors

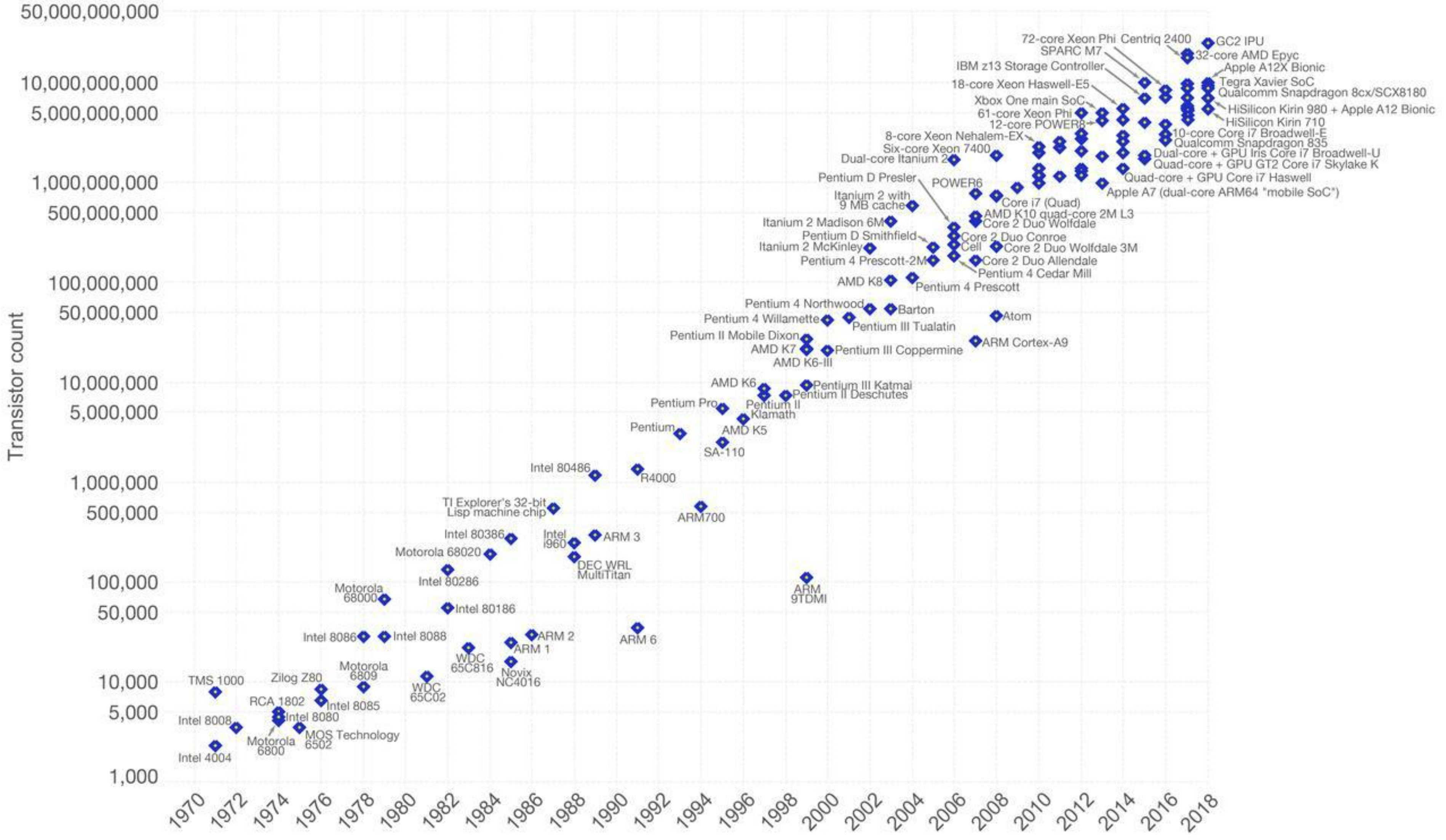
automatic control

actuation

Components and Requirements by Example
- Processing Elements -

What can you do to increase performance?

From Computer Engineering



Data source: Wikipedia (https://en.wikipedia.org/wiki/Transistor_count)
The data visualization is available at OurWorldinData.org. There you find more visualizations and research on this topic.

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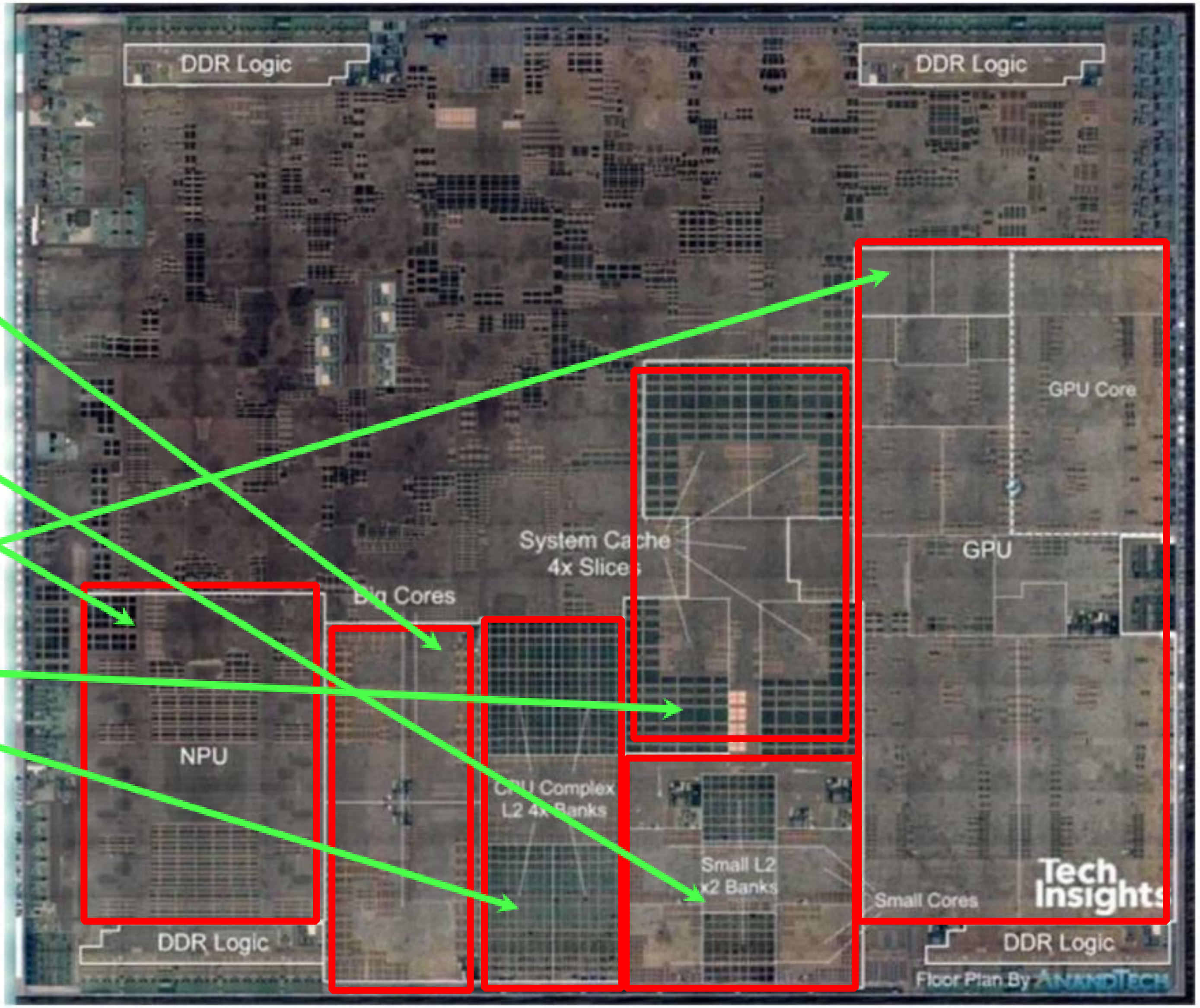
From Computer Engineering

iPhone Processor A12

- 2 processor cores
  - high performance
- 4 processor cores - less performant
- Acceleration for Neural Networks
- Graphics processor
- Caches



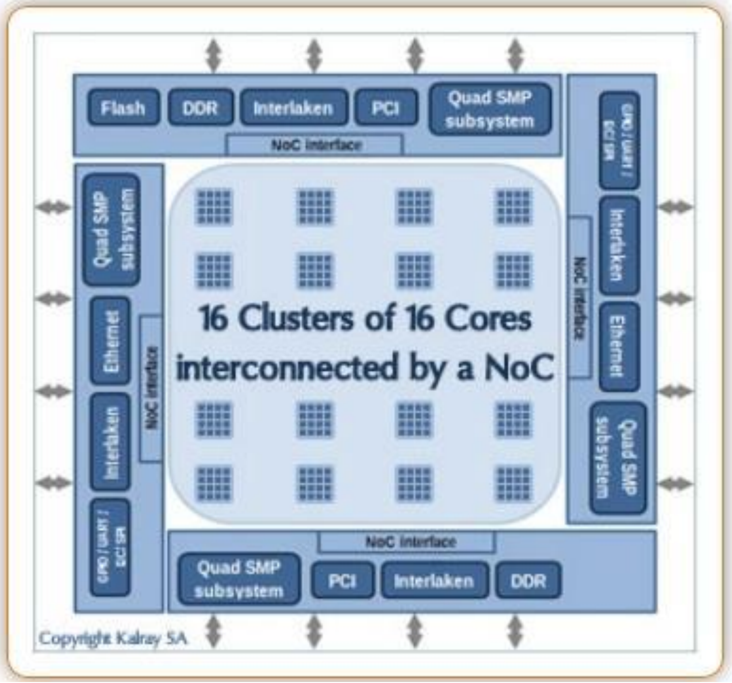
What can you do to decrease power consumption?

Embedded Multicore Example

***Trends*:**

- Specialize multicore processors towards real-time processing and low power consumption (parallelism can decrease energy consumption)
- Target domains:

Core Generation	Number of Processing Cores	GFLOPS/W	GOPS/W
Andey	256	25	75
Bostan (2014)	256	50	80
Coolidge (2015)	64/256/1024	75	115

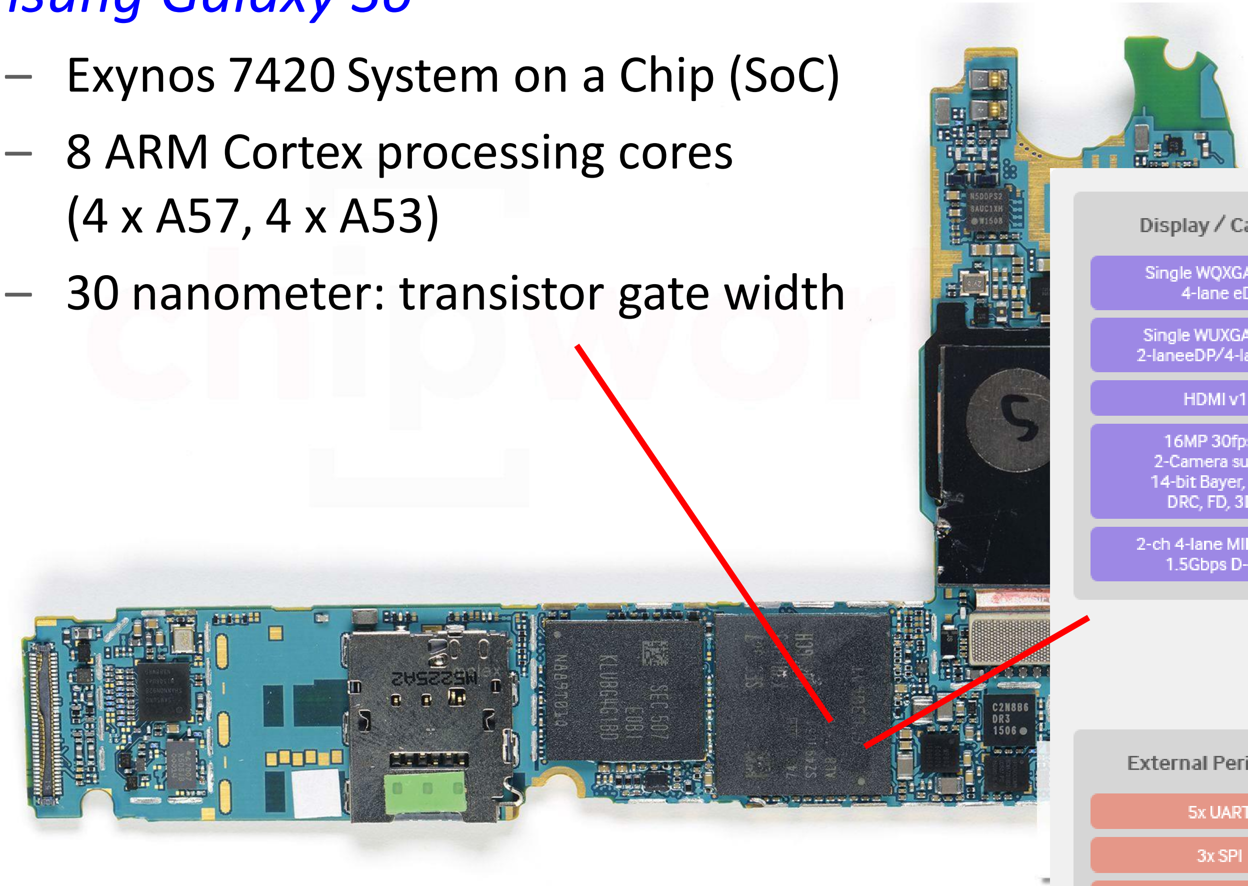


Why does higher parallelism help in reducing power?

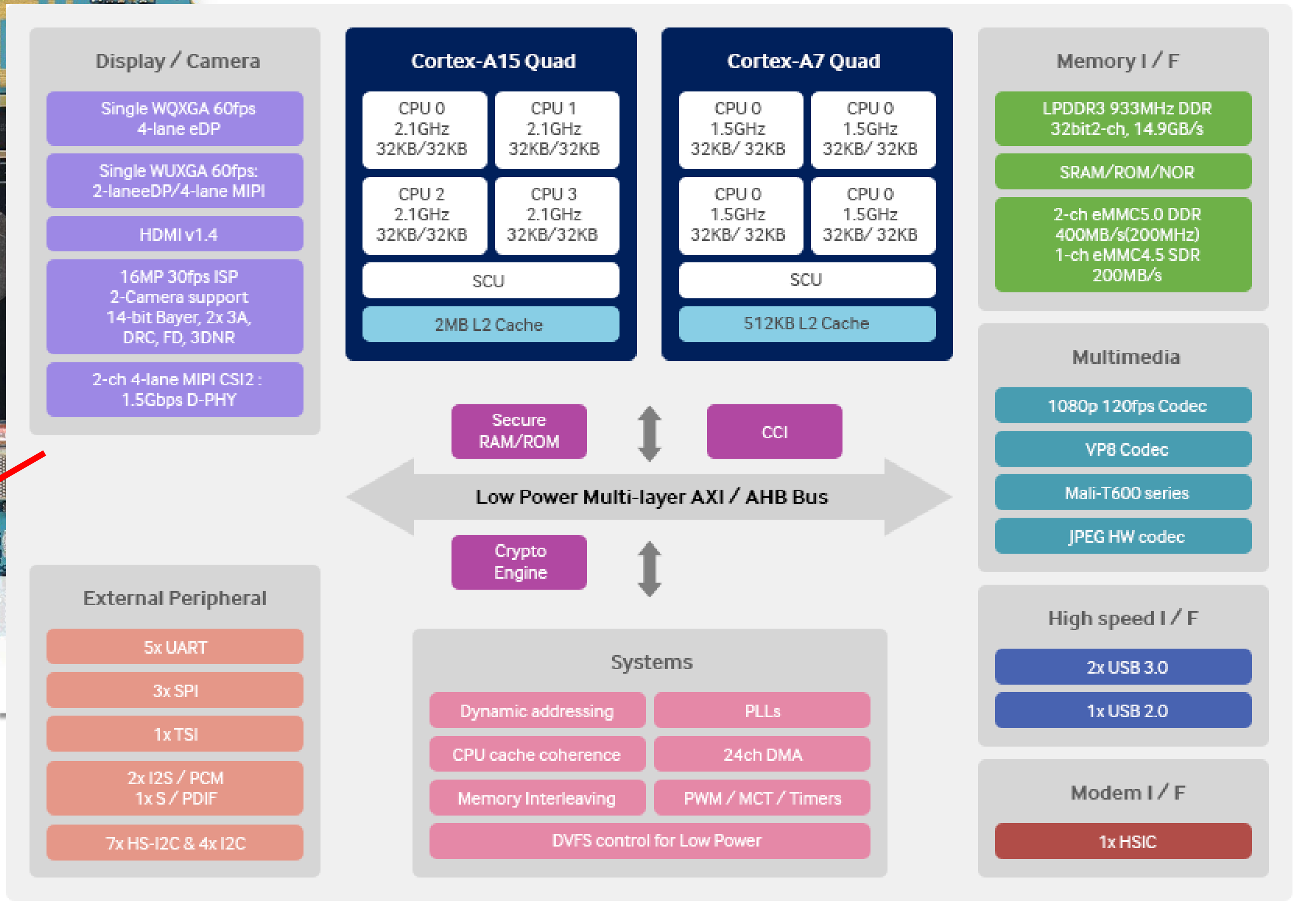
System-on-Chip

Samsung Galaxy S6

- Exynos 7420 System on a Chip (SoC)
- 8 ARM Cortex processing cores (4 x A57, 4 x A53)
- 30 nanometer: transistor gate width



Exynos 5422



How to manage extreme workload variability?

System-on-Chip

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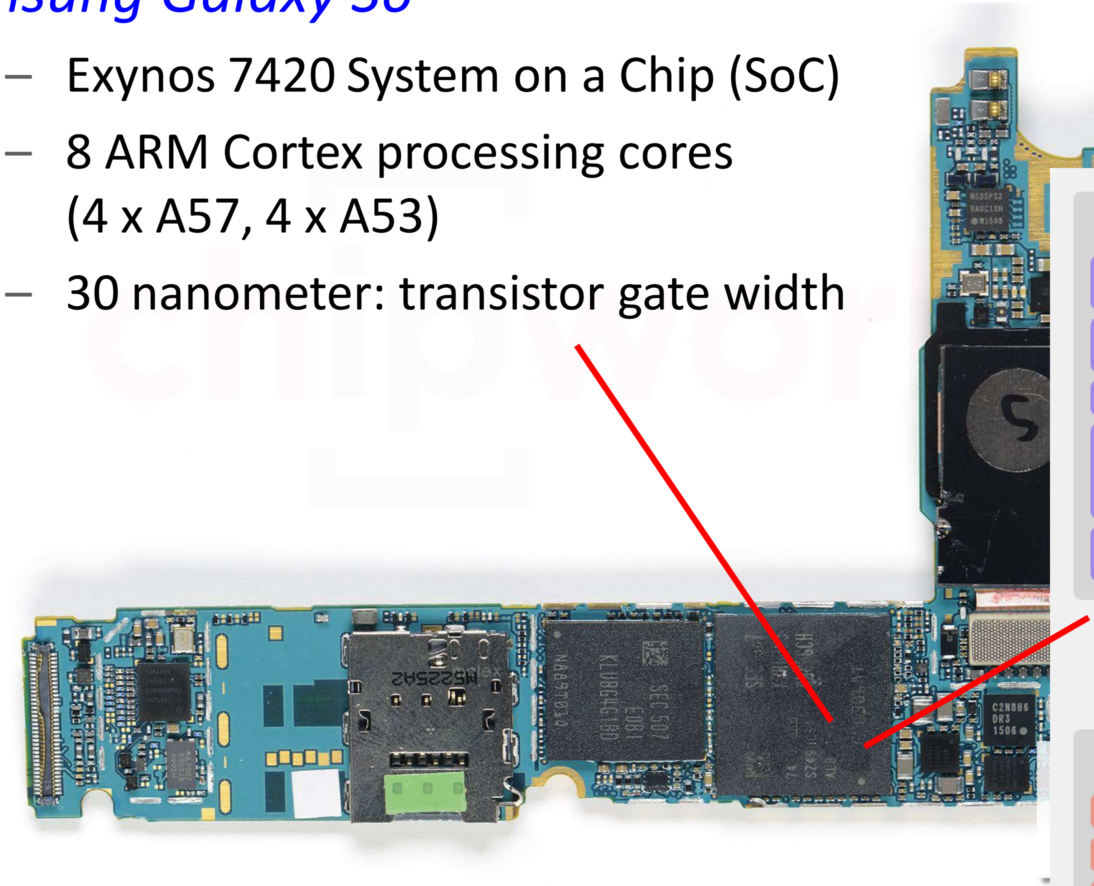
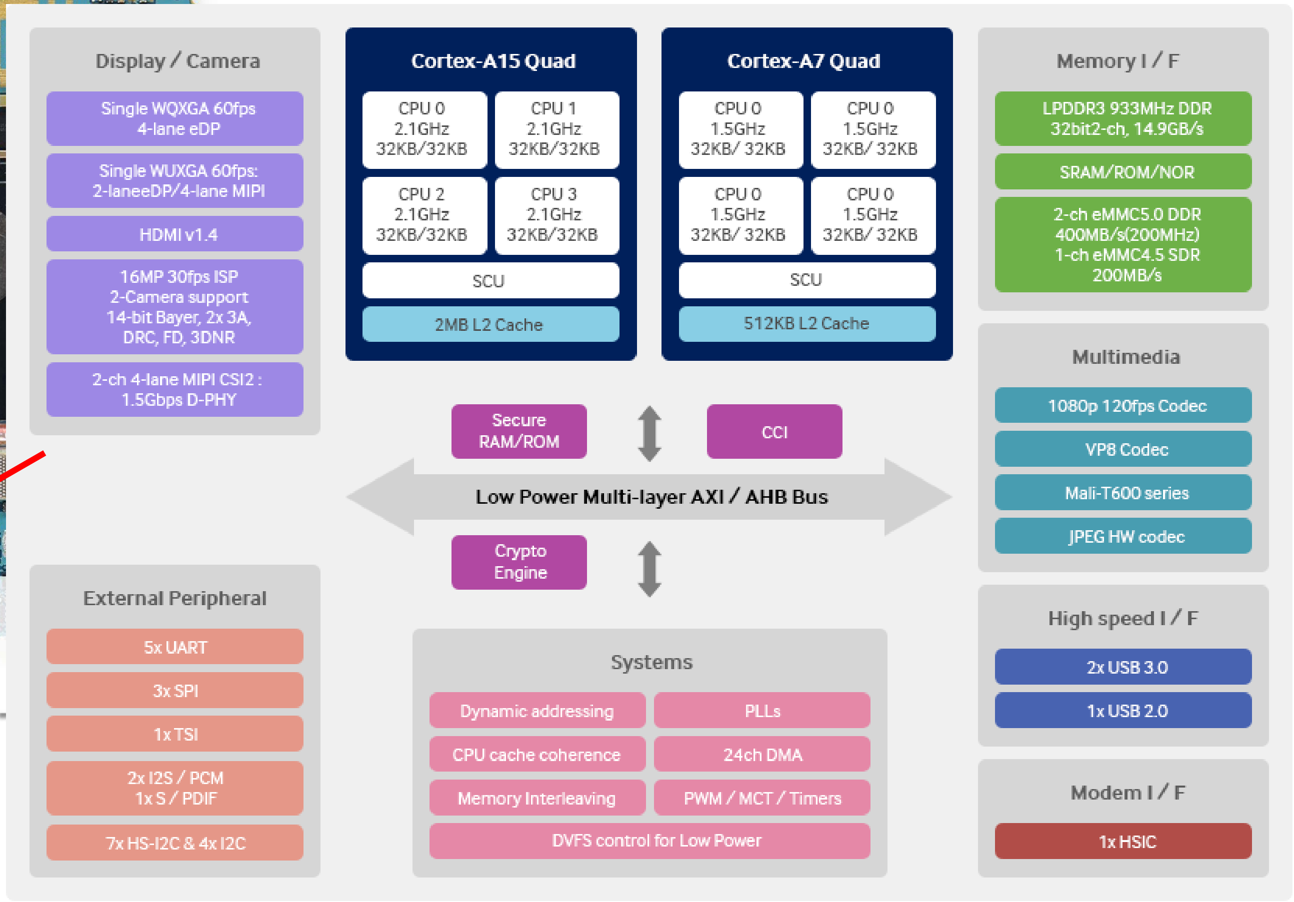


Exynos 5422



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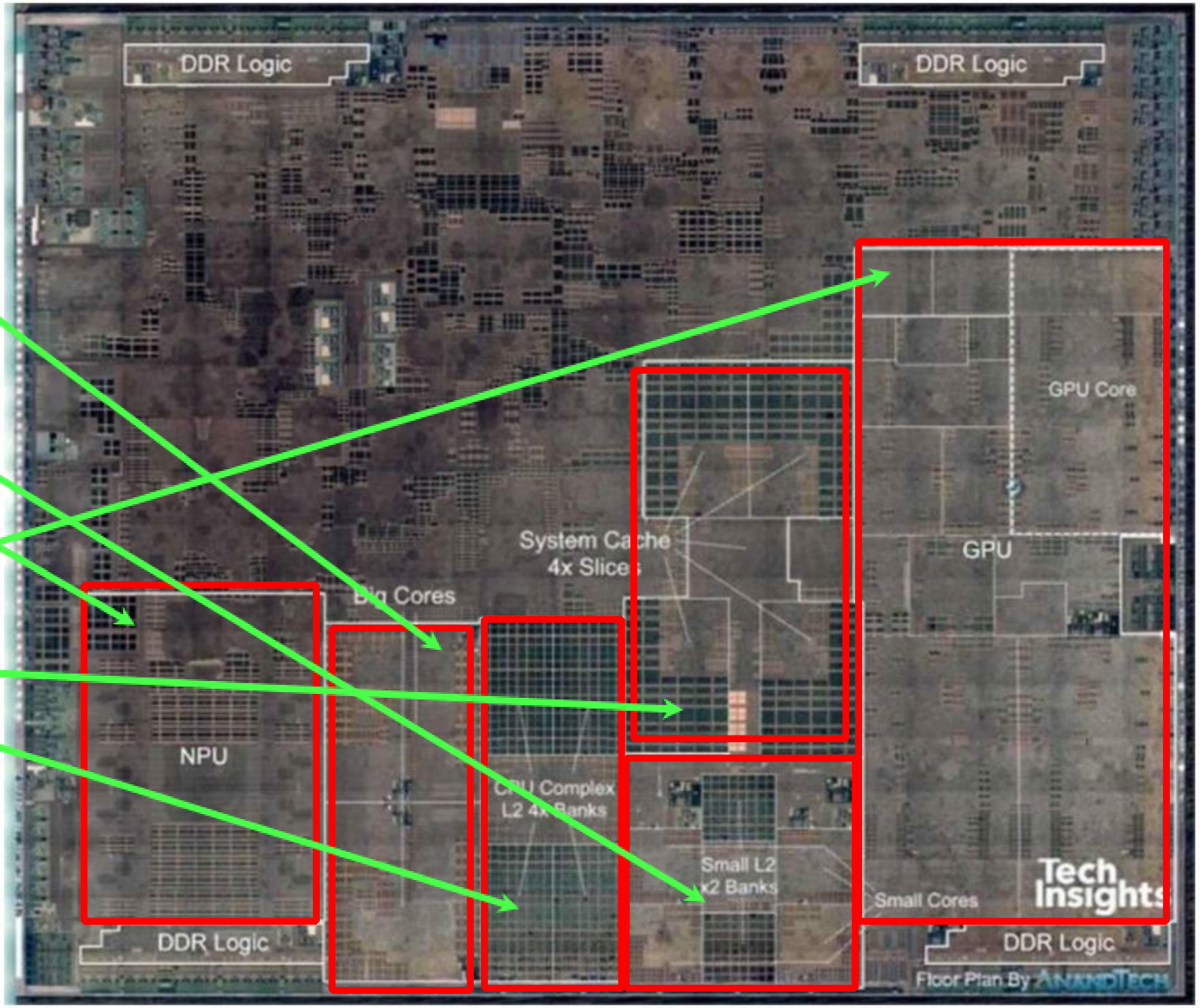
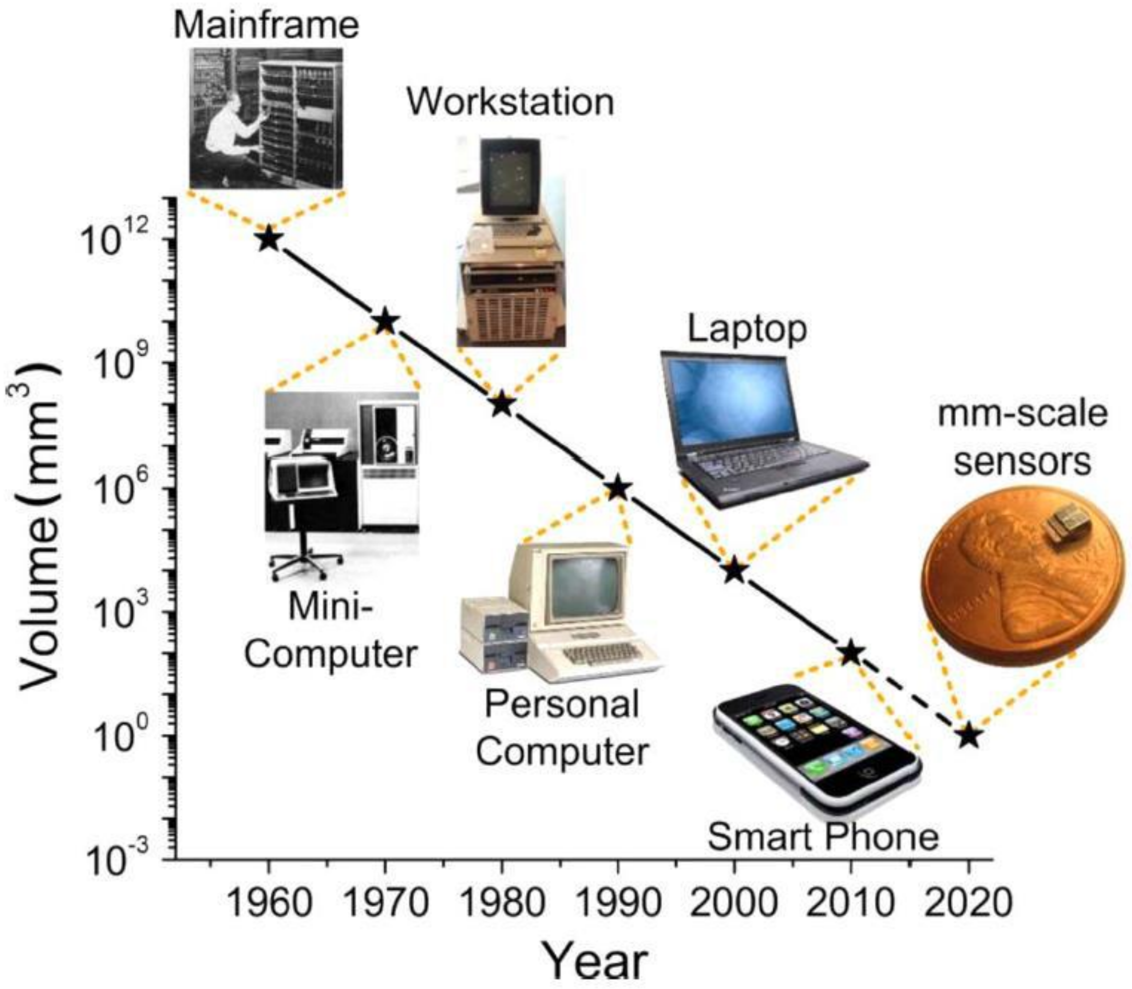


Components and Requirements by Example
- Systems -

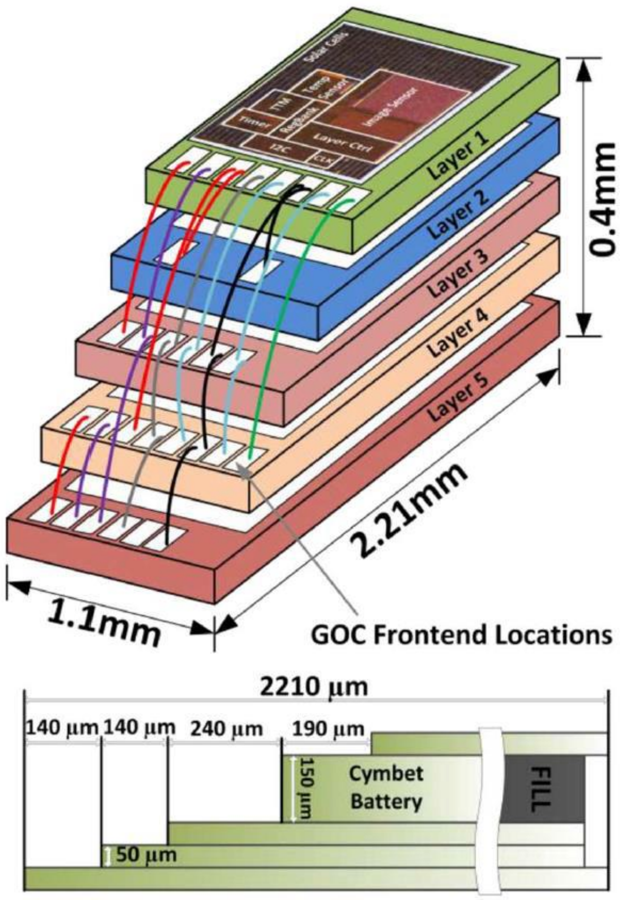
Zero Power Systems and Sensors

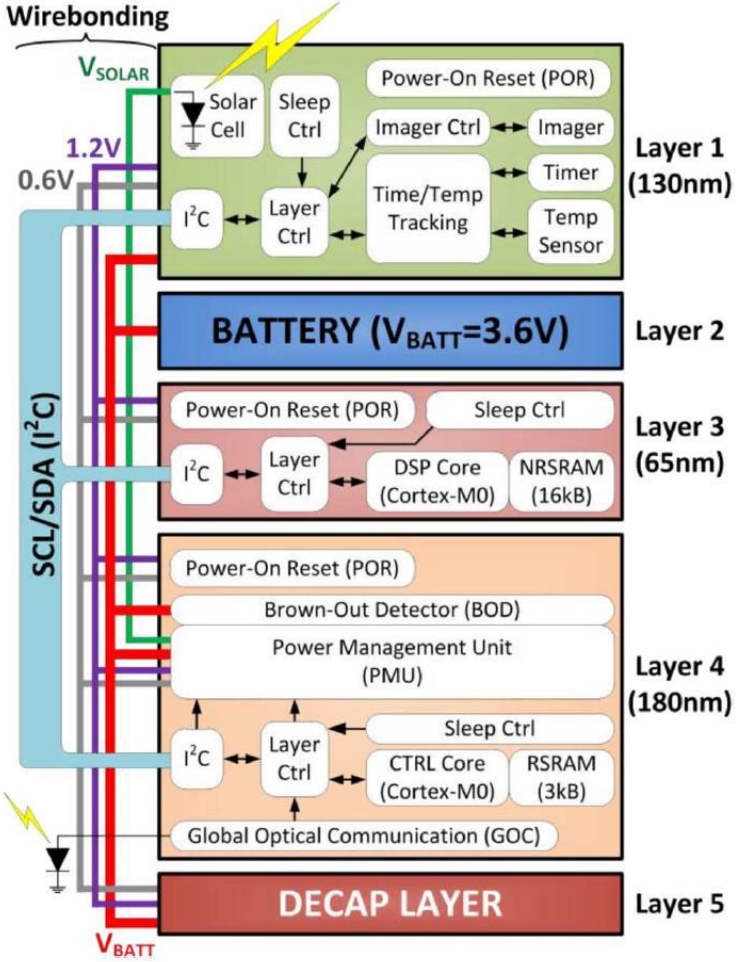


Streaming information to and from the physical world:

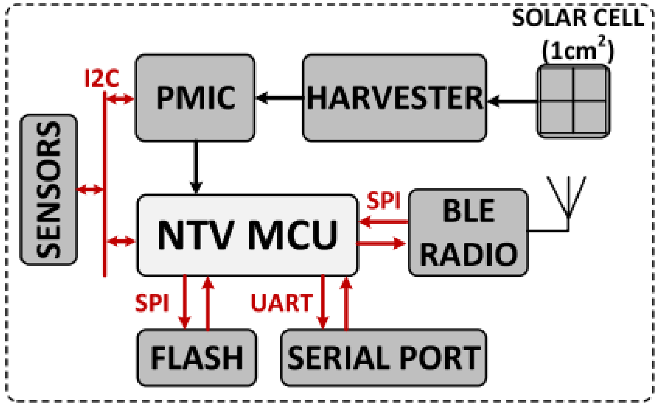
- “Smart Dust”
- Sensor Networks
- Cyber-Physical Systems
- Internet-of-Things (IoT)

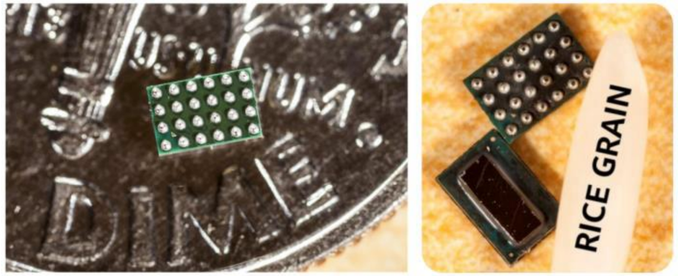
Zero Power Systems and Sensors





IEEE Journal of Solid-State Circuits, Jan 2013, 229-243.





IEEE Journal of Solid-State Circuits, April 2017, 961-971.

Trends …

- *Embedded systems are communicating with each other,* with servers or with the cloud. Communication is increasingly wireless.

- *Higher degree of integration* on a single chip or integrated components:
  - Memory + processor + I/O-units + (wireless) communication.
  - Use of networks-on-chip for communication between units.
  - Use of homogeneous or heterogeneous multiprocessor systems on a chip (MPSoC).
  - Use of integrated microsystems that contain energy harvesting, energy storage, sensing, processing and communication (“zero power systems”).
  - The complexity and amount of software is increasing.

- *Low power and energy constraints* (portable or unattended devices) are increasingly important, as well as temperature constraints (overheating).
- There is increasing interest in *energy harvesting* to achieve long term autonomous operation.