EE5726
Embedded Sensor Networks

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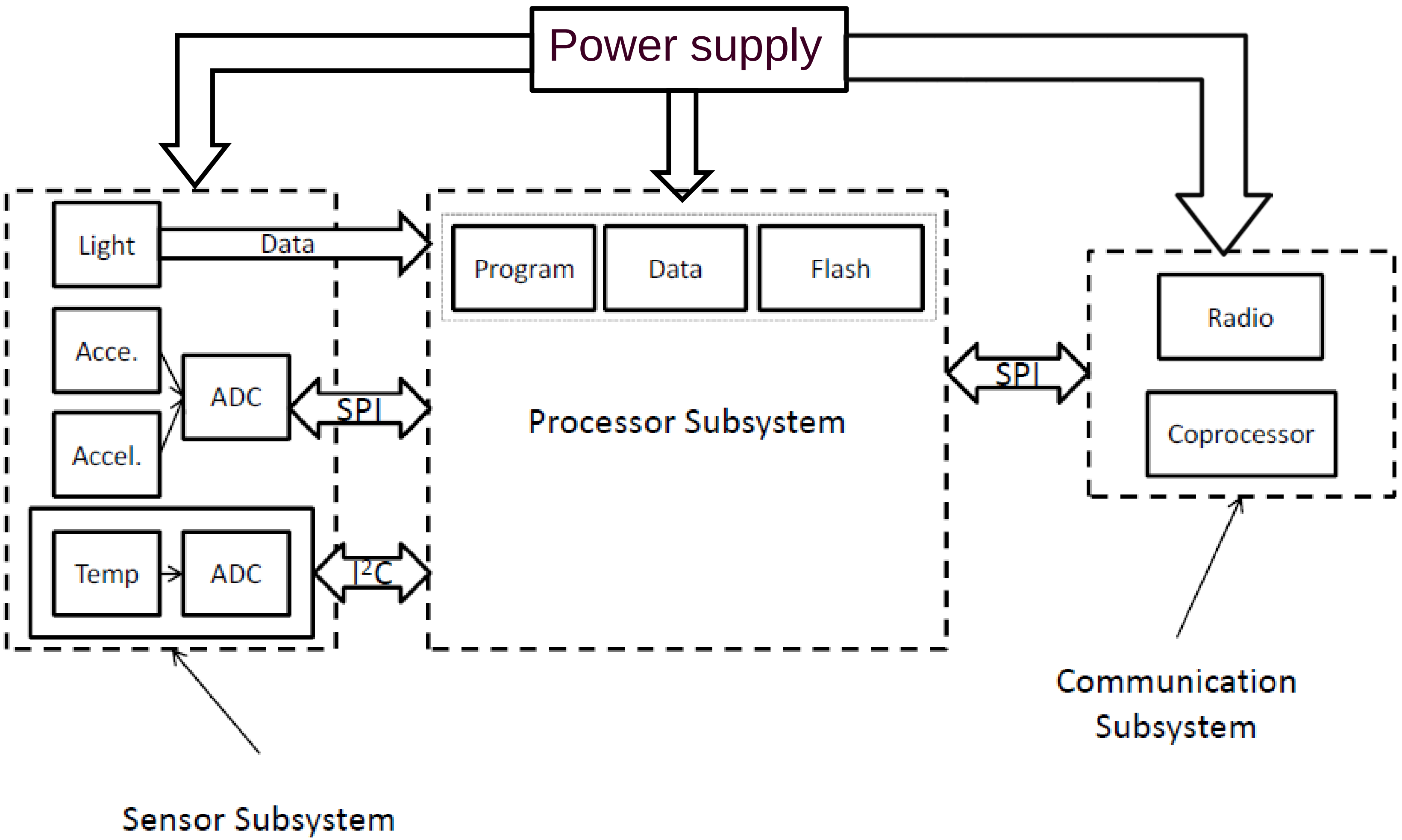
Today's Agenda

- Last Time: Introduction to Wireless Sensor Networks
  - Definition of WSNs
  - Characteristics of WSNs
  - Research challenges for WSNs
- Today: Single-Node Architecture
  - Hardware components
  - Energy consumption
  - Operating system
  - Prototypes

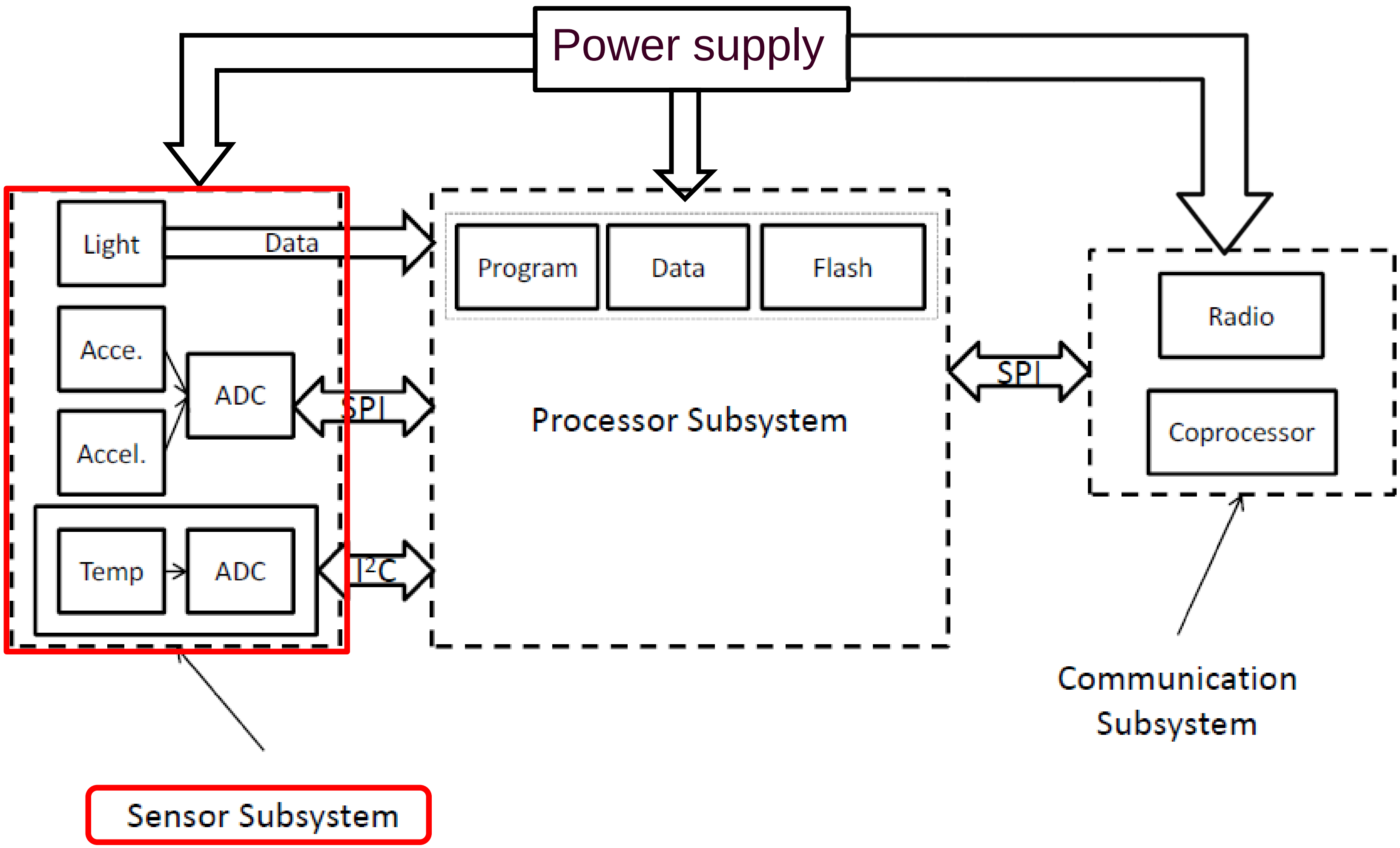
Node Architecture

- Wireless sensor nodes are the essential building blocks in a wireless sensor network
  - *Sensing, processing and communication take place through a node*
  - *Stores and executes the communication protocols as well as data processing algorithms*
- The node consists of a *sensing*, *processing*, *communication* and *power subsystems*

Node Architecture

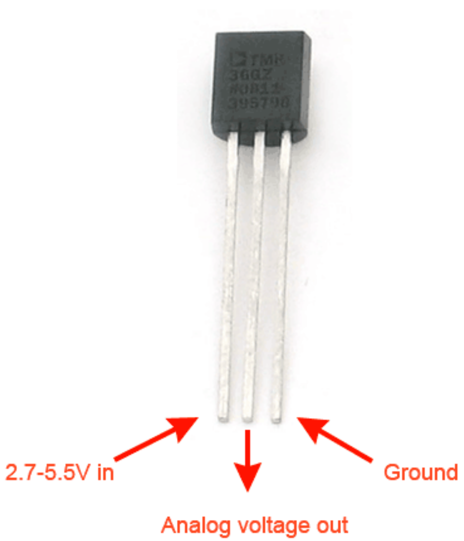


Node Architecture



The Sensing Subsystem

- The sensing subsystem integrates
  - *One or more physical sensors*
  - *One or more analog-to-digital converters*
  - *The multiplexing mechanism among sensors and ADCs*



Temperature sensors of various kinds

Sensors

- Sensors interface the virtual world with the physical world
  - *Houfeng Didong Yi (a seismoscope) by the Chinese astronomer Zhang, Heng in 132 A.D. to measure the movement of the Earth*

Sensors

- Sensors interface the virtual world with the physical world
  - *Houfeng Didong Yi by the Chinese astronomer Zhang, Heng in 132 A.D. to measure the movement of the Earth*
- Modern sensors: contain a device that converts one form of energy into another form of energy, typically into the electrical energy
- Categories:
  - *Passive, omnidirectional sensors: thermometer, air pressure*
  - *Passive, narrowbeam sensors: camera*
  - *Active sensors: sonar/radar sensors, seismic sensors*

The Sensing Subsystem: Types of Sensors

Sensor	Application Area	Sensed Event	Explanation
Accelerometer	AVM (active volcano monitoring)	2D and 3D acceleration of movements of people and objects	Volcano activities
	SHM (structure health monitoring)		Stiffness of a structure
	Health care		Stiffness of bones, limbs, joints; Motor fluctuation in Parkinson's disease
	Transportation		Irregularities in rail, axle box or wheels of a train system
	SCM (structure condition monitoring)		Defect of fragile objects during transportation
Acoustic emission sensor	SHM	Elastic waves generated by the energy released during crack propagation	Measures micro-structural changes or displacements
Acoustic sensor	Transportation & Pipelines	Acoustic pressure vibration	Vehicle detection; Measure structural irregularities; Gas contamination
Capacitance sensor	PA (precision agriculture)	Solute concentration	Measure the water content of soil

The Sensing Subsystem

Sensor	Application Area	Sensed Event	Explanation
ECG	Health care	Heart rate	
EEG		Brain electrical activity	
EMG		Muscle activity	
Electrical sensors	PA (precision agriculture)	Electrical capacitance or inductance affected by the composition of tested soil	Measure of nutrient contents and distribution
Gyroscope	Health care	Angular velocity	Detection of gait phases
Humidity sensor	PA & HM (habitat monitoring)	Relative and absolute humidity	
Infrasonic sensor	AVM	Concussive acoustic waves – earth quake or volcanic eruption	
Magnetic sensor	Transportation	Presence, intensity, direction, rotation and variation of a magnetic field	Presence, speed and density of a vehicle on a street; congestion
Oximeter	Health care	Blood oxygenation of patient's hemoglobin	Cardiovascular exertion and trending of exertion relative to activity
pH sensor	Pipeline (water)	Concentration of hydrogen ions	Indicates the acid and alkaline content of a water measure of cleanliness

The Sensing Subsystem

Sensor	Application Area	Sensed Event	Explanation
Photo acoustic spectroscopy	Pipeline	Gas sensing	Detects gas leak in a pipeline
Piezoelectric cylinder	Pipeline	Gas velocity	A leak produces a high frequency noise that produces a high frequency noise that produces vibration
Soil moisture sensor	PA	Soil moisture	Fertilizer and water management
Temperature sensor	PA & HM	Pressure exerted on a fluid	
Passive infrared sensor	Health care & HM	Infrared radiation from objects	Motion detection
Seismic sensor	AVM	Measure primary and secondary seismic waves (Body wave, ambient vibration)	Detection of earth quake
Oxygen sensor	Health care	Amount and proportion of oxygen in the blood	
Blood flow sensor	Health care	The Doppler shift of a reflected ultrasonic wave in the blood	

Analog-to-Digital Converter

- ADC converts the output of a sensor ---- which is a continuous, analog signal ---- into a digital signal. Two parameters:

  1. *The analog signal has to be quantized*
     - *Resolution of ADC in bits-- The number of bits that can be used to encode the digital output*
     - *Resolution pf ADC in voltage:*

$$Q = \frac{E_{pp}}{2^M}$$

     Where Q is the resolution in volts(volts per output code); Epp is the peak-to-peak analog voltage; M is the ADC's resolution in bits

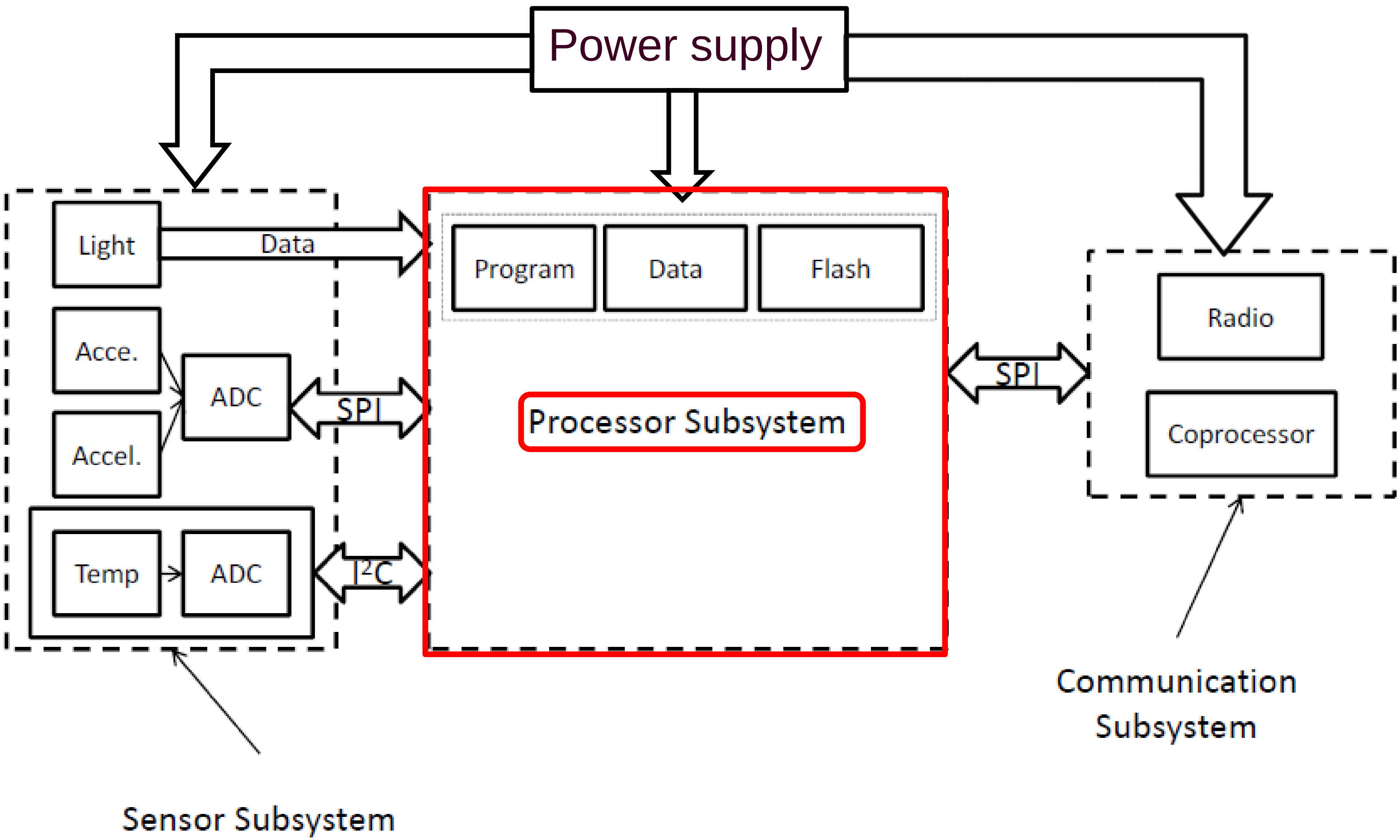
  2. *The sampling frequency*
     - *Oversampling is often needed: Nyquist rate does not suffice because of noise and transmission error*

  - *Allowable discrete values are influenced*

    (a) By the frequency and magnitude of the signal

    (b) By the available processing and storage resources

Node Architecture



The Processor Subsystem

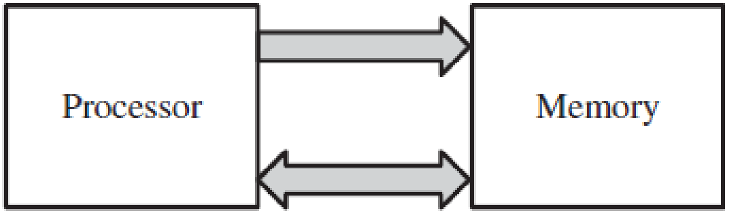
- The processor subsystem
  - *Interconnects all the other subsystems and some additional peripheries*
  - *Its main purpose is to store and execute instructions pertaining to sensing, communication and self-organization*
    - *Collects data from sensors*
    - *Processes the data*
    - *Decides when and where to send it*
    - *Receives data from other nodes*
    - *Decides on the actuator's behavior*
  - *It consists:*
    - *A processor chip*
    - *A nonvolatile memory ---- stores program instructions*
    - *An active memory ---- temporarily stores the sensed data*
    - *An internal clock*

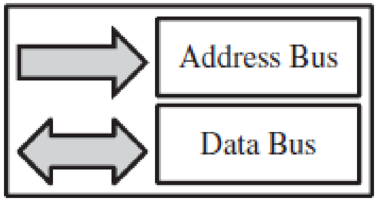
Architectural Overview

- The processor subsystem can be designed by employing one of the three basic computer architectures
  - *Von Neumann architecture*
  - *Harvard architecture*
  - *Super-Harvard (SHARC) architecture*

Von Neumann Architecture

- Von Neumann architecture
  - 1945 by John Von Neumann: Hungarian-born American
  - provides a single memory space ---- storing program instructions and data
  - provides a single bus ---- to transfer data and instructions between the processor and the memory
  - *Von Neumann bottleneck* ---- as program memory and data memory cannot be accessed at the same time, throughput is much smaller than the rate at which the CPU can work

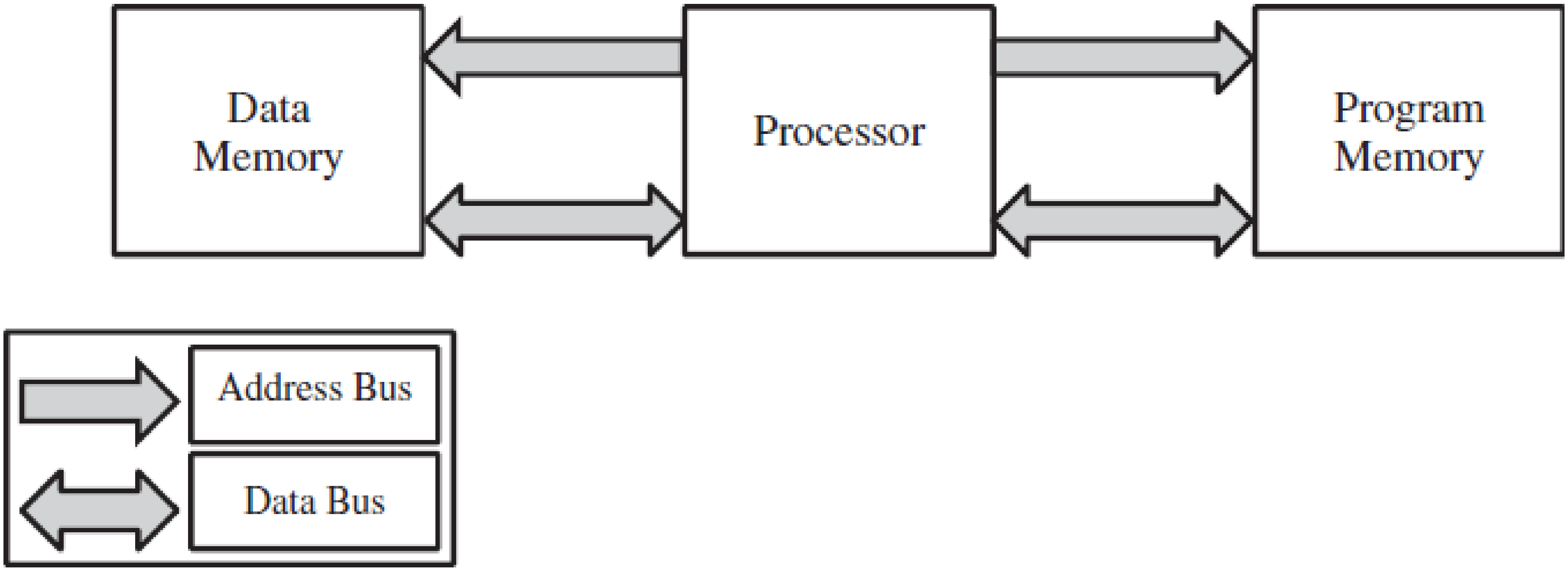




Harvard Architecture

- Harvard architecture
  - The term originated from the *Harvard Mark I relay-based computer*, which stored instructions on *punched tapes* (24 bits wide) and data in electro-mechanical counters (around 1944)
  - *Provides physically separate memory spaces ---- storing program instructions and data*
  - *Each memory space is interfaced with the processor with a separate data bus*
  - *Program instructions and data can be accessed at the same time*
  - *A special single instruction, multiple data (SIMD) operation, a special arithmetic operation and a bit reverse, and multi-tasking operating systems*

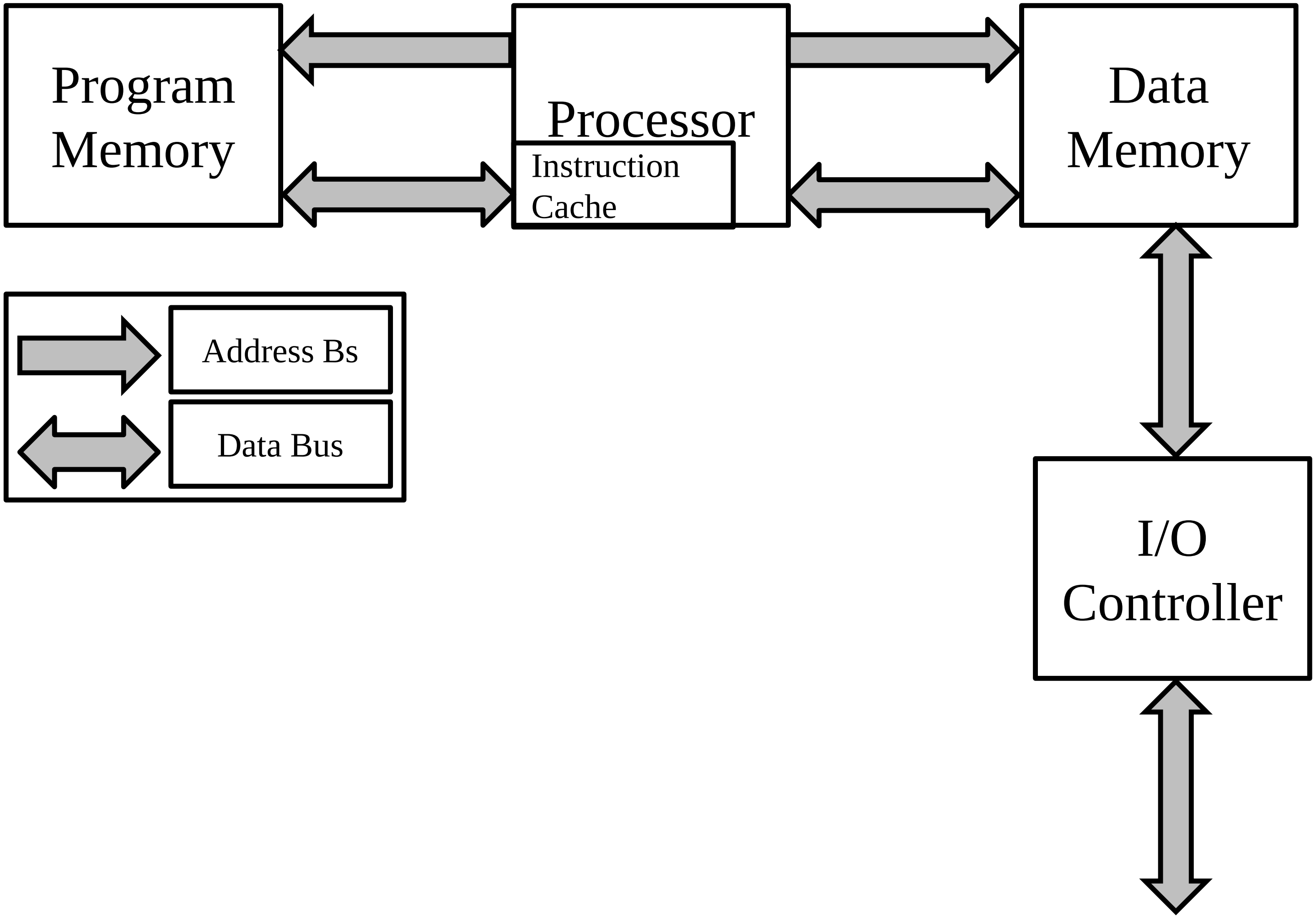
Harvard Architecture



Super-Harvard Architecture

- Super-Harvard architecture single-chip computer (Best known: SHARC)
  - *An extension of the Harvard architecture*
  - *Adds two essential components to the Harvard architecture:*
    - *Internal instruction cache ---- temporarily store frequently used instructions ---- enhances performance*
    - *An underutilized program memory can be used as a temporary relocation place for data*
  - *Direct Memory Access (DMA)*
    - *Program memory bus and data memory bus accessible from outside the chip*
    - *The costly CPU cycles can be invested in a different task*

Super-Harvard Architecture



Processors

- Available processors
  - Microcontroller
  - Digital signal processor (DSP)
  - Application-Specific Integrated Circuits (ASIC)
  - Field-Programmable Gate Arrays (FPGA)

Microcontroller

- Applications
  - elevators, household appliances, office machines, …
- Structure of Microcontroller
  - A microcontroller integrates the following components:
    - A CPU core
    - A volatile memory (RAM) for data storage
    - A ROM, EPROM, EEPROM or Flash memory for program
    - Parallel I/O interfaces
    - Discrete input and output bits
    - A clock generator
    - One or more internal analog-to-digital converters
    - Serial communications interfaces

Microcontroller

- Advantages:
  - *suitable for building computationally less intensive, standalone applications, because of its compact construction, small size, low-power consumption and low cost*
  - *High speed of the programming and eases debugging, because of the use of higher-level programming languages (e.g., C language)*
- Disadvantages:
  - *Not as powerful and as efficient as some custom-made processors (such as DSPs and FPGAs)*
  - *Some applications (simple sensing tasks but large scale deployments) may prefer to use architecturally simple but energy and cost efficient processors (ASIC)*

Digital Signal Processor

- The main function:
  - *Process discrete signals with digital filters*
  - *Filters minimize the effect of noise on a signal or change the spectral characteristics of a signal*
  - *While analog signal processing requires complex hardware components, digital signal process (DSP) mainly requires simple adders, multipliers, and delay components*
  - *DSPs are specialized processors with highly efficiency*
  - *Most DSPs are designed with the Harvard Architecture*

Digital Signal Processor

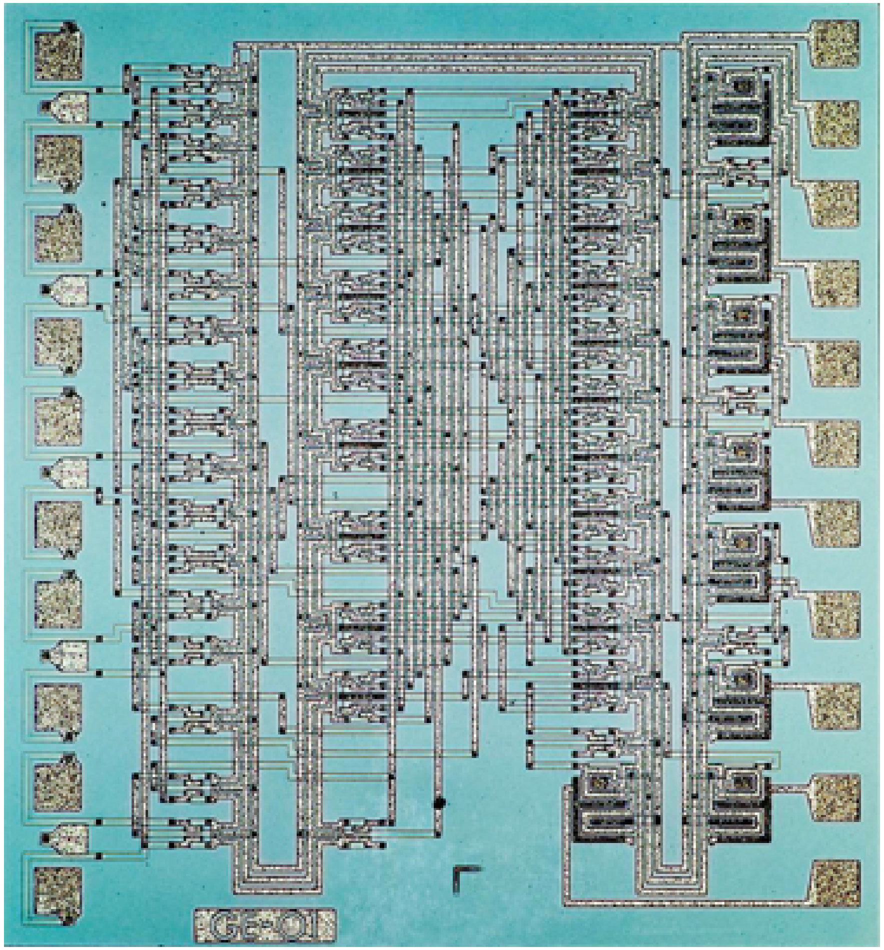
- *Advantages:*
  - *Powerful and complex digital filters can be realized with commonplace DSPs*
  - *Useful for applications: e.g.,*
    - *Detection and estimation*
    - *Applications requiring in-network processing, e.g., multimedia WSNs with data aggregation*
    - *WSNs in harsh physical settings: signal processing to suppress interference*
- *Disadvantage:*
  - *WSNs have other tasks, e.g., network management, self-organization*
  - *The networking protocols for these tasks are not necessarily numerical operations*

Application-specific Integrated Circuit

- ASIC is *an IC* that can be customized for a specific application
- Two types of design approaches: *fully customized* and *half-customized*
  - *A full-customized IC:*
    - *some logic cells, circuits, or layout are custom-made in order to optimize cell performance*
    - *Includes features which are not defined by the standard cell library*
    - *Expensive and long design time*
  - *A half-customized ASIC is built with logic cells that are available in the standard library*
  - *In both cases, the final logic structure is configured by the end user*

Application-specific Integrated Circuit

- Micromosaic - a 1968 standard cell design for GE Avionics. One of the industry's first designs for revenue



Application-specific Integrated Circuit

- *Advantages:*
  - *can be optimized to meet a specific customer demand*
  - *Multiple* microprocessor *cores and embedded software can be designed in a single* cell
- *Disadvantage:*
  - *Design difficulty, high* development *costs and lack of re-configurability*
- *Application:*
  - *ASICs are not to replace microcontrollers or DSPs but to complement them*
  - *Handle rudimentary and low-level tasks*
    - *To decouple these tasks from the main processing subsystem*
    - *e.g., processor core in the communication subsystems*

Field Programmable Gate Array (FPGA)

- The distinction between ASICs and FPGAs is not always clear
  - *FPGAs are more complex in design and more flexible to program*
  - *FPGAs are programmed electrically, by modifying a packaged part*
  - *Programming is done with the support of circuit diagrams and hardware description languages, such as VHDL and Verilog*

Field Programmable Gate Array (FPGA)

- *Advantages:*
  - *Support parallel processing*
  - *Higher bandwidth compared to DSPs*
  - *Flexible in their applications*
  - *Work with floating point representation, similar to DSPs*
  - *Greater flexibility of control by exposing processing speed to developers*
- *Disadvantages:*
  - *Complex*
  - *The design and realization process is costly*

How to choose the processor

- The processor subsystem is the central element of a node
- The choice of a processor determines the tradeoff among
  - *Flexibility (e.g., sensing goal changes, software update)*
  - *Performance*
  - *Energy consumption*
  - *Cost*

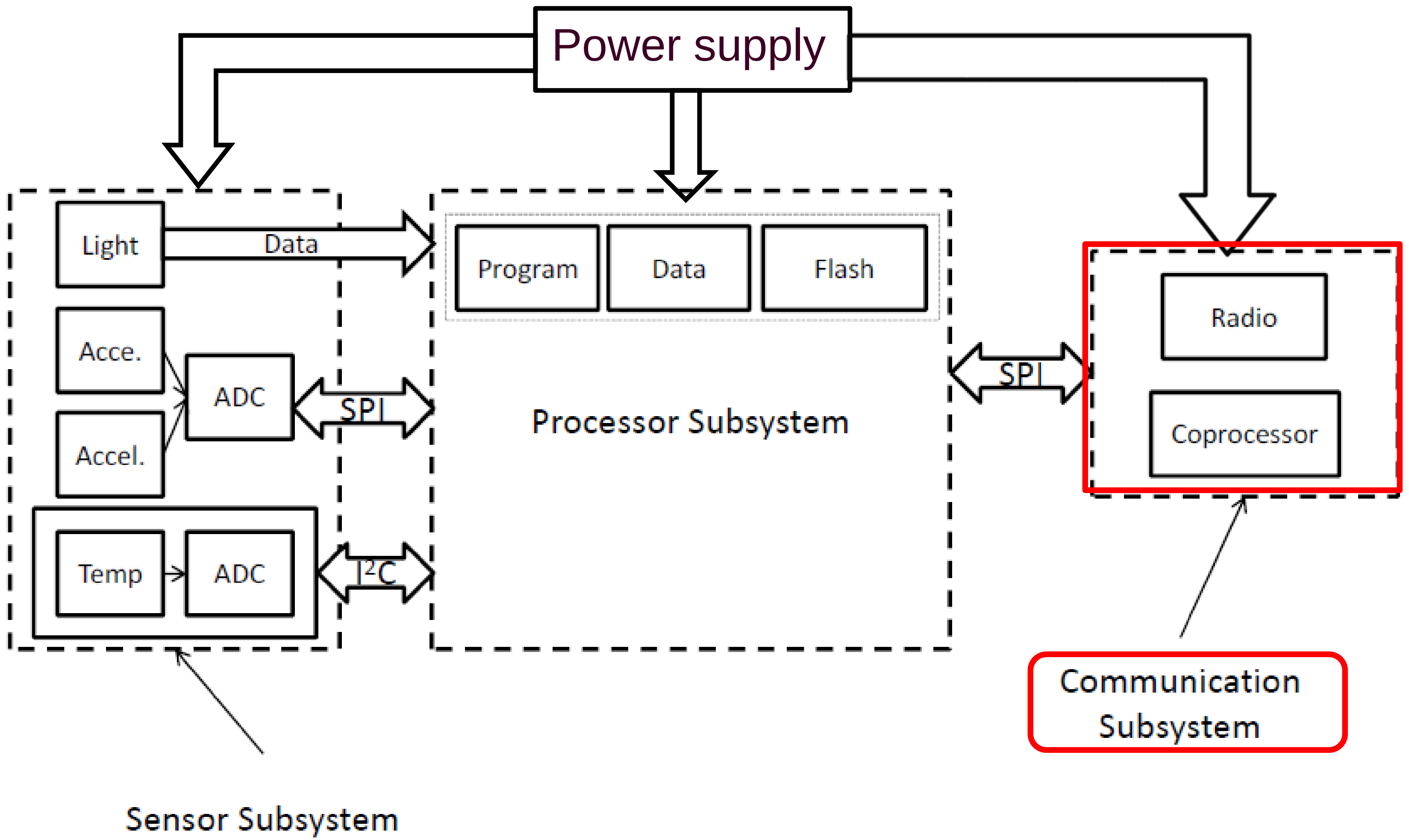
Comparison

- Working with *a micro-controller* is *preferred* if the design goal is *to achieve flexibility* (most popular in existing sensor nodes)
- Working with *all the other* is *preferred* if *power consumption and computational efficiency* is desired
- *DSPs* are expensive, large in size and less flexible; they are *best for signal processing*, with specific algorithms
- *FPGAs are faster* than both microcontrollers and digital signal processors and support *parallel computing*; but their *production cost* and the *difficulty with programming* make them *less suitable*

Comparison

- *ASICs* have *higher bandwidths*; they are *the smallest* in size, *perform much better* and *consume less power* than any of the other processing types; but have a *high cost* of production owing to the complex design process
  - *Integration of ASICs into other subsystems (e.g., communication subsystem)*

Node Architecture

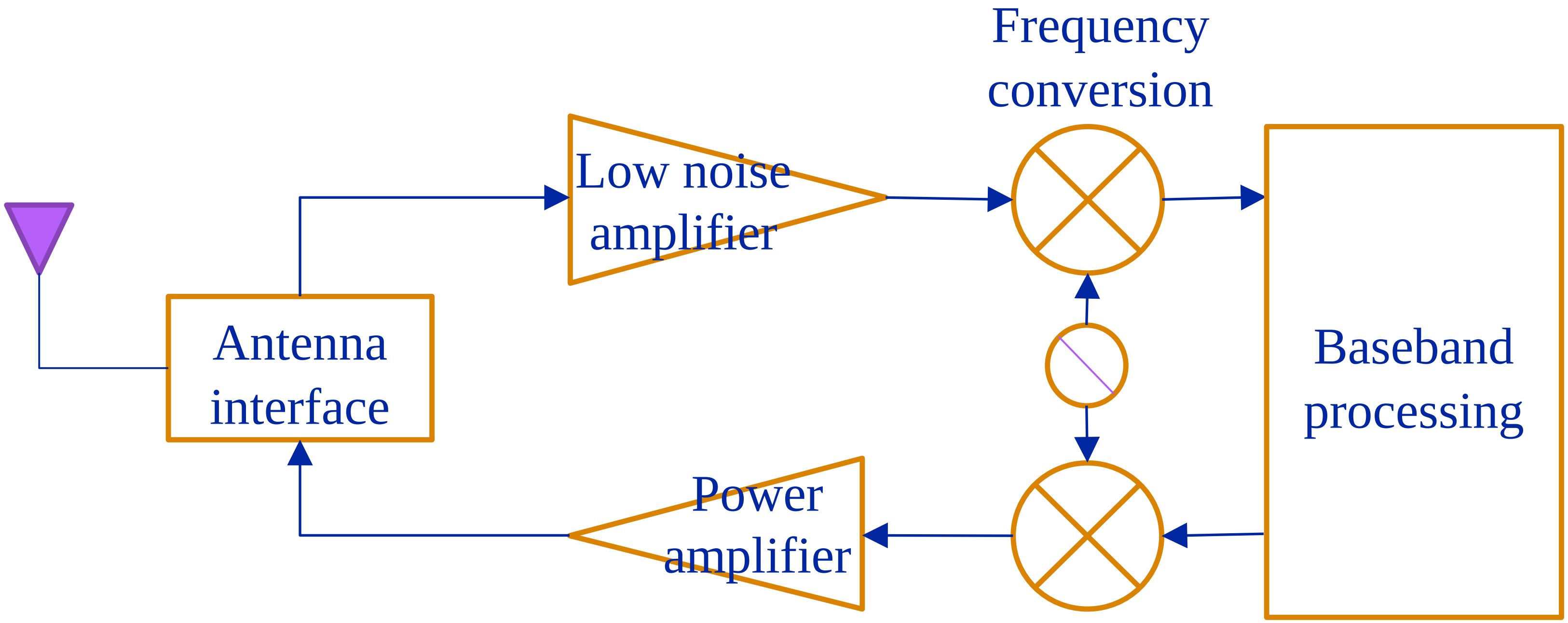


Communication Subsystem

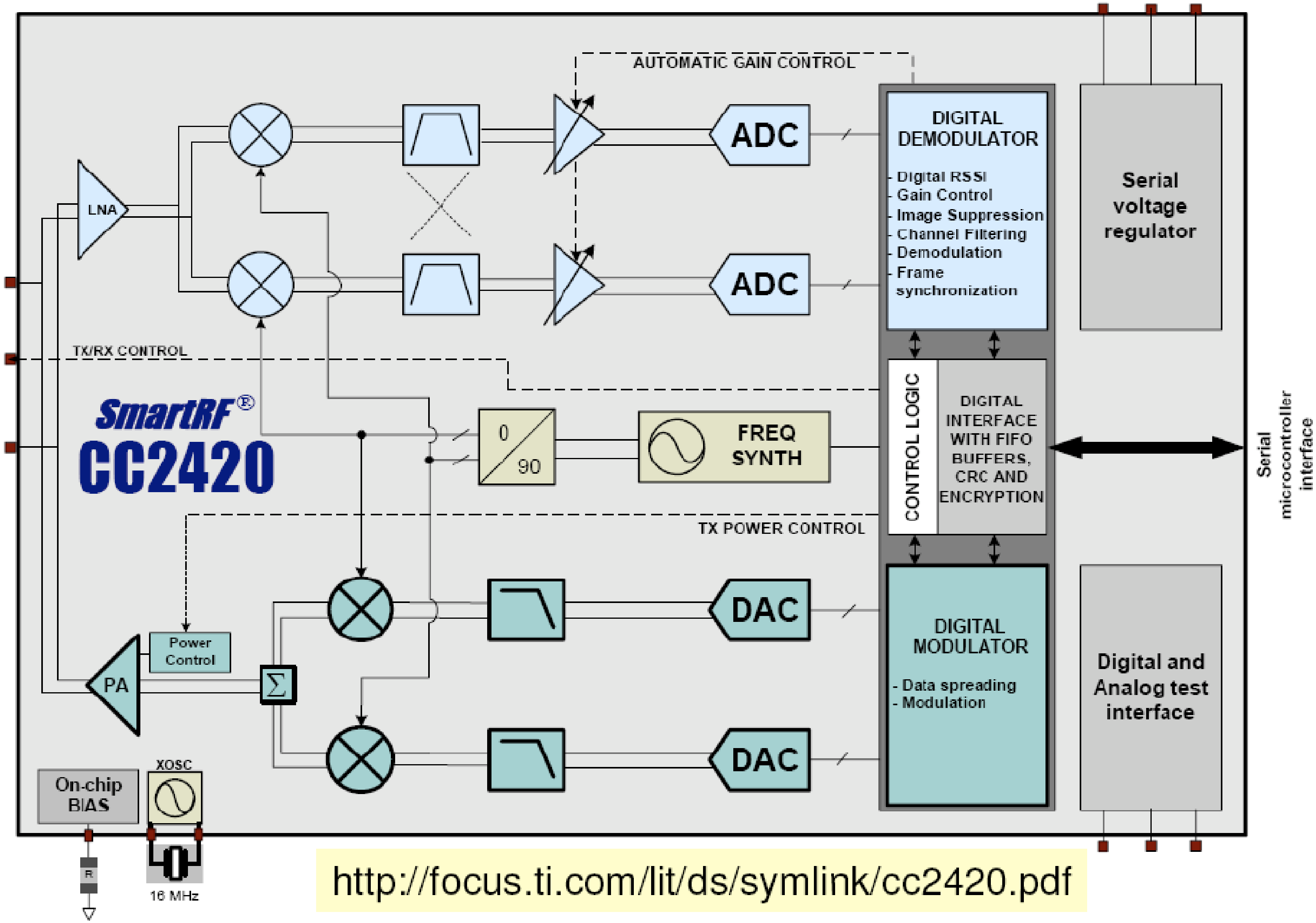
- Functionality: exchange data between individual nodes
  - *Converts bit streams from the processor to continuous waves and transmit them to the medium*
  - *Converts received continuous waves to bit streams and send to the processor*
- Wireless transmission medium
  - *Radio waves*
  - *Optics: Li-Fi*
  - *Acoustic waves*
  - *Magnetic inductance*
  - *...*
- The choice of the transmission medium is application dependent

Communication Subsystem

- Functionality: exchange data between individual nodes
  - *Converts bit streams from the processor to continuous waves and transmit them to the medium*
  - *Converts received continuous waves to bit streams and send to the processor*
- Structure: transceiver front end (*analogy processing)* +BP



802.15.4: PHY Hardware Implementation



http://focus.ti.com/lit/ds/symlink/cc2420.pdf

Transceiver Operational States

- Transceiver states:
  - *Transmit*
  - *Receive*
  - *Idle: ready to receive; some parts related to in-coming signal acquisition are active, others are switched off*
  - *Sleep: a majority of transceiver parts are switched off; sleep states differ in recovery time and start-up energy*
- Wakeup radio:
  - *Monitor the incoming packet during the sleep mode*
  - *Once a new packet arrives, wake up the main receiver*

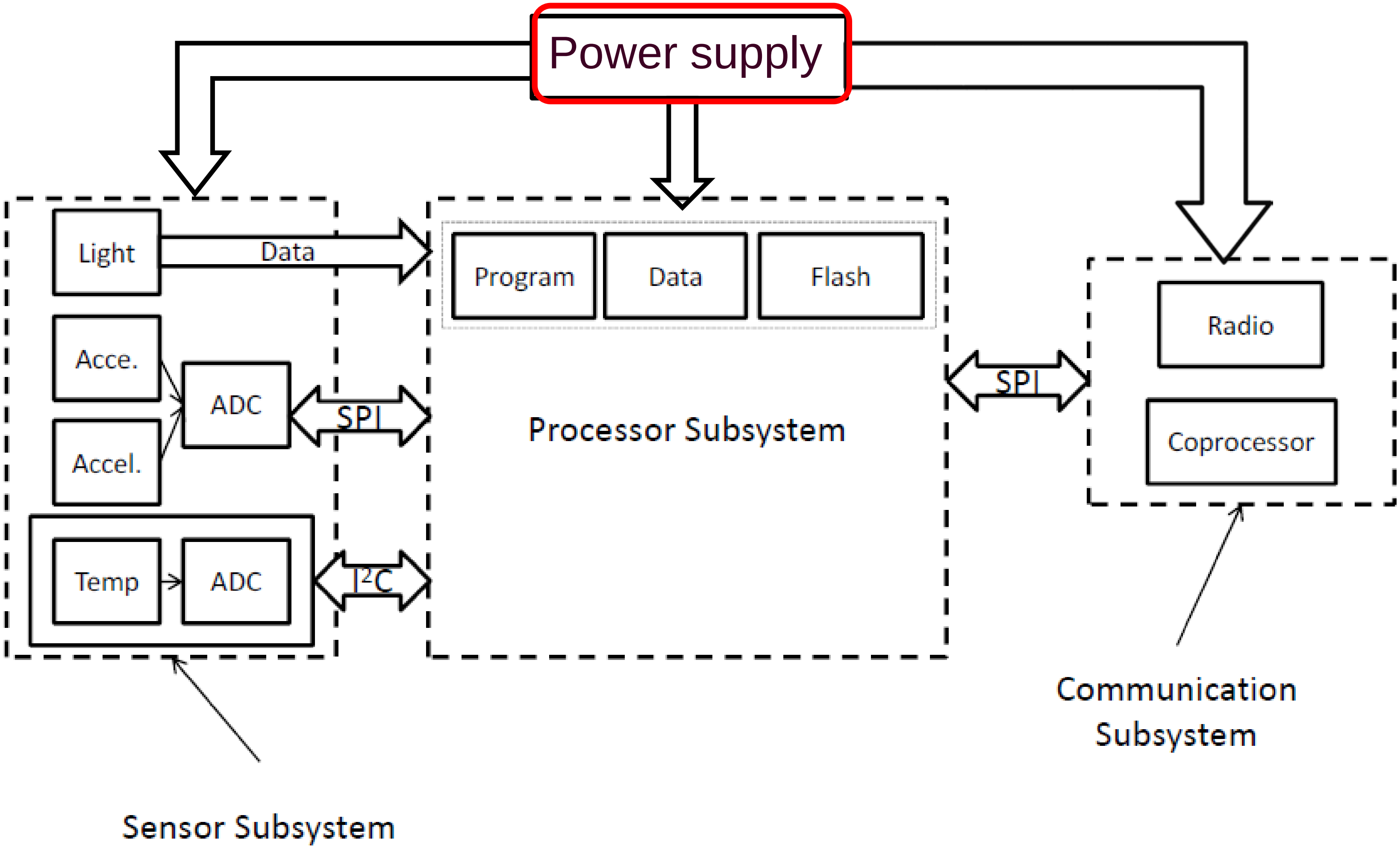
Transceiver Characteristics

- Capabilities
  - Supported frequency range?
    - Typically, somewhere in 433 MHz – 2.4 GHz, ISM band
  - Data rates?
  - Range?

- Energy characteristics
  - Power consumption to send/receive data?
  - Time and energy consumption to change between different states?
  - Transmission power control?
  - Power efficiency (which percentage of consumed power is radiated?)

- Radio performance
  - Modulation? (ASK, FSK, …?)
  - Noise figure? $NF = SNR_I/SNR_O$
  - Receiver sensitivity? (minimum signal power to achieve a given Eb/N0)
  - Blocking performance (achieved BER in presence of frequency-offset interferer)
  - Out of band emissions
  - Frequency stability (e.g., towards temperature changes)
  - Voltage range (a range of power voltage supply)

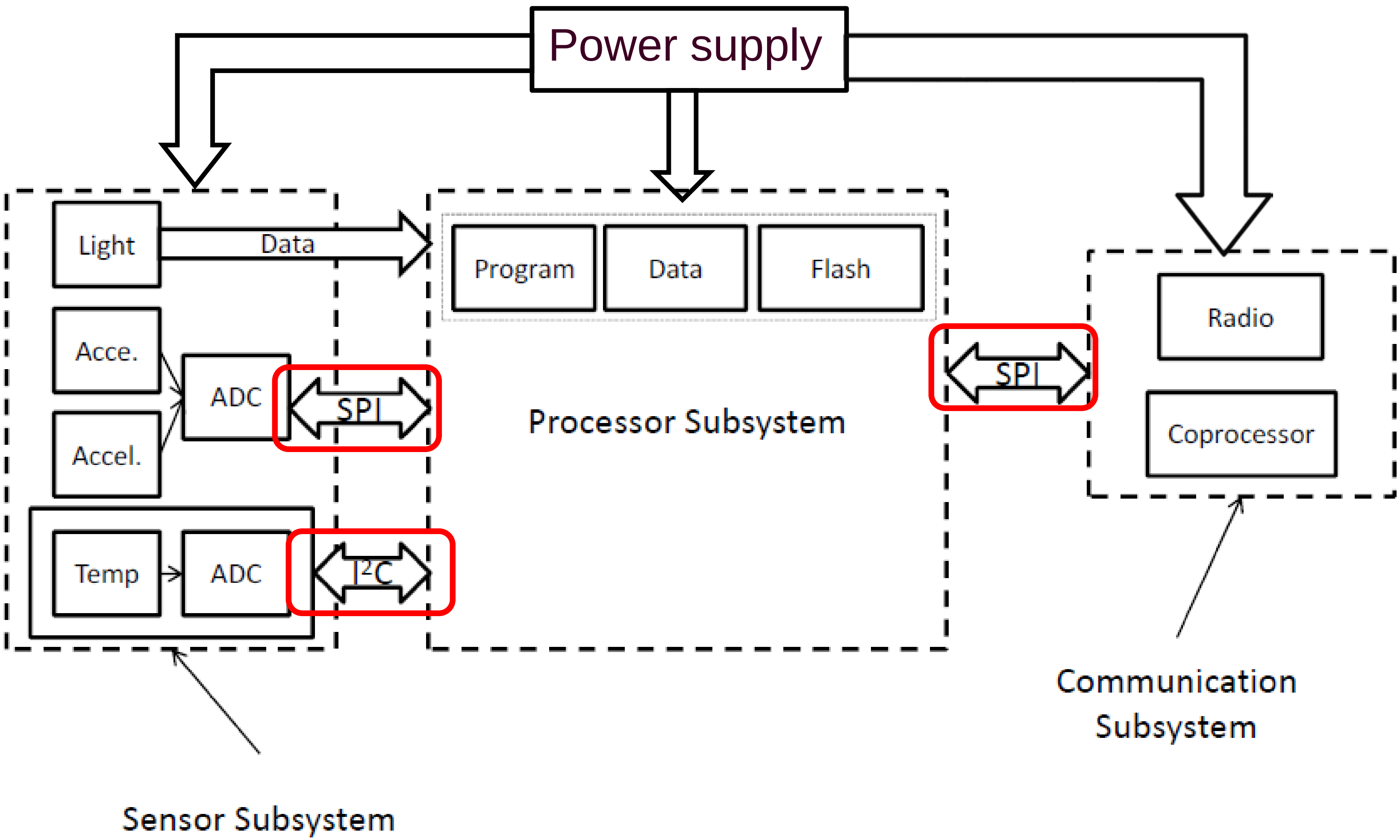
Node Architecture



Power Supply

- Power supply of nodes
  - *Storing energy into batteries:*
    - *node fails when power supply is exhausted*
  - *Energy scavenging: e.g., solar power, vibrations, wind turbines, wave power*
  - *https://www.youtube.com/watch?v=PQyP_J2s6DE*

Node Architecture



Summary

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- Today: Single-Node Architecture:
  - Hardware components
  - Energy consumption
  - Operating system
  - Prototypes