Mechatronics (ROB-GY 5103 Section A)

- Welcome Activity
- Syllabus
- **Today's lecture:**
  Introduction to Mechatronics, Microprocessor, PC, DAC, microcontroller
  (See Topic #1 from Main Text for details)

History

- Industrial revolution
- Semiconductor revolution
- Information revolution

Definitions and Concepts

Defining Mechatronics

- “The name **[mechatronics]** was coined by **Ko Kikuchi**, now president of Yaskawa Electric Co., Chiyoda-Ku, Tokyo.”

    R. Comerford, “Mecha … what?” *IEEE Spectrum*, 31(8), 46-49, 1994.

- “The word, mechatronics is composed of *mecha* from mechanics and *tronics* from electronics. In other words, technologies and developed products will be incorporating electronics more and more into mechanisms, intimately and organically, and making it impossible to tell where one ends and the other begins.”

    T. Mori, “Mechatronics,” *Yasakawa Internal Trademark Application Memo*, 21.131.01, July 12, 1969.

Defining Mechatronics

- "**Integration** of electronics, control engineering, and mechanical engineering."

  W. Bolton, *Mechatronics: Electronic Control Systems in Mechanical Engineering*, Longman, 1995.

- "Application of **complex decision making** to the operation of physical systems."

  D. M. Auslander and C. J. Kempf, *Mechatronics: Mechanical System Interfacing*, Prentice-Hall, 1996.

- "**Synergistic integration** of mechanical engineering with electronics and intelligent computer control in the design and manufacturing of industrial products and processes."

  F. Harshama, M. Tomizuka, and T. Fukuda, "Mechatronics-what is it, why, and how?-and editorial," *IEEE/ASME Trans. on Mechatronics*, 1(1), 1-4, 1996.

Defining Mechatronics

- “Synergistic use of precision engineering, control theory, computer science, and sensor and actuator technology to design **improved** products and processes.”

  S. Ashley, “Getting a hold on mechatronics,” *Mechanical Engineering,* 119(5), 1997.

- “Methodology used for the **optimal design** of electromechanical products.”

  D. Shetty and R. A Kolk, *Mechatronics System Design*, PWS Pub. Co., 1997.

- “Field of study involving the analysis, design, synthesis, and selection of systems that combine electronics and mechanical components with modern controls and microprocessors.”

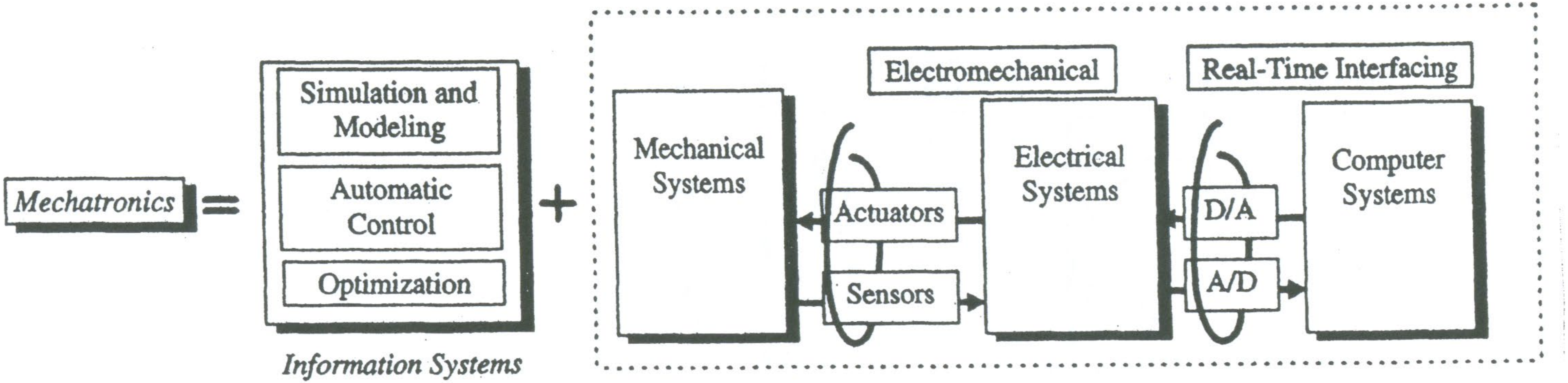
  D. G. Alciatore and M. B. Histand, *Introduction to Mechatronics and Measurement Systems*, McGraw Hill, 1998.

- More definitions at: http://www.engr.colostate.edu/~dga/mechatronics/definitions.html

Our Working Definition

- Mechatronics is the synergistic integration of sensors, actuators, signal conditioning, power electronics, decision and control algorithms, and computer hardware and software to manage complexity, uncertainty, and communication in engineered systems.

  - **Mechanical Engineering**
  - **Electrical Engineering**
  - **Computer Engineering**
  - **Computer/Information Systems**



Products and Processes

- Systems engineering allows design, analysis, and synthesis of **products *AND* processes** involving components from multiple disciplines.
  - **Multi-disciplinary**

    Bring multiple disciplines together to solve a problem
  - **Cross-disciplinary**

    Examine one discipline from the perspective of another discipline.
  - **Inter-disciplinary**

    Bring multiple disciplines simultaneously to solve a problem in an integrative process

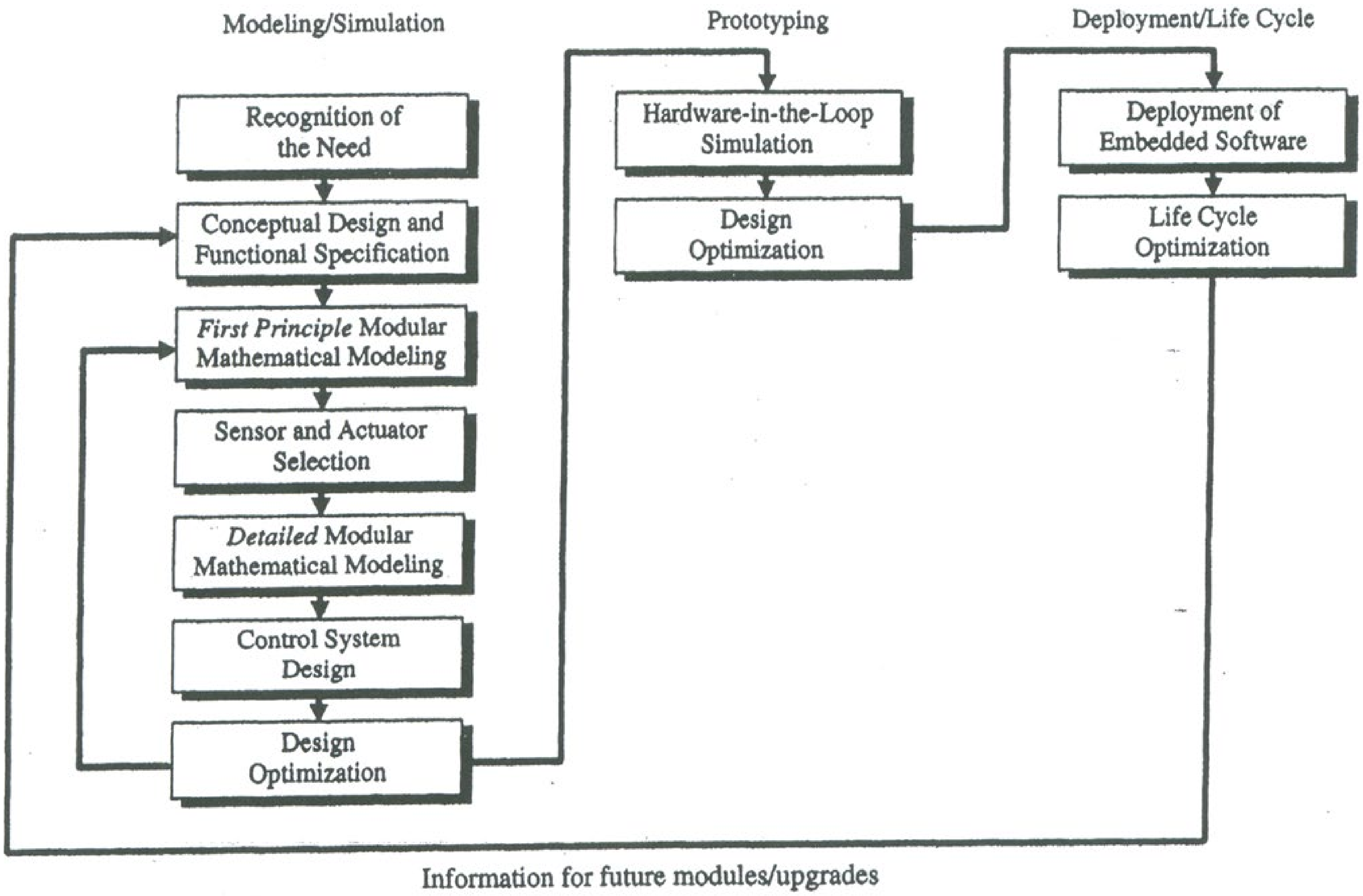
Sequential Product Realization

1. Design mechanical system “plant.”
2. Select sensors and actuators and mount on plant.
3. Design signal conditioning and power electronics.
4. Design and implement control algorithm using electrical, electronics, microprocessor, microcontroller, or microcomputer based hardware.

Mechatronics-based Product Realization

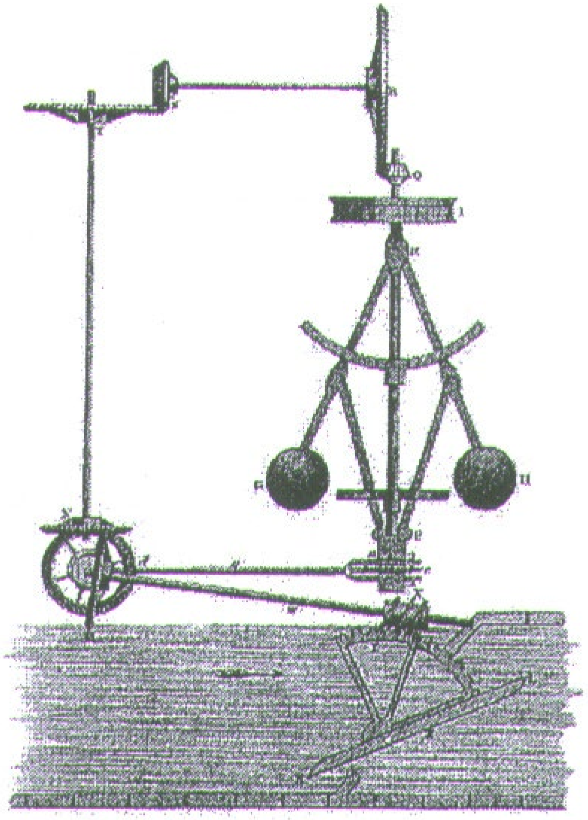
- Mechatronics exploits **systems engineering** to guide the product realization process from design, model, simulate, analyze, refine, prototype, validate, and deployment cycle.
    - ***Concurrent*** rather than ***sequential*** product realization.
- In mechatronics-based product realization: mechanical, electrical, and computer engineering and information systems are **integrated** throughout the design process so that the final products can be better than the sum of its parts **(synergy!)**

Mechatronic Design Process

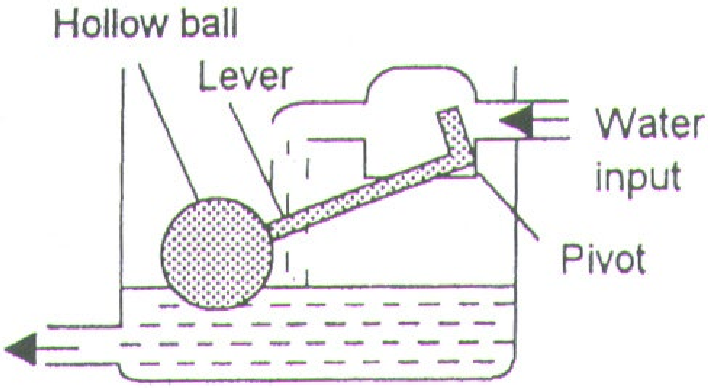


The Three Revolutions

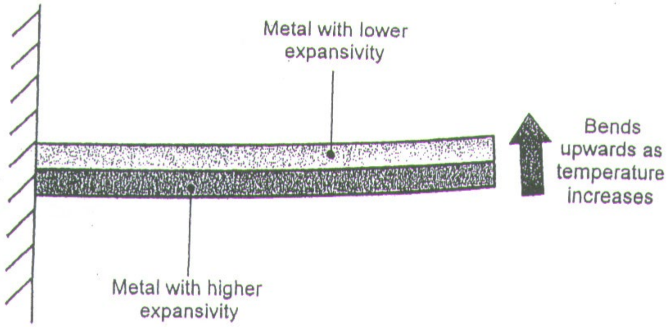
Industrial Revolution



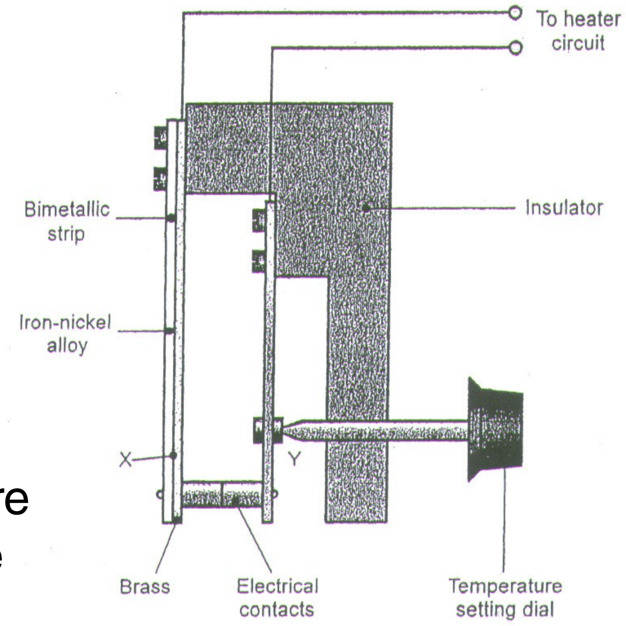
James Watt first applies a centrifugal governor to steam engines (1788)



Edmund Cartwright patents float valve for use in steam engines (1797)



John Harrison invents bimetallic strip to compensate for temperature effects in balance spring of marine chronometer (1759)



Industrial Revolution

- Allowed design of products and processes for energy conversion and transmission thus allowing the use of energy to do useful work.
- Engineering designs of this era were largely mechanical
  - e.g., operations of motion transmission, sensing, actuation, and computation were performed using mechanical components such as cams, gears, levers, and linkages).
- Purely mechanical systems suffer from
  - Power amplification inability.
  - Energy losses due to tolerances, inertia, and friction.

Semiconductor Revolution

- Led to the creation of integrated circuit (IC) technology.
- Effective, miniaturized, power electronics could amplify and deliver needed amount of power to actuators.
- Signal conditioning electronics could filter and encode sensory data in analog/digital format.
- Hard-wired, on-board, discrete analog/digital ICs provided rudimentary computational and decision-making circuits for control of mechanical devices.

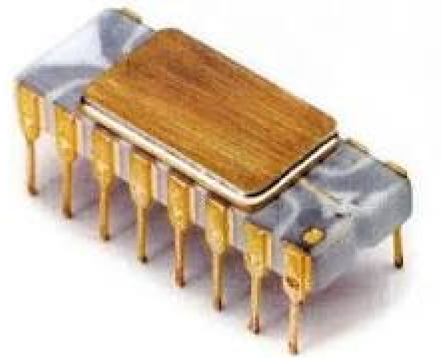
Integrated Circuit

A2D Converter

Operational Amplifier

Information Revolution

- Intel 4004, the world's first microprocessor, a complete general-purpose CPU on a single chip, is released in 1971.



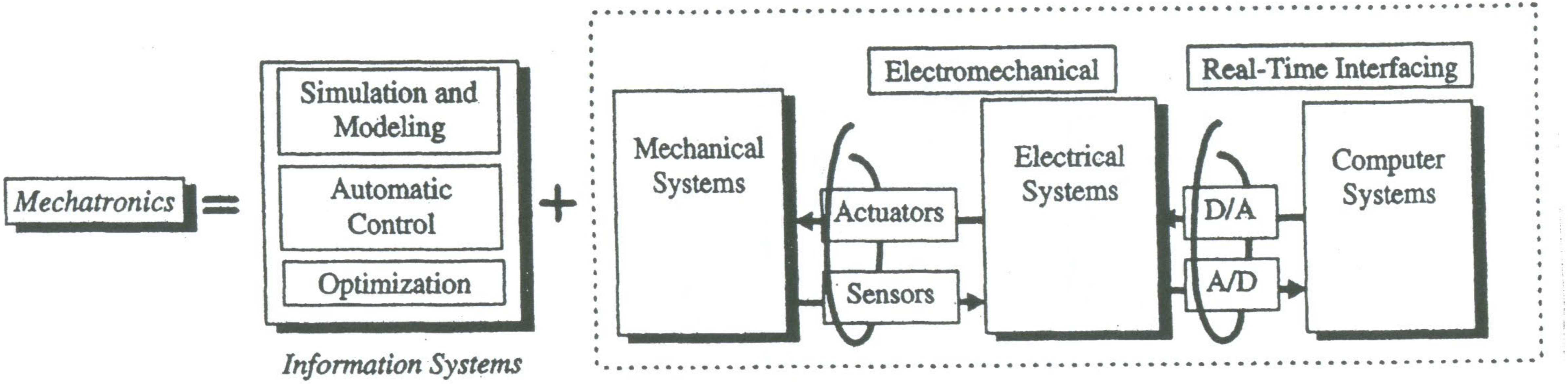
- Development of VLSI technology led to the introduction of microprocessor, microcomputer, and microcontroller.
- Now computing hardware is ubiquitous, cheap, and small.
- As computing hardware can be effortlessly interfaced with real world electromechanical systems, it is now routinely embedded in engineered products/processes for decision-making.

Information Revolution

- Highly efficient products and processes are now being developed by judicious selection and integration of sensors, actuators, signal conditioning, power electronics, decision and control algorithms, and computer hardware and software.

Building Blocks

Key Elements of Mechatronics

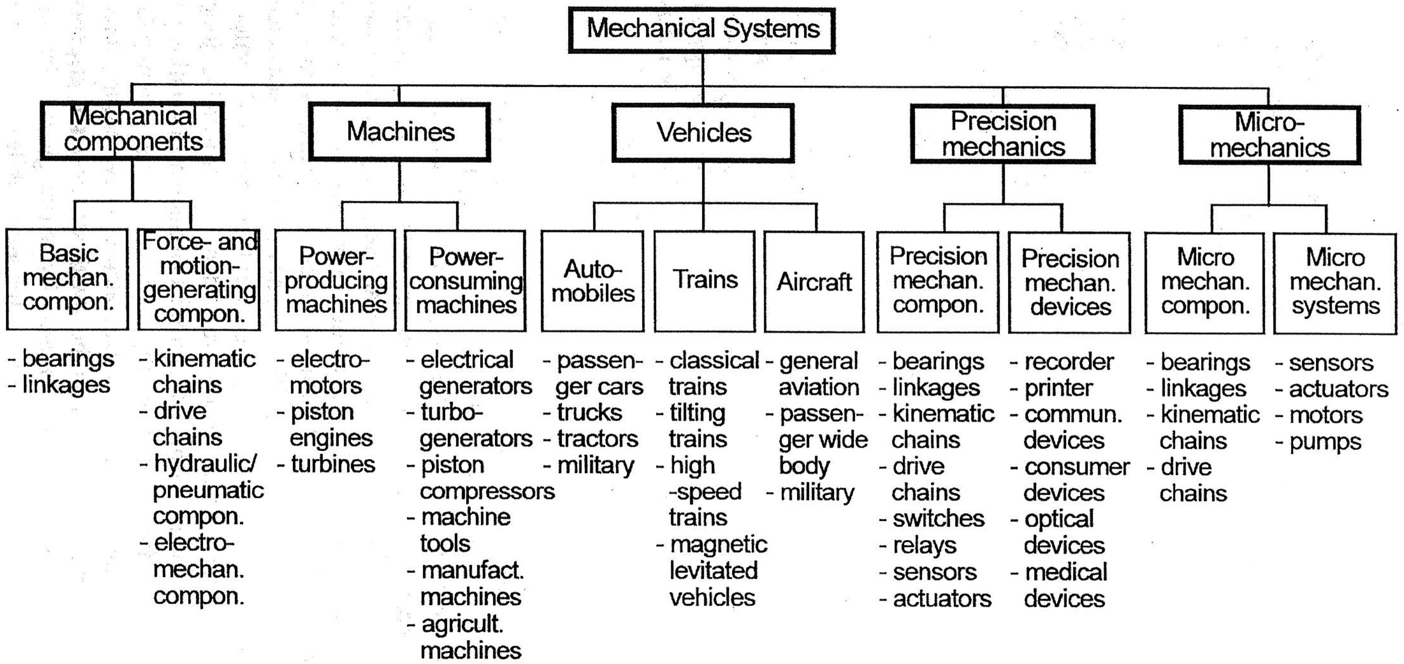


Mechanical Elements

- Inclined Plane/Screw
- Lever
- Wheel and Axle
- Belt and Pulley
- Gears
- Cams
- Springs
- Friction (Brake, Bearing)

Types of Motion

- Linear
- Rotary
- Reciprocating
- Oscillating



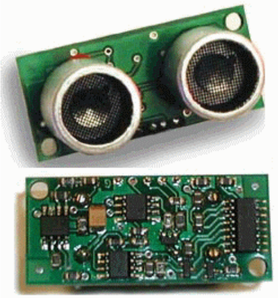
Electromechanical Elements

- Sensors and Actuators

Flexiforce Sensor

2-axis Accelerometer

Devantech SRF04



UltraSonic Ranger

GPS Receiver

Compass Module

Pneumatic Cylinder

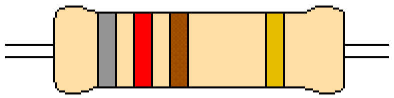
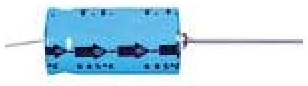
DC Motor

Electromechanical Elements

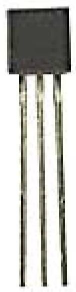
- Electromechanical elements refer to:
  - Sensors
    - A variety of physical variables can be measured using sensors, e.g., light using photo-resistor, level and displacement using potentiometer, direction/tilt using magnetic sensor, sound using microphone, stress and pressure using strain gauge, touch using micro-switch, temperature using thermistor, and humidity using conductivity sensor
  - Actuators
    - DC servomotor, stepper motor, relay, solenoid, speaker, light emitting diode (LED), shape memory alloy, electromagnet, and pump apply commanded action on the physical process
  - IC-based sensors and actuators (digital-compass, -potentiometer, etc.)

Electrical vs. Electronic Elements

- Electrical elements refer to:
  - Electrical components (e.g., resistor (R), capacitor (C), inductor (L), transformer, etc.), circuits, and analog signals
- Electronic elements refer to:
  - analog/digital electronics, transistors, thyristors, opto-isolators, operational amplifiers, power electronics, and signal conditioning
- The electrical/electronic elements are used to interface electro-mechanical sensors and actuators to the control interface/computing hardware elements

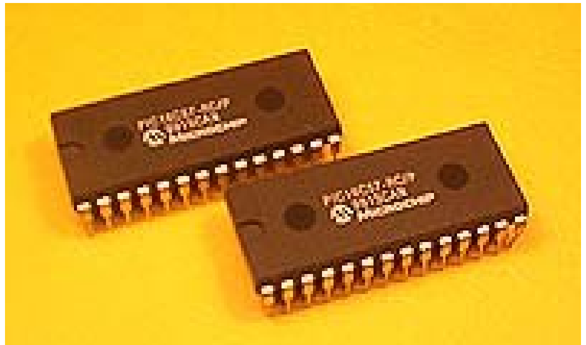



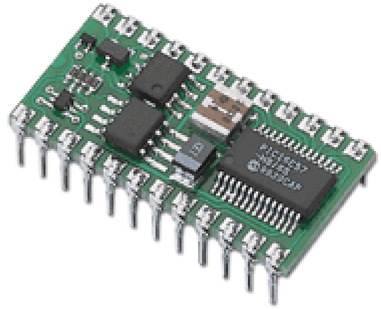




Control Interface/Computing Hardware

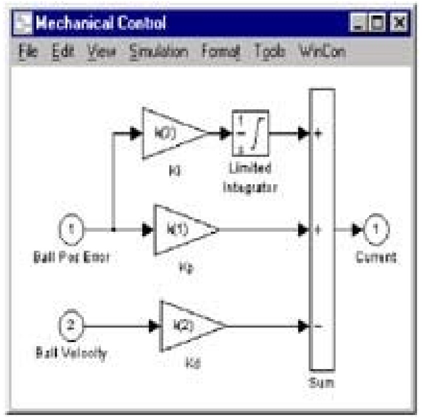
- Control interface/computing hardware elements refer to:
  - Analog-to-digital (A2D) converter, digital-to-analog (D2A) converter, digital input/output (I/O), counters, timers, microprocessor, microcontroller, data acquisition and control (DAC) board, and digital signal processing (DSP) board
- Control interface hardware allows analog/digital interfacing
  - communication of sensor signal to the control computer and communication of control signal from the control computer to the actuator
- Control computing hardware implements a control algorithm, which uses sensor measurements, to compute control actions to be applied by the actuator

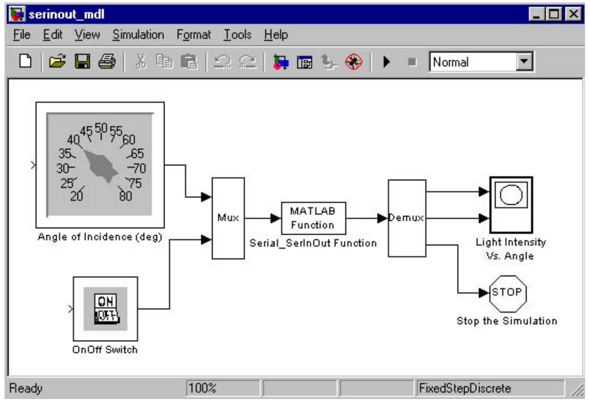




Computer/Information System

- Computer elements refer to hardware/software utilized to perform:
  - computer-aided dynamic system analysis, optimization, design, and simulation
  - virtual instrumentation
  - rapid control prototyping
  - hardware-in-the-loop simulation
  - PC-based data acquisition and control





Applications

Conventional vs. Mechatronics Design

conventional design	mechatronic design
added components	**integration of components (hardware)**
1 bulky 2 complex 3 cable problems 4 connected components	compact simple mechanisms bus or wireless communication autonomous units
simple control	**integration by information processing (software)**
5 stiff construction 6 feedforward control, linear (analog) control 7 precision through narrow tolerances 8 non-measurable quantities change arbitrarily 9 simple monitoring 10 fixed abilities	elastic construction with damping by electronic feedback programmable feedback (non-linear) digital control precision through measurement and feedback control control of non-measurable estimated quantities supervision with fault diagnosis adaptive and learning abilities

Conventional vs. Mechatronics Design

conventional design	mechatronic design
added components	**integration of components (hardware)**
1 electromechanical typewriter 2 mechanically controlled injection pump with rotating piston 3 many wiring 4 belt-driven auxiliaries	electronic printer high pressure pump and magnetic injection valves (common rail) bus cable decentralized driven auxiliaries
simple control	**integration by information processing (software)**
5 stiff drivetrain 6 mechanical gas pedal 7 feedforward-controlled actuator 8 manual steering of cars during spinning 9 monitoring of exhaust gases through maintenance or inspection 10 rail vehicles	elastic drivetrain with algorithmic damping through engine control electronic non-linear throttle control feedback-controlled actuator with friction compensation feedback control of slip angle by state observer and individual wheel braking on-board misfire detection by speed measurement of engine crankshaft mobile vehicle with automatic navigation

Real-World Advanced Robots

Concrete Floor Surface Finishing Robot ([Takenaka Corporation])

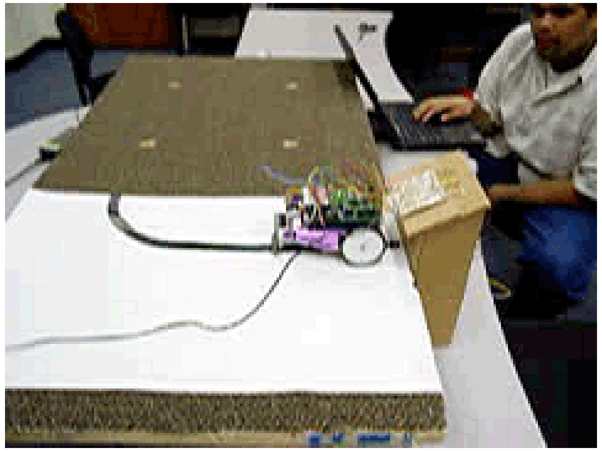
Autonomous Harvester ([NREC @ CMU])

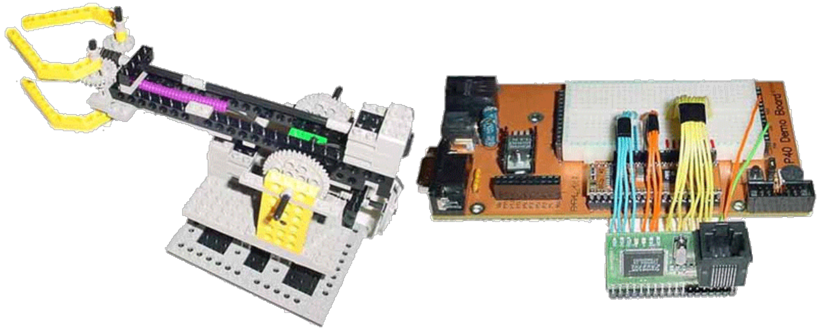
Robo-Mule ([Boston Dynamics])

Robotic Excavator

[Robo Mine-Sweeper]

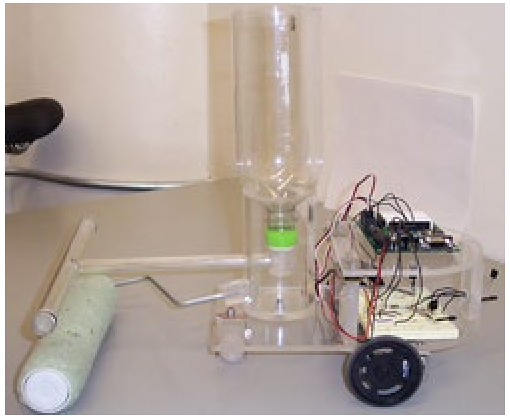
Think about what you would like to build

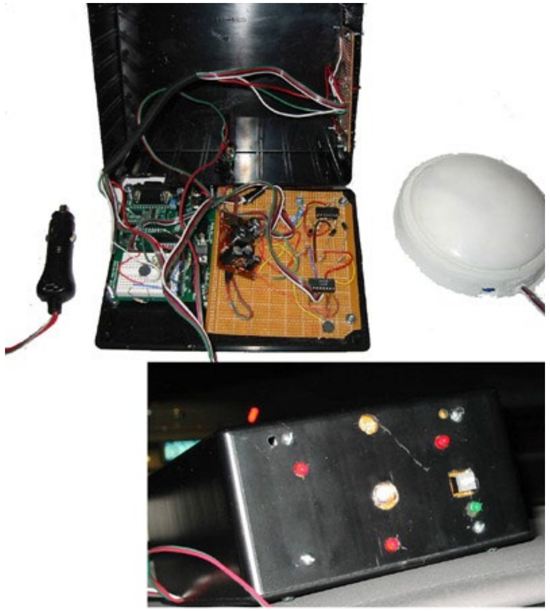




Remote Robot Arm Manipulation

Smart Irrigation System





Autonomous Polyurethane Applicator

Safe N Sound Driver

Smart Cane

Computing

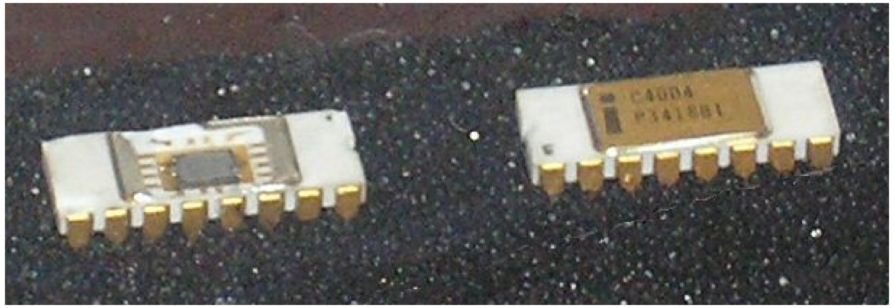
Microprocessor (μP)

- μP constitutes the **central processing unit (CPU)** of a microcomputer/PC
- μP was introduced by Intel in 1971.
  - Intel 4004 (4-bit)
  - Killer app: **portable calculators**
- Next came Intel’s 8080 (8-bit) in 1974.
  - Killer app: **desktop computers**
- First major μP was 8088 (16-bit) introduced in 1979.
  - Killer app: **IBM desktop computers** in 1982
- Prior to the development of μPs, computers were built using discrete ICs!

Microprocessor (μP)

- μP is a single very–large–scale–integration (VLSI) chip.
    - It contain many digital circuits.
    - It is a complete computation engine fabricated on a single chip.

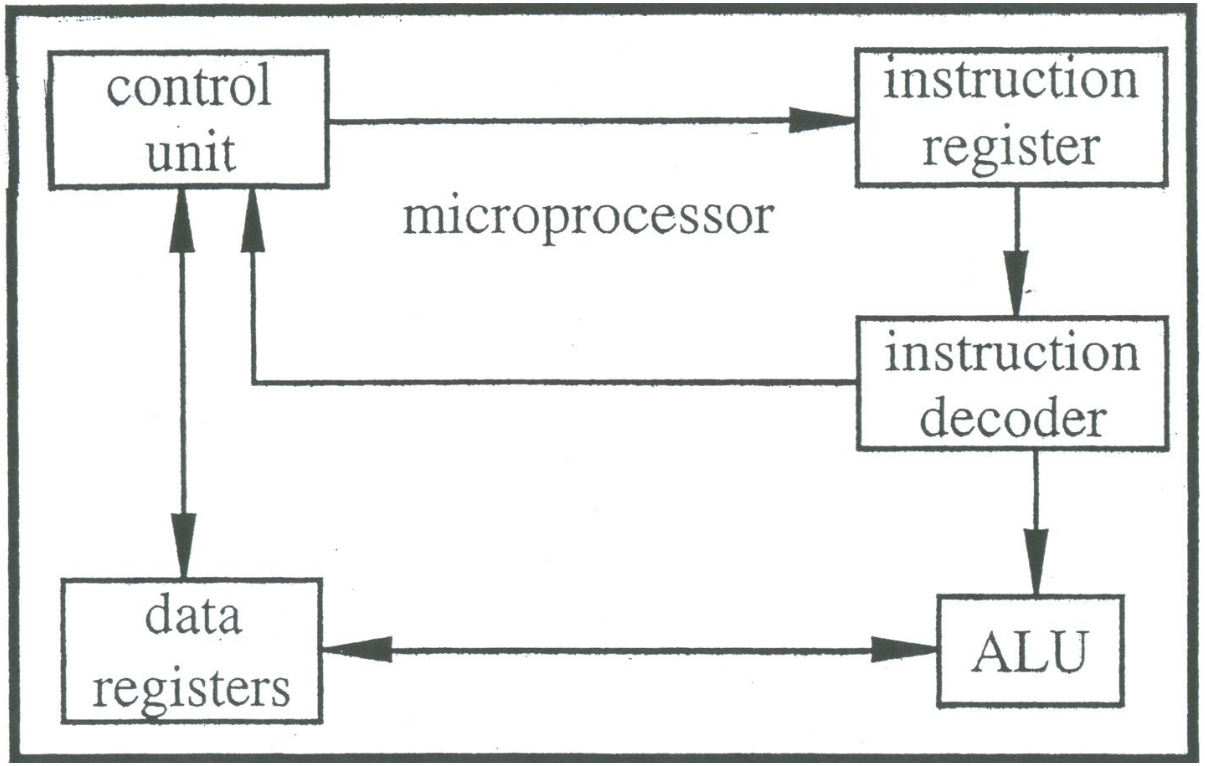
- Elements of a μP are:
    - Arithmetic/logic unit (ALU)
    - Instruction registers and decoders
    - Data registers
    - Control unit



Intel 4004 (right)
Cover removed (left)

Microprocessor (μP)

- Instructions tell ALU 2 things:
  - What to do
  - What data to do it to
- Data is IDed by its address
- Instructions are given in codes (that activate appropriate digital circuits in the control unit)



Microprocessor (µP)

- µP is programmed using:
  - Machine language (binary)
  - Assembly language (human readable)
- Examples of µP:
  - **Intel**
    - 4004 (4-bit)
    - 8080, 8085 (8-bit)
    - 8088 (16-bit)
    - 80x86 (32-bit)
    - Pentium X (32-bit)
  - **Motorola**
    - 6800
  - **Zilog**
    - Z80

Microprocessor Functions

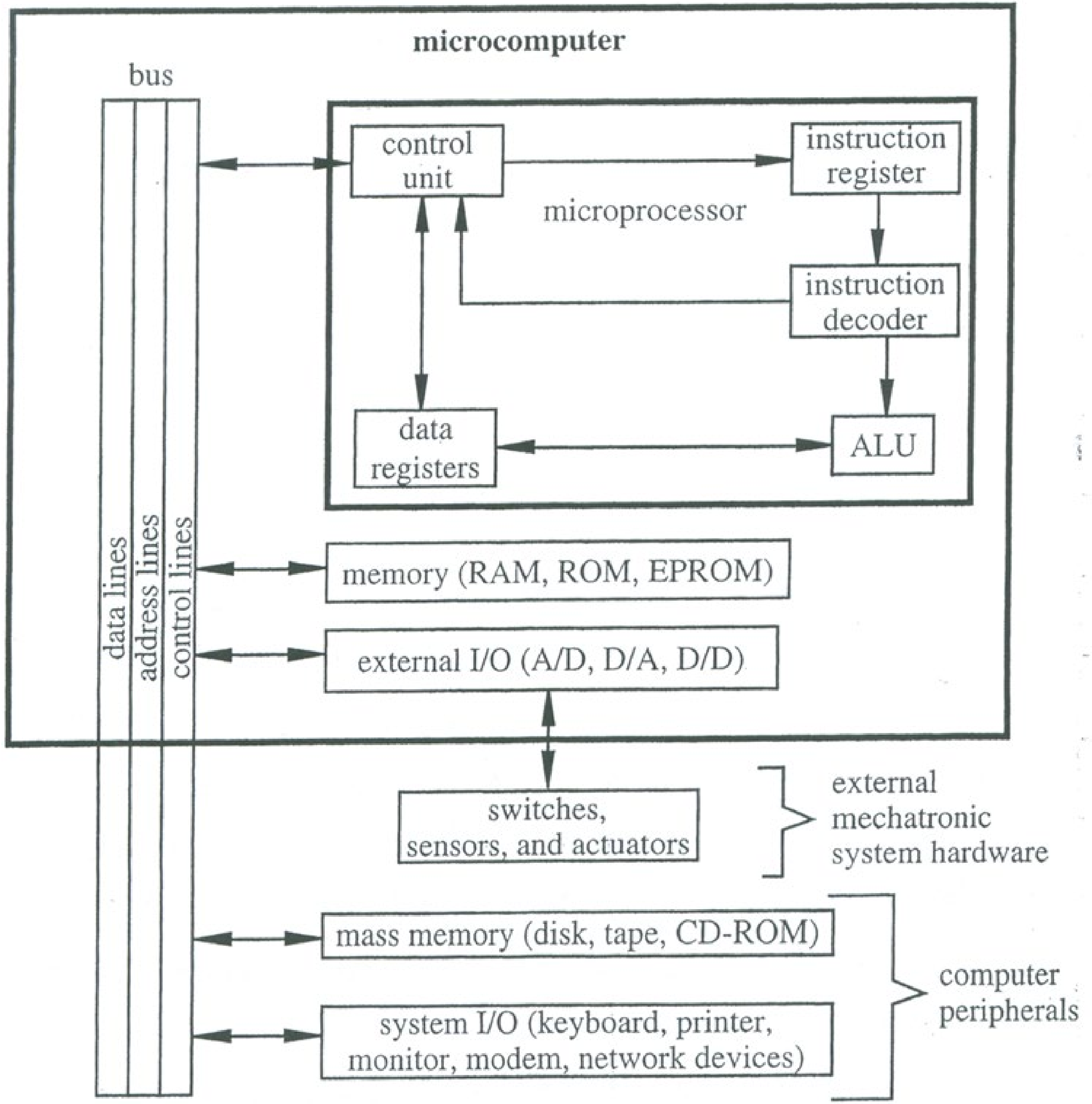
- μPs perform 3 primary functions/operations.
  - Mathematical operations: add, subtract, multiply, divide.
  - Move data from one location to another.
  - Make decisions and redirect the program flow based on decisions (i.e., based on decisions, redirect the program to a new set of instructions).

Microcomputer/Personal Computer/Desktop Computer

- Computer is a μP packaged on a single circuit board with interfaces and memory chips.
  - Types of computers: IBM and compatibles.
  - PC: “Personal computer” built around 8088/8086 μP with floppy disk drive.
  - XT: “Extended technology” built around 8088/8086 μP with hard disk drive.
  - AT: “Advanced technology” built around 80286 μP.
- Compared to μPs, computers are easy to program (use high level language of your choice, e.g., BASIC, FORTRAN, C, …).
- Modern day computers have significant computing power and excellent memory storage.
- PCs are purposefully designed to allow interaction and communication with humans.
- PCs are general purpose computing machines.

Microcomputer Architecture

- PCs consist of
  - **μP**
  - **Memory**
  - **Bus**
  - **External inputs/outputs** (or peripherals/interfaces)
- Recall that the CPU of the μP performs the computing function.



Memory

- **RAM**
- **ROM**
- EPROM
- EEPROM
- **Mass Storage**

Memory — RAM

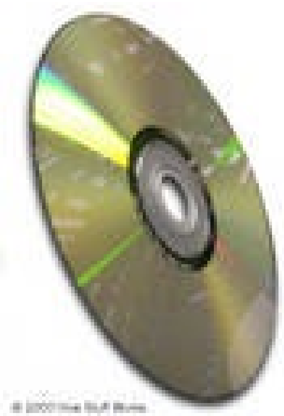
- **Random Access Memory (RAM)**
  - Read/write volatile memory.
  - Volatile memory $\rightarrow$ its contents are lost when power is removed.
  - CPU can access contents of RAM at very high speed during program execution.
  - When a program is to be executed, it is temporarily stored in RAM for high speed execution.
  - All intermediate results of computations are also stored in RAM for fast retrieval.
  - RAM is usually quite costly since high speed access costs more money.

Memory — ROM

- Read Only Memory (ROM)
  - ROM is written onto only once at the factory.
- Once ROM has been written onto it acts as a read only memory.
  - ROM is a nonvolatile memory → its contents are retained even when power is removed.
  - ROM stores program used by the microcomputer at its startup.
  - For example, on a PC Basic Input/Output System (BIOS) is stored in ROM.

Memory — Mass Storage

- The following fall under the category of mass storage memory:
  - Hard disk, floppy disk, tape drive, optical drive, etc.
  - This type of memory is both readable and write-able.
  - This type of memory is also nonvolatile.
  - This type of memory usually costs significantly less compared to RAM.
  - Downside: CPU takes significantly longer time to access the contents of mass storage memory vis-à-vis RAM.



Bus

- Industry Standard Architecture (ISA) bus dominated the PC market until mid to late 1990s.
- Micro-Channel Architecture (MCA) bus (IBM's proprietary design, used in PS/2)
- Extended ISA (EISA) bus
- Personal Computer Memory Card International Association (PCMCIA) bus
- Originally intended for removable memory cards on portable computers.
- Presently it is also used for interfacing miniature adaptor cards to PCs.
    - e.g., serial port, modem, network card, hard disk, data acquisition and control (DAC) card.
- Other buses: PCI (replaced ISA), IEEE 488, Centronics Parallel Port, Serial buses (RS232, RS422, RS485, USB), etc.

External Interfaces/Peripherals

- Outputs such as:
  - Video monitor, speaker, printer, plotter.
- Inputs such as:
  - Keyboard, mouse, joystick, microphone, camera.
- These external interfaces of PCs allow humans to connect to, interact/communicate with the CPU.

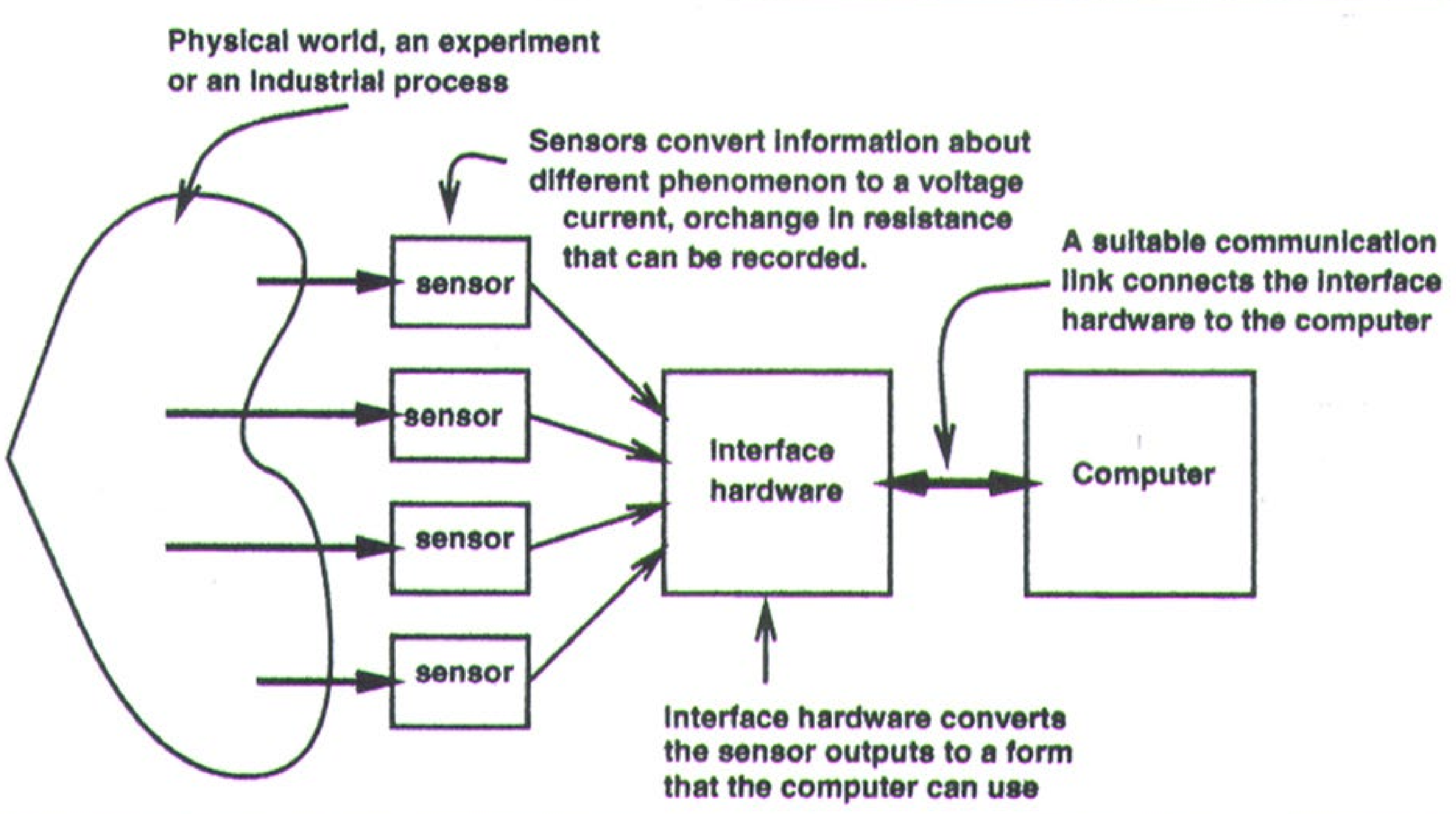
Data Acquisition (and Control)

Data Acquisition (DAQ)

- In common computer applications, data comes from a keyboard or a storage disk.
  - This type of data is prepared and entered in the computer by a human operator.
- **Data acquisition (DAQ)** has to do with getting data into computer from a real-world process automatically without human intervention.
  - DAQ is more than simple automation of the process of acquiring data.
- DAQ refers to automatic acquisition of real-world sensory information where the data may
  - be stored for later use
  - need on-line processing
  - be analyzed in real-time
  - have to be presented in real-time
- DAQ is used for test instruments, condition monitoring of industrial machinery, process industry, medical instruments, environment monitoring, robotics, etc.
- DAQ can be used to develop virtual instruments for productivity enhancement.

PC-Based DAQ: A Pictorial Representation

Figure *Block diagram of a typical automated data acquisition system.*



PC-Based DAQ: Pros/Cons

- Advantages:
    - PC provides a flexible solution to DAQ problem since the it can adapt to changing needs of DAQ applications/users.
    - PCs have a wide market base.
    - Human resources with technical background in PC use readily available.
    - Numerous packages exist for scientific, mathematical, engineering, and statistical computing/analysis that could be readily used to analyze acquired data.
- Disadvantages:
    - PC platform is not ideal for DAQ applications requiring guaranteed/deterministic acquisition time.
    - Aside: The above drawback may be overcome to some extent using real-time kernel programs that allow real-time process to run with a high priority.

PC-Based DAQ: Selection Considerations

- Required data acquisition speed (slow versus very high): availability of corresponding sampling rate
- Data collection is event driven
- Connection to internet, intranet, telephone
- PC interface (Serial port, parallel port, PC bus, communication)
- Signal conditioning
- Number of analog input channels, voltage ranges, digital I/Os
- Resolution (# of bits of ADC)
- Accuracy
- Isolated inputs
- Plug-in DAQ cards (ISA, EISA, MCA, PCI, PCMCIA, …)
- Stand alone DAQ cards (communication-based)

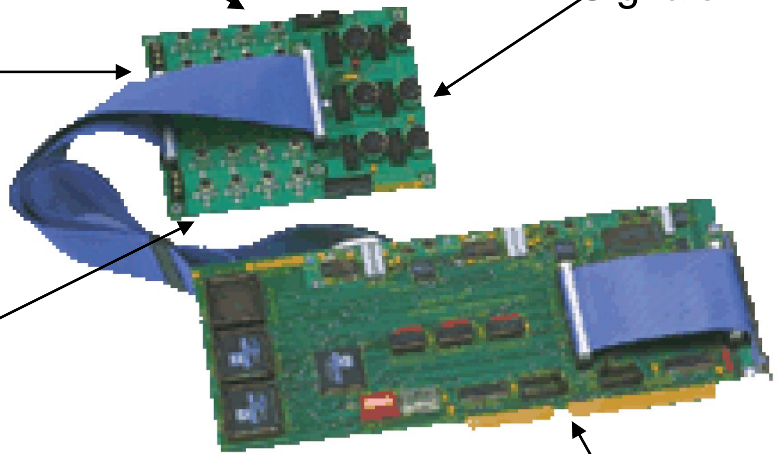
Example: Plug-In & Stand Alone DAQ Cards

8 Analog Inputs

Digital I/Os

8 Encoder Signals

Terminal Board



8 Analog Outputs

ISA DAC Board

MultiQ DAC Board

LabPro

2 digital channels

4 analog channels

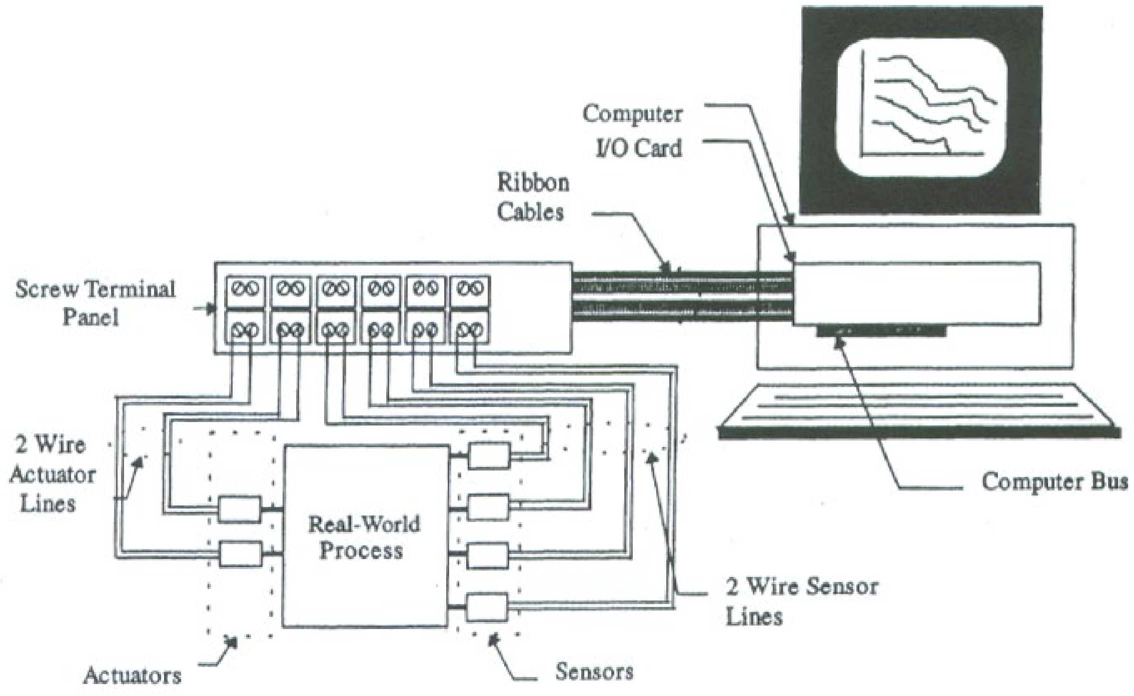
Plug-in versus Stand-alone DAQ Cards

- Plug-in:
  - Easy installation and configuration
  - New plug-in cards even have plug-and-play capability
  - # of available slots in a PC limits extensibility of plug-in cards
  - Lack of robustness, ruggedization, and portability needed in a shop floor environment
- Stand-alone:
  - Processor independent can be connected to a PC or a **Programmable Logic Controller (PLC)**
  - Ruggedized to operate in hostile environment
  - Portable
  - Communicate to PC via Serial port, parallel port, TCP/IP, etc

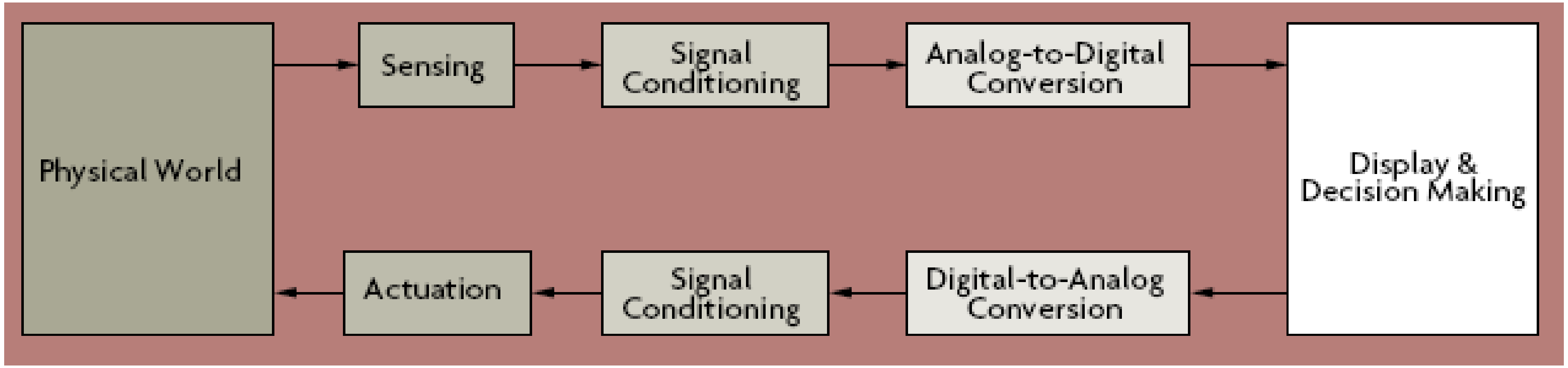
Data Acquisition *and Control* (DAC)

- DAQ systems enable one to collect real-world data into the computer.
- DAQ systems are useful for monitoring and data analysis.
- On the other hand, if one needs to command a real-world device into action based on the measurement of some real-world phenomenon, then a DAQ system is not sufficient.
  - In this case one needs a data acquisition and control (DAC) system.
- A DAC system
  - collects data from sensors,
  - using computing resources of a PC or an on-board computer
  - processes sensory information
  - computes control command, and
  - commands control actuators.

DAC System: A Pictorial Representation



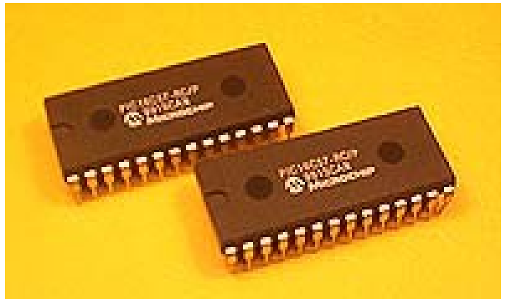
Major components of a DAC system and their interconnection for a system with four sensors and two actuators



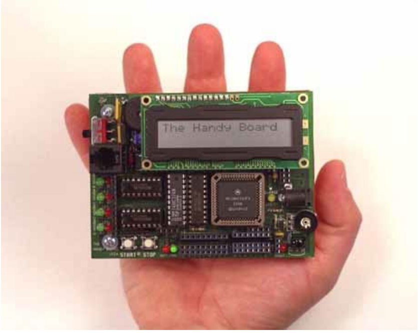
Functional Diagram for a DAC system

Microcontroller

Microcontroller (μC)



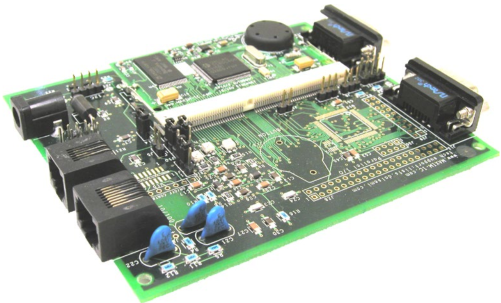
Microchip: PIC series μC



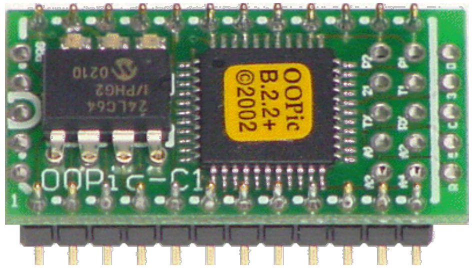
Motorola: 68HC11

(MIT Handy board)

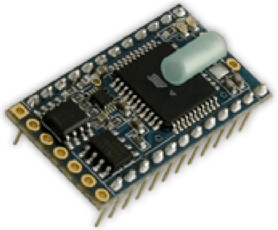
Intel: 8096, MCS 96296



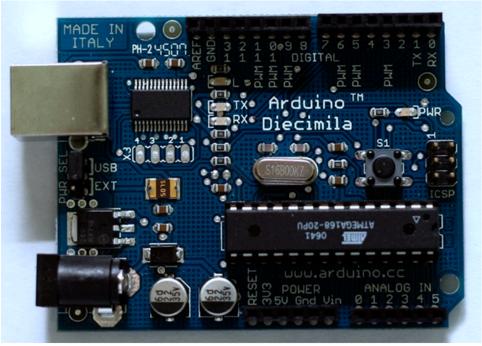
Dallas Semiconductor: TINI



OOPic



BasicX



Arduino

- Each μC manufacturer has a diverse variety of μCs with differing parts, features, and functionality.
- The various μCs are marketed as: low end, mid range, and high end.

μC Function

- Microcontrollers are specifically designed to:
  - Read input devices, such as buttons and sensors.
  - Process data or information.
  - Control output devices, such as lights, displays, motors and speakers.
- Add a **“brain”** to your mechatronic system with sufficient processing power while maintaining **low cost** and **high flexibility**

μC vs. General Purpose Computers

- μC is a **special purpose microcomputer**.
  - μC is a single IC containing many specialized and sophisticated circuits and functions.
    - Often attached to a larger board.
  - **Embedded computing/embedded systems/physical computing** applications to impart computing, decision making, and intelligence capabilities to machines, products, and processes.
- Whereas **general purpose computers**, i.e., PCs, are designed explicitly to interface with humans, μC are purposely designed to interface, interact, and communicate with
  - electrical/electronic devices;
  - sensor/actuators;.
  - machinery/equipment;
  - high-tech gadgets; etc.

Cost of μC

- Peripheral Interface Controllers (PIC) from Microchip Inc.
  - **PIC16C57**
    - Qty 1: $7.50
    - Qty 100: $4.50
    - Qty of several 1000: $3.50
- Intel 8049 μC costs approx. $0.95
- Circuits built using discrete logic components are not very versatile and usually more expensive than μC.

Cost vs. ASIC

- Application specific integrated circuits (ASIC) require engineering design for each particular problem at hand from scratch.
  - Engineering design fee
  - Custom-made IC die
- Costs of ASICs can be several tens to hundreds of dollars depending on production volume.
- Is it appropriate to install a $30 brain on a $20 toaster to add intelligence to it?
  - In consumer products costs issue is very sensitive since one way to operate, survive, thrive, and profit in an increasingly competitive marketplace is to keep prices low.
  - Even when a company innovates by adding intelligence to an otherwise routine consumer product, it has to do so with smallest cost increase!

Cost vs. PC-based DAC

- Cost of a general purpose desktop PC: approx. **$500+**
- Plug-in DAC/stand-alone DAC cost: several hundred dollars to over a thousand dollars (each A2D channel costs **$75+**).
- Software: DAQ/DAC drivers, data processing/analysis software (LabVIEW, Simulink-RTW, etc.), real-time kernel for Windows O.S. (e.g., VentureCOM) — easily over **$500**.
- Is it appropriate to spend all this amount to impart intelligence to a $400 washing machine?
- A one of a kind mobile robot may demand and justify this type of expense, but the standard desktop PC form factor is not suitable for mobile robotics application.

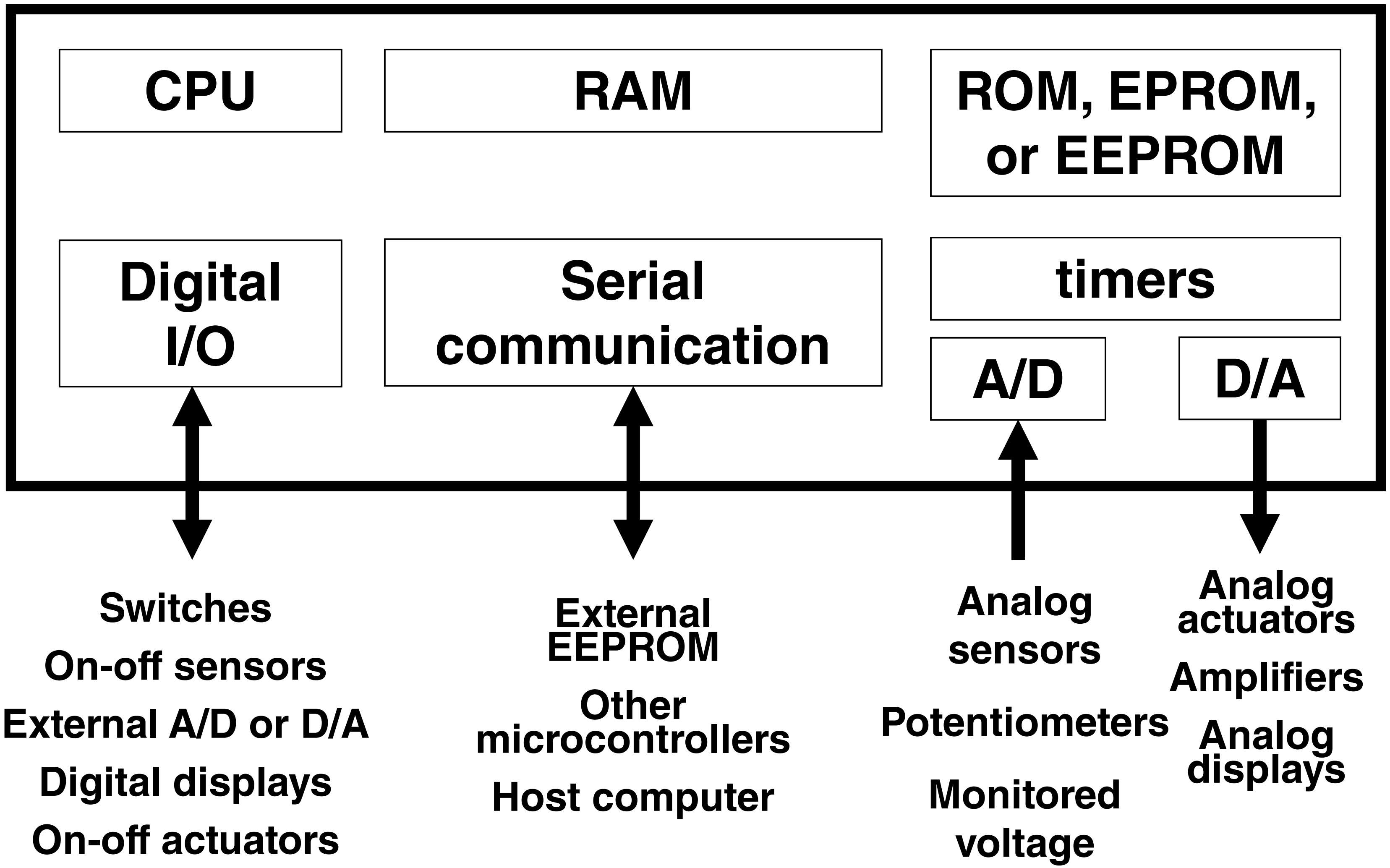
Flexibility of μC

- A μC-based design provides the ability to fix design after it has been completed.
- A μC provides flexible firmware thus μC functionality can be changed by downloading new firmware.
- A μC represents a flexible hardware to which additional devices can be added on the unused pin. Not only that I/O pins can be reassigned with relative ease.

μC Elements

- According to one standard, a μC must contain at least two primary components:
  - **RAM**
  - **CPU with instruction set** (list of all commands and their corresponding functions)
- μCs may additionally have one or more of the following elements.
  - Various types of memory (ROM, EPROM, EEPROM, PROM)
  - I/O functionality
    - Digital I/O (to connect switches, LEDs, on-off sensors and actuators, etc.)
    - Analog I/O (high end μCs have built-in A2D, D2A, etc.)
    - Pulse-width-modulation outputs (PWM) to connect PWM-type actuators
    - Clock generators
    - Reset function
    - Watchdog timer (resets controller after a problem occurs)
    - Interrupt
    - Timers
    - Communication (RS-232, I2C, 1-wire, etc.)

Components of a full featured μC



μC Selection

- Requirement of task at hand
  - Memory, speed, I/O, other interfaces, floating point computation
- Availability of software development tools
  - Emulators, programmers, compilers
- Availability of parts and components
- Existing user base and support services
- Availability of application notes
- Power requirements
- Clocking and reset requirements
- Cost

Choosing Processing Power

Choosing Processing Power

- Processing power depends on:
  - Clock speed
  - # of clock cycles to execute one instruction
  - Instruction set
- μC A has 10 MHz clock speed and takes 10 clock cycles to execute each instruction $\rightarrow$ μC A processes each instruction @ the speed of 1 MHz.
- μC B has 5 MHz clock speed and takes 2 clock cycles to execute each instruction $\rightarrow$ μC B processes each instruction @ the speed of 2.5 MHz.
- A or B?

Choosing Processing Power

- If a particular μC has a sufficiently complete instruction set it may be that case that one can perform operations such as multiply and divide using just one instruction.
- Alternatively, if another μC of same processing speed per instruction does not have a complete instruction set, then it may be the case that multiply and divide operations require multiple instructions $\rightarrow$ slower speed.
- Sufficiently complete instruction set will require a larger ROM to store the instruction set.
- Usual design trade-off (no free lunch).

PIC μC

PIC μC

- Peripheral Interface Controller (PIC)
- Code developed for low-end PIC μC is upward compatible
- PIC device packaging
  - Dual Inline Package (DIP): plastic package containing one-time programmable (OTP) EPROM
  - Ceramic package with glass window (JW): contains EPROM which is erased by exposing glass window to UV light
  - Surface mount technology: component pins are soldered on raw card
  - Chip on board technology

Memory Types

- Erasable programmable ROM (EPROM): OTP DIP package and UV erasable and re-programmable (JW). Use for fast access.
- Electrically EPROM (EEPROM): No need of UV light exposure for erasing program. In BS2 we download our program to EEPROM.
- ROM: Program built into the chip at the factory. μC instruction set is stored in ROM.
- PIC's CPU: Harvard architecture
  - Variable and I/O register/memory are separate from program memory.
- PIC series μCs:
  - 8bit: PIC10, PIC12, PIC16, PIC18
  - 16 bit: PIC24F, PIC24H, dsPIC30, dsPIC33
  - 32bit: PIC32