

# Embedded System Design Part I

Assist.Prof.Dr.Osman Kaan EROL

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## References

- EDN Europe
- EPN
- Atmel, Philips 8051 Family Microcontrollers Data Books
- TI MSP430 Application Notes.
- PIC 12Cxxx Series Microcontrollers Data Book.
- Maxim/Dallas Application notes
- Cypress PSoC DataBook

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## Survey

Have you:

- Got a windows PC? (or linux?)
- Programmed in assembly and C?
- Ever used a logic analyzer?
- Ever worked with microcontrollers before?
- Ever soldered before?
- Ever built anything for fun?

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## Course Outline

- Embedded Systems Overview
- Embedded System Components
- Electronic Design Aid Tools
- Printed Circuit Board Design Techniques
- Summary and Future Vision

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## Embedded System Overview

- A digital processing system is mainly divided into two parts:
  - Hardware
  - Software

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## Hardware

- Physical part of an IT system
- Examples of hardware structures:
  - computer mainboard
  - cell-phone apparatus
  - human body
  - genetic code, DNA

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## Software

- Is software really soft?
- Physical aspects of a software
- Examples of software:
  - Computer programs
  - MP3 files (used as part of a program)
  - Cell-phone operating systems, Symbian etc...
  - Interactive digital media middlewares
  - Lecture notes,
  - Knowledge

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## Embedded System

- Any microcontroller having the SW code within its own HW (CPU, I/O) is called embedded system.
- SW resides inside the CPU IC.
- Other peripherals are integrated upon market request. Those are ADC, DAC, PWM, I2C, CAN, UART, USB, RF etc...

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## Microcontrollers

- Microcontrollers
  - Don't have keyboard and monitor jacks
  - Must use ports to perform I/O
  - Inputs – to sense things
  - Outputs – to control things
- Related Component Topics
  - Cool Parts
  - Common Interfaces
  - Part Packages

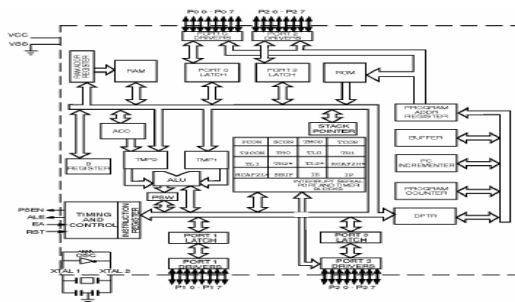
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## Non-PC Applications

- Nearly 2 billion microprocessor chips are manufactured each year, over 95% go into non-PC "embedded" devices – IDC
- Vending machines, washing machines, digital thermostats, cell-phones, cars, test instruments etc...

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## Typical Embedded System (8051)



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## Versatil versus Specific

- Embedded systems are specific in the view of:
  - Predefined peripherals, appropriately scaled for the job,
  - Limited RAM/ROM space,
  - Predefined structure, task specific,
  - Small and easy-to-use
- Electronic system design differs from embedded systems in:
  - Grouping large possibility of components
  - Modifications possible
  - Large PCB requirement

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## System-on-chip Advantages

- Lower power
- Greater reliability
- Lower cost

But,

- Enormous investments in technical expertise, automated design equipment, engineering effort.

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## Path to Embedded Systems

- Before getting integrated, most novelties appears as a discrete integrated circuit.
  - Transistor before IC
  - ADC before ADC implementation,
  - ARM controllers before ARM based system-on-chip products...
- When standardized, these discrete parts are integrated within the more "attractive" component. Example ADC within a microcontroller.

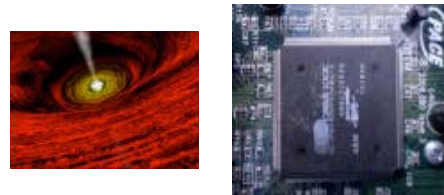
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## Integration Space

- End of integration means end of life. Today no electron tubes.
- There will always be new components around embedded systems as long as electronic engineering exists.
- Embedded systems are the center of attraction of electronic circuits.

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## Center of Attraction



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## Embedded System Business Models

- Fabless companies
- Core/library vendors
- Foundries
- EDA companies

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## SoC Device Technologies

- Masked ASICs
- Programmable logic devices
  - OTP
  - UV
  - Flash devices
  - Battery back-up logic devices
  - Microcontrollers with FRAM memory

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## Semiconductor Cores

- Processor cores
  - 8051 based
  - ARM based
- Memory cores
  - 1K, 64K, ...
- Analog cores
  - ADC, DAC, RF transmitters, etc...

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## Adding Value to Embedded Systems

- No hardware modifications (refer to 8051 architecture)
- Suitable part selection (among architectures, manufacturers, suppliers)
- Software
- Quality of manufacturing
- Service (if required)

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## Part Selection (courtesy of ATMEL)

Device	Description
<a href="#">AT89C51ED2</a>	High performance 8-bit microcontroller 64 Kbytes Flash, 2 Kbytes EEPROM
<a href="#">AT89C51IC2</a>	AT89C51IC2 is a 80C51 8-bit microcontrollers featuring a 32K bytes Flash code memory and a two-wire interface (TWI).
<a href="#">AT89C51ID2</a>	High performance 8-bit microcontroller 64 Kbytes Flash, 2 Kbytes EEPROM and Two Wire Interface (TWI).
<a href="#">AT89C51RB2</a>	High performance 8-bit Microcontroller 16 kbytes Flash
<a href="#">AT89C51RD2</a>	High performance 8-bit microcontroller with 64 Kbytes Flash
<a href="#">AT89LS51</a>	Low-Voltage Microcontroller with 4K Bytes In-System Programmable Flash
<a href="#">AT89LS52</a>	Low-Voltage Microcontroller with 8K Bytes In-System Programmable Flash
<a href="#">AT89LS51</a>	Low Voltage, Downloadable MCU with 12k bytes Flash
<a href="#">AT89LS52</a>	Low Voltage, Downloadable MCU with 8K bytes Flash and 2K bytes EEPROM.
<a href="#">AT89S51</a>	8-bit Microcontroller with 4K Bytes In-System Programmable Flash
<a href="#">AT89S52</a>	8-bit Microcontroller with 8K Bytes In-System Programmable Flash

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## Same Component Manufacturers

- Sometimes more than one manufacturer produce the same component with small variations in the name (example Philips P89C51, ATMEL AT89C51)
- The more manufacturers produce the same component, the lesser the risk of not finding the component.
- Prices decrease.
- Your differentiation decrease also.

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## Adding Software to Embedded Systems

- A language must be chosen
- A programmer is required for OTP or PROM devices. In-system programmable components may not require any programmer.
- Debugging tools are required.

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## Languages

- Low level languages: Assembly language
  - microcontroller specific
  - not portable or difficult to port
  - efficient code
- High level languages: C, C++, Linux
  - microcontroller assembly codes are transparent to the user
  - easily portable
  - may require lot of memory space

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## Third Party Programmer Manufacturers

- Data IO
- CEIBO
- Adventech
- EETools
- HiLo
- Needhams
- Xeltek

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## Designing an Embedded System – Thanks Ahmet

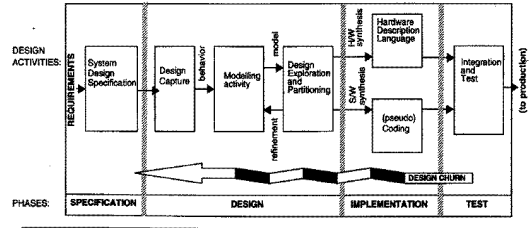
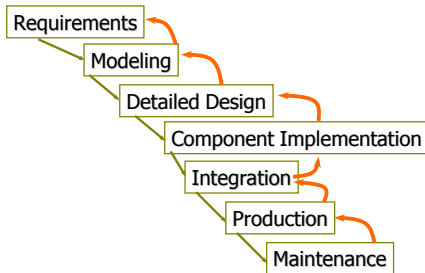


Figure 1.2 Typical design flow for complex systems.

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## Some Models of Development

The Waterfall model



Naïve in representing actual development cycle...

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## The Spiral Model

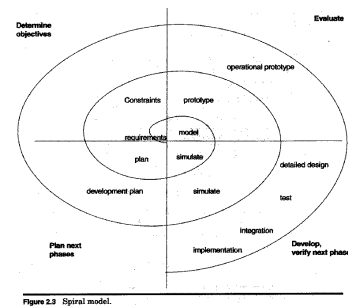


Figure 2.3 Spiral model.

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## Example Project Requirements

- Requirements:
  - DC motor one-directional power control
  - Operation of up to 50V DC, 40V nominal
  - Able to drive currents of up to 30Amps
  - %0 to %100 PWM ratio
  - Linear response
  - One acceleration button (with predefined acceleration ratio)
  - One deceleration button (with predefined deceleration ratio)
  - One immediate shut-down button
  - IP56 casing
  - Fuse (30A)

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## Modeling Phase

- Selection of appropriate lowest cost possible components to perform the requirements.
- Requirement fulfilling checking of all the components together.
- Components ordering.
- PCB design by using EDA tools and ordering.
- Software first phase
- Prototype manufacturing
- Software second phase and debugging.
- Completing the Spiral Model as required.

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## Understanding the Constraints

- Constraints may arise because of:
  - The electronic components used (globally suitable component may cause extra constraints that can be easily overcome).
  - Mechanical dimensions,
  - Software ROM size limits.
- To better understand the constraints, we need to know the electronic components properties first.

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## Basic Embedded System Components

- Digital IO ports
- ADC
- DAC
- EEPROM
- RAM
- ROM
- UART
- Timer / counter
- POR
- WDT
- I2C, SPI

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## Control & Set-up of Embedded System Components



Table 2.1. 8086Map

8086 Address	8086 Internal Address				8086
0000					0000
0001					0001
0002					0002
0003					0003
0004					0004
0005					0005
0006					0006
0007					0007
0008					0008
0009					0009
000A					000A
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00AA					00AA
00AB					00AB
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00CA					00CA
00CB					00CB
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00CE					00CE
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00D8					00D8
00D9					00D9
00DA					00DA
00DB					00DB
00DC					00DC
00DD					00DD
00DE					00DE
00DF					00DF
00E0					00E0
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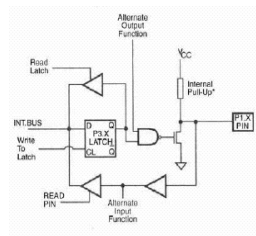
## Digital IO Ports

- Ports are the inputs and outputs to outside world.
- Generally speaking an IO port has the following modes:
  - input mode
  - output mode
  - bidirectional mode (weak pull-up)
- The differences among the modes are due to internal electrical structure.

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## A Quasi-bidirectional IO Port

- Ports may have or not internal pull-ups
- Reading the latch is not equal to reading the port pin.
- Read-modify-write operations



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## Read-modify-write operations

- Some examples of read-modify-write instructions:
  - ANL (logical AND, e.g., ANL P1,A)
  - ORL (logical OR, e.g., ORL P2,A)
  - XRL (logical EX-OR, e.g., XRL P3,A)
  - CPL (complement bit, e.g., CPL P3.0)
  - INC (increment, e.g., INC P2)
  - DEC (decrement, e.g., DEC P2)

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## You can not Get Logic 1 with Heavy Load and Weak Pull-up



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## IO Control

- P0
- P1
- P2
- P3

are the SFR latches of Ports 0 to 3 respectively.

- MOV P1, #83 writes data to Port1 while MOV A, P1 reads data from P1.

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## Analog to Digital Converters

- Matches digital numbers to analog measurements.
- May have separate pins or mostly share the IO pins.
- Generally multiplexed (8 ch is common)
- 8 bit to 10 bit resolution is widely used.
- Easy configuration and conversion procedure
- Resolution means the smallest voltage difference that can be detected.
- Quantization errors.

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## Resolution & Input Voltage Range

- Resolution is the length of the word. Eg 8 bit, 10, 12, 16 bits..
- High numbers mean longer conversion time and higher accuracy.
- 12 bit ADC ->  $2^{12}$  quantization levels -> 4096 different values.
- Input voltage range is the maximum allowable input signal strength. Different signals can feed the same ADC via different gain amplifiers.
- Resolution = (Input Voltage Range) / ( $2^{\text{Number of bits} - 1}$ )
- Input signal must cover the input range of the ADC. ADC is the last stage in the analog path hence its gain must be kept as low as possible. High gain amplifiers must be very close to the signal source.

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## Sampling Frequency

- Can be considered as time resolution of an ADC.
- Fast enough to keep track the changes
- Slow enough not to be difficult to analyse the data
- Slow conversion mean noise filtering: an advantage
- Nyquist frequency concept. Minimum sampling frequency = 2 x maximum frequency of a signal
- Audio CDs have 44kHz sampling frequency.
- Number of channels affect maximum allowable sampling frequency per channel.

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## Inside the ADC

- To measure several channels all together, the below methods can be considered:
  - 1 ADC per channel (expensive)
  - S&H before the multiplexer (expensive)
  - S&H after the multiplexer (normal)
  - no S&H amplifiers
- What is S&H Amplifier? Gain =1. Holds analog data longer than conversion time.

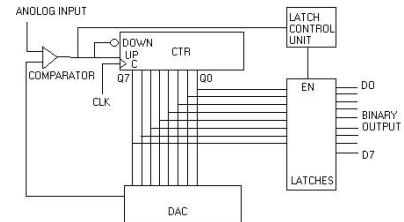
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## Successive Approximation Process

- A DAC output is compared to input voltage.
- Procedure:
  - Set MSB to 1. If signal > VD<sub>DAC</sub>, keep this bit as 1, else reset it.
  - Do iteratively above step until LSB.
- Reason why longer digital data means longer conversion time.
- Counter may be reset to 0 or kept tracking the input signal.

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## SAR Conversion Block Diagram



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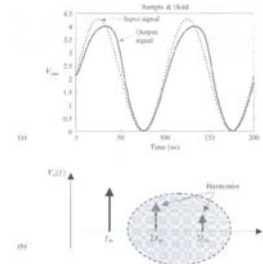
## Flash ADCs

- Offers highest speed available.
- Used in radars, high speed test equipments, medical imaging, digital communication.
- Conversion takes place parallelly.
- 8 bit resolution requires 256 comparators.
- Also a large digital encoding section is required.

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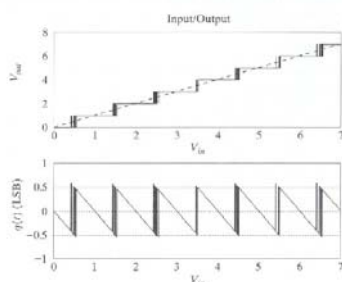
## Errors Due to ADCs Thanks again Ahmet

- Effect of S&H Nonlinearity



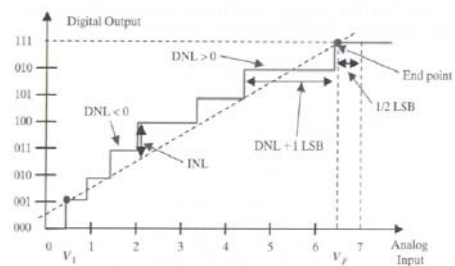
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## Undeterministic nature of ADC level changes



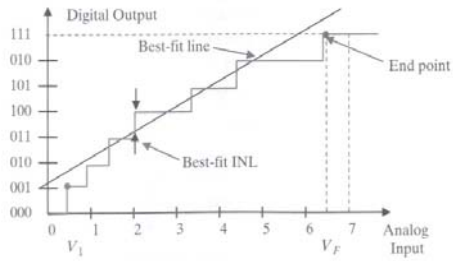
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## Differential nonlinearity of ADC



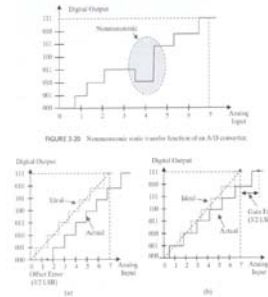
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## Integral nonlinearity in ADC



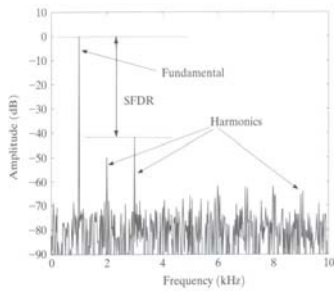
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## Other ADC measures



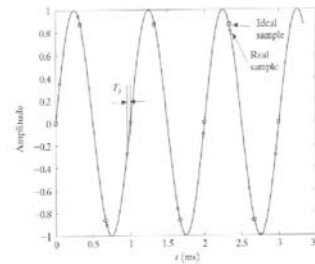
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## Spurious Free Dynamic Range (SFDR)



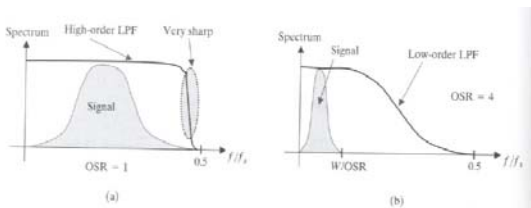
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## Sampling time jitter as a source of noise



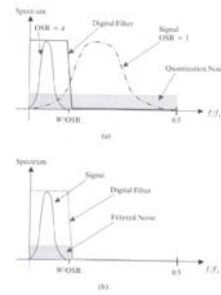
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## Advantages of oversampling 1



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## Advantages of oversampling 2



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## Basic Interface to uC

- Start conversion: starts analog to digital conversion
- Output enable: puts digital data on the data bus.
- End-of-conversion: signals the end of conversion

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Is it too much?  
- it's the beginning -



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## Tip:

- To be pessimistic when designing will make you optimistic when evaluating.
- Devil is hidden under the details.

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## Example

- Application: Designing an Power Line Energy Meter by using MSP430 microcontroller.
- Errors caused by the time delay between voltage and current samples.

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## What is DAC?

- Real world signals are usually analog.
- Accomplishes digital to analog conversion.
- Popularity of digital devices + real world interface -> DAC
- Opposite of ADCs
- DAC selection parameters are linearity, resolution, speed and accuracy.

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## Digital-to-Analog Converters -Basic Categories-

- Standard DACs
- Digital potentiometers
- Digital trimmers
- PWMs

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## Standard DACs

- Converts digital content to analog voltage or current.
- Example: 00H -> 0V, FFH -> 5V
- Can be used to drive loudspeakers, headphones, control valves, etc.

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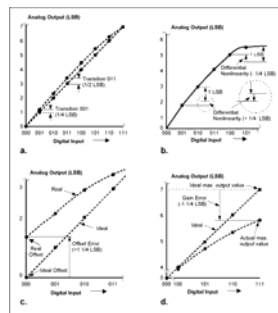
## DAC Resolution

- First step in selecting a DAC is the determination of the required resolution like ADCs.
- Resolution does not mean accuracy. Other sources of errors must be taken into account (Ref: ADCs)

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## DAC Errors

- Integral nonlinearity error (a)
- Differential nonlinearity error (b)
- Offset error (c)
- Gain error (d)



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## Dynamic Output Characteristics

- Settling time
- Propagation delay
- Limited slew rate
- Digital feedthrough: Every transition in the input -> noise at the output.

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## Interfacing ADC and DACs to uC

- Industrial medium is noisy
- Spikes, electromagnetic waves cause important voltage fluctuations at the input and output of analog components.
- Galvanic isolation principle.
- Serial ADC or DACs are most suitable to galvanic isolation.
- Unidirectional serial data lines are required (eg: SPI, not I<sup>2</sup>C)
- In non-isolated systems, RC filters, spike suppression devices and clamping diodes must be used for protection

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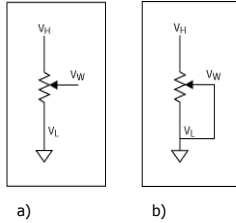
## External Reference

- Some DACs as well as ADCs require the use of external voltage reference.
- Output signal quality is one to one related with the reference voltage.
- The reference voltage must be noise-free
- Some DACs with external reference can operate in multiplying mode (like MAX5170)
- There are also current output DACs.

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## Digital Potentiometers

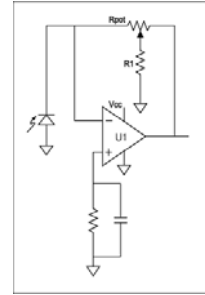
- A potentiometer is used in a three-terminal mode (a) or two-terminal mode (b)
- Attention to wiper current!



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## Application Example of Digital Potentiometer

- Transimpedance amplifier
- Audio volume control
- Tone control
- Frequency adjustment
- LCD contrast adj.



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## Digital Trimmers

- Trimmers are like potentiometers except they don't require frequent adjustment.
- A digital potentiometer may have full range digital input or up and down control inputs.
- Trimmers must keep the set value even on power absence.

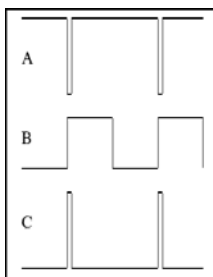
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## PWMs

- A Pulse Width Modulator can also be used as DAC.
- Output is in digital-like signal but LP filtering of the signal gives an analog voltage
- PWMs can be used for DC motor speed control, light dimmer etc.

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## Example PWM Output For DC Motor Drivinig



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## Memory Management in uC

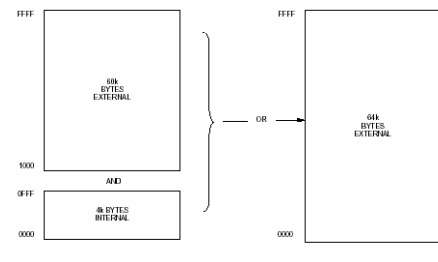


Figure 1. 80C51 Program Memory

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## Data Memory of 8051

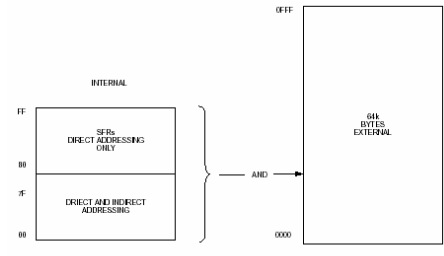


Figure 2. 80C51 Data Memory  
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## Internal RAM Organisation

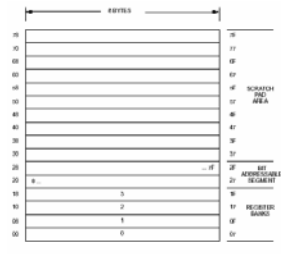
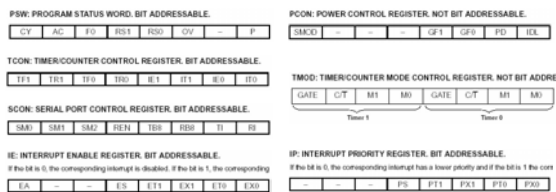


Figure 3. 128 Bytes of RAM Direct and Indirect Addressable

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## SFR's



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## EEPROM

- Variable data storage
- Data retention in the absence of power
- Long write process time
- Short read process time (like internal RAM)
- EEBUSY flag must be checked. This indicates write operation in progress and no reading nor writing can be performed. (AT89C51ED2)

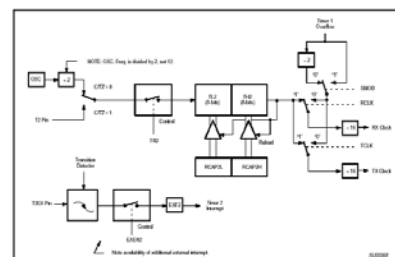
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## UART

- UART: Universal Asynchronous Receiver Transmitter
- Almost exist in every 8051 variants.
- It can be used to drive RS232, RS485, SPI like serial communications.
- Must be used in conjunction of appropriate voltage converters (eg +10V, -10V for RS232)
- SCON and SMOD registers must be initialized.
- Requires one timer module to generate baudrates.

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## Timer/Counter Module



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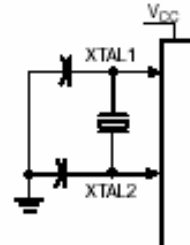
## Crystal Selection

- UARTs require precise clock pulses
- Even small differences between theoretical oscillator frequency and baudrate generation may lead to serial communication failure.
- Example, 11.0592MHz Crystal is required for 9600 and 19200 bps. Using 12MHz crystal will not be appropriate for solution.

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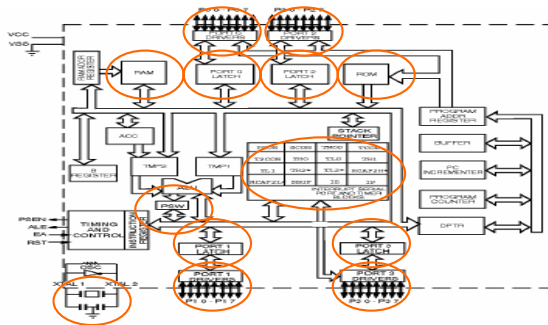
## Crystal Connection

- 30pF +/- 10pF for crystals
- 40pF +/- 10pF for ceramic resonators



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## What We Have Seen?



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## Basic Hardware Design

- Start with requirements:
  - 5V supply
  - Three logic inputs
  - One LED output
- Will perform: if buttons A and B are pressed simultaneously, then LED will turn on, will stay illuminated till button C is pressed.

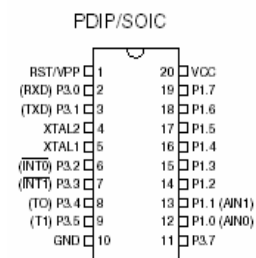
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## Very Simple Design

- Start by choosing right microcontroller:
  - AT89C1051
- 20 pin. Reduced pin count.
- Member of well known 80C51 family.
- Has flash program memory, no need to replace the component during debugging. This is very important.

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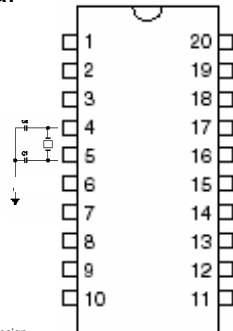
## What Does It Look Like?



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## Start By Placing Crystal

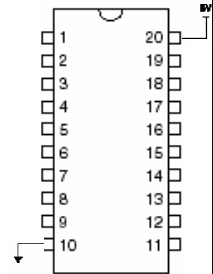
- Start always by placing vital components eg: oscillator circuitry.



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## Power Supply

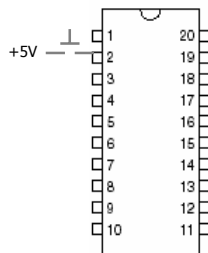
- The next most important connection is the power supply. I assume we have 5V regulated power supply.
- Power supply design will be covered in detail in the next chapters.
- For the simplicity, crystal connection is not shown.



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## Then Comes The Reset

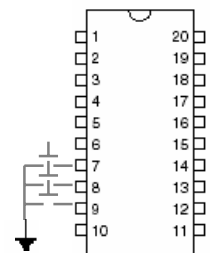
- The simplest way to reset an IC is to use a push-button.
- Attention to the reset logic: is it positive or negative?
- AT89C1051 has positive reset input, therefore it must be connected to +5V to reset the IC



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## Three Logic Inputs

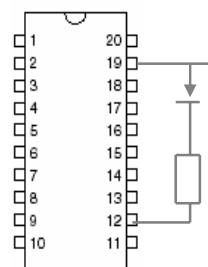
- It is highly advisable to connect push buttons to ground level due to the outputs of the IC are quasi-bidirectional.



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## LED Output

- The output of the IC can sink up to 20 mA per channel but can not source current.
- LED must be connected so that the IC will sink current, therefore its positive pin must be connected to +5 V
- Don't forget the current limiting resistor. Its value is  $(5-0.2-1.5)/10 \text{ kOhm} = 330 \text{ Ohm}$



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## Hardware Is Finished

- The schematic of the required circuit is now complete.
- When power on, nothing will happen ☺
- This very important, because even the uC is programmed, it will take some time till it accomplish the first program commands. The circuit must be "born not to burn itself"
- When reset the IC will have all I/O pins logic 1, therefore +5V. No current will flow through the LED.

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## Hardware Implementation

- Always use a socket for the uC. It may require to remove the IC and reprogram it. Desoldering is not a good way to remove the uC.
- For such basic circuits, there may not need to build a PCB.
- Pre-wired and drilled PCB's are well suited to accomplish the task.
- Protoboards are also wellcome, but take extra care to wires, loose connections, shorts etc...
- PCB design will be covered in detail in the next chapters.

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## Software:

- The remaining part of our circuit is the program of the uC.
- The program and the constants (such as divide X by 5 -> here 5 is constant) reside in program memory -> in the flash)
- The variables reside in the RAM. Their addresses are separated, therefore the same address can be used for both the program and the variables.

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## Where To Write

- You may use any text editor such as edit, wordpad, ultraedit, notepad etc.
- The editor must be able to save the file as is, it must not insert special control characters such as indentation, tabs, CR, LF, etc... Wordpad with save as in text format can be used.

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## A Basic Program

- Start always by specifying the uC
- Always put a label
- Always put a brief explanation about what the program does
- A good programmer puts comments after nearly all program lines.

```
,***** A2D02 *****  
$MOD752  
;  
;THIS PROGRAM IS TO TEST EXTERNAL COMPARATOR  
;WITH INTERNAL TIMER FOR A/D CONVERSION.  
;  
LDELAY EQU 03FH ;COUNTER FOR DELAY  
HDELAY EQU 03BH ;COUNTER FOR DELAY  
DISPL EQU 03DH ;LOW DISPLACEMENT
```

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## Next Steps

- Decision of the below cases is important:
- Do we need any variable?
- Do we need any constant?
- Do we need any repetitively called piece of program?
- Do we need any initialization?
- Will there any program part we can use in the future?
- In our example, we don't need any of the above cases.

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## What Do We Need?

- Bitwise port pin reading,
- Caring bitwise logic operations,
- Bitwise port pin output.
- Also we need complementing. We will need to complement logic inputs (when button is pressed, we will actually read logic 0, but we use logic one for TRUE, the same operation must be done for LED output.

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## Boolean Variable Manipulation

BOOLEAN VARIABLE MANIPULATION				
CLR	C	Clear carry	1	12
CLR	bit	Clear direct bit	2	12
SETB	C	Set carry	1	12
SETB	bit	Set direct bit	2	12
CPL	C	Complement carry	1	12
CPL	bit	Complement direct bit	2	12
ANL	C,bit	AND direct bit to carry	2	24
ANL	C,bit	AND complement of direct bit to carry	2	24
ORL	C,bit	OR direct bit to carry	2	24
ORL	C,bit	OR complement of direct bit to carry	2	24
MOV	C,bit	Move direct bit to carry	2	12
MOV	bit,C	Move carry to direct bit	2	24
JC	rel	Jump if carry is set	2	24
JNC	rel	Jump if carry not set	2	24

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## The Commands We Can Use

- MOV C, Px.x
- MOV Px.x, C
- JC address, JNC address
- ANL C, rel
- ORL C, rel

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## Start Writing The Program Driving the LED

- \$MOD51 ;This is assemble directive
- Loop:
- MOV C, P3.5 ;read pin 9 – button C
- JC Cont ;if not pressed then continue
- SETB P1.0 ;if pressed, then reset the LED
- SJMP Loop ;return to the loop
- Cont:
- MOV C, P3.3 ;read pin 7 – button A
- JC Loop
- MOV C, P3.4 ;read pin 8 – button B
- JC Loop
- CLR P1.0 ;turn on LED
- SJMP Loop ;return to the Loop.

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## Conflicting Decisions

- Turning ON the LED and turning OFF conflict.
- One operation must have higher priority than the other.
- Same priority for both is not allowed. Turning ON and OFF successively is not a good way for logic outputs. The LED will stay illuminated but with less intensity.
- Stopping must have higher priority than starting. Think of car brakes.
- Here higher priority is assigned by writing the stopping criteria first.

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