Electrical measurment and Instrumentation covers:

i) Electrical parts:-

ii) Electronics parts

- Basic of measurment system
- Error Analysis
- Analog Instruments
  - PMMC
  - EMMC
  - MI
  - ESV Electrostatic voltmeter
  - Thermal Instruments
  - Rectifier type Inst
- Measurment of Results
  - D.C. Bridge
  - Measurment of L, C, M mut. Ind
  - A.C. Bridge
- Measurment of power
  - D.C. power measurment
  - A.C. power measurment
    - 1-ph AC
    - 3-ph. A.C.
- Measurment of energy
- Potentiometer
- Instrum. T/f
- power factor meter
- flux meter

Electronic part

- CJ-meter
- CRO
- DVM
- Transducer

Basic concept on Measurment

In each and every field of engineering, sciences-there is requirement of various quantities such as physical, mechanical, electrical, chemical, thermal etc. All such measurments are required for mantaning and observational analysis for valuable records, research and development.

? What is the purpose of measurment:

The purpose of measurment is to present measured value to numerical values.

e.g. - When we have to measure any physical quantity, its output should be in numerical value (if it is in numerical value then it is very easy to understand for everyone)

When we have to measure weight → first some numeric value is there and then its unit. e.g. 10 kg. 10 → numeric value kg its unit.

if Dist → I II 10 Km

I II
Current 10 Amp etc

Temp 98° F° etc. etc

→ What is measured value, what is true value, Diff.

1. Measured Value: → Any value or any reading calculated from measurment system or measuring instrument is known as measured values.

2. TRUE/ACTUAL values: → Any value calculated from rated values is known as true values.

Example: Let us we are having a motor (may be d.c/a.c) with its rated speed 3000 rpm. Then its N_T = 3000 rpm but we can measure the speed with the help of Tachometer. If tachometer reading is 2998 then N_m = 2998 rpm

Now 3000 − 2998 = 02 (Error)

↑ Measuring instrument → measured Quantity

Error :- It is the deviation of measured value from the true value

True value → Tachometer → Measured value

System → Measuring Instrument → System output measured value

i/p True value

$$\text{Error} = \delta = A_m - A_T \quad \text{---(1)}$$

(NM, NT)

OR Error = System o/p − System i/p

If $A_M > A_T \Rightarrow$ Error = +ve

$A_M < A_T \Rightarrow$ Error = −ve

Example:- If we are having two instrument - Inst. A & Inst B then which of the following instruments is more quality instrument?

Inst A: $\delta_A = 1$ amp

Inst B: $\delta_B = 10$ Amp

(a) only A (b) Only B (c) Both A & B (d) None of above ✓

[Till we are not aware about the true value of each instrum. bez of insufficient data]

[If three studs got marks A: 125, B: 220, C: 135 | we can't comment till we don't know about the max marks]

⇒ The quality of any instruments is decided by %. relative static Error or %. Limiting Error (L.E.)

%. RSE OR %. Relative static Error OR Limiting Error $= \frac{A_m - A_T}{A_T} \times 100 = \frac{\delta_A}{A_T} \times 100$

$$= \left(\frac{A_M}{A_T} - 1\right) \times 100 \quad \text{---(2)}$$

Now I will mention the value of true value A_T of each instrument :-

Inst A

$S_A = 1$ amp

$A_T = 2$ Amp

Now

$\%\text{-}RSE = \frac{S_A}{A_T} \times 100$

$= \frac{1}{2} \times 100$

$\%\text{-}LE = 50\%$.

Inst B

$S_B = 10$ amp

$A_T = 1000$ amp

$\%\text{-}RSE = \frac{S_A}{A_T} \times 100$

$= \frac{10}{1000} \times 100$

$\%\text{-}LE = 1\%$.

Therefor the Quality of B Inst is more.

Also., if also asked about to calculate accuracy.

Accuracy $= 100 - \%\text{-}L.E.$

$= 100 - 50$

$= 50\%$.

Here $= 100 - 1$

$= 99\%$.

$\Rightarrow$ Inst B is more Quality Inst.

Conclusion:- The quality of the instrument is always decided by % relative static error, the error is always expressed in term of true value of the variable.

BASIC Concept on Measurement:→ In each and every field of science, engineering, there is generally requirement of various quantities such as physical, mechanical, electrical, chemical, thermal etc. All such measurements are required for maintaining and observational analysis for valuable records, research and developments. There are various methods of for measurements that we study in measurment & Instrumentation.

The measurment is basically a comparison of given quantity with a standard fixed quantity (that is a predefined standard). The fixed quantity is taken as the basic is called a UNIT. The MEASURMENT can be defined as the process of comparison of given quantity in terms of its standard quantity or its basic unit.

"The process by which one can convert physical parameter into meaningful number."

Methods of measurments:→ i) Direct method ii) Indirect method

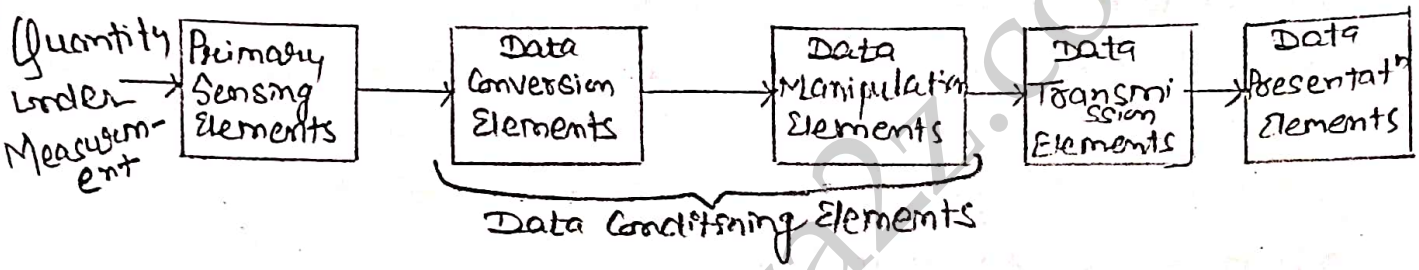
1. **Direct Method:→** The unknown quantity is directly compared with the known quantity. for e.g. (Simply height & weight.)
2. **Indirect measurment:→** In this method, either the current or voltage is converted into mechanical deflecting torque by means of electromechanical energy conversion. e.g. Ammeter Voltmeter Analog meter.
   → for example we use ammeter for measurment of current and voltmeter for voltage. (There is a deflection in pointer from 0 to some value - this deflection is due to supply of current (d.c value) to the ammeter & voltmeter).
   - Direct method is not suitable for electrical circuit measurment.

Elements of Generalized Measurement System: →

It is important to have a systematic organisation and analysis of measurement system. Mainly the measurement system contain three main functional elements:

1. Primary Sensing Elements
2. Variable Conversion Elements and
3. Data presentation elements.

The function of each elements are as under:



1. **Primary Sensing Elements:** → The quantity under measurement makes its first contact with the primary sensing elements. The quantity to be measured is first detected by primary sensing element. The quantity detected by the primary sensing element may be pressure, temperature, any mechanical quantity (that is non electrical quantity/signal) is converted into electrical quantity with the help of transducer. Transducer converts the physical quantity detected by primary sensing element into electrical signal.

2. **Data Conversion Element:** → Now, the output obtained from primary sensing element is in electrical form such as current, voltage, frequency etc. for a digital system of measurement such output signal will have to be converted from analog to digital which is done by variable/Data conversion element. Thus A/D Converter is data conversion element.

3. Data Manipulation Elements:→ The function of this element to manipulate the signal. Manipulation of the signal means changing its numeric value for example an amplifier. An amplifier amplifies the magnitude of the incoming signal while retaining its original nature. A variable manipulation element can be connected befor or after Data Conversion element. If connected after Data variable element, it is used to amplify the incoming, whereas if connected before then its functions as an attenuator.

the transducer used earlier converts the data in a small signal, So that the manipulation element can amplifies the signal for its further transmission (of data). [Data को उचित form में convert करना जिसको हम transmit कर सके] Thats is possible by amplifier and attenuator. [Bcz the transducer have generated a small signal that can't be displayed directly).]

4. Data Transmission Elements:→ Sometime it is noticed that where we are performing the experimented work or data manipulation then we have to process the the data to any other place. So if Location of recording and Location of processing are not matching So ~~that~~ we have to transmit the data. The data transmission transmits the data from one stage to another if the elements of the system are physically separate.

5. Data presentation Elements:→ The transmitted data is used for the purpose of monitoring and controlling purposes. The data presentation elements presents the information in proper form to the end user for the effective analysis. If data is to be monitored then visual display devices are used as presentation element. Readers, cameras or magnetic tapes are used for recording of data.

for controlling and analysis a data presentation element consist of computers, microcontrollers or microprocessors.

Instruments and measurment System:→ The instruments are used for the measurement with means of determining quantities or variables. the instruments are consist of single unit which gives an output reading or signal according to the unknown variable (measurend) applied to it. A measuring instrument may consist of several separate elements. There elements may consist of transducing element which convert the measurend to an analogous form. The analogous signal is then processed by some intermediate means and then fed to the end device to present the results of the measurment for the purpose of display and control.

Types of Electrical measuring Instruments:→

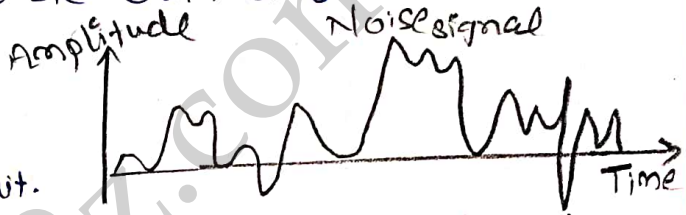
1. Active & Passive Inst. 2. Null OR Deflection type Inst.
3. Analog & Digital Inst. 4. Absolute & Indirect Instruments.

Secondary Inst

a. Indicating Inst.
b. Integrating
c. Recording

Noise:- in an Electronic System:

- In electrical terms, noise may be defined as unwanted form of energy which tends to interfere with the proper reception and reproduction of transmitted signal.
- Noise is unwanted signal which interfere with original message signal and corrupts the parameters of the message signal
- It is likely to be entered at the channel or reciever etc.



→ Noise is some signal which has no pattern and no constant freq or amplit.

→ It is quite random and unpredictable.

→ Measures are usually taken to reduce it, though it can't be completely eliminated.

⇒ To improve the system performance, usully we want to eliminate the noise, but it is difficult to remove out, it can be reduced as much as possible.

There are some examples of noise such as

Noise can observed in radio receiver, in receiver several electrical disturbances produces noise and therefore modifying the required signal in an unwanted form. So in case of radio receiver the noise may produce HISS type of pattern (at the output of loudspeaker)

→ If we talk about TV receiver, the noise may produce SNOW, the snow actually superimposed with the picture o/p. So SNOW and FLICKER are the kind of noise in case of TV receiver.

→ BUZZ sound almost telephonic conversation.

⇒ Noise is a factor which is going to impact a lot on signal quality and Noise may Limit the performance of the electronic or the communication system

Effects of Noise:-

- Noise Limit the operating range of the system
- " " " performn. of the system
- Noise affect the sensibility of the receivers.

Noise in An Electronic System:→

↳ In electrical terms, noise may be defined as an unwanted form of energy which tends to interfere with the proper reception and reproduction of transmitted signal. For example in receivers, random electrical disturbances produce noise and thus modifying the required signal in an unwanted form. In T.V. receiver noise may produce 'snow' which becomes superimposed on the picture output. In actual the noise may limit the performance of the a communication system.

Noise is an unwanted, random and undeterministic electrical signal, which interfere with reception and reproduction of transmitted signal.

Noise can affect sensitivity of receivers and can also cause reduction in B.W.

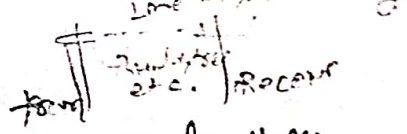
Classification of Noise:→ There are mainly two ways of classifying the noise as under: 1. External Noise
2. Internal Noise.

1. External Noise:- The noise created outside the receiver is called External noise. The external noise can't be analysed quantitatively thats why it cannot be controlled. The only to reduce the effect of external noise, the only way is to shift the communication system to other place or location which has comparatively smaller noise. Thus due to this reason, the satellite earth stations are generally located in noise free valleys.

External Noise can be classified as:
i) Atmospheric Noise 2. Extraterristrial Noise
iii) Industrial Noise.

i) Atmospheric Noise:→ Atmospheric Noise which is also called Static, is produced by lightning discharges in thunderstorm and other natural electrical disturbances which occurs in atmosphere Atmospheric noise contains spurious radio signals which are distributed over a wide range of frequency.

This is random and spread over RF spectrum used for broadcasting. It has been observed that the field strength of atmospheric noise varies approximately inversely with frequency. This conclude that large atmospheric noise is produced in low and medium frequency bands whereas very small noise in the VHF and UHF bands. Thus noise becomes less severe at frequencies above 30 MHz because higher frequencies are limited to LOS.



iii) Extraterristrial Noise:→ the extraterristrial noise is further subdivided as a) Solar Noise b) Cosmic Noise

a) Solar Noise:→ Solar Noise is produced by the radiations emitting from sun because sun is a large body at a very high temp (over 6000°C).

b) Cosmic Noise:→ the cosmic Noise is produced from distant stars (as they have high temperature). Also called black body noise or thermal noise and is uniformly distributed over the entire sky.

c) Industrial Noise :→ The industrial noise ranges between 1 to 60 mHz and occurs in urban, suburban & industrial areas. The industrial noise is produced by arc discharge. The source of this noise are automobiles and aircraft ignition, electric motor, switching equipments, leakage from high voltage line, heavy electrical machines etc.
E.g noise in substation (power t/f). also cover in indust. noise.

INTERNAL NOISE :→ Internal noise is that type of noise which is generated internally the circuit or within the system or receiver. Noise created by the active/passive devices found in receivers. Internal noise may be treated quantitatively and can also be reduced or minimized by proper system design. This noise is proportional to B.W. over which it is measured. Internal noises are further categorised into following types:

1. Thermal Noise :→ The thermal noise or the white noise which is generator in a resistor or the resistive component of the circuit. It is due to the rapid and random motion of molecules (atom) electrons) inside the resistance.

- Noise generated by a resistor is proportional to its absolute temperature and bandwidth over which noise is measured.

$$P_n \propto TB = KTB \Rightarrow$$

K is Boltzmann's Contt $= 1.38 \times 10^{-23}$ J/K

T = Absolute temp, K = 273 + C

B = Bandwidth, P_n = Noise power output of resistor.

$V_n = \sqrt{4KTBR}$ R is Resistance

2. **Shot Noise :→** This type of noise is caused by shot effect in all amplifying devices and active devices. This type of noise is caused by random variation in the arrival of electron or holes at the output electrodes of an amplifying devices.

e.g. for a diode, shot noise current is given by

$$i_n = \sqrt{2 e i_p B}$$

where i_n = r.m.s. shot noise current.

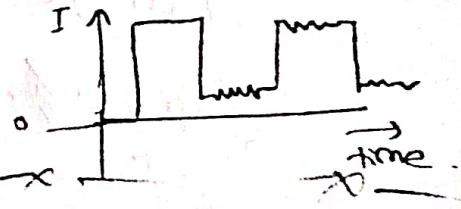
e = Electron charge $= 1.6 \times 10^{-19} C$

i_p = Direct diode current, B = Bandwidth of system.

3. **Flicker Noise :→** OR **Low freq. Noise :→** 1/f Noise

- This type of noise is observed below few KHz freq.
- Its spectral density ~~decreases~~ increases with decreases in freq. Thus known as 1/f noise.
- This noise becomes significant at freq. lower than 100 Hz.

4. **Burst Noise :→** It consist of sudden step like transition b/w two or more discrete voltage or current levels, order of several hundered microvolt. Current last from several ms to s.

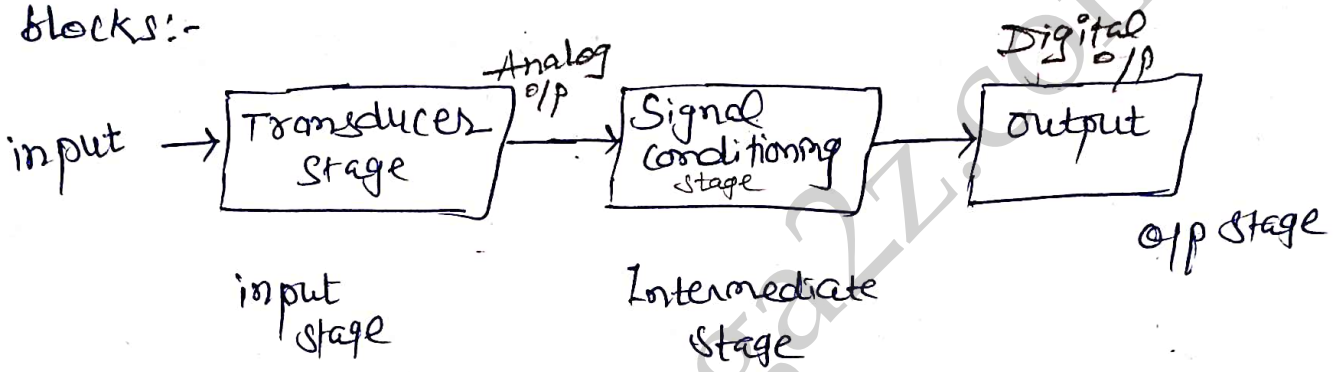


Signal Conditioning Circuits:→

inf? data input,

In generalized measurement system, discussed about the various data conditioning elements (Blocks) such as primary sensing elements, Data conversion elements, Data manipulation elements, Data transmission elements etc etc ⇒ All these are data conditioning elements.

Let us consider we are having Diff. intermediate blocks:-



Signal conditioning is the intermediate stage b/w output and input stage.

- what does the intermediate stage ⇒ it modifies the output of transdu cer according the output requirement.

⇒ It modifies the transducer output according to the output stage.

→ signal conditioning

- various types of input may be • Electrical, thermal • physical, chemical etc.

Here transducer → one physical quantity to another phy. Quantity. Here we will discuss about electrical/signal as it easy to modify it, we can modify it, attenuate, amplify etc. So here if physical quantity is converted into electrical signal then it is to be done by a i/p electrical transducer. Suppose at the o/p of transducer we are getting Analog o/p. and at the output stage we are having digital o/p (that to be measured). Now is it possible to measure the analog o/p (of transducer) by a digital (output stage) = No

Now this analog output (of transducer) is to be converted to digital by a signal conditioning circuit. Therefore the function of signal conditioning -

"It modifies the transducer output according to the output stage".

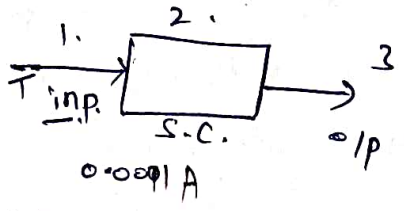
Various "function" of signal conditioning :→ Mainly there are two processes in signal conditioning circuits :- i) Linear process ii) Non linear process

Linear process	Non linear process
Amplification	Modulation
Differentiation	Demodulation
Integration	Clipping
Addition	Clamping etc.
Subtraction etc.	

It perform both (Linear and Non linear) function.

If we are amplifying a signal with small value 0.0001A. → The system is starting with zero. Then this signal will be amplify. Now multiplied by scale factor & Divide later on / After measured..

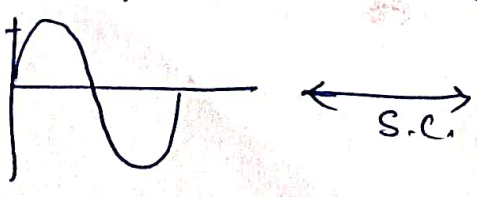
for example if we have to amplify a signal

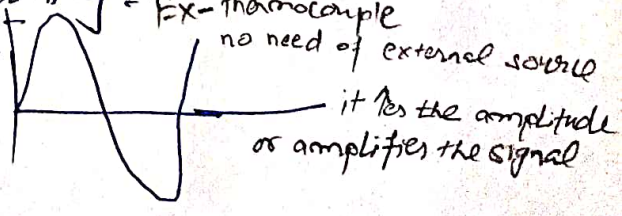


Op-Amp also perform the same functions (Also performs the operations also) It is also a signal conditioning ckt.

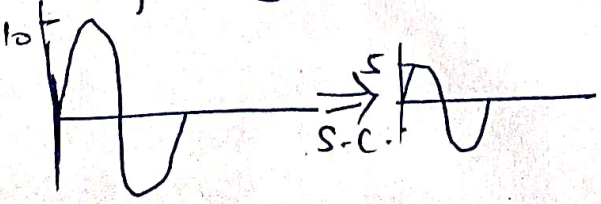
Various Conversion :→ from signal conditioning :- i) Active transducer, (Self) Ex- thermocouple no need of external source it Yes the amplitude or amplifies the signal

i) Amplification :-



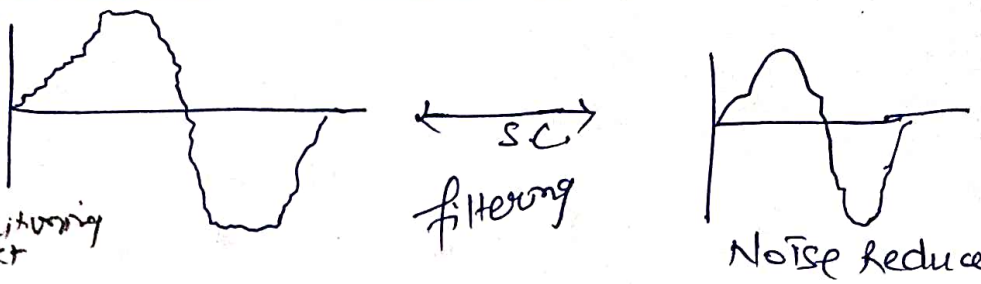


ii) Attenuation



c) Filtering :- → is a fn

Suppose we are having a noisy signal. If we will filter this signal if we pass it in signal conditioning ckt



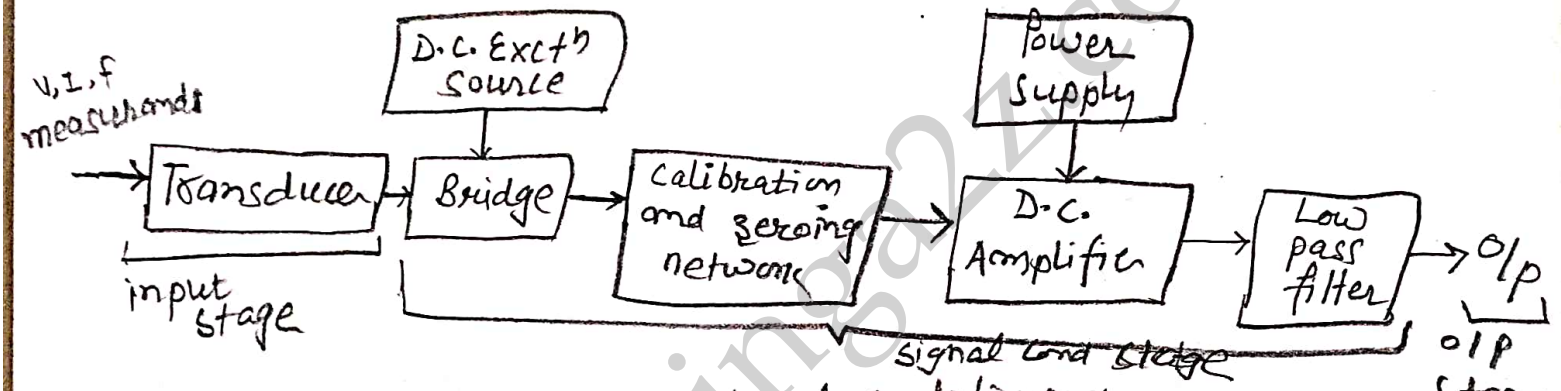
d) Excitation :- [Strain gauge, RTD] Passive transducer → which needs external power source for their operation.

- Signal conditioning also provide external (power) source to the transducer

⇒ S.C ⇒ Amp^n, Diff^n, Integ^n, Add^n, Sub^n etc.

Types of signal Conditioning :- ① D.C. Signal Condit^n
② A.C " "

① D.C. Signal Conditioning



- This is block diagr. for D.C. signal conditioning.
- first of all i/p to the transd^r - i/p may be measurands V, I, f, or any other phy Quan which is to be measure → that we will give in measurand
- Now this transducer will convert it into Electrical signal (Transd. are also two types - phys Q to El → Elect Transducer and Electrical to non physical ⇒ Inverse Trans).
- Various block/components in the signal conditioning stage will convert the o/p of the transducer as per the required output at output stage. we have to modify the signal acc. to o/p stage
- The output of the transducer will be given to the bridge.
- Example Strain Gauge - Two cases - Balanced & Unbalanced condition by using wheatstone Bridge

① Balanced

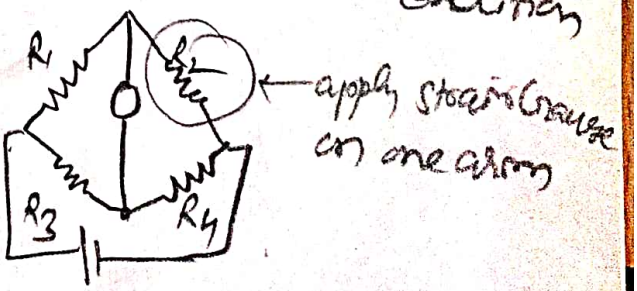
o/p Volt → 0

$R_1R_4 = R_2R_3$ | $V_o = 0$

Unbalanced

If we will apply strain dimension will change & it will unbalance

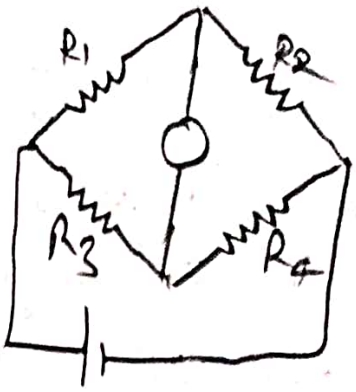
V_o = ?



- we have to balance the wheatstone Bridge by applying potentiometer on one arm

The o/p of t/d is given to bridge.

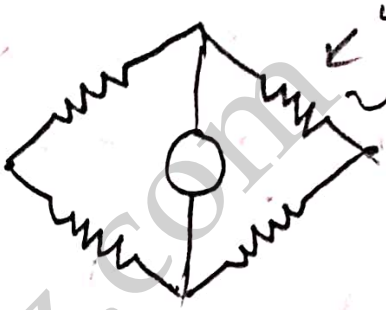
→ Here strain Gauge is used as a t/d. Now the bridge is balanced through potentiometer.
if it is balanced, then $V_o = 0$



Balanced
$V_o = 0$

$R_1 R_4 = R_2 R_3$

→ Now if we are applying strain gauge on any one arm or if we apply force, the the dimensions will be automatically changed.
↓ will be unbalance, Resisting (3) will be same. Now it will be unbalanced cond.ⁿ



The output will be unbalanced → this will be measured by calibrating & scaling now

Calibrating & zeroing n/w:- To measure unbalanced output of bridge ckt.

- Now unbalanced output of bridge ckt is measured
- Now this unbalanced o/p will be given to d.c. amplr
- It will amplify the o/p that is to to be measured easily.
- Now it will be supplied to Low pass filter.

Low Pass filter → it will remove the high frequency components (also reduce the noise signal)

Adv of D.C. ~~amplifier~~ amplifier:→ freq of m D.C

① It is easy to calibrate at Low freq.

② It is able to recover from an overload condn.

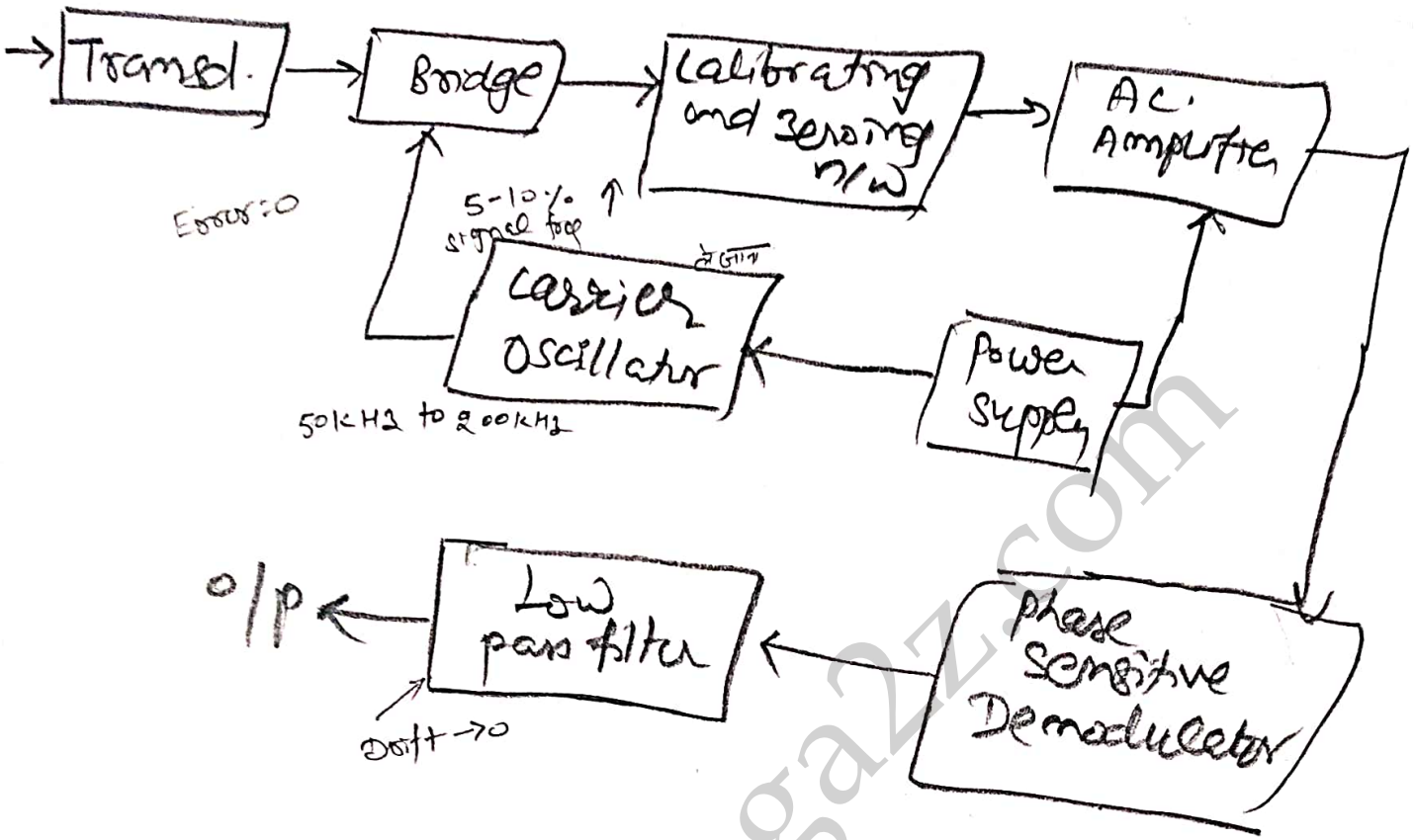
Disadv :- Drift / Error in reproducibility [Diff output with same input with individual person

- Low frequency spurious signal

Drift - Due to D.C. amplifier use — there is a drift in system. — that is unwanted signal →

How to Remove this Drift → by using A.C. signal conditioning

A.C. Signal Conditioning :- To remove the drift/Error in the signal



- This is block diag. for a.c. signal conditioning | one feedback signal is there through carrier oscill
- Electrical signal is provided through the Transducer.
- The o/p of t/dr is given to Bridge. → in prev. case there was a d.c. source on Bridge but here we are giving carrier oscillator (through the power supply - it ↑es the frequency) it will add the freq. (in prev. case reduced freq. (freq zero in D.C)).
- Now it is easy to compare the o/p from the amplifier. before using carrier oscillator it was not able to comp
- It will ↑es the η ⇒ signal will be transmitted in better way.
- In D.C. signal conditioning → freq Low → weak signal
- Phase sensitive Demodulator:- freq. was added by carrier oscillator Now it will remove / balance the freq.

Coz we didnot need the added freq. signal) To maintain the signal Quality
Now there will be original signal and this signal will be passed through LPF
- Noise will be reduced → we will obtain a pure signal.

Data Acquisition System: → Acquisition → Acquiring/collecting (collecting) something from the nature

→ Collecting the data from real / physical world and converting that data into signals that can be processed by computers for the use of engineers / scientist.

→ Data acquisition system is an information system that collects, stores and distributes information.

→ It is used in industrial and commercial electronics and environmental and scientific equipments to capture electrical signals or environmental conditions on a computer device.

→ this system capture, store & procces the data, therefore it includes different tools and technologies that are designed to accumulate the data

Data Acquition System consist of:- (DAS or DAQ)

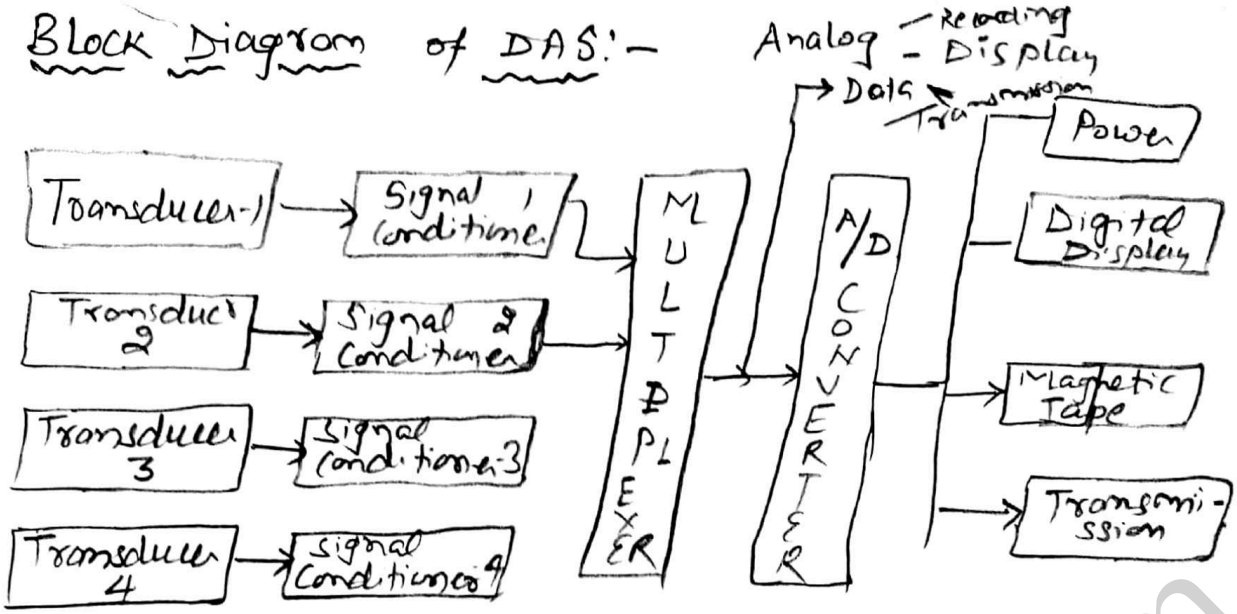
- → Sensor
- → Signal Conditioning
- → Data Conversion
- → Data processing
- → Multiplexing
- → Data Handling
- → Associated transmission, storage and Display devices.

• The data acquition system involves - 1st acquiring the data, procesing over it storing the data and then transmitting that data

So, for the capturing of data, it is having the sensor, for processing over that data is signal conditioning, data conversion, data processing, multiplexing, data handling units ⇒ After that for the storage, for the display for the transmission of data we are having different devices.

Broadly we can say that, it consist of these blocks or separate units and function of these unit is 1st acquiring the data, doing the process over it and then storage and transmission and display. Block diagram of such or DAS or function for each units / Blocks are:—

Block Diagram of DAS:-



This is the block diagram of data acquisition system, that consist of main units and subunits combined to form a bigger unit. The function of each block are as follows:-

① TRANSDUCER:→ / Sensor → It is the first comp. which acquire the data from physical world / or environment.

It is used to convert the physical quantity into electrical quantity. Also can they used to measure directly the electrical quantity.

Voltag Current Freq. Resist.

2. Signal Conditioner:- / Conditioning unit Earlier the transducer acquire the data/signal from physical world ~~now this~~ and convert it into electrical signal. Now these electrical signals coming from the transducer are weak signal (with low amplitude) / so to increase their amplitude, amplification has to be done, also if the signal is containing unwanted signal or noise is there so to ~~do~~ remove there noise and unwanted signal either alteration, filteration of those signal is being done. Therefore we can say that all these function are done in signal conditioning unit.

(that can't be used for further processing)

* To make the signals strong, various signal conditioners are used
  → Amplifier
  → filter
  → Modifier. etc.

3. Multiplexer :—

It accepts multiple analog inputs and provide a single output signal according to the requirement of signal.

* At the input of the multiplexer various inputs are there and a single output is there at the output end.

4. A/D Converter: → It converts the analog data to the digital output.

Why we convert into digital ⇒ • Easy processing
• Easy transmission, } • processing over digital data is easy
• Digital Display & storage of digital data is easy.

* In many electronic system, only the digital data is being used, bcz the transmission of digital data is very fast, also its processing is very fast, So in most of the areas digital form of data is used So conversion becomes very important hence A/D converts the analog data to the digital data

- Easy to process
- " " transmit
- processing over digital data is easy

} So due to easy display & storage → Digital data require less space, we are getting digital reading so the error are reduced. Therefore we can say that the digital data system has more advantageous than analog data. So there is a need of analog to digital data conversion that is done by A/D Converter.

5. Recorders & Display Devices :→

After conversion (A/D) the data, the transmission, display and storage of data is required/needed. So for that purpose we are having the Recorders & Display devices.

- Data is displayed in suitable form in order to monitor the input signals. So example of display devices are

→ Oscilloscope
→ Numerical Displays } giving Digital o/p
→ Panel meters

Recording can also be done (for future use)

→ Data can be either permanently or temporarely stored or recorded. e.g.

- Optical recorders
- Ultraviolet recorders
- Stylus and ink recorders
- Disc
- Tapes

* The data acquition system based on the output (provided) by it, is divided into two types:- i) Analog data Acq System
ii) Digital " " "

* Objectives of Data Acq. System:→

1. Must acquire the necessary data at correct speed.
2. Use of all data efficiency to inform the operator about the state of the input

Objectives :-

→ must be able to summerize & store data for diagnosis of operation and record purpose

→ must be flexible and capable of being expanded for future requirement.

→ must be reliable and not have a down time greater than 0.1%.

→ must provide an effective human communication system (must be easy to read / understand) not m/c readable

Appn → input or output D/A.

→ Digital are more complex than Analog. both in term of instrument & Analysis system.

* Industrial area — plant / workshop
Scientific area — Aerospace
biomedical field
Telemetry

Analog System Design

Definition

Analog design in the context of integrated circuit design is a discipline that focuses on the creation of circuits that operates in and are optimized for continuous time-domain behaviour.

Typical objectives of analog design include :-

- Signal fidelity
- Amplification
- Filtering

⇒ When term "integrated circuit design" is mentioned, most people think of the design of complex microprocessor. These circuits are designed using digital design techniques, which focus on the propagation of discrete values, i.e. "ones and zeroes".

⇒ Importance of Analog Design

Since all the basic devices in an IC respond to continuous time stimulus, analog design forms the foundation for all IC design. Modern IC technology presents many design challenges. There is significant variability in the manufacturing process for advanced technology nodes.

→ Analog design must compensate for all of these effects to ensure three basic qualities :-

- fidelity / Precision
- Consistency
- Performance

How to design Analog Circuits :-

Analog IC design typically involves a top-down design and implementation process followed by a bottom-up verification process.

→ Here are the basic steps —

- Develop a high level specification for the design. What function will it perform? What are the performance, power and area (cost) targets for the design?
- Develop a top level design to achieve the required results using macro-functions such as filters, comparators and amplifiers.
- Create the device level circuit descriptions to support the top level design using component such as resistors transistors and Capacitors.
- Verify that the design delivers on all its specification using simulation. The software used here will typically model the circuit using linear and non-linear elements that have been tuned for the targest fabrication process.

→ It is during this step that manufacturing process and operational variability will be modeled to ensure the device design remain robust in the face of these uncertainties.

- Implement a physical layout of the design by assembling the pre-defined layouts of all components. During this step, the density of the

layout is optimized to minimize cost.

→ Validation that these rules are followed occurs during this step, which is called physical verification.

◇ The equivalent circuit is then extracted from the layout. The extracted design is also compared to the original design to ensure the correct devices were used and connected correctly. The process is called logic verses schematic checking.

◇ Any structures required for testing the circuit are added during this phase as well. Once complete, the design is ready for either manufacturing or integration into a larger digital design.

Integrating analog designs into a larger digital design is referred to as AMS, or analog/mixed signal design.

Analyse the interfacing of Analog and Digital System.

Ans:- In which first of all instructional objectives are :- ① know the interfacing of analog signal to microcontrollers/microprocessors.

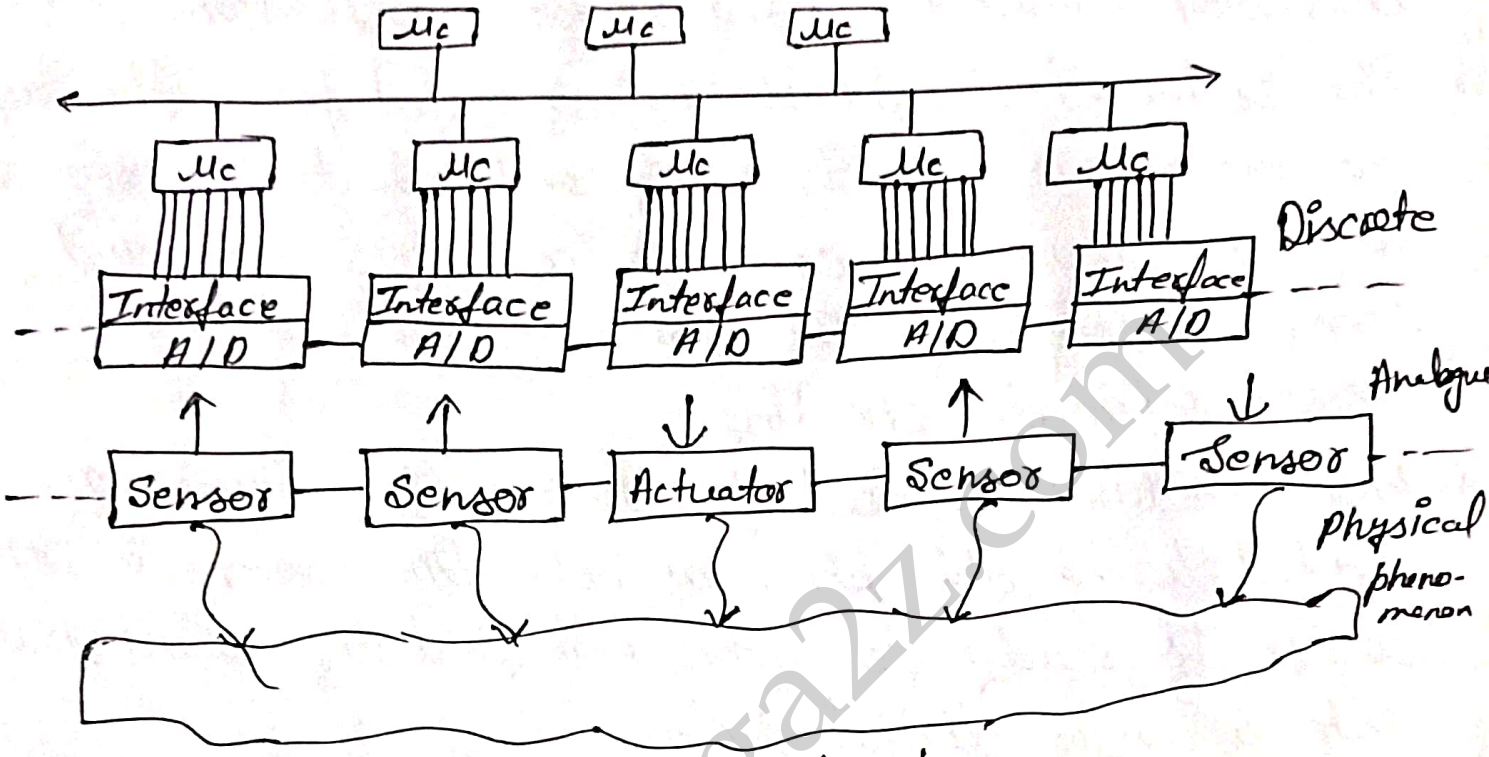
② Generating Analog Signals

③ Designing AD and DA interface

④ Various methods of acquiring and generating analog data.

→ In which below figure shows a typical sensor network you will find a number of sensors and actuates connected to common bus to phase information and

drive a collective decision. This is Complex embedded system. Digital camera falls under such a system.



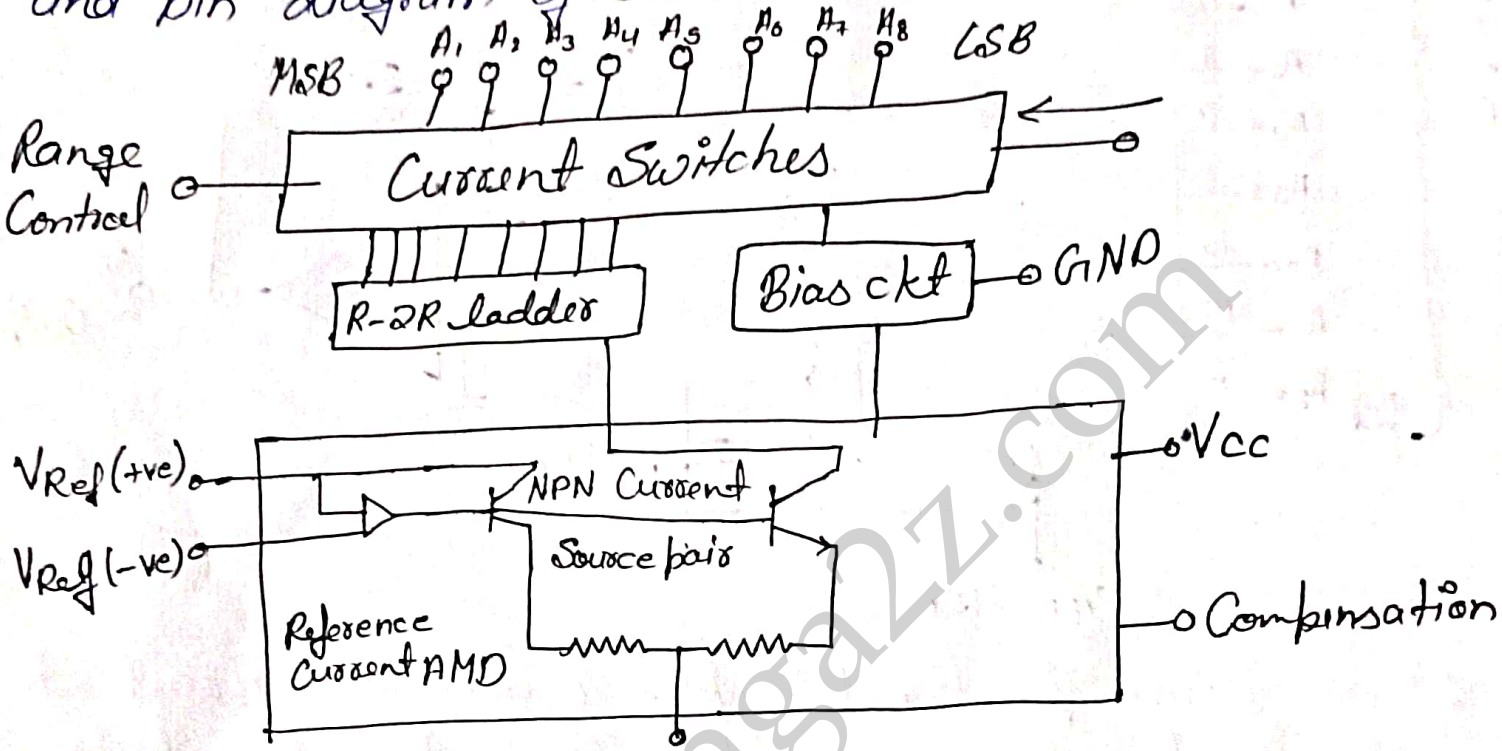
fig(a). Analog Interfacing Network

Different Stages -

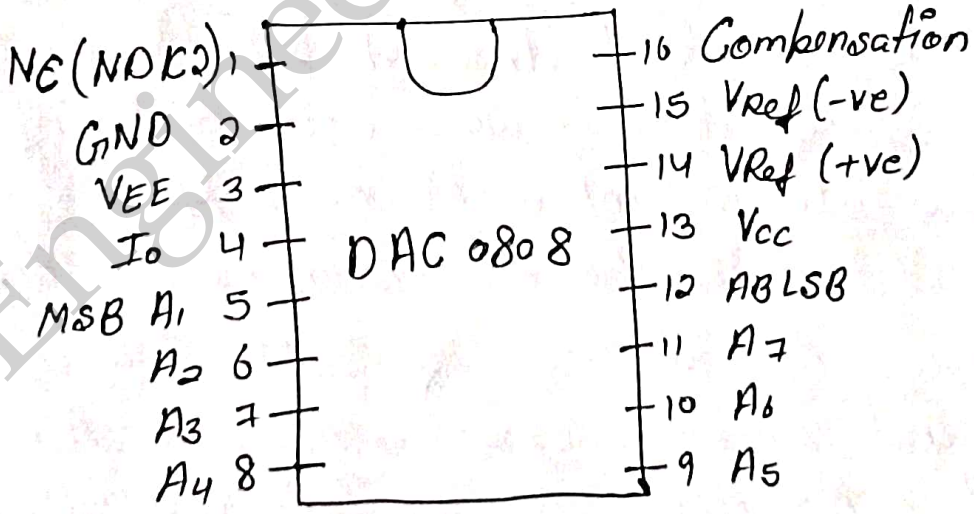
Stage 1. Signal Amplification and Conditioning
Stage 2. Anti Aliasing factor
Stage 3. Sample and Hold
Stage 4. Analog to Digital Convertes
Stage 5. Digital Processing and Data Converter manipulation in a processor.
Stage 6. Processed Digital values are temporarily stored in a latch before DA Conversion.
Stage 7. Digital to Analog Conversion
Stage 8. Removal of glitches and spikes
Stage 9. Final low pass filtering

→ The DA Converter DAC 0808

The DAC 0808 is an 8 bit monocithic digital to Analog Convertor (DAC). Below figure shows architecture and pin diagram of such a chip.

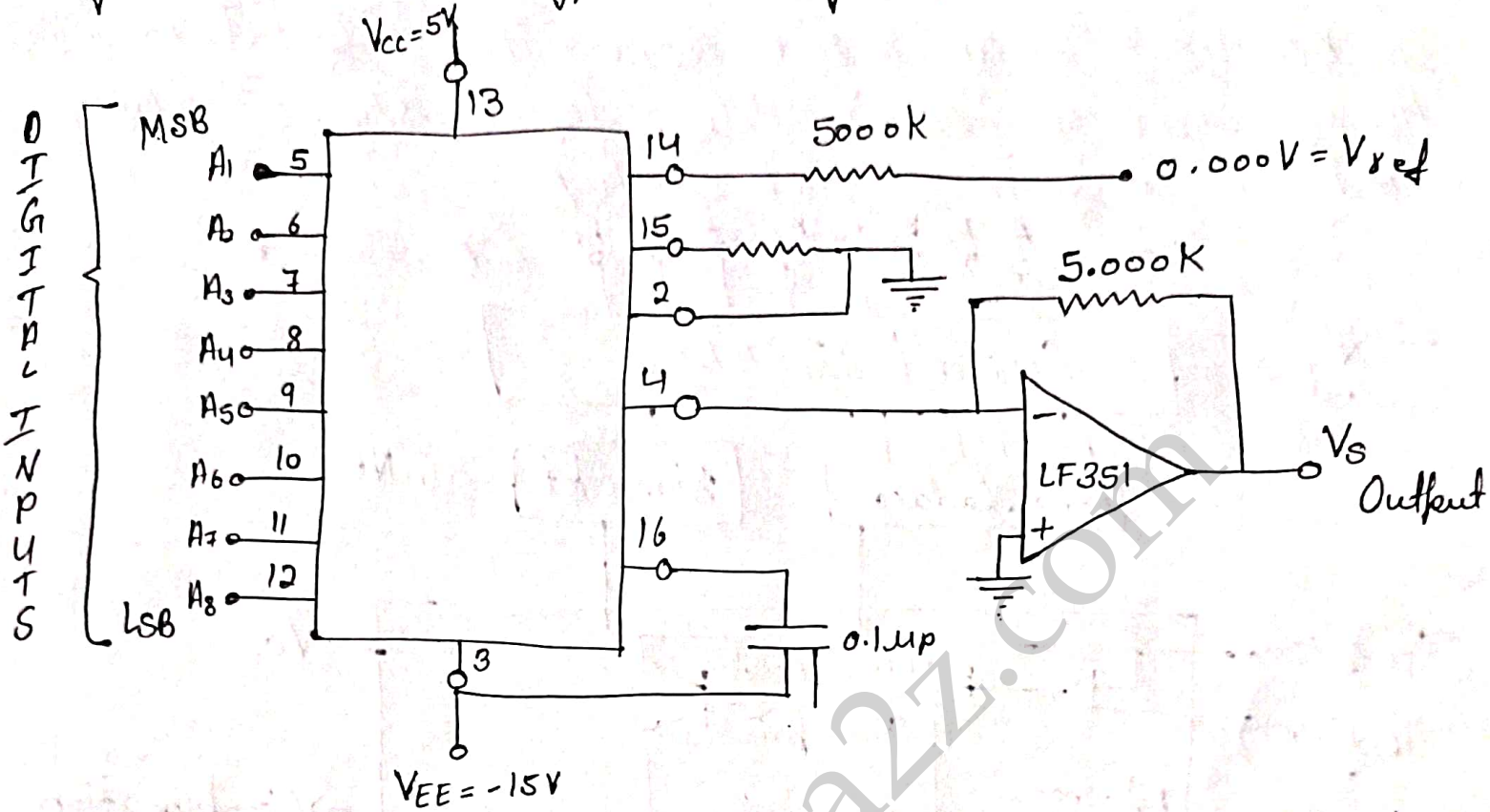


The DAC 0808 Signals



The D/A Converter has an output current, instead of an output voltage. An op-amp converts the current to a voltage. The output current from pin 4 ranges between 0 to Imax 255/256 when all the Inputs are also 1. The O/P of D/A Convertor takes place some time to setter.

Figure shows the typical Interface —



LF351 is an operational Amplifier used as current to proportional voltage convertor. The 8 digital Inputs at A_8-A_1 is conversed into proportional current at pin 4 of DAC. The reference voltage (10V) are supplied at pin 14 and 15 C grounded through resistance.

→ Important specifications ±0.19% Error settling time: 150ns slew rate → 8mA/μs Power supply voltage range ±4.5V to ±18V Power Consumption: 33mW @ ±5V.

→ The Internal A/D Convertors of 80196 family of processor the external microprocessor compatible A/D Converter. A typical 8-bit DA converter Both the ADCs use succesive approximation technique. ADCs are complex and therefore generation difficult VLSI ckts unsuitable for coexistence on the same chip. Sigma Delta need very high sampling rate.

That is all about interfacing of Analog and Digital System.

UNIT-III

Complex programmable Logic Devices (CPLDs) :→

Complex programmable logic devices are basically LSI devices which are suitable in cases where the logic design has large no. of inputs and outputs. Actually the simple programmable logic devices such as PALs, EEPLDs and GALs etc have limited no. of input and output that can support upto about 32 total no. of input and outputs only.

When the no. of inputs and outputs is still higher than the capacity of existing PLDs, it is necessary to increase the density. If the PLDs are made large in terms of inputs, output and product term they becomes slower due to capacitive effect, leakage current, decrease in speed, PC board area increases etc. At the same time, this solution does not make any cost effective use of chip area. Hence instead of increasing the inputs, outputs and AND terms, it is better to have multiple PLDs structure having programmable connectivity.

Complex programmable logic devices (CPLDs) are originated from this idea. CPLD is a collection of individuals PLDs on a single chip with a programmable interconnection structure that allows the PLDs to get connected as the user wants as shown in fig-1.

Generally, 2-input NAND Gate are used for any digital IC chip. A typical PAL has 8 macrocells, if each macrocell represents about 20 equivalent gates, then the PAL can accomodate a circuit that needs up to about 160 gates. For circuit requiring a very large no. of gates, CPLDs having large no. of macrocells can implement circuit of about 1,000 equivalent gates.

Block Diagram:-

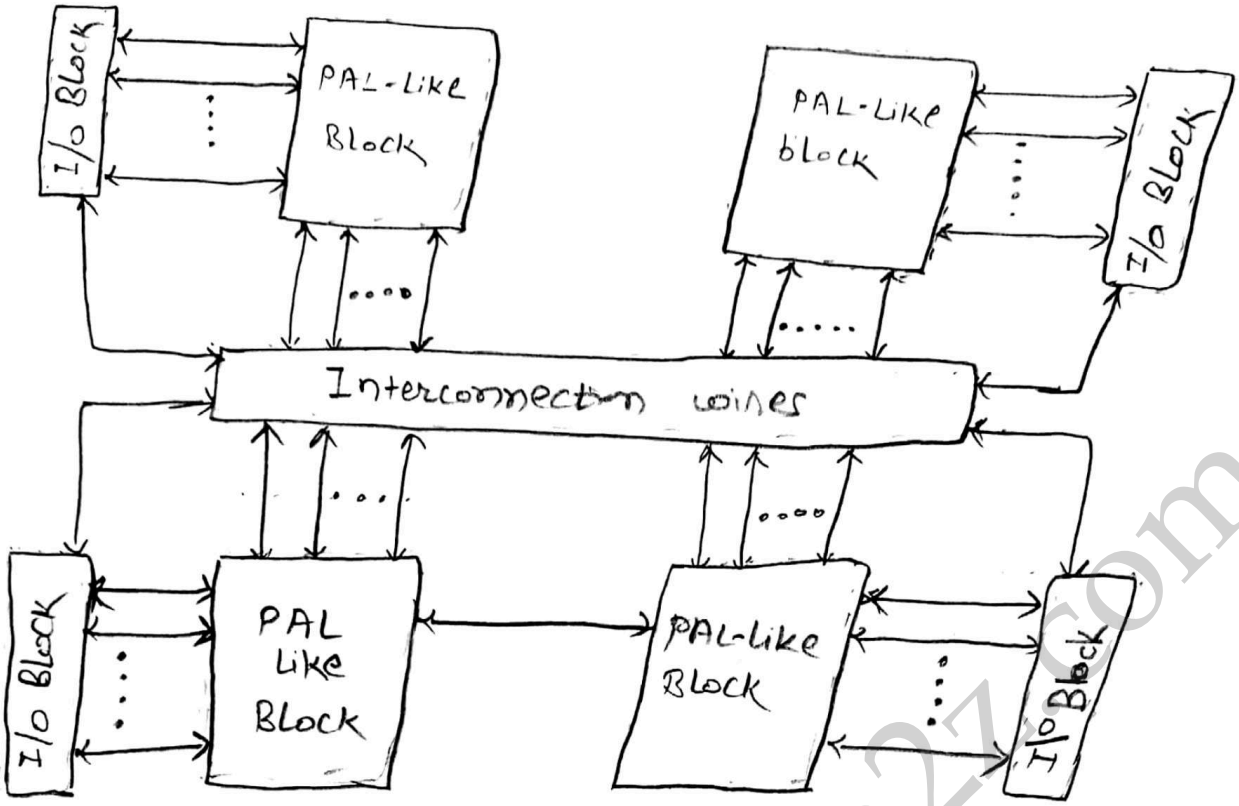


Fig-1. Block diagram of a CPLD

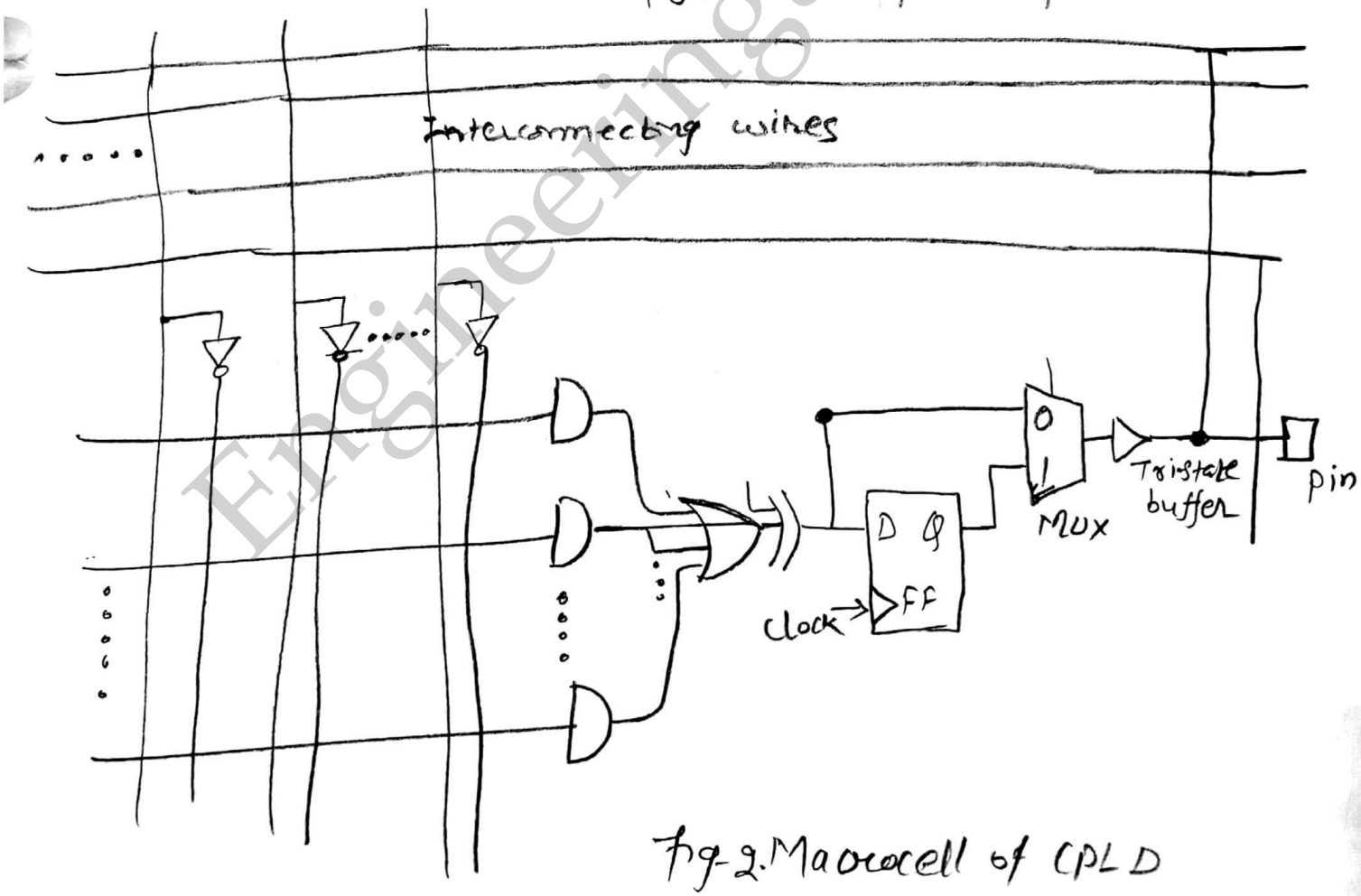


Fig-2. Macrocell of CPLD

fig-1 shows the block diagram of a complex programmable device (CPLD). It consists of number of PAL-Like blocks, I/o blocks, and a set of interconnection wires.

* the PAL Like blocks are connected to a set of interconnections wires and each block is also connected to one input output (I/o) blocks to which a number of chip's input and output pins are ~~connected~~ attached.

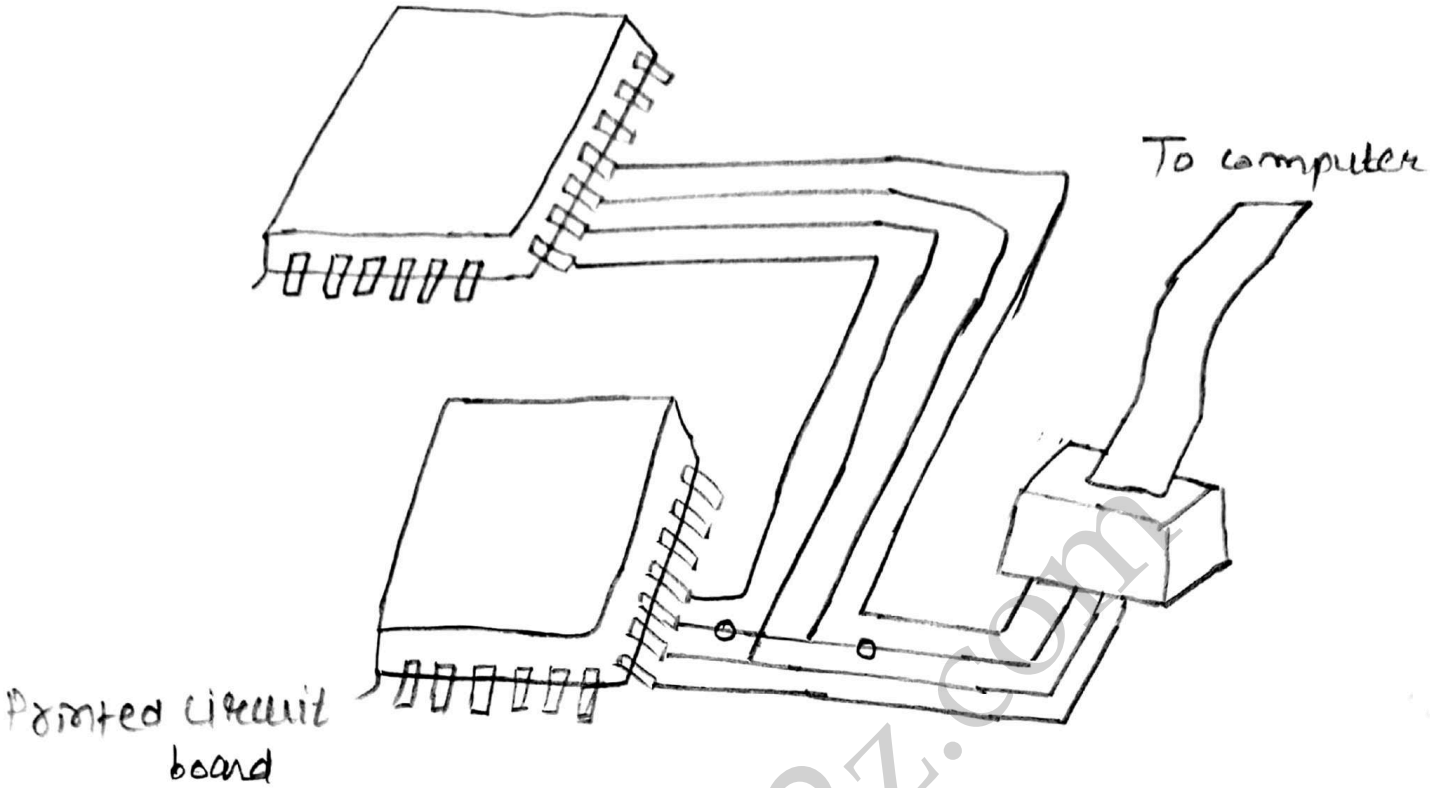
- A PAL- block consist of about 16 macro cells. Each macro cell consist of an AND-OR configuration, an EX-OR gate a flip-flop, a multiplexer and a tri-state buffer as shown in fig-2.
- Each AND-OR configuration consist of 5-20 AND Gates and an OR gate with 5-20 inputs.
- An EX-OR gate is used to obtain the o/p of OR Gate in inverted or non inverted form depending upon its other i/p beings 1 or 0 resp.
- A D-FF stores the output of the EX-OR gate
- A multiplexer selects either the output of the D-FF or the o/p of the EX-OR gate depending upon its select input (1 or 0)
- The tri-state buffer acts as a switch which enables the chip's pin to be used either as an output (tri-state enabled) or as an input (tri-state-disabled). In case the chip's pin is used as an ~~output~~ input pin, an external source can drive a signal on to the pin which can be connected to the other macrocells using the interconnection wire. when it is used as an input pin the macrocell becomes redundant and it is wasted.

PROGRAMMING:→

Programmable Logic devices SPLDs and CPLDs are implemented using electrically erasable programmable read only memory (EEPROM) technology. These are programmed in the same way as EEPROMs. The SPLD chips have small no. of pins and can therefore be taken out of the circuit board without any disturbance. In case of CPLDs, instead of relying on a programmer, a chip is attached to the circuit board itself and this method of programming is known as in system programming (ISP). There are mainly following reason to employ the ISP:-

- CPLDs have large no. of pins (may exceed 200) on the chip package and these pins can be easily bent.
- A socket is required to hold the chip in a programming unit.

For programming SPLDs and CPLDs a large no. of switches are required therefor it is difficult to operate manually due to large no. of switches. So a computer Aided design (CAD) system is employed. By using this CAD tool, a programming file or fuse map is generated that specifies the state of each switch. A computer system that run the CAD tool is connected by a cable to the programming unit. In case of ISP technique a small connector is included on the PCB that houses the CPLD and computer system is connected by a cable to this connected as shown in fig. The programming envolves transforming the programming file generated by the CAD system from the computer into the CPLD through this cable. The circuitry on the CPLD that allow in system programming is usually called as JTAG port. JTAG stands for joint test action group. It uses four wires to transfer information b/w the computer and the device being programmed.



JTAG ISP programming.

Ques:1. Explain Embedded System.

Ans:- Embedded system means something that is attached to another thing. An Embedded system can be thought of as a computer hardware system having software embedded in it. An embedded system can be an independent system or it can be part of a large system. It is a micro controller or microprocessor based system which is designed to perform a specific task.

Characteristics of Embedded System

① Single functioned → An embedded system usually performs a specialised operation and does the same repeatedly.

② Tightly Constrained → All computing systems have Constrained on design metrics, but those on an embedded system can be specially tight.

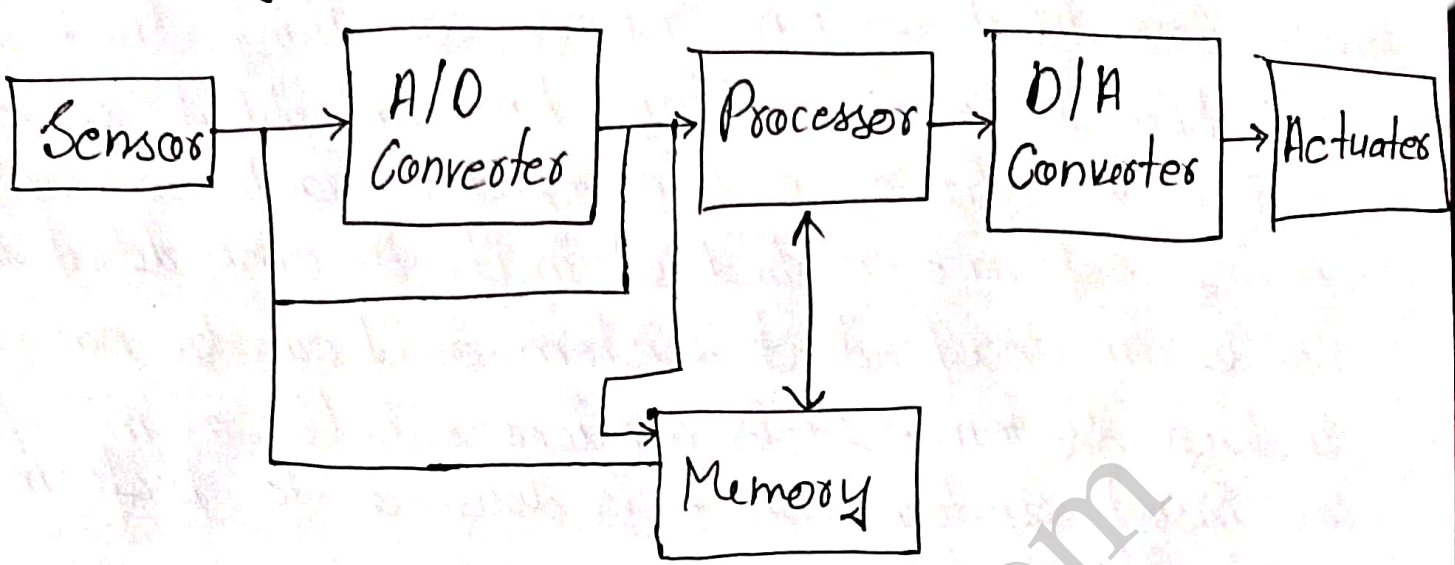
③ Reactive and Real time → Many embedded system must continually react to changes in the system's environment and must compute certain results in real time without any delay.

④ Memory → It will have a memory, as its software usually embeds in ROM. It does not need any secondary memories in the computer.

⑤ Connected → It must have connected peripherals to connect Input and Output devices.

⇒ Basic Structure of an Embedded System is given below —

⇒ Block Diagram of Embedded System



① Sensor → It measures the physical quantity and converts it to an electrical signal which can be read by an observer or by an electronic instrument like A2D Converter. A sensor stores the measured quantity to memory.

② A-D Convertors → An analog to digital converter converses the analog signal by the sensor into digital signals.

③ Processor → Processor process the data to measure the output and store it to the memory.

④ D-A Convertor → A digital to analog converter converts the digital data to measure the output and store it to memory by the processor to analog data.

⑤ Actuator → The actuator compares the output given by D-A Converter to actual (expected) output stored in it and stores the approved output.

That is Embedded System.

From the conditions (iii) and (iv), we observe that the OR gate is avoided and therefore, it becomes a high speed path. In this way, p-term passes through the EX-OR gate rather than sum term which saves typically 0.3 ns delay time of the OR gate. This path is especially useful for microprocessor address decoding for fast operation. This approach can also be used to build faster shift registers, counters, and some simple state machines.

Design Security

In CoolRunner-II CPLD designs can be secured during programming using four independent levels of security provided on-chip. This eliminates any electrical or visual detection of configuration patterns, which prevents either any accidental overwriting or pattern theft via readback. The security bits programmed can be reset only by erasing the entire chip.

In-system programming

All CoolRunner-II CPLD parts are 1.8 V in-system programmable. They derive their programming voltage and currents from the 1.8 V V_{CC} on the part.

12.6 FIELD-PROGRAMMABLE GATE ARRAY (FPGA)

The programmable logic devices(SPLDs and CPLDs) are based on similar basic architecture—the programmable array logic (PAL) or the programmable logic array (PLA). Over the years, programmable arrays have increased in size and complexity, and highly configurable output macrocells have been added to enhance their flexibility and expandability. To increase the effective size and to add more functionality in a single programmable device, alternative architectures have been developed which are known as *field-programmable gate arrays* (FPGAs). The logic densities of FPGAs are much higher than those of CPLDs. They range in size from a few thousands to hundreds of thousands equivalent gates. From modern standards digital circuits with hundreds of thousands of gates is not too large. FPGA devices support implementation of relatively large complex logic circuits.

The FPGAs do not contain AND, OR planes, instead they provide logic blocks for implementation of the required digital functions.

An FPGA is composed of a number of relatively independent configurable logic blocks (CLBs), configurable I/O blocks, and programmable interconnection paths (known as routing channels). All the resources of the device are uncommitted and that these must be selected, configured and interconnected by a user to form a logic circuit for his application. The basic architecture of an FPGA is shown in Fig. 12.45.

There are a number of manufacturers of FPGA devices. The various families of FPGAs manufactured by different manufacturers differ primarily in the number of logic modules (from few hundreds to hundreds of thousands), supply voltage range, power consumption, speed, architecture, process technology, number of pins, and type of packages, etc. Some of the major manufacturers of FPGAs manufacturing a wide range of products to suit various types of requirements are given in Table 12.8.

The basic FPGA architecture consists of an array of configurable logic blocks (CLBs). The logic blocks are surrounded by configurable input/output blocks. There are rows and columns of programmable interconnection paths. The I/O blocks can be individually configured as input, output, or bidirectional.

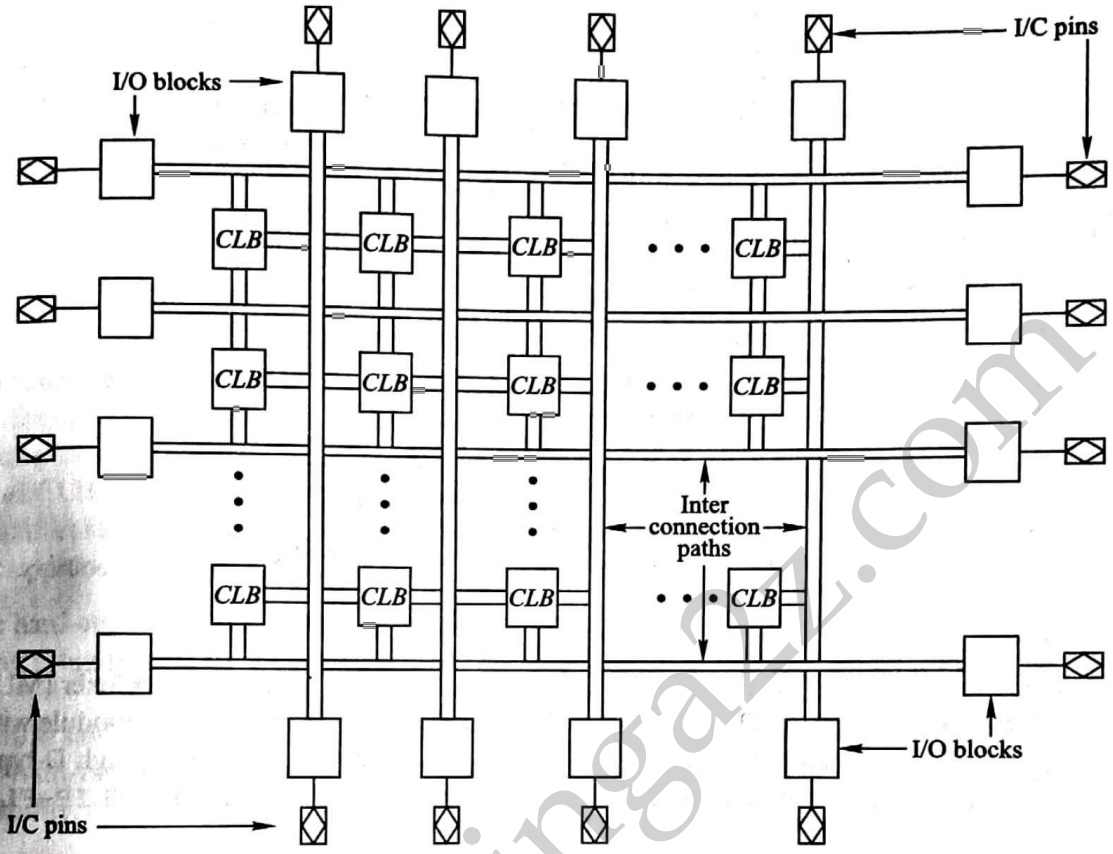


Fig. 12.45 ***Basic Architecture of FPGA***

Table 12.8 ***FPGA Manufacturers***

Manufacturer	FPGA products	www locator
Actel	Act 1, 2, 3, IGLOO	http://www.actel.com
Altera	Flex 6000, 8000, 10K, APEX 20K, Stratix II, III, IV	http://www.altera.com
Atmel	AT6000, AT40K	http://www.atmel.com
Lucent	Lattice SC, ECP2, XP2	http://www.lucent.com
Quick Logic	PASIC 1, 2, 3, Eclipse	http://www.quicklogic.com
Vantis	VF1	http://www.vantis.com
Xilinx	XC4000, XC5200, Virtex, Spartan	http://www.xilinx.com

Configurable Logic Blocks

There are a number of configurable logic blocks (CLBs) in an FPGA organized as an array of rows and columns. The logic blocks are connected to the I/O blocks through common row/column programmable interconnects. The common row/column interconnects are known as global interconnects. A logic block consists of a number of logic modules (LMs). The logic modules are the basic logic elements in an FPGA. The logic modules within a CLB are connected through local programmable interconnects. Figure 12.46 shows a CLB.

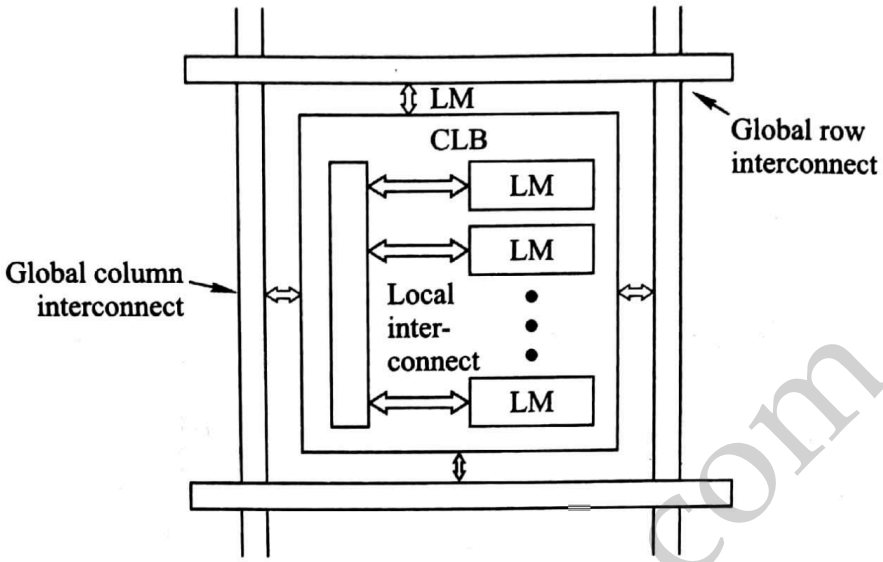


Fig. 12.46 ***Basic Configurable Logic Block***

Logic Module

A logic module consists of an LUT (look-up table), a D-type `FLIP-FLOP` and a mutliplexer (MUX). Most of the FPGAs are based on 4-input LUT. Figure 12.47 shows a block diagram of a logic module with 4-input LUT. Output of the LUT becomes the output of the logic module either directly or through D-type `FLIP-FLOP`. Thus, the output can be configured for combinational or registered (i.e., through `FLIP-FLOP`).

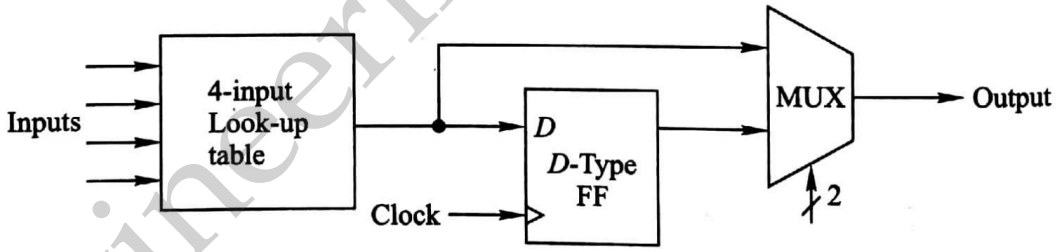


Fig. 12.47 ***Block Diagram of a Logic Module***

Look-Up Table (LUT)

An LUT (look-up table) consists of a programmable memory and it can be used to generate logic function in SOP form. For example, from Table 11.4, we can see that this table is similar to a 4-input and one output logic circuit's truth table. Therefore, a memory can generate canonical product terms. Figure 12.48 shows a block diagram of an LUT. It consists of a memory and a multiplexer (MUX). Let us assume the memory contents as given in the figure. Since, it is an 8-bit memory, therefore an 8 : 1 multiplexer is required. If the 3-bit logical input is $A_2 A_1 A_0$, then

$$Y = \overline{A}_2 \overline{A}_1 A_0 + \overline{A}_2 A_1 \overline{A}_0 + A_2 \overline{A}_1 \overline{A}_0 + A_2 A_1 A_0$$

The look-up table in most of the commercially available FPGAs is 4-input circuit. Larger LUTs would allow for more complex logic to be performed per logic block, thus reducing the wiring delay between blocks as fewer blocks would be needed. This will require larger multiplexer and an increased chance of waste if all of the functionality of the larger LUTs were not to be used. On the other hand, smaller look-up tables

may require a design to consume a large number of logic blocks, thus increasing wiring delay between blocks while reducing per logic block delay. Therefore, 4-input LUT structure makes the best trade-off between area and delay for a wide range of circuits. However, some of the latest FPGAs have been designed with 6-input LUT structure. The Xilinx Virtex-5 family of FPGAs have used 6-input LUT technology.

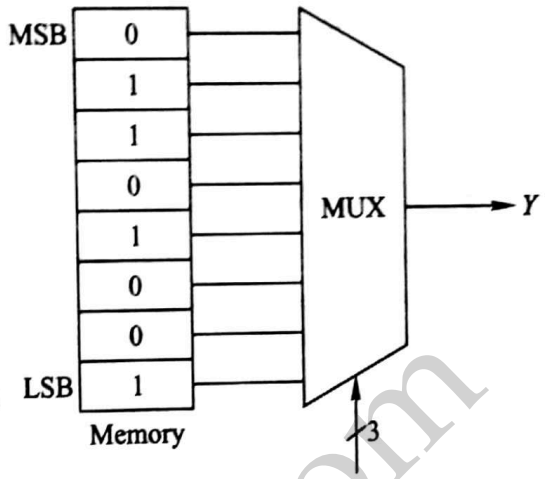


Fig. 12.48 ***Block Diagram of an LUT***

FPGA Cores

A commercially available FPGA may have all the CLBs available for a user to program them according to his requirements. However, some FPGAs are available in which a portion of CLBs is used by the manufacturer to provide a specific built-in function that can not be changed by a user. This is referred to as *hard-core* logic. The hard-core logic approach has the following advantages:

- The hard-core logic may normally be implemented using lesser number of CLBs than the same logic being programmed by a user. This saves the available chip resources, i.e., programmable area to the user.
- There is saving in the development time of user in developing a digital system.
- The built-in hard-core function can be thoroughly tested by the manufacturer, thereby increasing its reliability.

Some of the commonly used functions, such as microprocessors, standard I/O interfaces, and digital signal processors (DSPs) are available in hard-core FPGAs. Since the hard-core designs are developed by the manufacturers', therefore, these are the manufacturers' *intellectual property* (IP).

In case, the manufacturer's programmed function has some programmable features also, it is known as a *soft-core* function. Some intellectual properties may be combination of both hard-core and soft-core functions. The FPGAs containing either or both hard-core and soft-core embedded processors and other functions are known as the *platform FPGA* because they can be used to implement an entire system without the need for any external devices.

FPGA Process Technology

There are different process technologies used by various FPGA manufacturers. These are:

- SRAM technology—It is based on static memory technology. The CMOS devices are fabricated by this technology and these are in-system programmable (ISP) and are reprogrammable.
- Antifuse technology—The antifuse technology developed by Actel Corporation of America is used for processing CMOS FPGAs which are one-time programmable (OTP).
- EPROM technology—It may be one-time programmable (OTP) or ultraviolet erasable type of CMOS device.
- EEPROM technology—It is electrically erasable which may be in-system programmable type or off-system programmable type CMOS technology.
- Flash technology—It is flash-erase CMOS technology which may be in-system programmable type.
- Fuse technology—It is a bipolar one-time programmable FPGA.

Configuration Memory

Most of the modern FPGAs use SRAM. The SRAM bits are used to hold the user defined configuration values.

12.6.1 Xilinx Virtex FPGAs

The field-programmable gate array was invented by Xilinx in 1984 and they are the leading manufacturers of FPGA devices. There are two major lines of Xilinx FPGAs, Spartan and Virtex. The Extended Spartan-3A and the Virtex-5 families are the latest available FPGAs from Xilinx.

Configurable Logic Blocks

There are a number of CLBs organised as an array. Each CLB contains multiple basic logic units called logic cells (LCs). The logic cells are same as the logic modules (LMs) discussed earlier. The logic cells are LUT based. Each logic cell consists of an LUT, a FLIP-FLOP, and a multiplexer. In the Virtex-4 family, XC4VLX200 FPGA has CLB array of 192X116 containing 200,448 logic cells. The number of LUTs and the internal registers, i.e., FLIP-FLOPs is 178,176 each. In the Virtex series of FPGAs there is a concept of *slice*. A CLB of Virtex-4 family of FPGAs consists of 89,088 slices. There are two LUTs and two FFs in each slice. A CLB is made up of four slices.

The Virtex-5 family of FPGAs has a maximum of 240 × 108 array of CLBs, 51,840 slices, each slice contain four LUTs and four FFs. A CLB of Virtex-5 family FPGAs is made up of two slices. The function generators are configurable as 6-input LUTs or dual-output 5-input LUTs.

In addition to function generators and storage elements (FFs), each slice in both of the above FPGA families, contain arithmetic logic gates, large multiplexers, and fast carry look-ahead chain.

Configuration

The devices of Virtex family are configured by loading the bitstream into internal configuration memory in various modes.

IP Cores

In these devices, there are IP cores for commonly used complex functions including DSP, bus interfaces, processors, and processor peripherals.

Process Technology

The Virtex-4 family of FPGAs are produced using 90-nm copper CMOS process technology, whereas the Virtex-5 family of FPGAs are produced using 65-nm copper CMOS process technology.

12.6.2 Altera Stratix FPGAs

Altera Corporation of America is producing wide range of FPGAs to meet different requirements. The Stratix series of FPGAs started in 2002 with the introduction of Stratix family. Subsequently, Stratix GX(2003), Stratix II (2004), Stratix II GX (2005), Stratix III (2006) and Stratix IV (2008) were introduced in the years mentioned in parentheses along the family. The basics of Stratix II family of FPGAs have been chosen for discussion here.

Stratix FPGAs contain a two dimensional row- and column-based architecture to implement custom logic. A series of column and row interconnects of varying length and speed provides signal interconnects between logic array blocks (LABs) and various other blocks, such as memory block structures and digital signal processing (DSP).

Logic Array Block (LAB)

The configurable logic block (CLB) is called as logic array block in Altera FPGAs. Each LAB consists of eight adaptive logic modules (ALMs). An ALM is the basic building block of logic for efficient implementation of user logic functions. LABs are grouped into rows and columns across the device. In addition to eight ALMs, each LAB contains carry chains, shared arithmetic chains, LAB control signals, local interconnect, and register chain connection lines. The LAB structure is shown in Fig. 12.49. The local interconnect transfers signals between ALMS in the same LAB. The local interconnect is driven by column and row interconnects, ALM outputs in the same LAB, and neighbouring LABs from the left and right through the direct link connection. The direct link connection feature helps in minimising the use of row and column interconnects which increases the performance and flexibility. Multiple LABs are linked together via the global row and column interconnects.

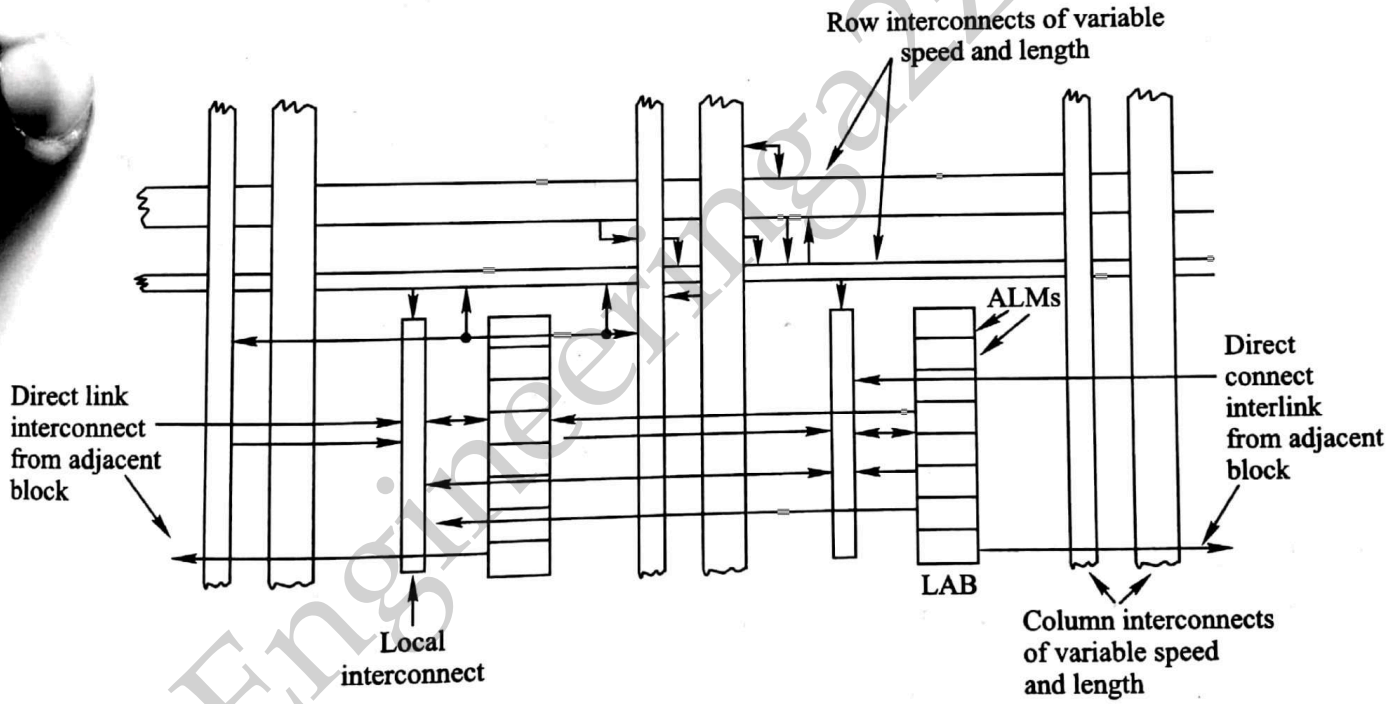


Fig. 12.49 ***Stratix II LAB Structure***

Adaptive Logic Modules (ALMs)

The basic building block of logic in these FPGAs is the adaptive logic module (ALM). Each ALM contains a variety of look-up table (LUT)-based resources that can be divided between two adaptive LUTs (ALUTs). There are eight inputs in an ALM and one ALM can be used to implement various combinations of two functions including any function of upto six inputs and certain seven input functions.

In addition to the two ALUTs, each ALM contains two programmable registers (D-type FFs), two dedicated full adders, a carry chain, a shared arithmetic chain, and a register chain. Using these resources, the ALM can

implement various arithmetic functions and shift registers. Each ALM drives all types of interconnects: local, global row and column, carry chain, shared arithmetic chain, register chain, and direct connect interlinks. Figure 12.50 shows block diagram of the ALM. The eight data inputs are: data a, data b, data c, data d, data e0, data f0, data e1, and data f1. The first four data inputs, data a, data b, data c, and data d can be shared by the two LUTs, whereas data e0 and data f0 are dedicated to adder 0 and reg 0, and data e1 and data f1 are dedicated to adder 1 and reg 1.

Each ALM has two sets of outputs (combinational and registered) that drives the global and local routing resources. The combinational output can be either LUTs output or adder output. For combinational output, the register is by passed. The registered output is obtained via the register. The two sets of outputs are independent.

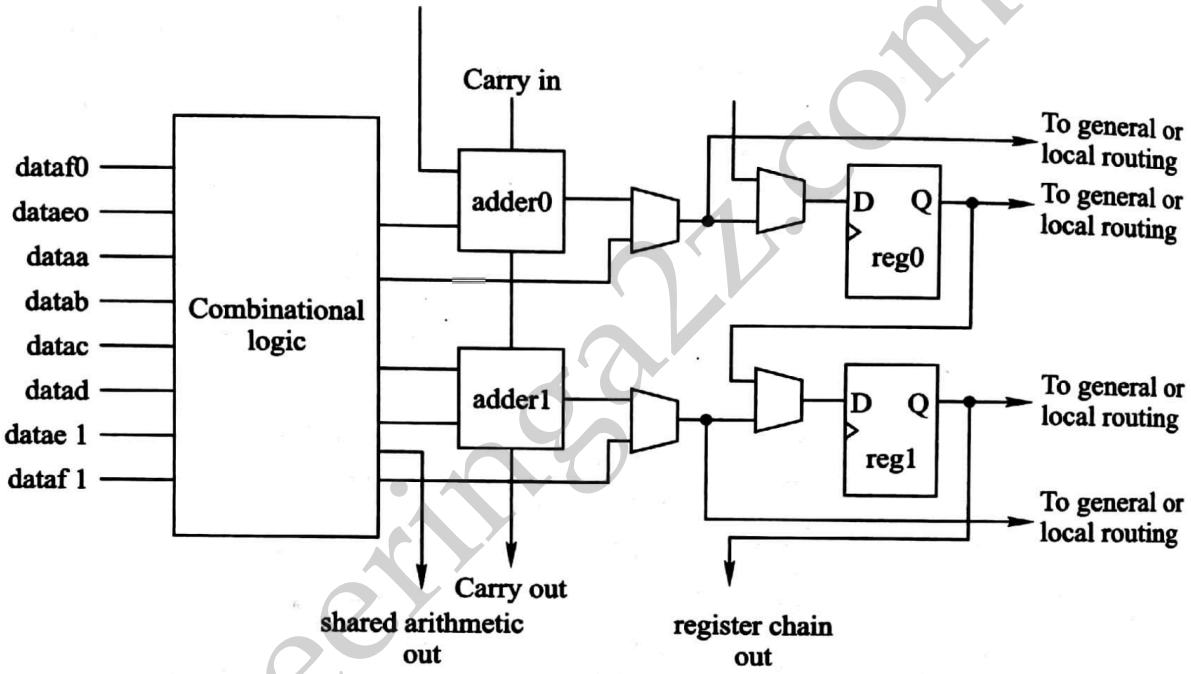


Fig. 12.50 ***Block Diagram of ALM***

Operating Modes of ALM

The ALM of Stratix II can operate in one of the following modes:

- Normal mode
- Extended LUT mode
- Arithmetic mode
- Shared arithmetic mode

Normal Mode In the normal mode combinational logic functions are generated. Two combinational functions in various combinations of 8 inputs can be implemented or a single function of upto six inputs can be implemented in this mode. Figure 12.51 shows the various combinations of logic functions generated using the two LUTs. In Figs. 12.51(*a*) and (*b*), the inputs are independent for the two LUTs, whereas in Figs. 12.51 (*c*), (*d*), and (*f*) 1, 2, and 4 inputs respectively are common between the two functions.

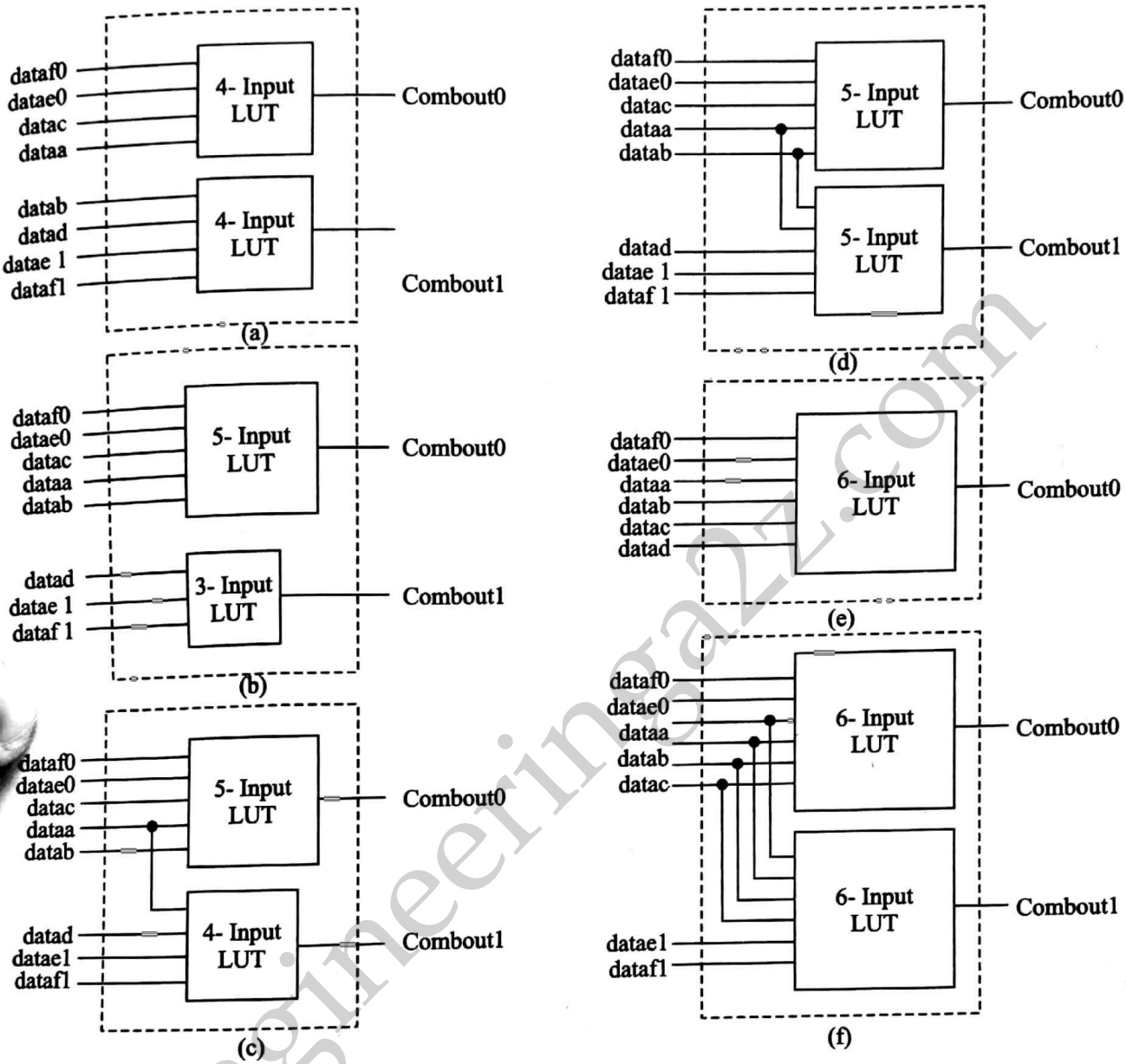


Fig. 12.51 ***Various Combinations of Logic Functions Generated using an ALM (a) Two 4-Input Functions (b) 5 and 3 Input Functions (c) 5 and 4 Input Functions (d) Two 5-Input Functions (e) 6-Input Function (f) 6 and 2 Input Functions***

Extended LUT Mode Some specific seven-input functions can be implemented by making two five input functions, sharing four inputs, and applying these two five-input functions to a 2 : 1 multiplexer. Figure 12.52 shows its implementation.

Arithmetic Mode The arithmetic mode is used for implementing adders, counters, accumulators, comparators, and parity functions. In arithmetic mode, an ALM uses two sets of two four-input LUTs alongwith two dedicated full adders.

Shared Arithmetic Mode In shared arithmetic mode, an ALM can implement a three-input add. In this mode, the ALM is configured with four 4-input LUTs.

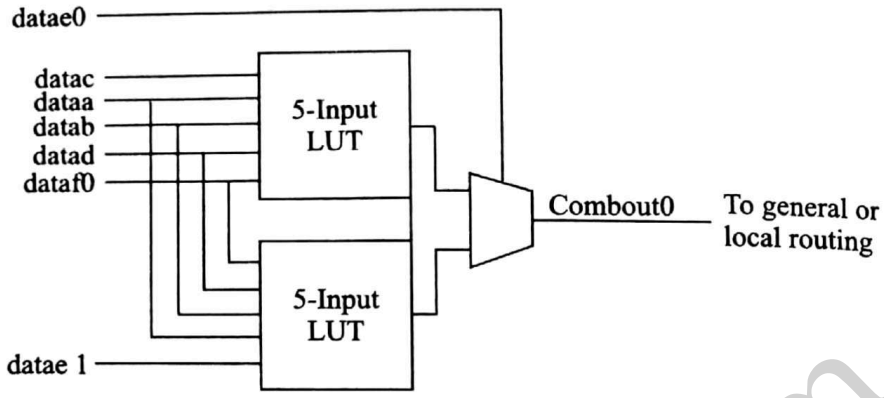


Fig. 12.52 ***Extended LUT Mode of an ALM***

SUMMARY

The basic concepts of programmable logic devices and programmable gate arrays have been introduced. With the development of these devices, it has become possible to design complex digital systems. However, high-level design techniques and computer-aided tools are required to produce efficient PLD and FPGA implementations. Testing of PLD and FPGA implementations also require computer-assisted test tools. The design and test tools for these programmable devices are beyond the scope of this book.

The emergence of these devices has revolutionized the design of digital systems similar to the emergence of microprocessor. The programmable logic concept has emerged as a technology that has given the power to design one's own custom ICs which cannot be copied by others.

The design of embedded systems in small size has become possible by using FPGAs with intellectual properties, such as microprocessors, and DSP, etc. The embedded systems without using external devices and battery operated digital systems have proved very useful because of the availability of low-power FPGAs with intellectual properties.

GLOSSARY

Antifuse A programmable element invented by Actel Corporation named as PLICE (programmable low-impedance circuit element).

ASIC (Application specific integrated circuit) An IC configured by the manufacturer as per the specifications supplied by the user for a specific application.

BGA (Ball grid array) An IC package used for ICs requiring large number of pins. The pins are of small round ball shapes.

CLB (Configurable logic block) A logic block in an FPGA consisting of logic modules and local programmable interconnect that is used to connect logic modules within the CLB to generate required logic functions.

Configuration memory A memory in an FPGA meant to store bit pattern for configuring the FPGA.

CPLD (Complex programmable logic device) A programmable logic device containing a large number of equivalent gates.

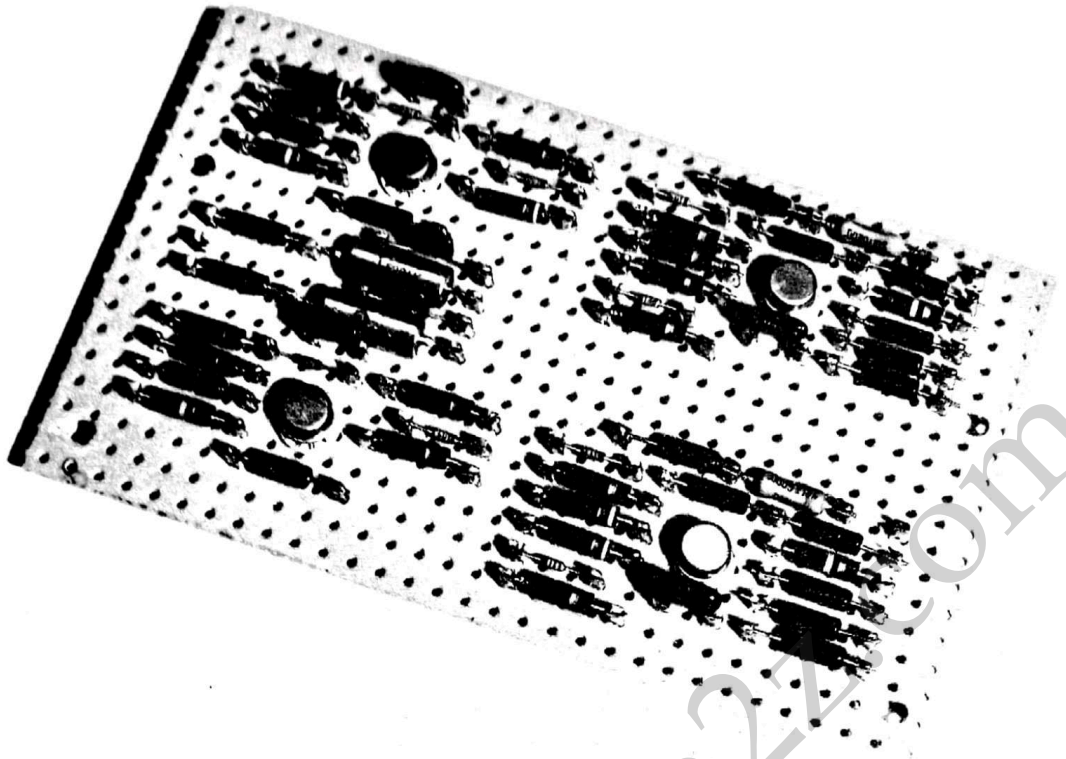


Figure 12.2. "Perfboard" can be handy for prototype circuits constructed with discrete components, although it is not particularly good for ICs. The terminals are press-fit into the holes (or flared with a special tool) and wired underneath.

of Wire-Wrap board is available with the pins on the *component* side of the board (the usual procedure is to have the pins stick out the other side). Although this type of board is less dense (fewer ICs per square inch), it is easier to use with discrete components, since you can see them while wrapping, and it allows closer spacing between adjacent circuit boards, since both components and Wire-Wrap pins take space on the same side. This kind of board without sockets is actually quite convenient for construction of linear or digital circuits. Figure 12.4 shows an example. In Figure 12.5 we have compared a prototype circuit built on a Wire-Wrap panel with the final printed-circuit version used in production. Printed circuits are much easier to produce in quantity; they are superior electrically and less cluttered than Wire-Wrap panels. We will talk about PC cards next.

PRINTED CIRCUITS

12.04 PC board fabrication

The best method of constructing any electronic circuit in quantity is to use a printed circuit, a stable insulating sheet of material with thin plated copper lines bonded to the sheet forming the circuit paths. Although early printed circuits were associated with poor reliability (Remember the advertisements stressing the superior quality that only handcrafted television sets without printed circuits could provide?), the process of manufacturing board material and producing finished boards has been perfected to the point that printed-circuit boards now have very few problems. In fact, PC boards offer the most reliable fabrication technique. They are routinely used in computers, spacecraft, and military electronics where high reliability is essential.

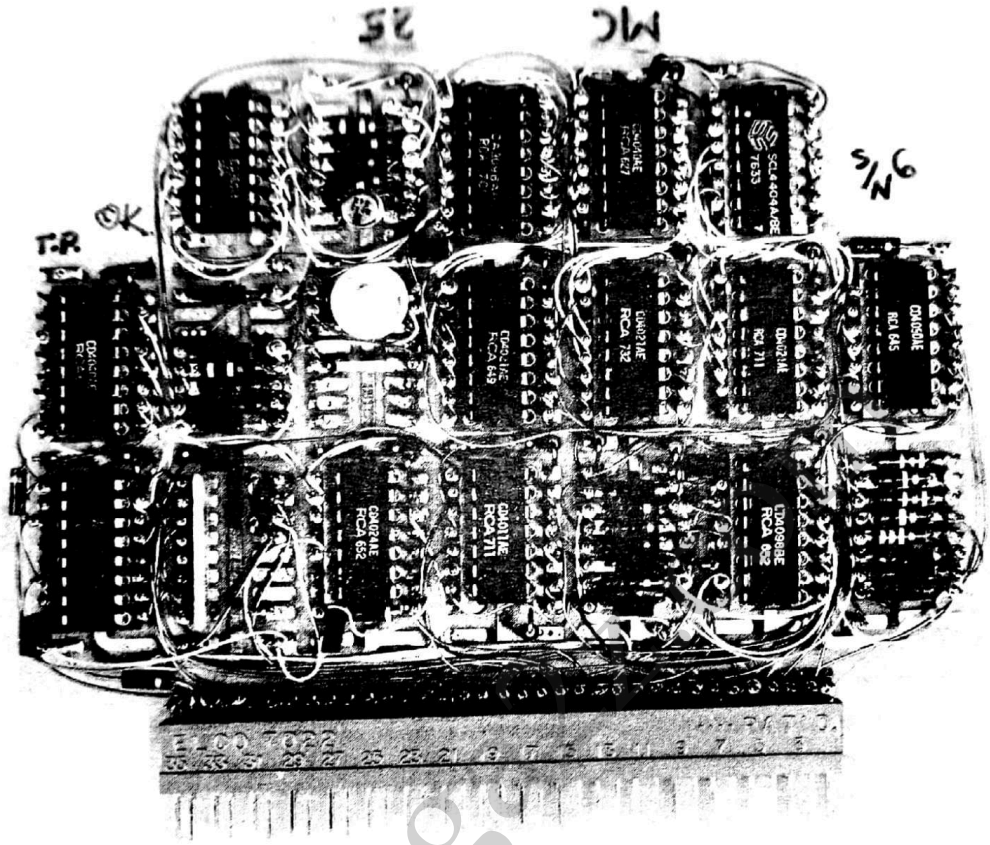


Figure 12.4. Wire-Wrap boards provide a neat and fast construction method particularly good for circuits made with digital ICs. This board uses a printed-circuit pattern to bring out the Wire-Wrap pins on the component side, an alternative to the usual underside pin configuration. Its peculiar shape is dictated by the interior of the oceanographic pressure cell into which it fits.

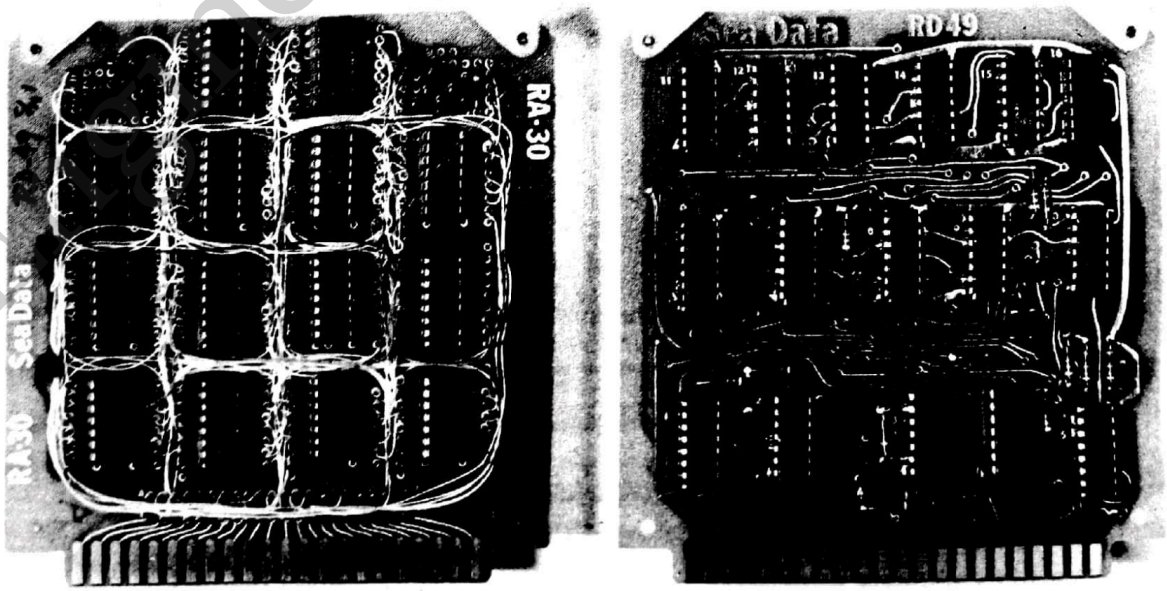


Figure 12.5. A Wire-Wrap prototype board and its printed-circuit successor. PC boards are less cluttered and far easier to fabricate in quantity. They eliminate wiring errors, too.

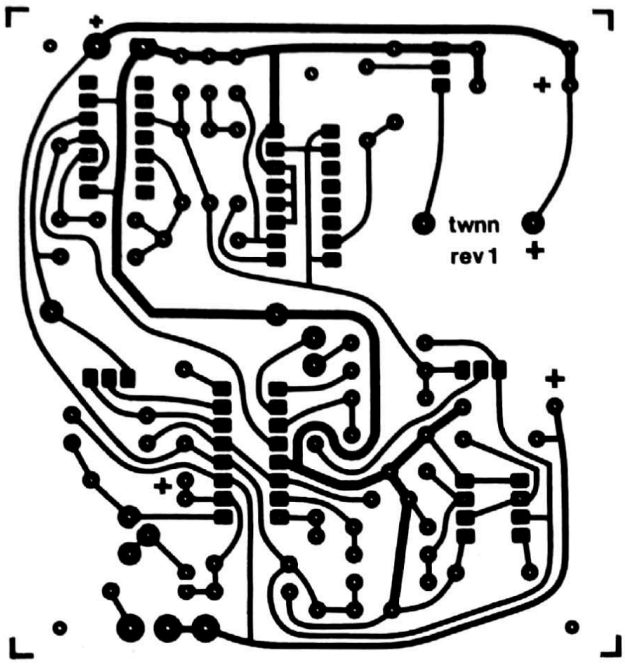


Figure 12.6. Foil pattern for a simple single-sided PC board. This "layer positive" was photographically reduced from a double-sized hand-taped Mylar pattern. The circuit board is 3.25×3.5 inches and has 4 ICs, 24 resistors, 11 capacitors, 5 diodes, 1 trimmer, and 1 piezo buzzer.

The "Mylar" or photoplot

Printed-circuit-board production begins with a set of actual-size transparencies on which an opaque pattern delineates the desired circuit traces and "pads" (Fig. 12.6). There are lots of rules and tricks in this business, but the basic idea is to figure out how to make all the interconnections the circuit demands by running lines around a board. As we will describe shortly (Section 12.08), these transparencies are usually produced directly on film by computer-driven photoplotters or laser plotters, working from a description of the circuit that you produce on a CAD (computer-aided design) system. However, for simple circuits, you may choose to do the layout manually, sticking opaque tape and patterns onto clear Mylar film. In the latter case you usually make the taped Mylar pattern twice actual size, from which you photographically produce an actual-size transparency.

No matter what the parentage of the final 1:1 transparency, the result is a set of conductor patterns on film. For the simplest boards you may be able to make all the needed connections (perhaps aided by a few wire "jumpers") with a *single-sided* board, which has all its traces on the underside (officially called the "solder" side; the top is called the "component" side). Most often, however, you need traces on both sides of the board. Such *double-sided* boards invariably use *plated-through* holes (the holes in the board are lined with foil, connecting corresponding pads on both sides of the board). This really makes a difference when you are attempting to route traces, because you can always switch sides (using a "via" hole) when a trace runs into a dead end, whereas with a single-sided board you often get hopelessly boxed in. As an important side benefit, the use of plated-through holes ensures a superior solder joint to the component leads, because the solder wicks up through the hole.

For complex digital circuits you often see laminated multilayer PC boards, in which interior layers (called the "core") are used to carry ground and power-supply voltages, and sometimes signal lines as well. Four-layer and six-layer boards are pretty routine these days, with occasional use of more layers (up to 40!) in desperate situations.

Manufacturing

The board material (usually 1/16 inch of so-called FR-4 board, a fire-resistant epoxy-bonded fiberglass) comes clad on both sides with copper ("2 ounce" thickness is standard; the copper is 0.0027 inch thick). The first step is to drill the holes, using a template or automated drilling machine keyed to the full-size photopositive from the photoplotter or the Mylar

pattern. The holes are then "plated through" by a tricky multistep copper plating process, creating continuous conducting paths from one side of the board to the other.

The next step is to create a tough "resist" material, adhering to both sides of the board everywhere except where the foil for the circuit is to remain. This is done by (a) coating the board with a light-sensitive film (usually a thin adhesive "dry film"), then (b) exposing the board to light with the full-size photopositive accurately sandwiched on top, and (c) chemically "developing" the film (as in conventional photography) to make the exposed areas permanent. A step analogous to photographic "fixing" then removes the unexposed film, in precisely the pattern that will ultimately become the circuit traces. Then the board, with the pattern of resist now masking the areas where the copper foil is ultimately to be removed, is immersed into a solder-plating bath. The result is to plate solder (a tin/lead alloy) everywhere that the foil pattern is to remain, including the insides of the holes.

Next the resist is removed chemically, exposing the copper that is to be removed, and the board is treated with a copper-etching compound. That leaves the desired pattern of solder-plated copper, complete with plated-through holes. At this point it is important to carry out a step known as "reflow soldering," which consists of heating the board to make the thin solder plating flow. This prevents the formation of tiny slivers of metal (from the undercutting action of the etching bath) that could otherwise cause conductive bridges. Reflow soldering also improves the solderability of the finished board; a reflow-soldered board is a delight to "stuff" with components.

The next step in board manufacture is to electroplate the edge-connector fingers with gold. The final process in board manufacture consists of applying a tough "soldermask" coating over the entire board, covering all of the foil except for the pad areas. This greatly reduces the tendency to form "solder bridges" between closely spaced traces during subsequent soldering operations. It also makes the board moisture- and scratch-resistant. Soldermask materials can be applied by silk-screen methods ("wet mask") or by the same photographic "resist" methods used to create the foil circuit pattern ("dry mask"). You can recognize the soldermask by its dark green color and by the observed fact that it is practically impossible to remove. In industrial board manufacture, the board might then be stuffed by automatic machines, with all joints soldered in a few seconds in a "wave-soldering" machine. The alternative is to stuff and solder by hand.

There is a simpler process of board manufacture that is sometimes used, especially in small production situations or for single-sided boards, where plated-through holes aren't needed. In this method you begin by coating the board with photo-resist, then expose it through a full-size *negative* (rather than positive) of the desired pattern, i.e., a photographic film that is transparent wherever you want foil to *remain*. The resist is developed, and then the unexposed resist is dissolved away. This board then has a layer of tough resist covering the copper that is to remain, so you simply expose it directly to the etching compound (omitting the solder-plating step, above). After the superfluous copper has been etched away, the remaining resist is washed off with solvent, leaving the desired pattern in copper. At this point it is best to treat the board with an "electroless" tin-plating bath in order to cover the copper with a metal less susceptible to corrosion. As before, the edge-connector fingers will then be gold-plated. The final step in this process consists of drilling the holes by hand, using the actual conductive pattern as a guide (each "donut" pad has a small

opening in the center to aid in drilling the finished board).

□ 12.05 PC board design

There are several important decisions you have to make during PC board design, during component "stuffing," and finally when the board is used in an instrument. In this section we will try to touch on the most important of these.

□ *PC board layout*

To make a printed-circuit board, you must ultimately convert your schematic diagram into a corresponding pattern of desired copper-foil traces that will compose the finished board. There are basically two ways: (a) Working from the manually drawn schematics, you can use pencil and paper (and lots of erasers!) to figure out a set of interconnection paths ("routes") that does the job, then manually apply opaque tape and preformed connection patterns accurately onto clear polyester film to make the finished "Mylar" masters, or (b) you can convert your hand-drawn schematic to a connection "netlist," then use a CAD (computer-aided design) program to figure the trace routing, producing a set of precision machine-drawn "photoplots" directly; better still, you can replace the manual schematic drafting with CAD-based "schematic capture," in which you draw the diagrams directly on a graphics workstation, using a graphic tablet or mouse.

CAD-based circuit drawing and layout (option b, above) has many advantages, including automatic netlist extraction, painless documentation, the ability to check for design and layout rule errors, the ability to make changes relatively easily, and the ability to produce complex multilayer boards with precise alignment of pads and traces. It is the method of choice for nearly all complex and high-density PC board production. However, we would like to begin simply, by briefly describing manual methods of PC board layout (option a, above). Once you know how to do a PC board layout by hand, you will understand what you're trying to make with the complex computer-based CAD tools. Furthermore, for simple jobs the manual methods may be all you need, and they are cheaper (and sometimes quicker) than CAD-based methods. They are particularly appropriate for the uncrowded boards you might use in simple unsophisticated instruments, of the sort you might build in small quantities for research laboratory use. They are also well adapted to boards containing parts with unusual shapes and lead spacings. Later, in Section 12.08, we will describe the CAD methods that are mandatory for high-density digital multilayer boards intended for large production.

There are several stages along the way from a schematic diagram to a final printed circuit. Beginning with the diagram, you generally work out trial pencil sketches of component layouts and interconnections, eventually working these together into a final pencil layout drawing. From this you make the "Mylar," consisting of accurately aligned "pads" (terminal areas for component connections) and taped interconnections. Precut patterns are used for IC and transistor pads and for ribbon and edge connectors, since these have standard spacings and dimensions. The pencil sketch and Mylar are usually made double size to allow greater accuracy (and to keep your eyes from popping out!). When the Mylar (two Mylars for double-sided boards) is completed, it is photographically reduced to an actual-size negative, from which a trial board is made as described previously. You generally "stuff" the prototype board with components, turn on the power, and then hunt down the errors; this lets you correct the Mylar artwork to produce final boards. The following subsections provide some further details and hints.

☐ *Initial sketch*

We recommend doing the initial layout with pencil on grid paper (5 lines/inch), with two colors to indicate foil patterns on the top and bottom (assuming it is a double-sided board). We usually use black pencil for runs on the bottom and green or red for the top (component) side. Since you're likely to do plenty of erasing, it is best to use vellum graph paper. The 0.2 inch gridding corresponds to 0.1 inch final size, the universal measure for IC pin spacings, transistor pinouts, edge connectors, etc. Your drawing should be the view from the component side; i.e., the sketch of the component-side (top-side) foil pattern looks like the final pattern, and the sketch of the bottom foil pattern is what you would see looking down through the finished board with x-ray eyes. While working on the layout, indicate component outlines with a pencil of a third color. All this work should be freehand. Don't waste time with an outline template; just use the grid lines as a guide to draw IC and component pinouts.

It is generally best to work up some trial layouts on a piece of scratch paper, particularly for sections of the circuit that may require special layout to minimize long lines or capacitive coupling. It may take some experimentation to arrive at good component arrangements. A trial layout might consist of a block of the circuit with two or three op-amps, or perhaps the input or output section of the circuit. These blocks should then be worked together onto the large gridded vellum, with adjustments being made as you go. Don't hesitate to do lots of erasing!

☐ *Layout dimensions and hints*

Try to have all ICs pointing in the same direction, preferably in straight rows. Likewise, resistors should be in even rows, not staggered. We use 0.030 or 0.040 black tape for signal runs, with wider tape for power supplies (0.05 or 0.062 inch) and very wide ground runs (0.1 to 0.2 inch, or even wider; it's common to broaden the ground runs with lots of tape). Be sure to include plenty of bypass capacitors, one 0.1μF for every two to four ICs. As you scratch your head, trying to juggle the tangled maze of interconnections, don't forget that components act as "jumpers" – they can hop over runs on the board.

Dimensions and spacings: On the actual-size PC board, we recommend holes spaced 0.4 inch for resistors ($\frac{1}{4}$W size), with spacing of 0.1 or 0.15 inch between resistors (with 0.15 inch spacing you can get a tape run between adjacent pads). We favor CK05 and CK06 types of ceramic capacitors, with their controlled 0.2 inch lead spacing, or the "DIP" 0.3 inch types (AVX type MD01, or Kemet C630C104M5U); they can also be spaced 0.1 inch from other capacitors or resistors. Leave some room around ICs for logic clips: a minimum of 0.2 inch to the next IC pads and a minimum of 0.15 inch to the nearest resistor or capacitor pads. Leave 0.030 inch spacing between tape runs, and don't run anything closer than 0.25 inch from the edge of the board, to allow room for card lifters, guides, standoffs, etc. Avoid running lines between the 0.1 inch spaced pads of an IC, unless necessary. You can fit up to six tape runs lengthwise between the pads of a standard DIP IC pattern (they're spaced 0.3 inch).

Recent PC design practice generally favors much higher line densities (both thinner lines and closer spacing) than the values recommended above; the latter would be called "15-15" design rules, signifying 0.015 inch minimum line width with 0.015 inch minimum conductor clearance. In the PC board industry, 15-15 rules are considered quite relaxed, with 12-12 pretty standard; 12-12 rules let you run one trace between adjacent IC pads on 0.1 inch centers (check for yourself that this is permitted, providing the pads aren't larger

than 0.064 inch in diameter). High-density boards often use 10-10 or 8-8 rules, with which you can squeeze *two* traces between adjacent IC pads (the maximum pad diameters are then 0.050 and 0.060 inch, respectively). Occasionally you see daring boards with 0.006 inch or thinner traces; the designers of such boards are trading the increased circuit density (*three* traces between adjacent pads, 20 down the center channel!) against smaller plated-through holes and other compromises that result in poorer production yield and board robustness.

☐ Connections to the board

For the majority of boards it is probably best to bring out all connections through "edge-connector" contacts, which mate directly with sockets available in a variety of contact configurations. The most commonly used spacings are 0.156 inch, 0.125 inch, and 0.100 inch between fingers. Generally you'll put an edge-connector pattern at one end of the card, bringing power-supply voltages and signals through that connector. The card is mechanically supported, and it plugs in at that end (more on that shortly).

Often you see an edge-connector pattern at the other end of the card also, used instead of a flat ribbon connector to bring some other signals off the board or to other boards. Another method for bringing out signals is to use flat ribbon cable terminated in DIP plugs; such cables plug right into IC sockets on the board. You can buy these cables prefabricated in various lengths, or you can make them yourself with a kit consisting of flat cable, unassembled DIP plugs, and a crimping tool. Ribbon cables can also connect to the board via in-line or "mass-termination" connectors, which use one or two rows of pins on 0.1 inch centers.

For simple boards the best method of connection may be to use swage-solder terminals or PC-type barrier strips with screw terminals. Avoid the use of large pads alone for connection of external wires to PC boards.

Figure 12.7 illustrates a variety of PC board connection techniques.

☐ Odds and ends

With plated-through boards, use several holes to join ground foils on opposite sides of the board. Try to avoid using multiple passes through the board to reach your destination, since plated-through connections where no component is mounted are more likely to give trouble. The layout of a double-sided board generally winds up with most tape runs going horizontally on one side, vertically on the other.

General philosophy: Use smooth curves or 45° turns, rather than right-angle turns, for hand-taped layouts. Bring lines into pads as if heading for the center of the pad, rather than coming in at an oblique angle. Don't mount heavy components on boards (a couple of ounces ought to be the limit); assume that the instrument will be dropped 6 feet onto a hard surface sometime during its life! Put polarity markings on the component side for diodes and electrolytic capacitors, and label IC numbers and pin 1 location (if there's room). It is always nice to label test points, trimmer functions (e.g., "ZERO ADJ"), inputs and outputs, indicator light functions, etc., if you have room.

☐ Taping the Mylar

General advice: Use an illuminated "light table" with a piece of precision gridded Mylar taped to it. Don't confuse this with the inexpensive gridded plastic films that are neither accurate nor dimensionally stable; a piece of precision gridded film will set you back at least $20. Put your clear Mylar over, and stick down the IC pads accurately on it. Use the pencil sketch for guidance while taping. Wash

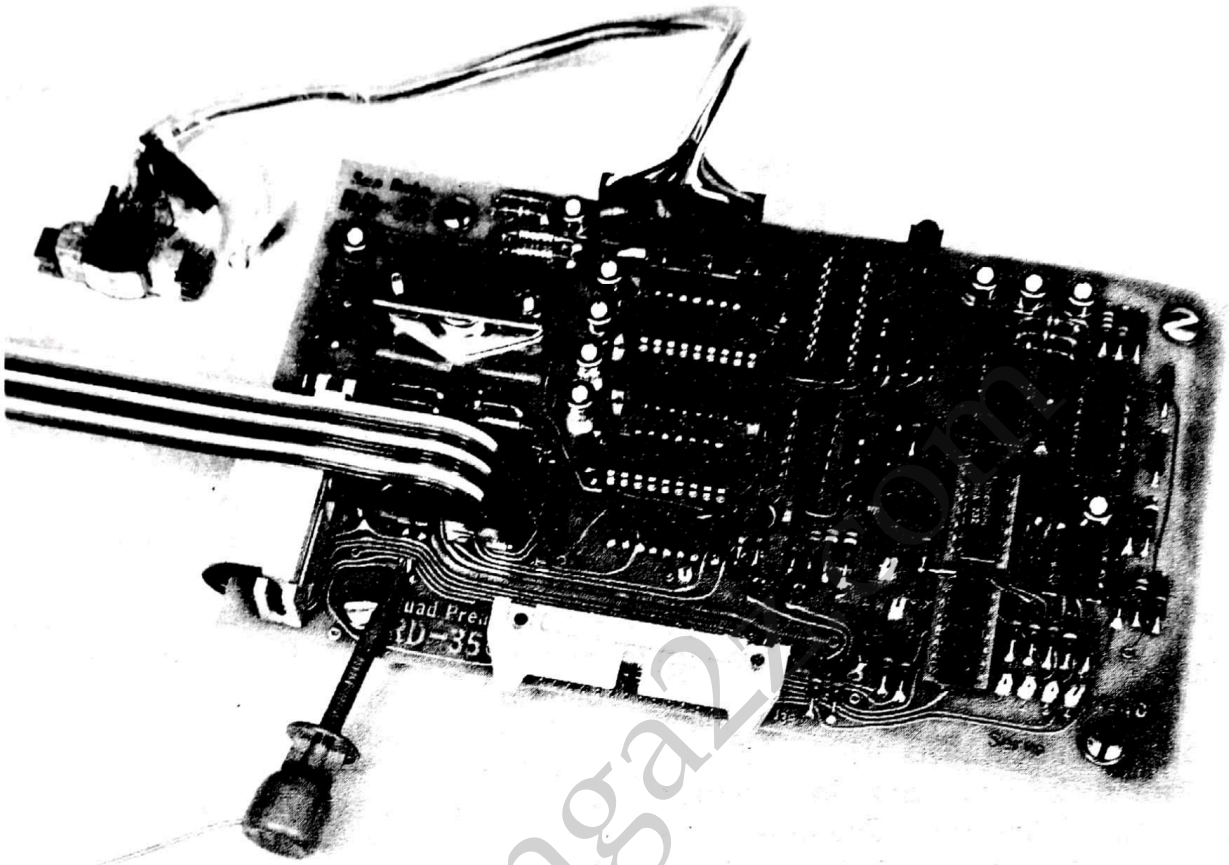


Figure 12.7. Several connection techniques are illustrated in this digital recorder printed-circuit card. The tape head connects via an in-line connector (which mates with a row of Wire-Wrap-type pins), and other signals are brought out with "mass-termination" ribbon connectors and a dual in-line ribbon connector. A test lead is shown clipped onto a "test point" terminal. This board also illustrates PC board heat sinking (upper left), a logic-state indicator (upper right), miniature single-turn trimmers, and single in-line (SIP) resistor networks.

your hands often to prevent deposition of oily film on the Mylar, and use alcohol to wipe any areas that might become oily. Use an Xacto knife with curved blade for tape and outline cutting, and learn not to cut through the Mylar. Press the tape down firmly after positioning; otherwise it will eventually curl up. Allow generous overlap where tape meets pad, etc. When laying out tape, don't hold it under tension; it will shrink and pull away from pads. Use precut bends and circles for the larger tape widths (0.062 inch or wider) when navigating tight turns. After the Mylar is completely taped, check it against the schematic by going over each connection on the diagram with a red pencil. When all seems OK, seal up flaws on the Mylar with an indelible black felt-tip pen.

Precut PC graphics patterns are available from several manufacturers. Table 12.1 shows some recommended types. The Bishop Graphics catalog (5388 Sterling Center Drive, Westlake Village, CA 91359) includes extensive information on PC board layout and execution.

12.06 Stuffing PC boards

Your worries aren't over when you've got a finished board. You've got some decisions to make (e.g., whether or not to use IC sockets) and some important things to do (e.g., defluxing and lead trimming). Herewith, some thoughts on these subjects.

TABLE 12.1. SELECTED PC GRAPHIC PATTERNS

Pattern[a]	Bishop	Datak
Small pads (0.150" OD)	D203	JD-145
Medium pads (0.187" OD)	D104	JD-146
Large pads (0.250" OD)	D108	JD-150
Giant pads (0.300" OD)	D293	JD-343
0.150" thermal relief – pos	5272	JDS-532
0.150" thermal relief – neg	5278	–
0.187" thermal relief – pos	5232	–
0.187" thermal relief – neg	5238	–
16-pin DIP	6109	JD-64
16-pin DIP with in-betweens	6946	JD-179
20-pin DIP	6999	JD-575
20-pin DIP with in-betweens	–	JD-585
28-pin DIP	6904	JDS-398
28-pin DIP with in-betweens	–	JDS-591
TO-5 transistor	6077	–
TO-18 transistor	6274	JD-88
TO-92 transistor	–	JD-91
0.100" connector pads	5004	JD-145
0.100" edge-connector strip	6714	JD-123
0.156" edge-connector strip	6722	JD-121
0.031" black tape	201-031-11	–
0.040" black tape	201-040-11	–
0.050" black tape	201-050-11	–
0.062" black tape	201-062-11	–
0.100" black tape	201-100-11	–
0.200" black tape	201-200-11	–
0.062" universal corners	CU601	–
0.100" universal corners	CU607	–
0.200" universal corners	CU609	–

[a] for 2:1 artwork originals.

Sockets

There is great temptation to use IC sockets everywhere, for ease of troubleshooting. However, if you're not careful, the sockets may well cause more trouble than they prevent. In general, sockets are a good idea at the prototyping phase, where IC substitution may be necessary to convince you that the trouble you're having is a *design* error, not a bad component. They should also be used for expensive ICs (e.g., a D/A converter, microprocessor, or the like), ICs that you're likely to want to change from time to time (e.g., a program ROM), and ICs that have a good chance of being damaged sooner or later (e.g., chips that buffer input or output signals from outside the instrument).

The problem is that a poorly designed socket may prove unreliable over extended time periods. A nonsoldered joint must have a gas-tight seal, such as that created by a mechanical metal-to-metal wiping action, with the seal then being left undisturbed. PC edge connectors, for example, used to be somewhat unreliable; with time, manufacturers learned some good tricks: bifurcated contacts (two independently sprung contacts for each finger), gold plating on the socket and on the edge fingers, and good mechanical design to ensure firm contact pressure during wiping and afterward. Joints that aren't gas-tight can be expected to fail after some time, perhaps a year or so. This sometimes happens inadvertently, e.g., by inserting a component in a PC board and then forgetting to solder it. Such connections have the maddening property of working fine at first, then becoming intermittent months or years later, owing to the formation of corrosion. A different problem can arise when heavy ICs (24 pins or more) are held in sockets. They can work their way out of the sockets after repeated vibration or shock.

We have found that the pin-and-jack type of IC socket (popularized by the Augat 5*xx*-AG series), although expensive compared with many other socket types, gives good reliability.

Soldering and defluxing

The usual procedure is to insert some components, turn the board over and bend the leads aside to hold the components