Generating Digital Signals

Overview

In this lesson we will

- ✓ Study the control of several different kinds of motors commonly found in embedded applications.
- ✓ Examine LEDs and LED displays.
- ✓ Briefly examine asynchronous system inputs and associated problems.
- ✓ Learn to measure several common time and frequency domain input signals.

Introduction

Are a number of different kinds of digital signals
  That may be required in an embedded application

Applications may include

- ✓ Control of various kinds of motors
- ✓ Interface to some form of display
- ✓ Control for a piece of equipment such as
  Printer, keyboard, CDROM, or video imager

Let's examine representative examples of several more common of these applications

Motors and Motor Control

Ability to control different kinds of motors
  Important in a host of contemporary applications
    Ranging from

- ➢ Assembly robots to
- ➢ Remotely controlled vehicles to
- ➢ Precision positioning of medical instruments

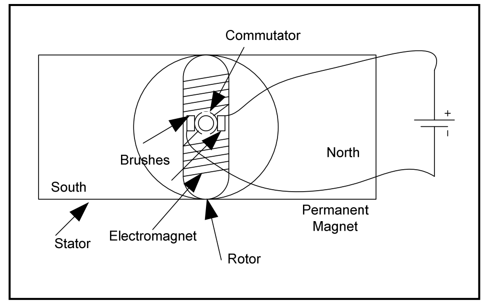
Motors typically found in such applications fall into three categories

- DC motors
- Servo motors
- Stepper motors

Let's look at each

DC Motors

Accompanying figure gives a high-level diagram
Basic components of a DC motor



These comprise
- ✓ Stationary permanent magnet called a *stator*
- ✓ Movable (rotating) electromagnetic called a *rotor*
- ✓ Moving part of electrical switch called a *commutator*
- ✓ System to connect power to the electromagnetic called brushes and

Operation of the motor proceeds as follows
When a voltage is applied across the electromagnetic
Magnetic poles of the *rotor*
Are attracted to the opposite poles of the *stator*
Thereby causing the *rotor* to turn
As the rotor turns
The electromagnet becomes polarized
In the opposite direction
Poles of the rotor are now
Repelled by nearer poles
Attracted to the opposite poles of the permanent magnet
Causing the rotor to turn once again

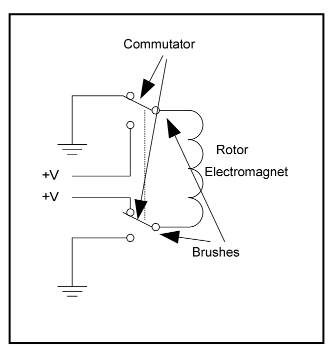
Observe
The commutator is a split ring
Against which the brushes make physical contact

One portion of the commutator
Connected to one end of the electromagnet
Other portion
Connected to the opposite end

Through the action of the commutator
Direction of the field in the electromagnet continually switched
Causing the rotor to continue to move

The actions of
- ✓ Commutator
- ✓ Brushes
- ✓ Electromagnet

Illustrated through the simple model in adjacent figure



The *brushes* are fixed however as the *rotor* rotates
Commutator - which is attached to the *rotor*
Acts like a switch connecting the voltage source
First one way then the opposite way across the electromagnetic
Thereby changing its polarization

When power is applied
DC motor has the ability to continuously turn through 360 degrees
In one direction

If the applied voltage is held constant
Speed of the motor is also held constant
Increasing or decreasing the applied voltage
Will have a corresponding affect on the motor's speed

Using scheme called *pulse width modulation PWM*
The average magnitude of the applied voltage
Can effectively be controlled
Thereby so can the motor's speed

Will learn how to do this shortly

As the speed of the motor decreases so does its torque

If the polarity of the applied voltage is reversed
Motor will run in the opposite direction
Will use a circuit called an H bridge to manage the reversal

Generally a DC motor is not used for positioning tasks
Unless it is incorporated into a control system
That can provide position (and possibly velocity) feedback information

Servo Motors

A servo motor is a special case of a DC motor
Position or velocity feedback circuitry
Added to implement a closed loop control system
Like the DC motor
Servo motor can rotate in either direction
Generally the range is less than 360 degrees
Is controlled by a pulse width modulated signal
However the signal is used to control position rather than speed

Servo motor finds common use in systems such as

- Remotely controlled systems
- Robotics applications
- Numerically controlled machinery
- Plotters or similar systems where
    - Starts and stops must be made quickly
    - Accurate position is essential

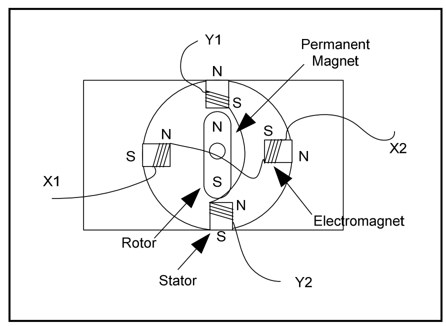
Stepper Motor

Stepper motor is different from yet similar to both the DC and the servo motors
One major difference
Each of the latter motors moves in either the forward or reverse direction
With a smooth and continuous motion
Stepper motor moves in a series of increments or steps

Accompanying diagram
Presents a high-level view of the essential elements of a stepper motor.

The first point to observe

- The *rotor* rather than the *stator* is a permanent magnet
- The *rotor* in the motor in the diagram has 2 teeth
- The *stator* has 4 poles and 4 electromagnets



In a stepper motor
Size of each step
Specified in degrees
Varies with the design of the motor
The step size is selected
Based upon the precision of the positioning required

The simple motor given above has a step angle of 90 degrees
Based upon the spacing of the poles
Connections are made to the electromagnets
Through the signals marked X1, X2, Y1, and Y2

Like the DC motor
The stepper can
Rotate through 360 degrees
Rotate in either direction
Speed of the motor is determined
By the repetition rate of the steps

With this brief introduction to motors

Let's now see how to control their operation

Controlling DC and Servo Motors

DC Motors

Both the DC motor and the servo motor

Require a pulse width modulated signal to control either speed or position

Pulse Width Modulation – PWM

Process of using the width of a pulse

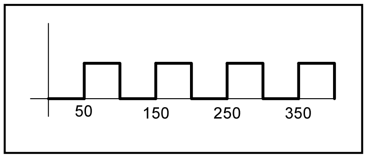
To convey information in a digital signal

Think about using

Frequency – FM

Amplitude – AM

Suppose that we have the following perfect square wave



From the diagram

The period of the signal is fixed

In this case to 100 time units

The signal is in the high state 50 time units out of 100 possible time units

Thus, the signal is ON for half of the period

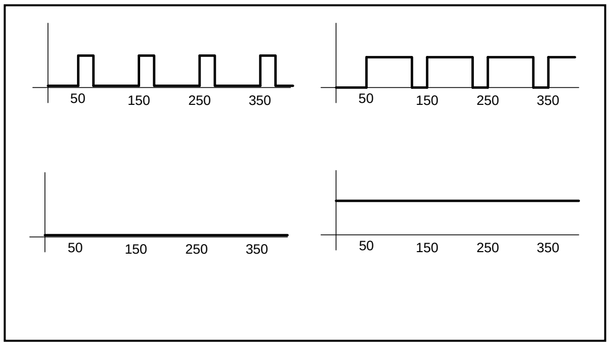
The signal is said to have a 50% duty-cycle

Duty-cycle of a signal is defined as

Percentage of time the digital signal is in the high state

During the waveform's period.

Using this definition signals in following diagrams have



- 25% duty-cycle
- 75% duty-cycle
- 0% duty-cycle
- 100% duty-cycle

Assume that a DC motor is driven by a voltage signal ranging from 0-12V

To run the motor at full speed

A 12V signal is applied

To run the motor at half speed

A 6V signal is applied

To run the motor at one-quarter speed

A 3V signal is applied

Based upon the timing diagrams above

If a signal with a 100% duty cycle is applied to the motor

One would expect it to run at full speed

If a signal with a 0% duty cycle is applied

The motor should stop

If a signal with a 75% duty cycle is applied

What should one expect

The average voltage applied to the motor during each waveform period

Given by following equation

$V_{ave} = 0.75 \bullet 12VDC + 0.25 \bullet 0\ VDC$

$= 9.0\ VDC$

That is one should expect the motor to run at 75% of full speed

By using such a pulse-width modulated signal

Speed of a DC motor can be controlled

Because it is the average voltage that determines its speed

Today it's not uncommon to find PWM capability

Built in to microprocessors or microcontrollers

Under such circumstances implementing software side of PWM capability

Reduces to programming the desired period and duty cycle

According to the device's data sheet

If PWM capability is not supported

If microprocessor or microcontroller has a built in timer

Generating a PWM signal to output ports is rather straightforward

For example, suppose

That PWM signal with a 75% duty-cycle required

The signal's period has been set to 100ms

Signal can be implemented as follows

Configure a timer to time 75 ms

Turn a digital output ON

Wait for the timer to expire

When the timer expires

Turn the digital output OFF

Time 25ms

Process can be executed repeatedly

To generate the 75% duty-cycle PWM signal

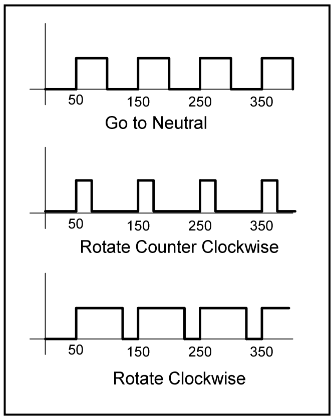
Observe that the frequency of the signal is not changing
- Only its duty cycle.

In either case
- Motor generally cannot be driven directly
  - From microprocessor's digital output ports
- One must ensure that the hardware motor drivers
  - Can support the current requirements for the intended motor
- Several alternate implementations will be discussed shortly

Servo Motors

Can use PWM signal to control the position of a servo motor
Every servo motor has a neutral or base position
Servo is put into that position
- By applying a continuous train of pulses
  - With width specified by the manufacturer

An internal feedback control system
- Holds the servo in the commanded position
- To cause the servo to move one direction
  - Width of the pulse is increased
- To effect movement in the opposite direction
  - Width of the pulse is decreased



Change in pulse width causes the movement
The repeated sequence holds the position

These actions are illustrated in the accompanying timing diagrams

The design may place a number of requirements on the servo motor
- These may include
  - Ability to control to very tight tolerances the
    - Acceleration
    - Velocity
    - Position
- *Slew rate*
  - Time that it takes for the servo to change from one position to another
    - Often another critical parameter

As with so many other parts of the design
Constraints must be identified and included in design specification
Not during the prototype development

Motors are mechanical devices
Typically have much looser time constraints
Than one frequently finds in control of their electronic counterparts
It's reasonable to consider controlling them by command
Directly from a microprocessor
Unless there are other overriding considerations

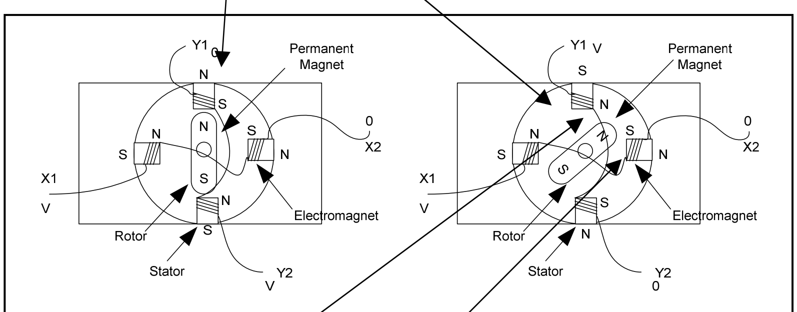
Controlling Stepper Motors

Controlling stepper motors
Not that much more complicated than controlling DC motors
It may seem a lot like juggling trying to keep all the signals straight

The earlier figure of the stepper motor repeated for reference

The polarization of the electromagnets as illustrated
Requires that the indicated input signals are applied to X1, X2, Y1, and Y2
V to X1 and Y2
0 to X2 and Y1

If the input signals next set to
V on X1 and Y1
0 to X2 and Y2
The polarization on the electromagnets changes as shown



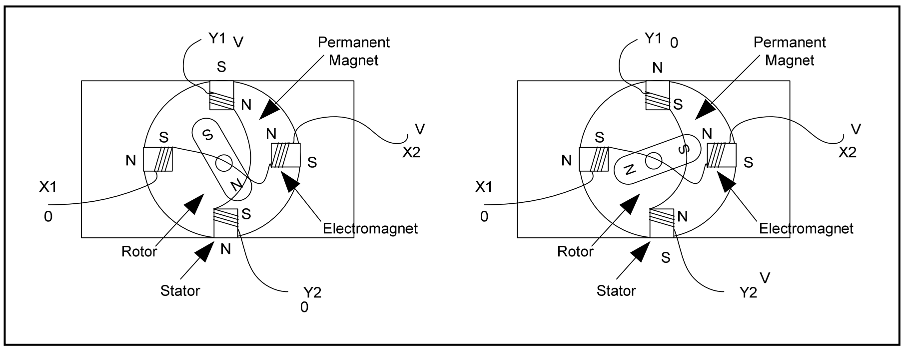
The two north poles at the top of the drawing
Will repel
The north pole on the rotor
Will be attracted to the south pole on the right hand side of the stator

The rotor will thus move 90^{o} in the clockwise direction

Changes to the input signal levels shown in the accompanying table

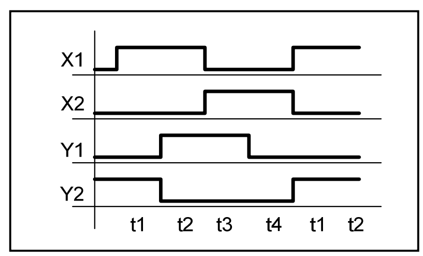
X1	X2	Y1	Y2	Position
V	0	0	V	0^o
V	0	V	0	90^o
0	V	V	0	180^o
0	V	0	V	270^o

Produce the rotor movements shown in following figure



Extending the design to motors with greater number of poles or stator teeth
Is a straight forward application of the pattern illustrated

The variable will be
Number of times that the pattern will have to be repeated
To achieve a full rotation
Since the number of degrees per step will decrease



The timing diagram for one cycle (not full rotation) is given

Such a pattern can be generated in several ways
Utilize 4 digital output lines from the microprocessor
Base the signal timing on an internal timer
Utilize 2 digital output lines from the microprocessor and an external decoder
That will map the 4 possible combinations of the output lines
To the necessary drive signals
The timing is based upon an internal timer.

Implement an external up/down counter (for bidirectional rotation)
Counter can be based upon a 4 flip-flop design
Directly replicating the pattern in 1 above
Thereby minimizing the combinational decoding

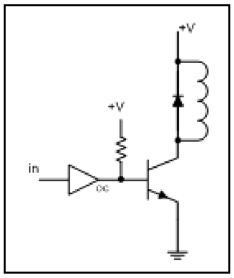
Alternately the design can utilize 2 flip-flops and a decoding network
Thereby replicating the design in 2 above

Motor Drive Circuitry

Motors generally require more drive current
Than a typical microprocessor, TTL, or CMOS gate can provide
To provide that current - control signals being discussed connected to
Driver circuit rather than directly to the motor

Unidirectional Drive

For unidirectional drive
Any number of variations on the accompanying design can be used
The drive transistor
Must be able to sink the required motor current
The buffer
Is an open collector driver
When the digital signal in is a logical 1
The base current for the transistor is supplied
Through the pull-up resistor rather than from the buffer
When the digital signal in is a logical 0
The buffer can sink more current than a standard gate

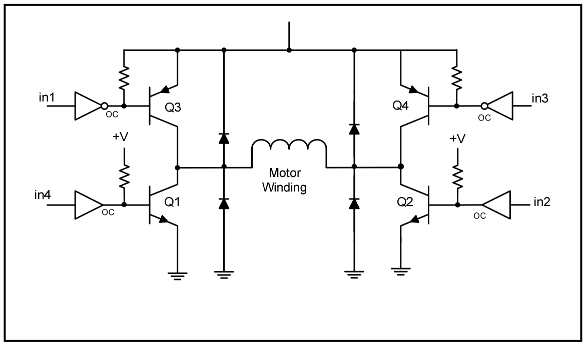


The diode
Used to suppress the flyback voltage
Generated by the collapsing field in the coil
When the motor is switched OFF
If it is not included
Resulting voltage can damage other parts in the circuit

Bidirectional Drive

If the motor must support bidirectional rotation
Commonly used driver designs are
- H bridge
- Variant called a half H bridge

The circuit has acquired such an appellation
Because its topology resembles an upper case H
One such design for an H bridge is given in following figure



All four of the gates are open collector or open drain devices

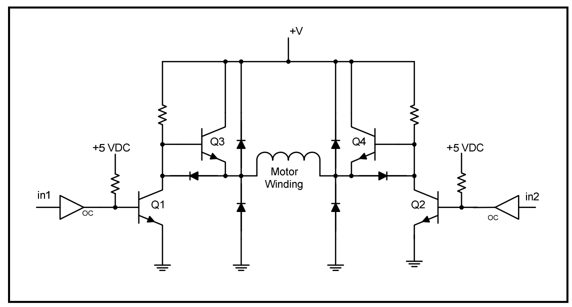
If input in1 is in the logical 0 state
- Output of the open collector device is floating
- Base of Q3 is pulled to the supply voltage thereby cutting it off

If transistors Q2 and Q3 are turned ON and transistors Q1 and Q4 turned OFF
- Current will flow from left to right through the motor winding

Conversely if the states of the four transistors are reversed
- Current will flow in the opposite direction
- The motor will rotate in the opposite direction

The four diodes suppress the flyback voltage
- Generated by collapsing field in coil when
  - The motor is switched OFF
  - The direction is changed

Half H bridge design given in adjacent figure



Today there are a numerous vendors
- Who provide an excellent selection of
  - H bridge
  - Half H bridge
  - Other types of motor drive integrated circuits

These should satisfy most design specifications

DC or Servo Motor Control

To control a DC or servo motor
- The PWM signal is connected to one pair of the input signals IN1 or IN2
  - While the other input pair is connected to ground
- To reverse the direction of rotation
  - Input connections are reversed

Stepper Motor Control

Connections for a stepper motor follow in a similar manner
- For the stepper motor, one bridge will be required for each winding

Motor Drive Noise

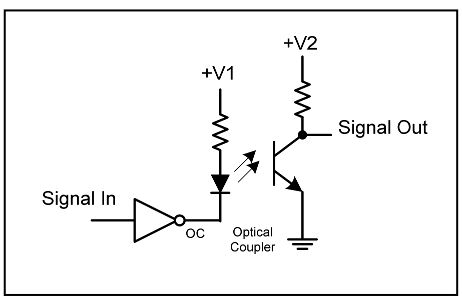
Electric motors are notorious sources of noise
Such noise arises from the switching currents in the windings in the motor
Can readily see from the simple equation for the voltage drop across an inductor

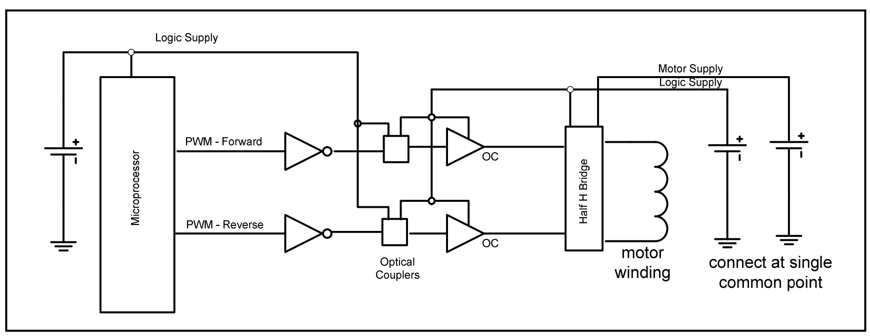
$$\boxed{V = L\frac{di}{dt}}$$

Large switching currents common in motors
Give rise to noise that eventually appears throughout the ground distribution system
Called *ground bounce*
Movement of ground away from the reference 0.0 V

One way to address such a problem
Put the motors onto a power and ground system physically separate from
The rest of the logic
Any precision analog circuitry
Necessary control signals are optically coupled into the isolated subsystem

Such a scheme is illustrated in following drawings





LEDs and LED Displays

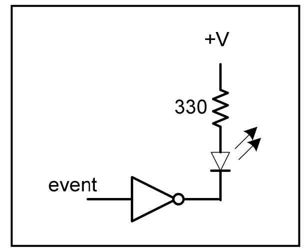
Light emitting diodes (LEDs), dot matrix, and multi segment LED displays
Common in many embedded applications
Amount of necessary external hardware determined by
Current drive capabilities of the microprocessor output ports
I/O space limitations in the design

Assume limited hardware support from the processor
Therefore most of the design must be implemented outside of the processor
Designs can easily be migrated to software
If the necessary resources are available

Individual LEDs

Most TTL and CMOS devices sink current better than they source it
An open collector or open drain device works very well as a driver
Such devices are designed
To sink substantially more current than the standard gates
Are available as either inverting or non-inverting drivers

Assume an application specifies that an annunciation be given
When a certain event is TRUE
Assume the event is an active HIGH or HIGH TRUE signal
Inverting device should be selected as a driver

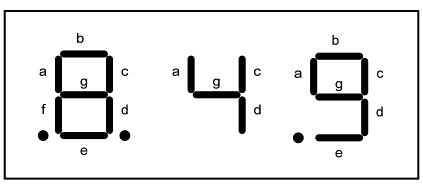


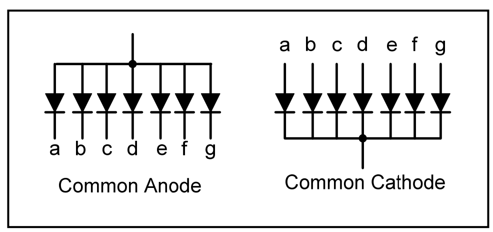
Schematic in adjacent figure illustrates the design of the annunciator
The resistor is incorporated to limit the current through the LED
Which ranges from 10-60 mA

With LEDs, as the current level is increased, the brightness does as well

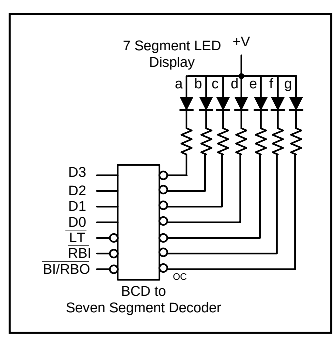
Multi – LED Displays

The ubiquitous seven segment or numeric display
Simply combines a number of individual LEDs into a package
With an appropriate lens
To enable the display of any of the 10 decimal digits (plus decimal points)
When the proper LEDs are illuminated
A top view of the device and several possible digits are shown





The LEDs within the display
Connected in either a common anode or common cathode configuration
- All the anodes are connected together
  Drive signal is applied to the individual cathodes
- All the cathodes are connected together
  Drive signal is applied to the individual anodes



To drive the device to display decimal digits
BCD to Seven Segment Decoder can be used
Part takes 4 input signals
Encoded as a BCD number
Produces 7 output signals

If those signals are connected to a seven segment display as shown
Proper LEDs will turn on to display the corresponding BCD number

Decimal points if necessary would be controlled separately

The outputs on the decoder are implemented as open collector devices

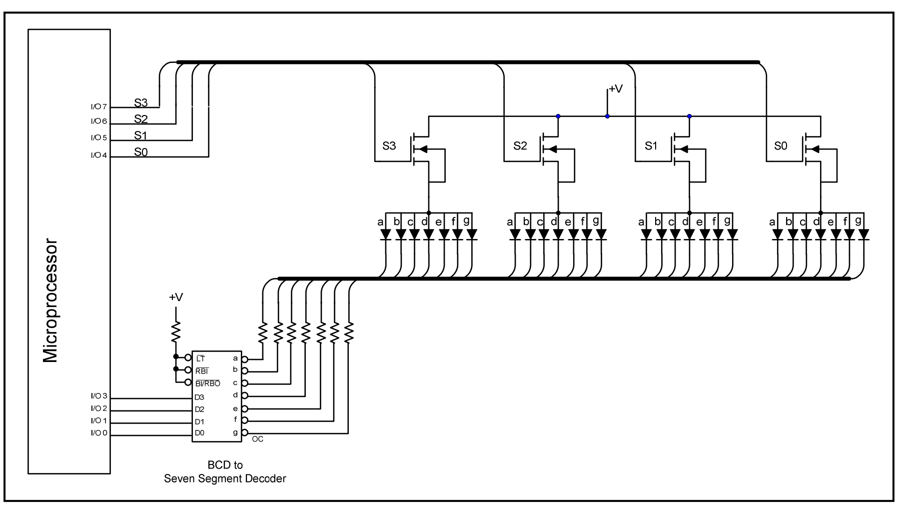
In addition to the four data inputs
Decoder has three active low control inputs

1. ~LT – Lamp Test
   When active turns all seven segments ON

Remaining two support leading zero suppression in multidigit displays
When enabled the number 00789 would display as 789

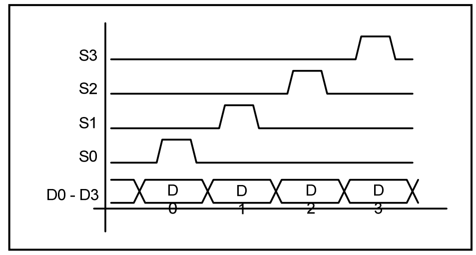
2. When the signal ~BI – Blank Input is active
   All data outputs are OFF independent of the input data
3. When the signal ~RBI – Ripple Blank Input is active
   All data inputs are low
   All data outputs are OFF
   Signal ~RBO is active

When implementing a multi digit display
To save power, weight, and the cost of parts
The decoder can be multiplexed amongst all of the display devices
As illustrated in the following figure



The design takes advantage of the fact that the human eye
Able to integrate out short term transients in an image
So that it appears to be constant.

The operation proceeds as shown in the timing diagram



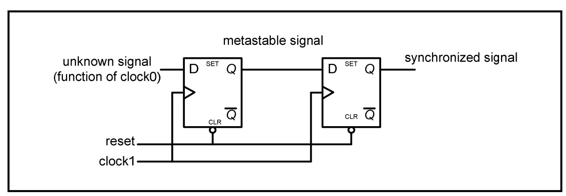
The data for each digit to be displayed
Successively written to one of the microprocessor’s I/O ports
As the input to the BCD to seven segment decoder
A short time later a strobe is issued to turn ON the transistor
In the corresponding display digit
The cycle is repeated for all digits in the display

The update rate must be high enough that interdigit flicker is not perceivable
Because each digit is only enabled for (1 / number of digits) of a display cycle
Its average current will be correspondingly reduced
To ensure the same brightness as a non-strobed implementation
The current limiting resistors will need to be modified

Working with Asynchronous Signals

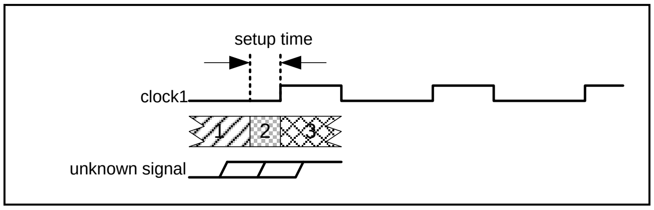
When working with digital signals coming into the system
That are asynchronous to the internal clock
Must be aware of and properly manage metastable behavior
Synchronize such signals to the internal clock
Prior to trying to do any significant work with them

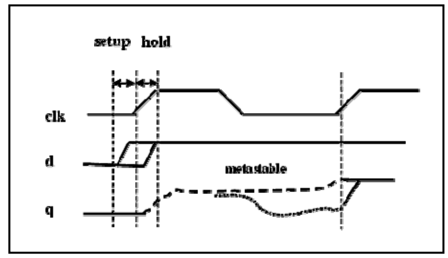
There are a number of different approaches to deal with the problem
One of the simpler is given in following figure



The unknown or incoming signal
Is a function of some clock outside of the system

Consequently there is no way of knowing
When a state change will occur with respect to internal clock1
The incoming signal may or may not violate the setup time for the flip-flop
If the set up time is violated
Output of the first flip-flop may enter a metastable state for some time





- If the unknown signal changes state in region 1
  - It will be recognized correctly by the first clock pulse
- If it changes state in region 3
  - It will be missed by the first clock pulse
  - Recognized by the second
- A state change in region 2 creates a potential problem
  - In such a case the first flip-flop can enter a metastable state

The metastability
- Will be ‘filtered out’ by the synchronizer
- The unknown signal will be recognized and synchronized properly if
  - The unknown signal persists longer than two cycles of the internal clock
    - In this case, clock1
  - The metastable state is shorter than
    - Period of clock1 minus the flip-flop set up time

Measuring Digital Signals

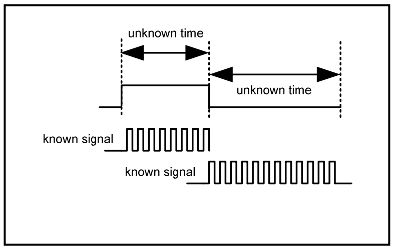
The most common digital signals that are measured
- Those in the time and frequency domains

In the time domain, we measure any of the following
- ✓ The period of a periodic signal
- ✓ The duration of a signal
- ✓ The elapsed time between two events

In the frequency domain we measure,
- ✓ The frequency of a periodic signal
- ✓ The number of events per time for a periodic or aperiodic signal

We now look at a portion of the detailed design of a counter

- To implement a time domain measurement
  - Known signal is measured for an unknown time
- To implement a frequency domain measurement
  - Unknown signal is measured for a known amount of time



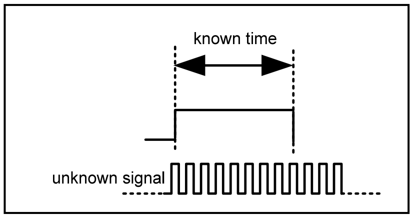
These are expressed in the accompanying figure

For the measurements illustrated
- There is a signal of an unknown duration
  - As reflected in the two regions marked as unknown time
- If that signal used to enable a second signal of known frequency into a counter
  - Actually it's the period that's important
- The value in the counter at the end of the unknown time
  - Will provide a measure of the duration of the unknown signal

- The resolution of the measurement
  - Is a direct function of the frequency of the clock to the counter
- If the frequency to the counter is 1 MHz
  - It is known ….
    - That 1000 counts will occur during a 1 ms interval
    - That the resolution of the measurement will be 1 μsec

- If at the end of the measurement
  - 654 counts have accrued
  - The duration must have been 654 μsec.

The following diagram simply reverses what is known
- The time is known
- Goal is to determine frequency of the unknown signal



- If the known duration is now used as an enable to a counter
  - At the end of the time the counter will have accumulated a number of counts
    - We have events per time or the frequency for a periodic signal
    - For an aperiodic signal count can be interpreted as
      - An average frequency or events per time

- We will return to such measurements shortly

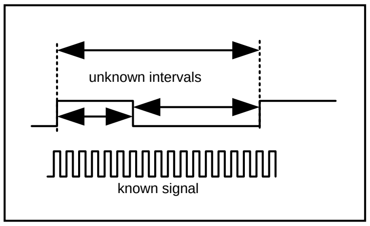
Measuring Frequency and Time Interval

Consider measuring the frequency of a signal in the range of 1 MHz

There are several ways to do this

- ✓ Measure the period of the signal then converted to frequency

  Approach gives the period or interval measurement as well
- ✓ Gate the signal into a counter for a known interval

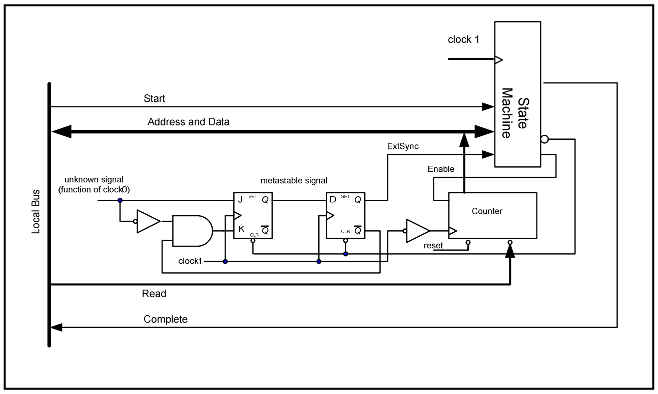


Measuring the Period

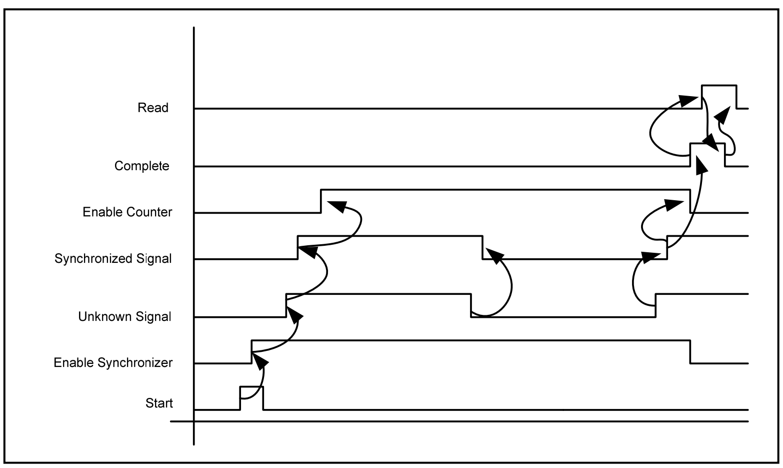
If the measurement is implemented hardware outside of a microprocessor

  It is possible to achieve very good accuracy and precision

One such implementation is shown in following figure



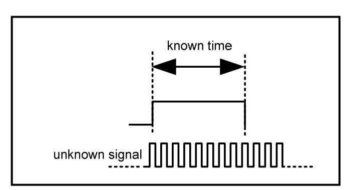
The high-level timing diagram for the system follows



- The Start signal initiates the measurement
- In response the state machine enables the synchronizer

    The synchronizer serves a dual role
    In addition to synchronizing the external signal to the internal clock
      The second synchronizer flip-flop delimits the measurement

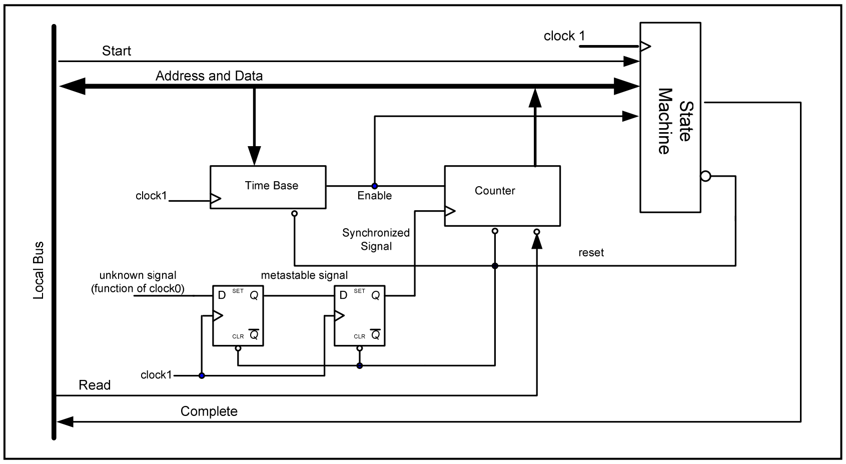
- One to two clock1 pulses after the external signal makes a 0 to 1 transition
  The Enable signal is asserted by the state machine to start the counter
- On the second 0 to 1 transition by the external signal
  The Enable is deasserted and the Complete event is signaled
- The state of the counter representing the period of the unknown signal
  Can be read at any time after that



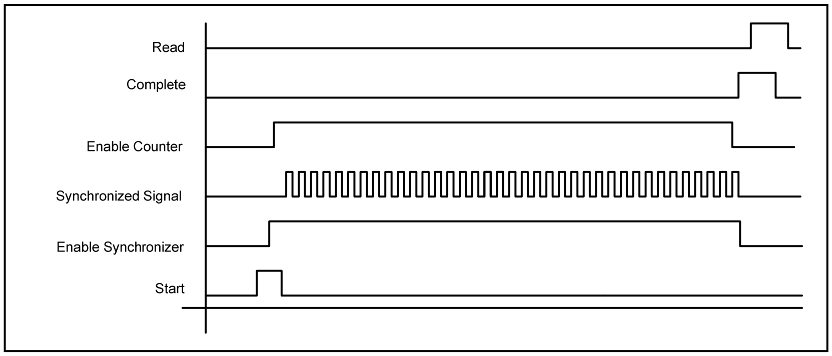
Counting for a Known Interval

The measurement can easily be implemented in hardware

Such a design is presented in following figure



The high-level timing diagram is given



In this design the process commences when the Start command is issued

In turn the state machine enables

- ✓ Time base
- ✓ Synchronizer
- ✓ Counter

The time base generates a window – Enable Counter

For a length of time consistent with the measurement being made

When the window duration has expired

The Complete signal is asserted

The state of the counter can be read

Summary

In this lesson we

- ✓ Studied the control of several different kinds of motors commonly found in embedded applications.
- ✓ Examined LEDs and LED displays.
- ✓ Briefly examined asynchronous system inputs and associated problems.
- ✓ Learned to measure several common time and frequency domain input signals.