Digital Measurement Interfaces and Computer-Aided Data Acquisition

Prof. R.G. Longoria

Fall 2006

Motivation

- Why do we need to involve computers in measurement (and control)?
- When do we need to involve computers in measurement (and control)?
- What do we need to know to effectively involve computers in our measurement (and control) application?

Overview

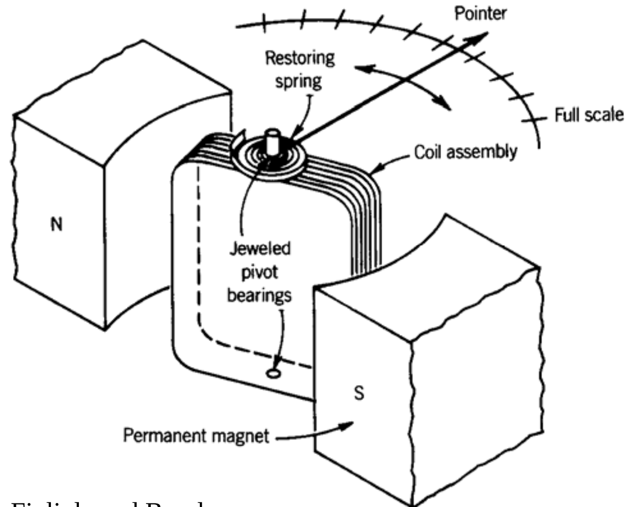
- Review concepts that help make valid measurements of signals using computer-based instruments.
- Review components that make up a computer-based data acquisition system.
- Introduce the role of software computer-based measurement applications.

Topics

- A Look at Analog Measurement Devices
- Sampling Concepts and the Sampling Theorem
- Digital-to-Analog (D/A) Conversion
- Analog-to-Digital (A/D) Conversion
- Data Acquisition System Components
- Data Acquisition Software

Concept of Analog Sensing

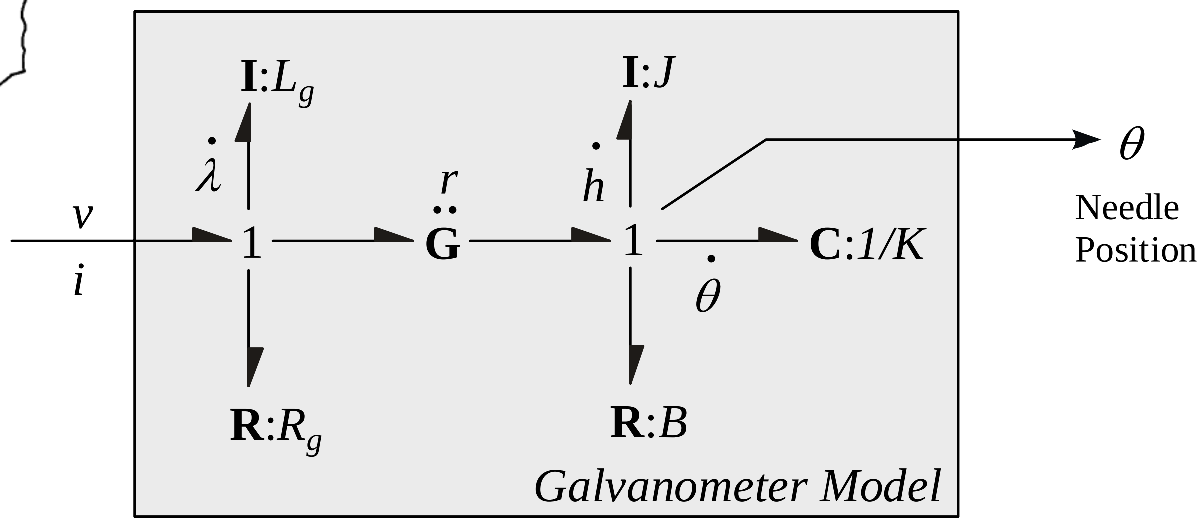
FIGURE 6.3 Basic D'Arsonval meter movement.



From Figliola and Beasley, "Theory and Design for Mechanical Measurements", John Wiley and Sons, 1995.

The D'Arsonval meter movement is a basic EM device that responds to electrical voltage or current signals.

Still in use, but digital measurement prevails.



Digital Measurement Interface

- The advent of the computer, and potential for very broad application of digital analysis of data has made digital measurement of electrical signals very common.
- Some limitations of analog measurement also makes the digitizing of signals more attractive.
- Digitizing signals also has certain *disadvantages* that should be understood when specifying equipment for an application, and in using the equipment.

What do you need to know?

- Resolution and range
- How fast to sample*
- How many times to sample

General Concepts

- Device selection and configuration (MAX)
- Connecting the signals the right way
- What channels to sample
- How to deal with the data*

Hardware Specific

The lab experiments will force you to deal with each of these issues.

General Concepts

Sampling

- **Sampling** - the act of acquiring data from an analog signal, usually at discrete intervals of time

- Digital sampling requires that you specify how often in time, Δt, you measure a signal. We call this the **sample rate**, f_s, where $f_s = 1/\Delta t$ (units of samples/sec or Hertz, Hz).

- The sample rate must be selected by balancing two very basic objectives: 1) to minimize the amount of data you have to store, and 2) to retain sufficient information in the signal. Obviously, these requirements can vary considerably from one application to the next.

Signal Quantization

- Signal representation in the digital world is not only discrete in time but also in amplitude.
- The **quantization** of a sampled signal refers to how it must take on a value dictated by the Q quantum levels 0, 1, 2, ..., Q-1.
- The spacing width or quantization interval is dictated by the maximum and minimum values and by then number of widths, $\Delta V = (max-min)/(Q-1)$.
- These quantities can be very important when you are trying to establish the error contributed by the sampling process.

Signal Measurement Objectives

- One of the most basic objectives is to be able to reproduce the signal you sampled.
- By “reproduce”, we mean that we want to retain in the digital representation the <u>parts</u> of the signal that contain the information we need. It is convenient to think of those ‘parts’ as frequency-based components.
- If you performed a Fourier series on a sampled signal, for example, you would hope to compute coefficients that would allow you to reconstruct a waveform that is a “good” representation of the original signal.
- It turns out that you can achieve this objective if you follow a well-known sampling theorem attributed to Nyquist.

Extracting Information by Sampling

- Usually, we seek to extract enough information from a 'signal' to answer a question of interest, so the sampling must be performed correctly.
- When sampling signals, we should consider:
  - frequency content of measured analog signal
  - time interval between samples (sample rate)
  - total observation period
- If a time domain signal is sampled correctly, a Fourier series can be used to **reconstruct** the signal (recall, as the summation of sines and cosines).

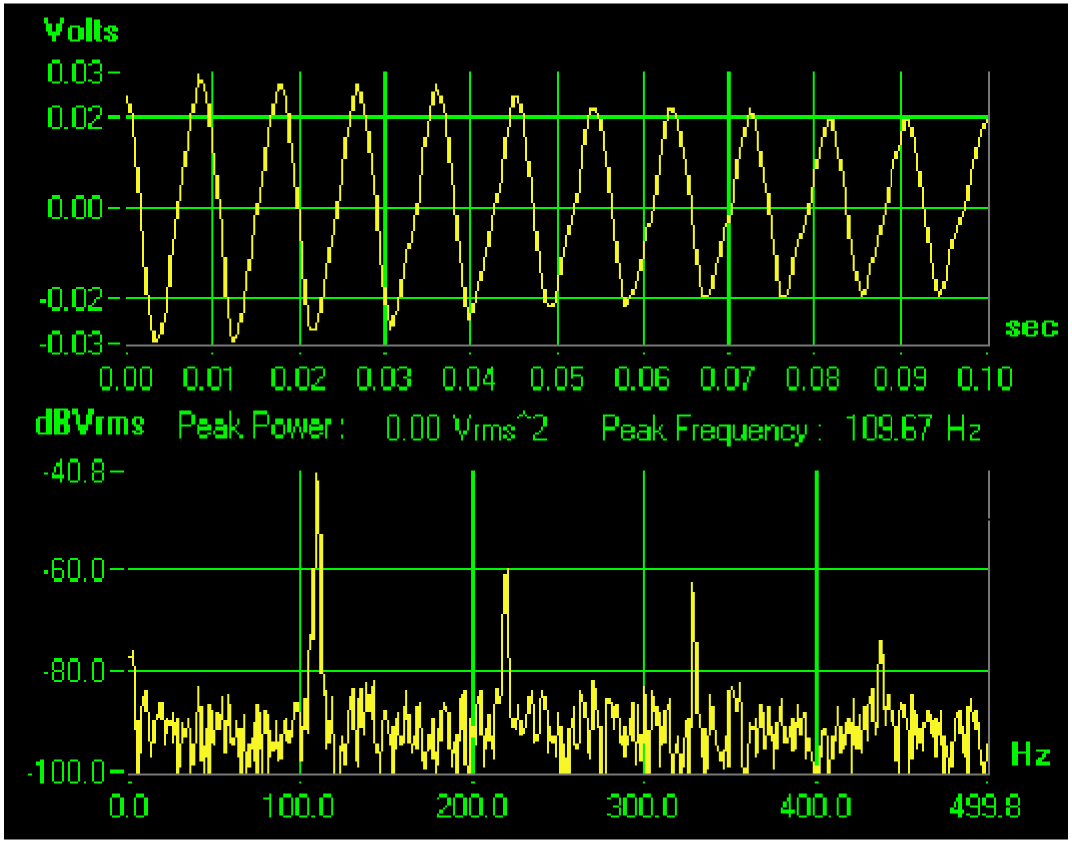
Frequency Analysis Example

6 (open) strings of a classical acoustic guitar vibrate at the following frequencies: E2 string = 82.407 Hz, A2 string = 110. Hz, D3 string = 145.832 Hz, G3 string = 195.998 Hz, B3 string = 246.942 Hz, and E4 string = 329.628 Hz

(The number refers to the octave. Reference: H.F. Olson, "Music, Physics, and Engineering", Dover Publications, 1967).

The A string was plucked and the sound was monitored using a microphone.

The signal was fed directly into a National Instruments DAQCard-1200 and analyzed using an example spectrum analyzer virtual instrument in LabVIEW. (sample rate was 1000 samples/second):



109 Hz (slightly "flat"!)

Effect of Sampling
Aliasing and Quantizing

- **Aliasing** - due to sampling of a signal, a phenomenon taking place at one "rate" can appear to take place at another rate (alias – appears as something it is not)
  - Wagon wheel effect
  - Stroboscopic action
- **Quantizing** - the conversion of a signal **amplitude** to a discrete level at each sampling instant (remember, there are finite digital levels)

Selecting a Sample Rate (1)

- We can "faithfully" reconstruct the signal if the sampling frequency is at least two times the highest frequency **present** in the signal. This would be the **<u>Nyquist</u>** sampling rate, or

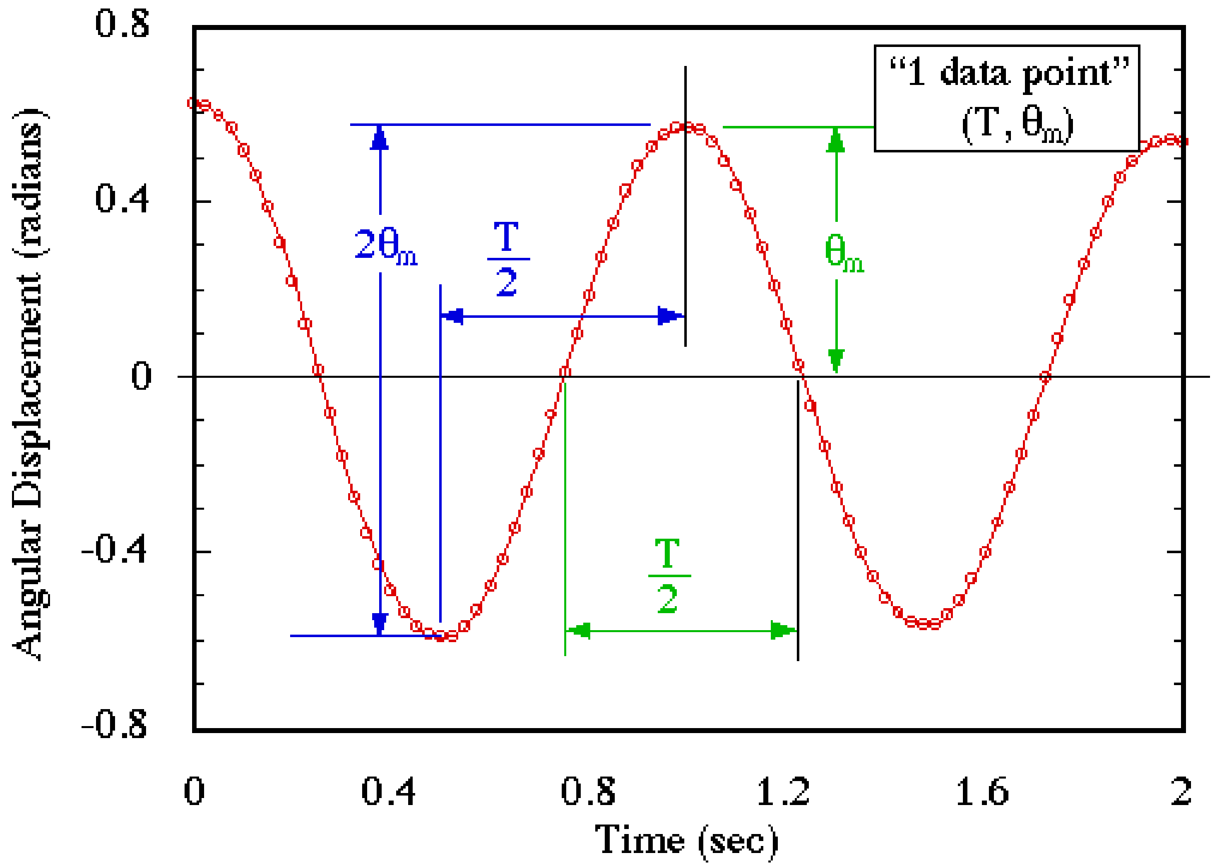
$$f_s \geq 2 \times f_m$$

- Why not just sample as fast as possible all the time?
  - Too much information; have to store it all
  - Computer may need to do other things

Selecting a Sample Rate (2)

- Note, the **sampling theorem** dictates that you pay attention to the highest frequencies that might be present, not just those that are of interest.
- High frequencies that you don't see can "creep" into the data. It is a common practice to **low-pass filter** (anti-aliasing filters) to reduce the effect, and to keep the sampling frequency low. This should be done using analog filters *before* you sample.
- Sometimes you want to over-sample. When?

Selecting a Sample Rate (3)

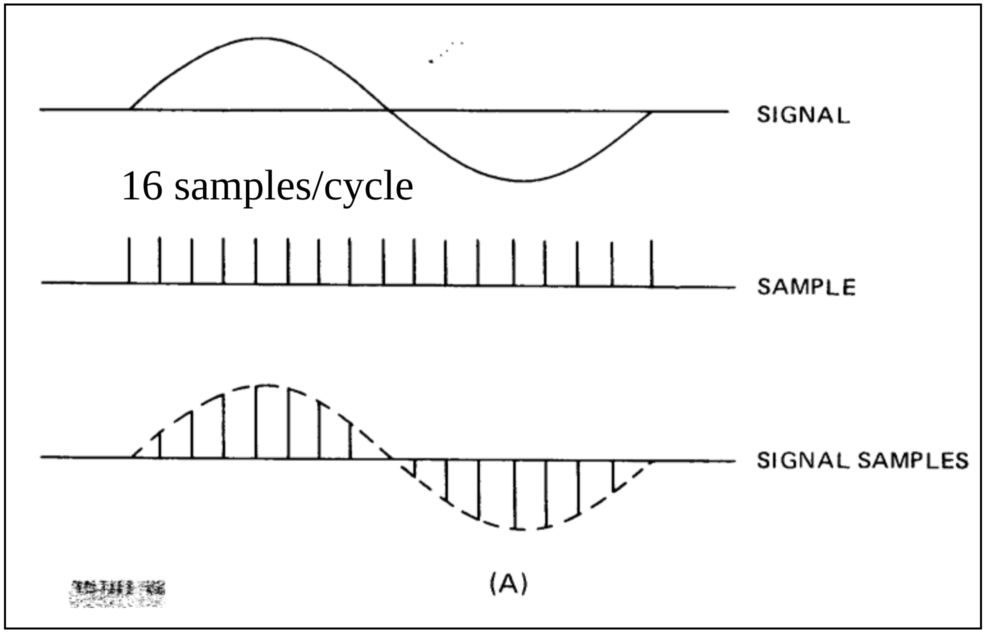


Depending on your objective, you might choose **scan rate** to satisfy Nyquist criterion.

But you might also want to have accuracy in **time** measurements.

Can you see how you have to balance how fast you sample, how many samples you collect/store, etc.?

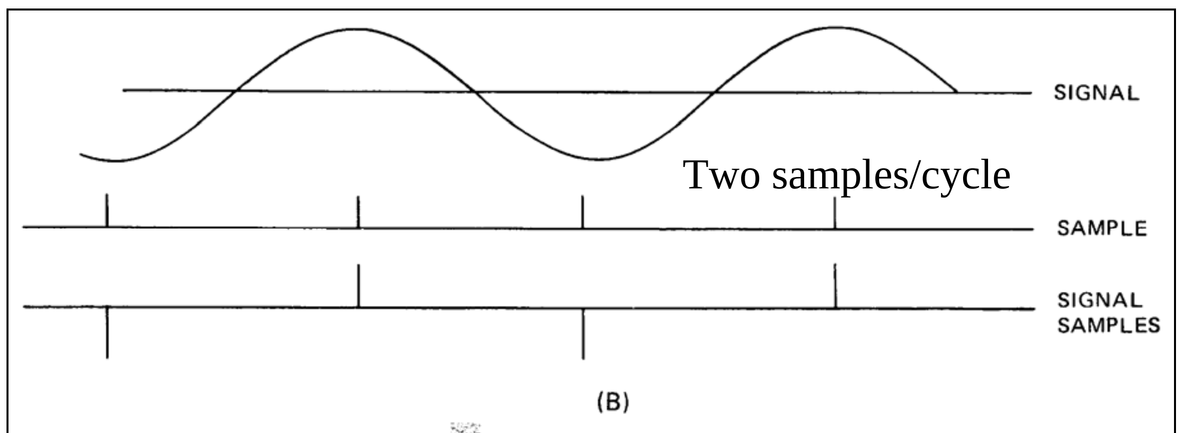
Analog to discretized signals (1)



Consider sampling at two different rates:

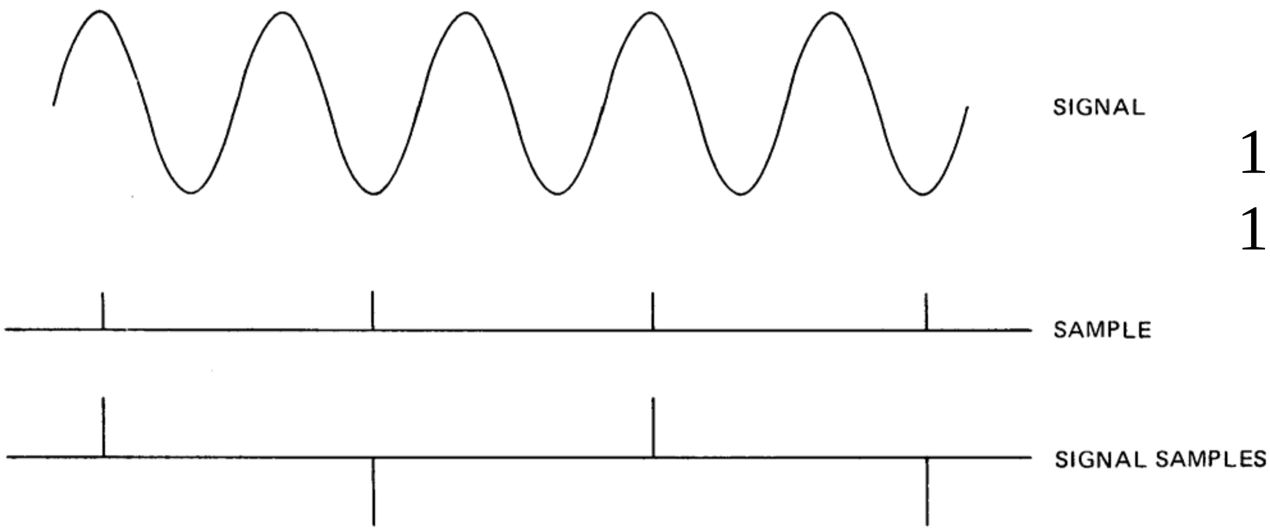
1) 16 samples/cycle
2) 2 samples/cycle

It appears that both of these signals could be reconstructed using Fourier series.



Analog to discretized signals (2)

Consider an alternate case:



(C)

1 sample per
1.5 cycles

This sampling would not satisfy the Nyquist sampling theorem.

There are many illustrative examples (animations, etc.) of aliasing on the web.

Analog-to-Digital Conversion

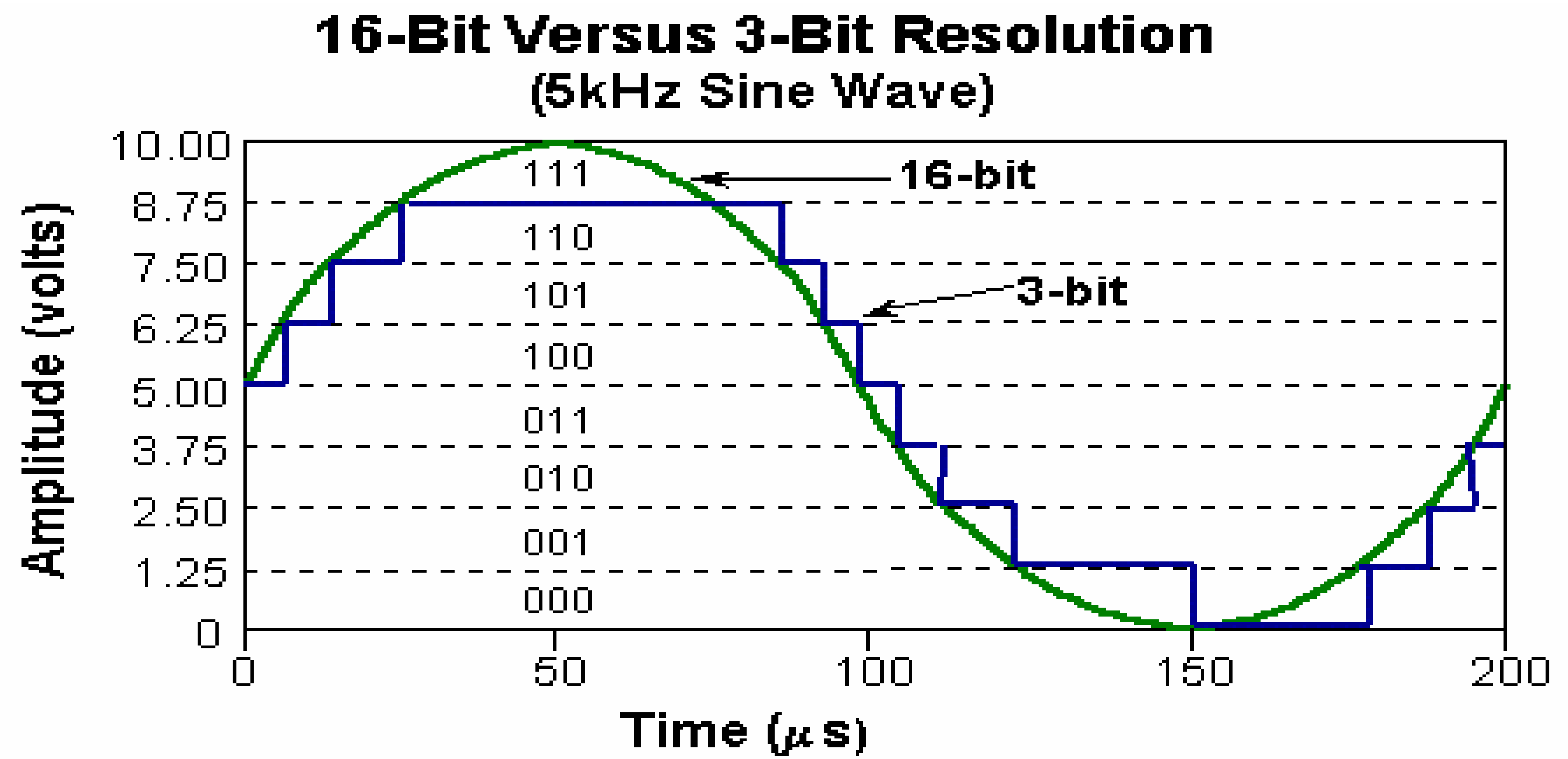
- An A/D converter (ADC) converts an analog voltage into a binary number through the process of **quantization**.
- ADCs have a **full-scale voltage range** (e.g., 10 V)
- The **number of bits** dictates how many discrete levels will be used to represent measured voltages.
- For example, an 8-bit converter with a full-scale voltage of 10 V will give you a resolution of 10V/256 which is 39.1 mV.

A/D Conversion

Signal entering the computer must be ***discretized*** in amplitude as well as time (sampling).
Contrast n = 3 versus n = 16

Resolution:

$$\Delta = \frac{V_{FS}}{2^n} = \begin{cases} \frac{10V}{2^3} = 1.25V \\ \frac{10V}{2^{16}} = 0.15mV \end{cases}$$



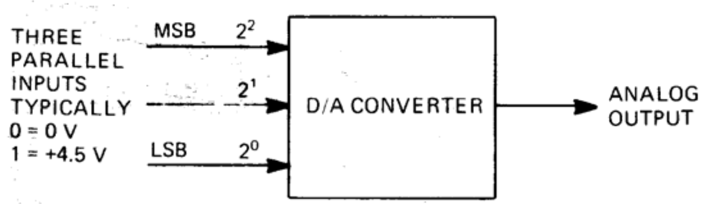
Summary on Sampling

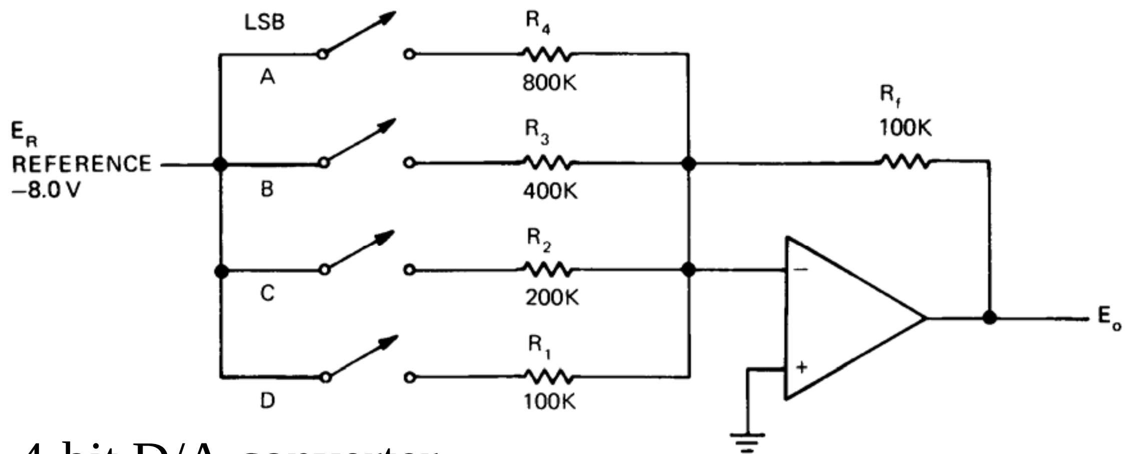
- The sampling theorem has a strict mathematical basis, but is easy to understand and apply.
- Don't just sample at the minimum rate, or Nyquist frequency. This gives the minimum data to satisfy Nyquist. Sample at higher rates, limiting based on *resources*.
- Aliasing disables your ability to faithfully represent an observed signal using a digitized form. For example, if a sampled signal lacks the correct frequency content, it becomes useless for further analysis.
- Quantization directly influences measurement uncertainty because of resolution.

Hardware Concepts

Digital-to-Analog Conversion

- A D/A converter (DAC) takes a logical binary input (usually in parallel) and converts this to an analog voltage





These are simple 3- and 4-bit D/A converters.

4-bit D/A converter

$$E_o = -\left[E_1\left(\frac{R_f}{R_1}\right) + E_2\left(\frac{R_f}{R_2}\right) + E_3\left(\frac{R_f}{R_3}\right) + E_4\left(\frac{R_f}{R_4}\right)\right]$$

DAC Performance Specifications (1)

- The output voltage can only take on a discrete number of values = 2^n.
- Common DACs have n = 8, 10, or 12-bit.
- The **resolution** will be based on the reference voltage.
  - **Example 1:** 4-bit DAC can take on 16 levels. If V_{ref} = 5 volts, then the **resolution** is 5/16 volts, or 0.3125 volts.
  - **Example 2:** 8-bit DAC having a 10 V reference has a **resolution** of 39.06 mV.

DAC Performance Specifications (2)

- DACs will have a **settling time** (time to reach final value)
- **Slew rate** is the maximum rate of change a DAC can produce (e.g.,
- No of **channels**
- **Voltage range**

Analog-to-Digital Conversion

- The A/D converter (ADC) converts an analog voltage into a binary number through the process of **quantization**.
- The ADC will have a full-scale voltage range over which it can operate.
- The **number of bits** will dictate how many discrete levels will be used to represent measured voltages.
- For example, an 8-bit converter with a full-scale voltage of 10 V will give you a resolution of 10V/256 which is 39.1 mV.

Analog-to-Digital Conversion

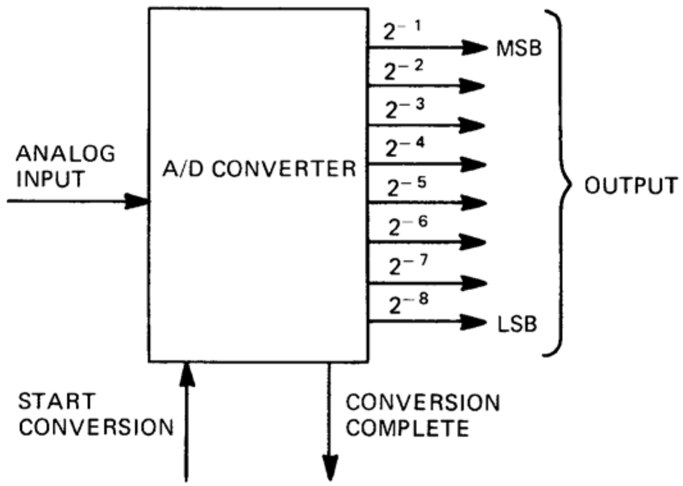
A/D conversion is generally more complicated than DAC; notably it may require a DAC for its function.

Main tradeoffs

•No. of bits
•speed of conversion
•cost

Types

•Simultaneous A/D (fastest)
•Successive approximation
•Single-ramp A/D
•Dual-ramp A/D

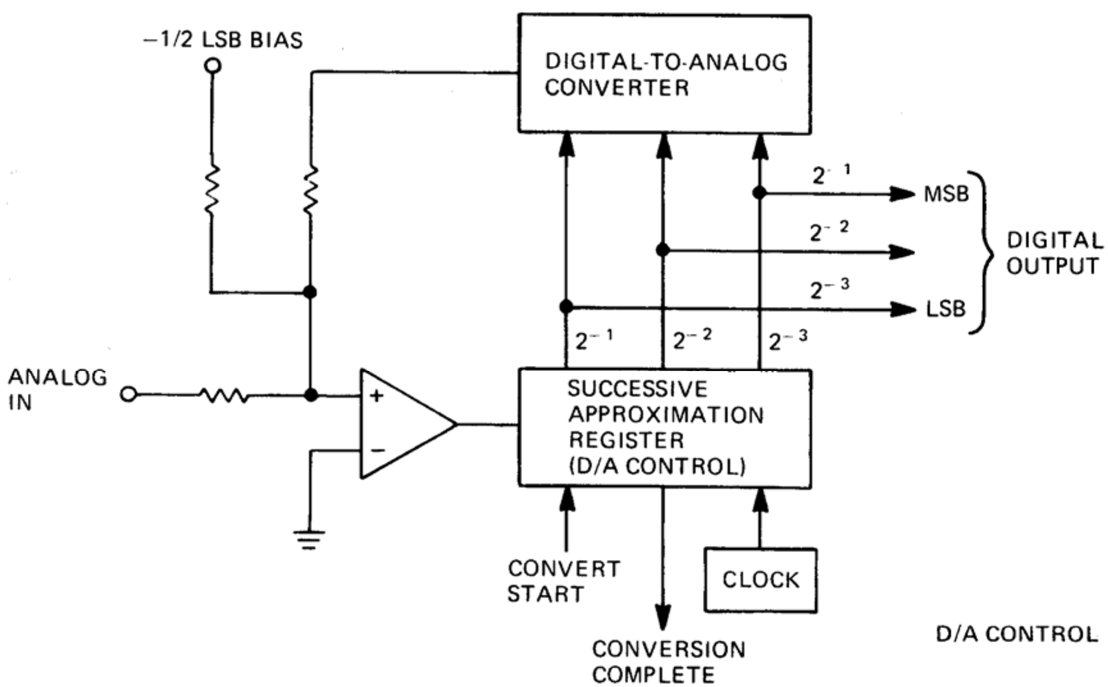


Basic A/D Converter

Error Types

Quantization error
Saturation error
Conversion error

Analog-to-Digital Conversion

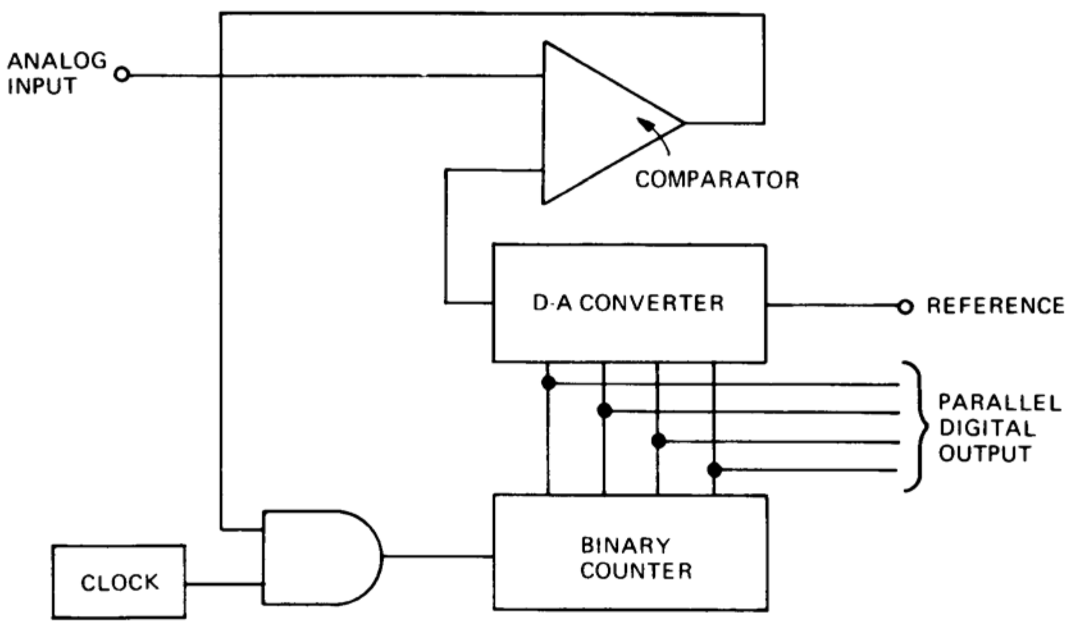


Successive Approximation Type

•Most common
•Relatively little hardware to make.
•Predictable conversion rate (2 to 100 microseconds)

D/A CONTROL MSB		LSB	D/A OUTPUT (FRACTION OF FULL SCALE)	D/A OUTPUT 10 V REF	D/A OUTPUT WITH 1/2 LSB BIAS
0	0	0	0	0	−0.625 V
0	0	1	1/8	1.25	+0.625
0	1	0	2/8	2.50	+1.875
0	1	1	3/8	3.75	3.125
1	0	0	4/8	5.00	4.375
1	0	1	5/8	6.25	5.625
1	1	0	6/8	7.50	6.875
1	1	1	7/8	8.75	8.125

Basic Ramp Type of ADC



"Counter-ramp" type

- For slowly varying signals
- Used in DMMs.
- Long conversion times (100 milliseconds)
- Also called "integrating type".

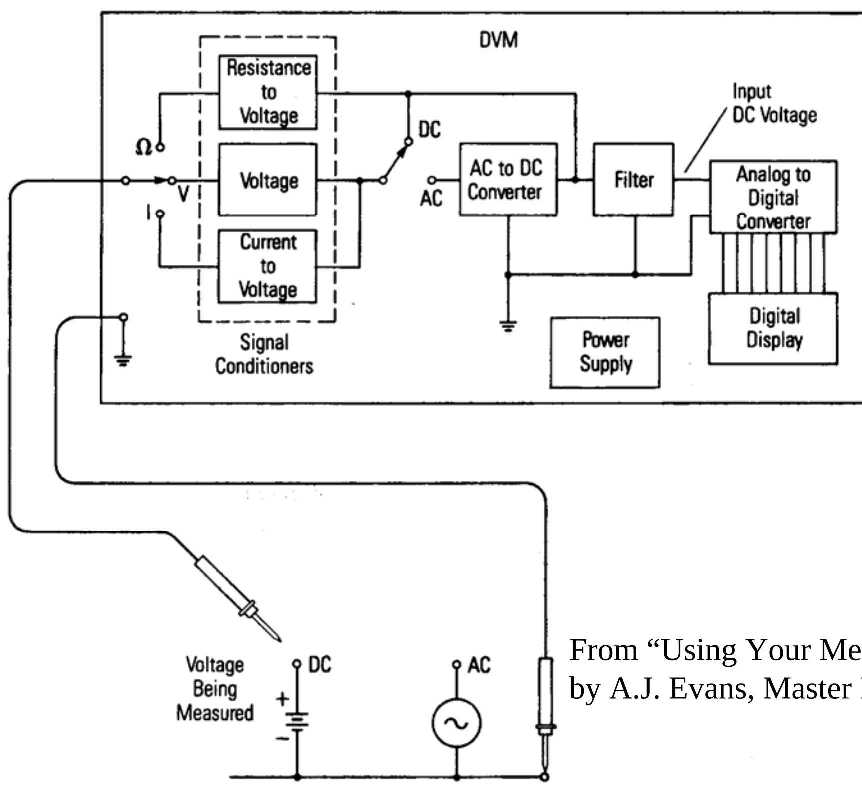
The analog input is converted to a time interval by a very linear ramp generator, and this time interval is measured by a digital counter. The final counter number is the output.

A/D Converter in DMM

Although it is not hard to find an analog multitester, digital devices are much more common.

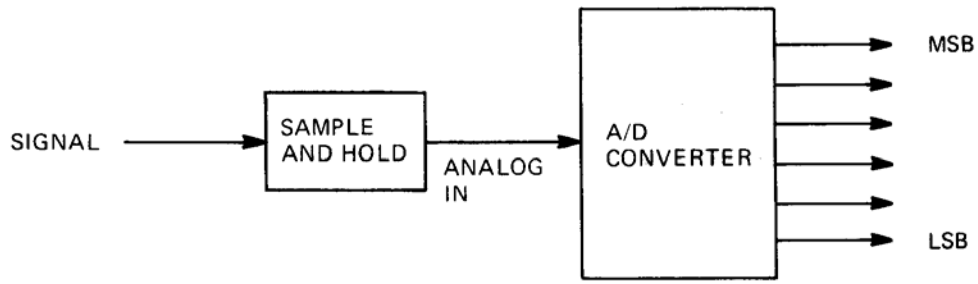
In a DMM, signal conditioners convert the quantity under measure into a voltage to be read by an A/D converter.

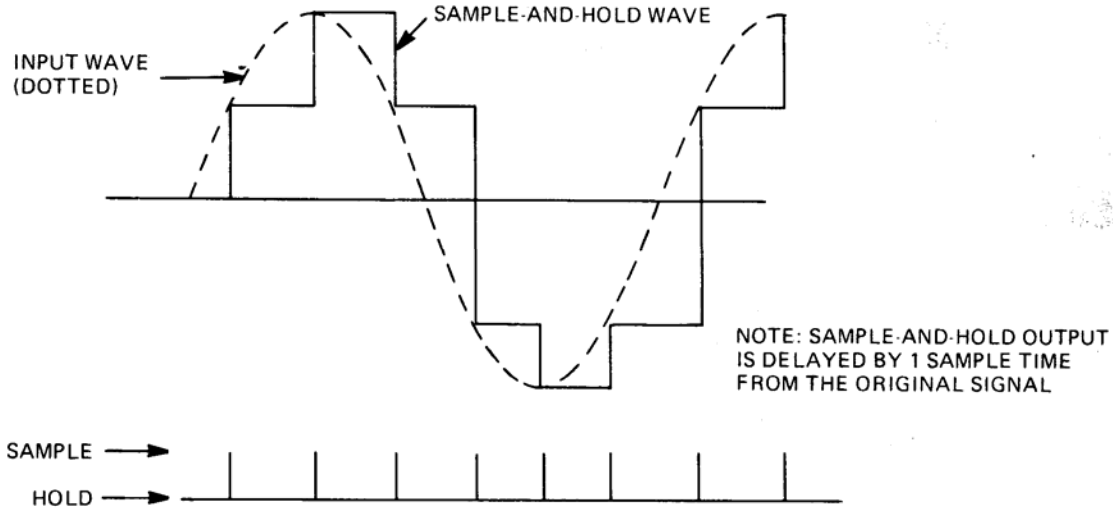
Figure 2-2. Block Diagram of a Basic Digital Voltmeter



From "Using Your Meter"
by A.J. Evans, Master Publishing, Inc., 1994.

Sample and Hold



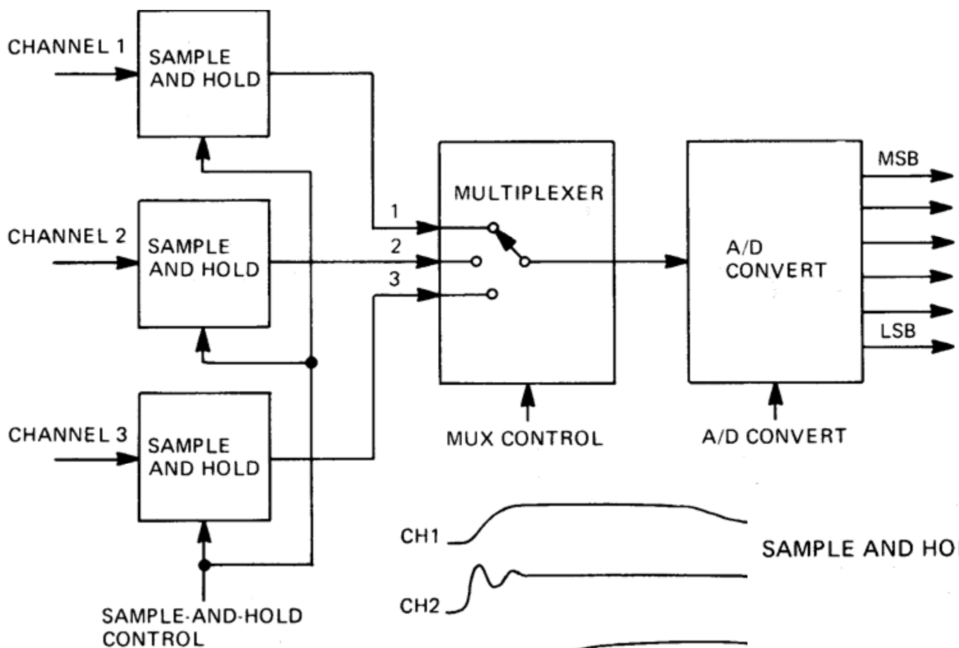


A sample and hold circuit will assure that the ADC has a constant voltage to "convert".

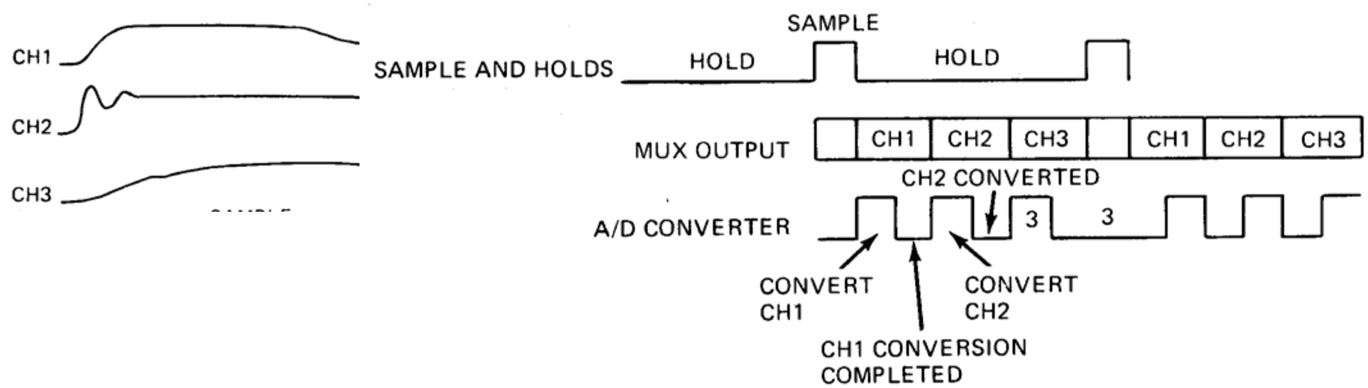
This can improve the performance (of ramp type ADCs), but there are limitations.

The circuit can have some "droop".

Sample and Hold in Multiplexing



It can be less expensive to have several SAH circuits that feed a multiplexer, which in turn switches the inputs to a single ADC.



ADC Specifications

- **Conversion time**.
- The quantizing effect will always introduce some error, so **no. of bits** can be critical and determines **resolution**.
- No. of **channels**
- **Range**
- **Acquisition time** applies to a sample and hold (time to come within certain % of final value)
- **Holding time** (for sample and hold)

Data Acquisition (DAQ) Systems

- Generalized concept of a data collection scheme

FIGURE 7.13 Typical signal and measurement scheme.

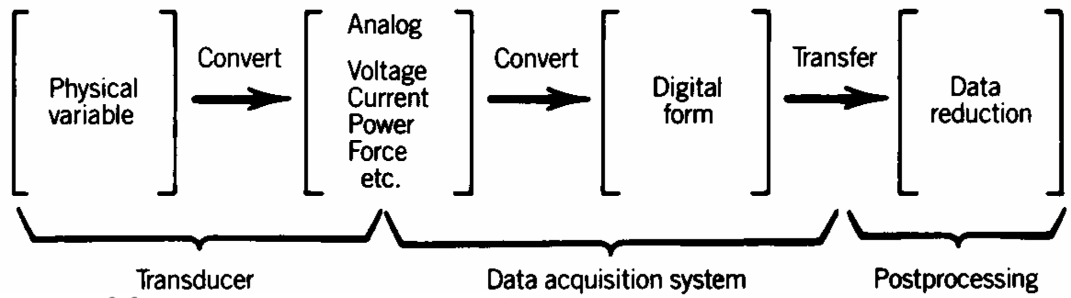
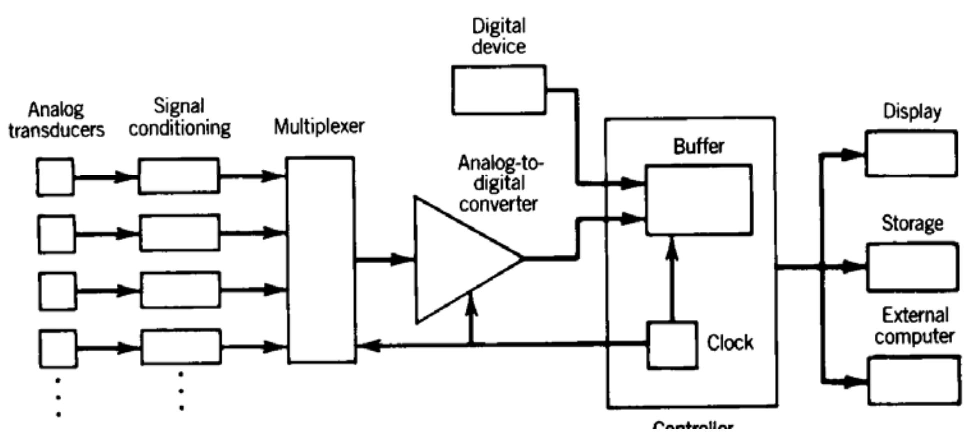
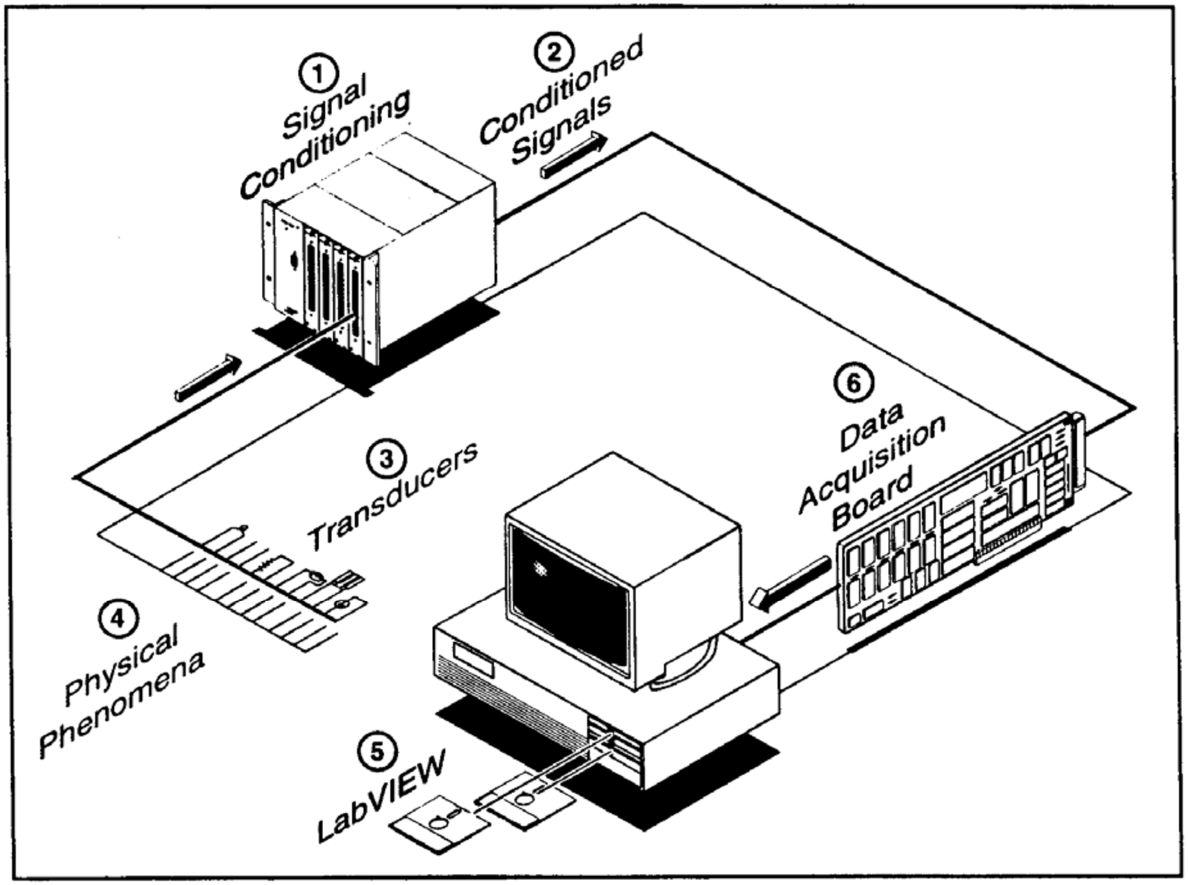


FIGURE 7.14 Signal flow scheme for an automated data acquisition system.



Data Acquisition (DAQ) Systems



National Instruments
concept drawing

Modern DAQ systems integrate software and hardware.

Signal conditioning provides a buffer between real world signals and computer-based circuits.

Data Acquisition Components

- Signal Conditioning
- Filters
- Amplifiers
- Multiplexers A/D and D/A
- CPU/Controller
- Memory/Bus/Buffers/etc..
- Refer to any book on basic measurements, which usually feature discussion on DAQ.

DAQ Functions Besides A/D

- Analog Output
  - Generate DC Voltages
  - General waveforms (Function Generator)
- Digital I/O
  - General low (0V) and high (5V) pulses
  - Read digital pulses
- Timing I/O
  - Generate pulse trains (square waves)
  - Read frequency, time values

DAQ Boards

- I/O Boards on PCs
  - Bus specific
  - e.g., PCMIA, PCI

- These boards plug right into the computer chassis and offer many advantages such as speed, versatility, multi-function (A/D, D/A, digital I/O, etc).

Grounded versus Floating Signals

- **Grounded signal sources** are referenced to a system ground (e.g., power supplies, function generators)
- **Floating signal sources** do not have an absolute reference (e.g., thermocouples, batteries, etc.)
- See Appendix

Connecting Signals to DAQ Boards

When using a DAQ board, it is very helpful to understand the following concepts

- Single-ended connections
- Common-mode voltage
- Ground loops
- Differential-ended connections
- Signal-conditioning modules

Some of these are explained in following slides.

Single-Ended Connections

- **Referenced single-ended** (RSE) connections are used in measurement systems when measuring relative to "building ground".
- **Non-referenced single-ended** (NRSE) connections assume all the signals are grounded to a common reference.
- Single-ended connections have the advantage of sharing a ground, and on a DAQ board will not take up a channel like differential connections.

Differential Connections

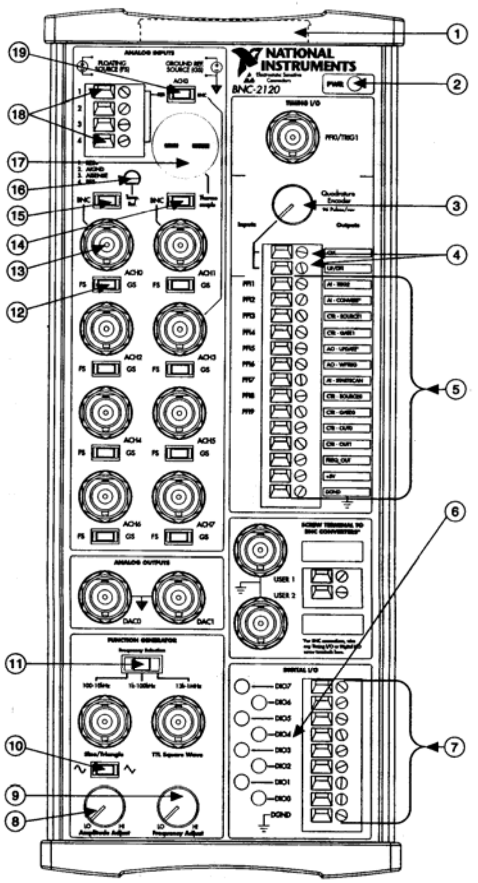
- **Ground loops** exist when there are potential differences between ground connections in a measurement system (hard to deal with).
- A signal connected for differential measurement does not need to be referenced to a ground.
- Differential measurement will reject common-mode voltages (ground loops, noise, etc.)
- Differential measurements are allowed on some DAQ devices, but such a configuration usually requires 2 physical A/D channels.

Summary on Hardware

- A/D and D/A hardware are physical systems, so they have input and output impedance…keep this in mind.
- These are generally LOW POWER connections to computers. Be aware of need for interface circuitry (signal conditioning).
- Grounds, grounds, grounds.
- The accuracy, speed, etc. is a direct function of cost (of course).

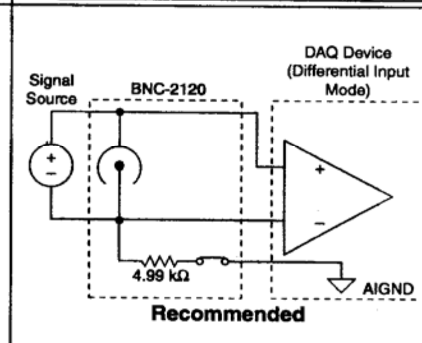
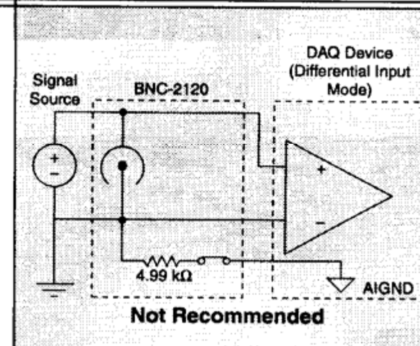
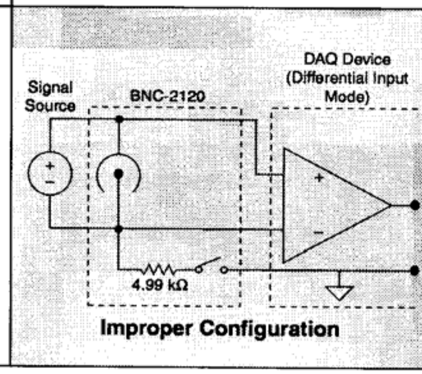
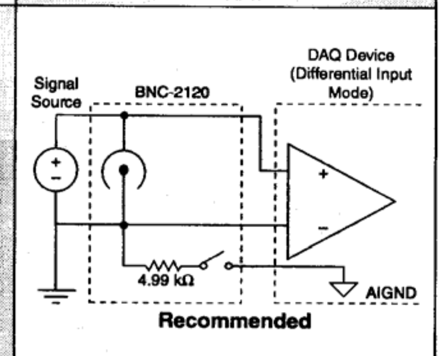
Example Interface

BNC-2120 from National Instruments



1. 68-Position I/O Connector
2. Power LED Indicator
3. Quadrature Encoder Knob
4. Quadrature Encoder Output Screw Terminals
5. TIO Screw Terminals
6. DIO LED State Indicators
7. DIO Screw Terminals
8. Function Generator Amplitude Adjust Knob
9. Function Generator Frequency Adjust Knob
10. Sine/Triangle Waveform Selection Switch
11. Frequency Range Selection Switch
12. Floating Source (FS)/ Ground-Referenced Source (GS) Switch
13. BNC Connector
14. BNC/Thermocouple Selection Switch
15. BNC/Temperature Reference Selection Switch
16. Temperature Reference
17. Thermocouple Input Connector
18. Resistor Measurement Screw Terminals
19. Resistor/BNC Selection Switch

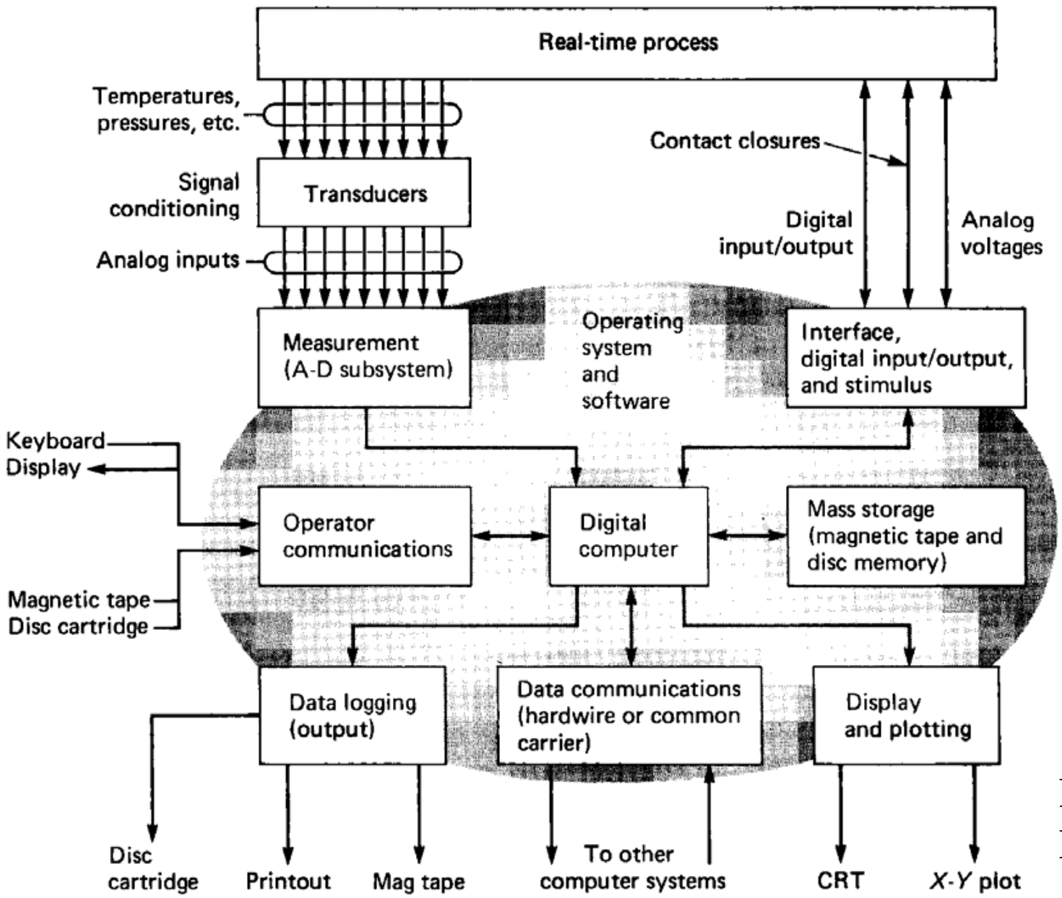
Table 1. Configuration Summary

BNC-2120 Switch Configuration	Signal Source Types	
	Floating Source	Ground-Referenced Source
Floating Source (FS)		
Ground-Referenced Source (GS)		

Communications

Measurement and Control System Concept

Figure 8.24 A block diagram illustrating the potential of an integrated measurement/control system. (Courtesy: Hewlett-Packard Co., Palo Alto, CA)

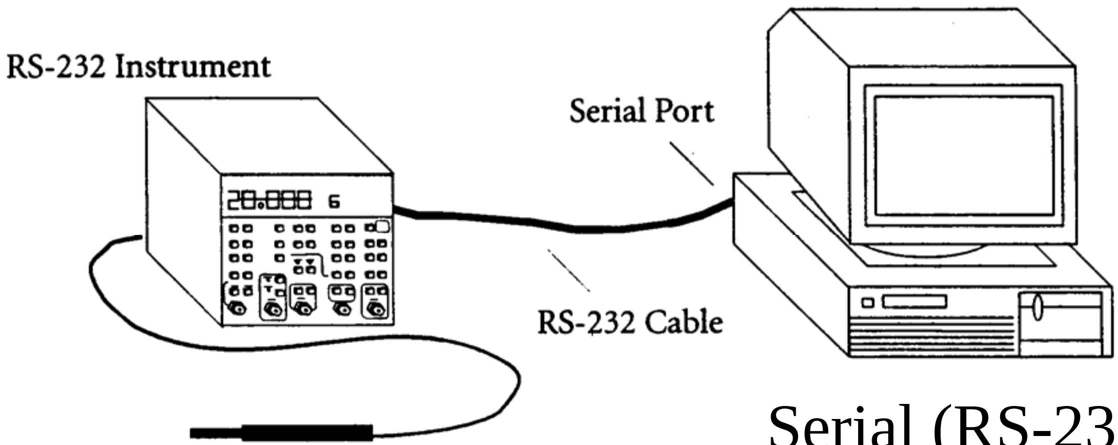


The data acquisition system is a critical part of many modern control systems.

Ref: Beckwith, et al, "Mechanical Measurements", Addison Wesley, 5th ed.

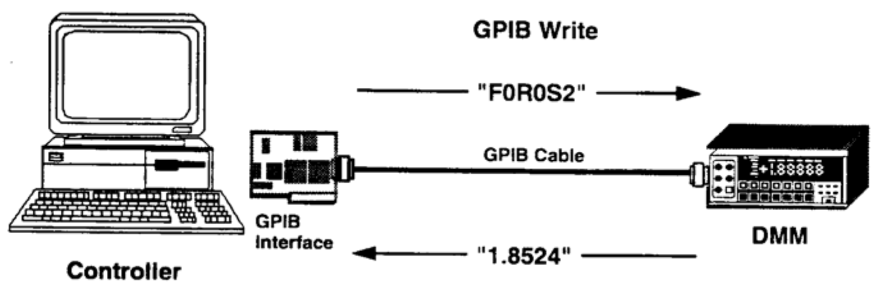
Communication with Existing Instruments

Serial, GPIB, and now USB (more and more common)!



Advantage of using an existing instrument which probably has very good measurement characteristics.

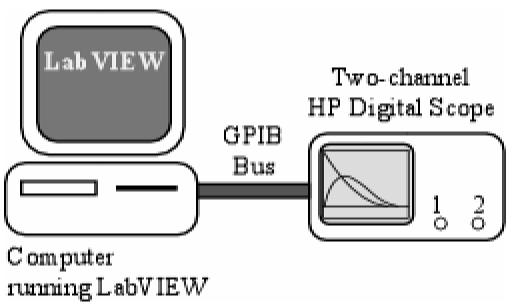
Serial (RS-232C, RS-422A, etc.)

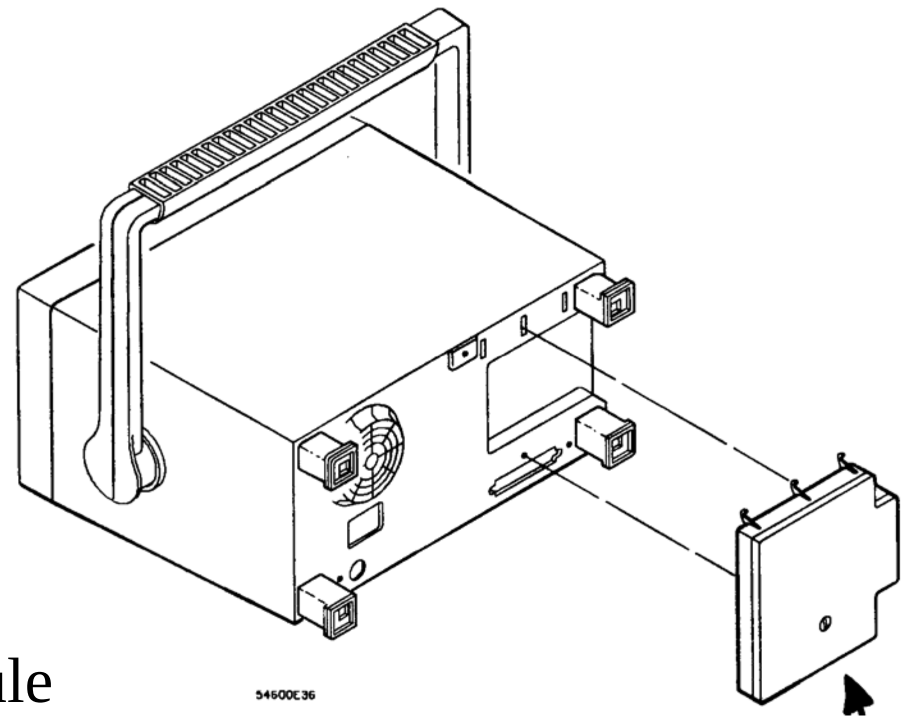


Parallel (GPIB, general purpose interface bus)

GPIB Control of a Digital Scope

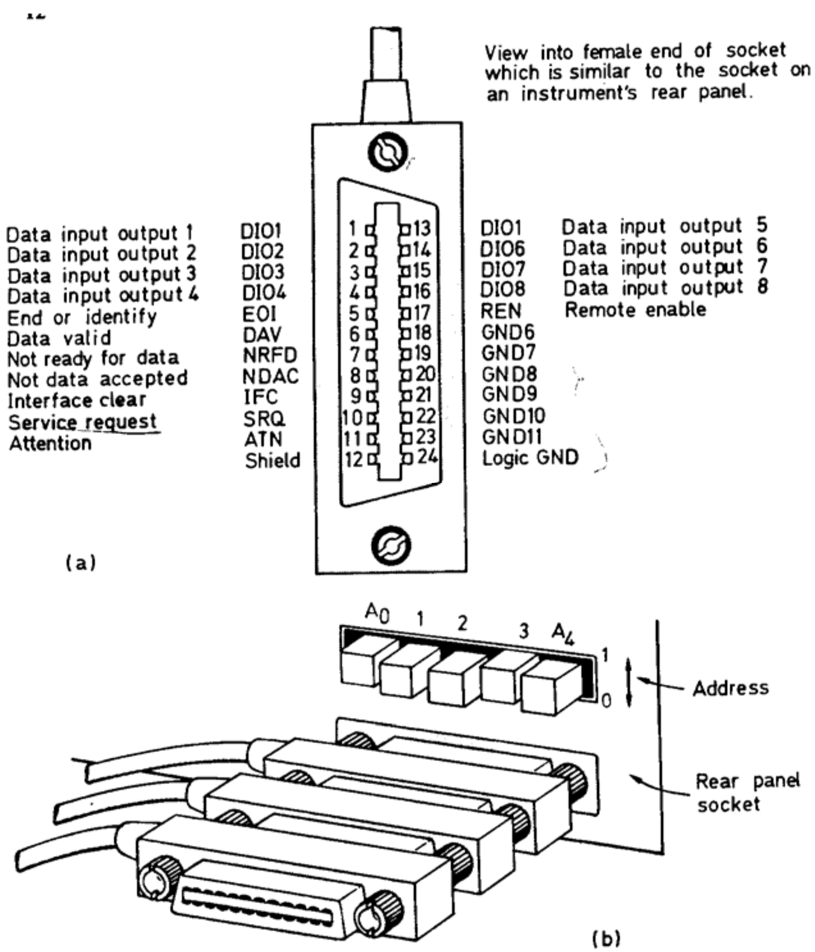
Computer-control of
digital scope





The GPIB interface module for this Hewlett Packard scope allows communication with a PC and also adds new functions to the scope (e.g., FFT capability, signal analysis functions, etc.)

GPIB (IEEE 488)



•The general purpose interface bus (IEEE 488) is a parallel communication bus that allows up to 32 devices to be connected together.

•Any instrument with a GPIB interface has circuitry that communicates with the bus and local functions that can be executed using GPIB "commands".

•This makes computer control of the instrument relatively easy.

•A controller is required (e.g., computer) on the bus, and it can receive signals from long distance (e.g., via modem, ethernet, etc.)

Software

Data Acquisition Software

- At the core of computer-based instrumentation is control of the hardware that communicates with the outside world (e.g., plug-in cards, external instruments, etc.) and hardware that performs communication functions.
- This control is possible with software.
- The lowest level of software control utilizes machine language, and this used to be the only way that computers could be integrated with instrumentation.
- Low level control using the assembly language of the computer offers the fastest performance. However, the programming is not very easy.

Basic A/D Hardware

The actual hardware for A/D.

An A/D converter that uses a "successive approximation".

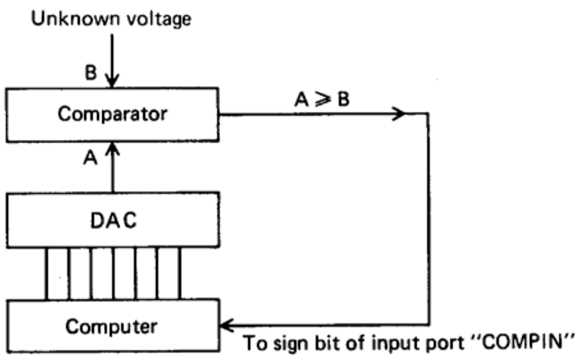


Figure 5.11 *A DAC and a comparator assembled to act as an A to D converter.*

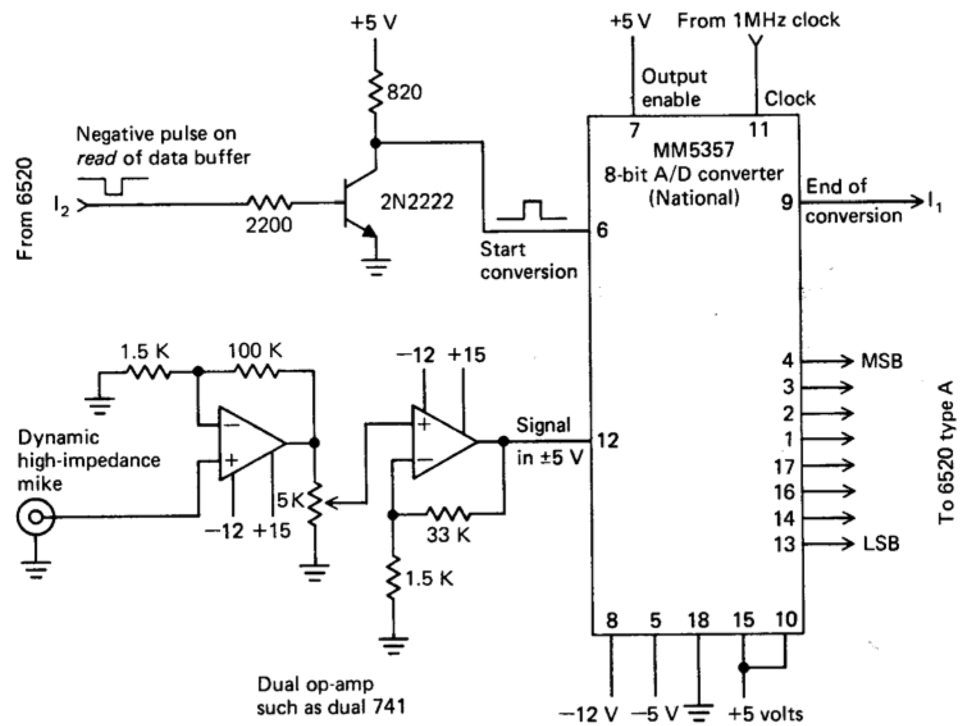


Figure 5.14 *Input circuitry for A to D conversion.*

Ref: Real-Time Programming by C.C. Foster, Addison-Wesley, 1981.

Low-Level Software for A/D

```
BEGIN:      LDAIM    128         Start at the midpoint.
            STA      STEP        Set the step size.
LOOP:       STA      TEMP        Set the size of the DAC output.
            OUTPUT   DAC
            INPUT    COMPVALUE   Read the state of the comparator.
            BMA      TOOBIG      DAC ≥ UNKNOWN.
TOO SMALL:  LDA      STEP
            ASR                  Divide step size by 2.
            BZA      DONE        If step size is down to 0, exit.
            STA      STEP
            ADD      TEMP
            JMP      LOOP        Try with a larger value.
TOO BIG:    LDA      STEP
            ASR
            BZA      DONE
            STA      STEP        Divide step size by 2.
            LDA      TEMP
            SUB      STEP
            JMP      LOOP        Try a smaller value.
DONE:
```

Assembly language code for a 6502 microprocessor ("ancient") for controlling an A/D process.

This code/hardware could take on the order of 25 microseconds for an 8-bit conversion.

Ref: Real-Time Programming by C.C. Foster, Addison-Wesley, 1981.

High-Level Software

- High-level languages such as BASIC, FORTRAN, C, etc., have also been used to program computer-based instrumentation functions.

- These languages do not directly support the functions required to control the base systems. Usually, a subroutine is available that can be called from a high-level language program. Subroutines then communicate information both ways.

Software Solutions

- Software programs exist that facilitate the programming of data acquisition and control functions.
- The **LabVIEW** program is one example of a graphical programming environment. This program is widely used in industry, education, and government laboratories.
- Programs such as LabVIEW also offer very advanced analysis routines.
- The relative ease in developing very sophisticated programs tailored to a particular application has made graphical computer-based instrumentation software extremely popular.
- Some particulars of the LabVIEW program will be introduced in the lab.

Summary

- Most textbooks on 'measurement' have entire chapters that review sampling, data acquisition, hardware, etc. For more information, check the library stacks
- National Instruments has extensive online discussion of data acquisition fundamentals: www.ni.com
- Check Omega Engineering also: www.omega.com
- There are numerous other vendors that provide tutorial information on the web.

Appendix

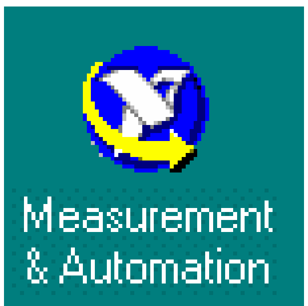
Practical Steps in Using LabVIEW

Practical Steps Using LabVIEW

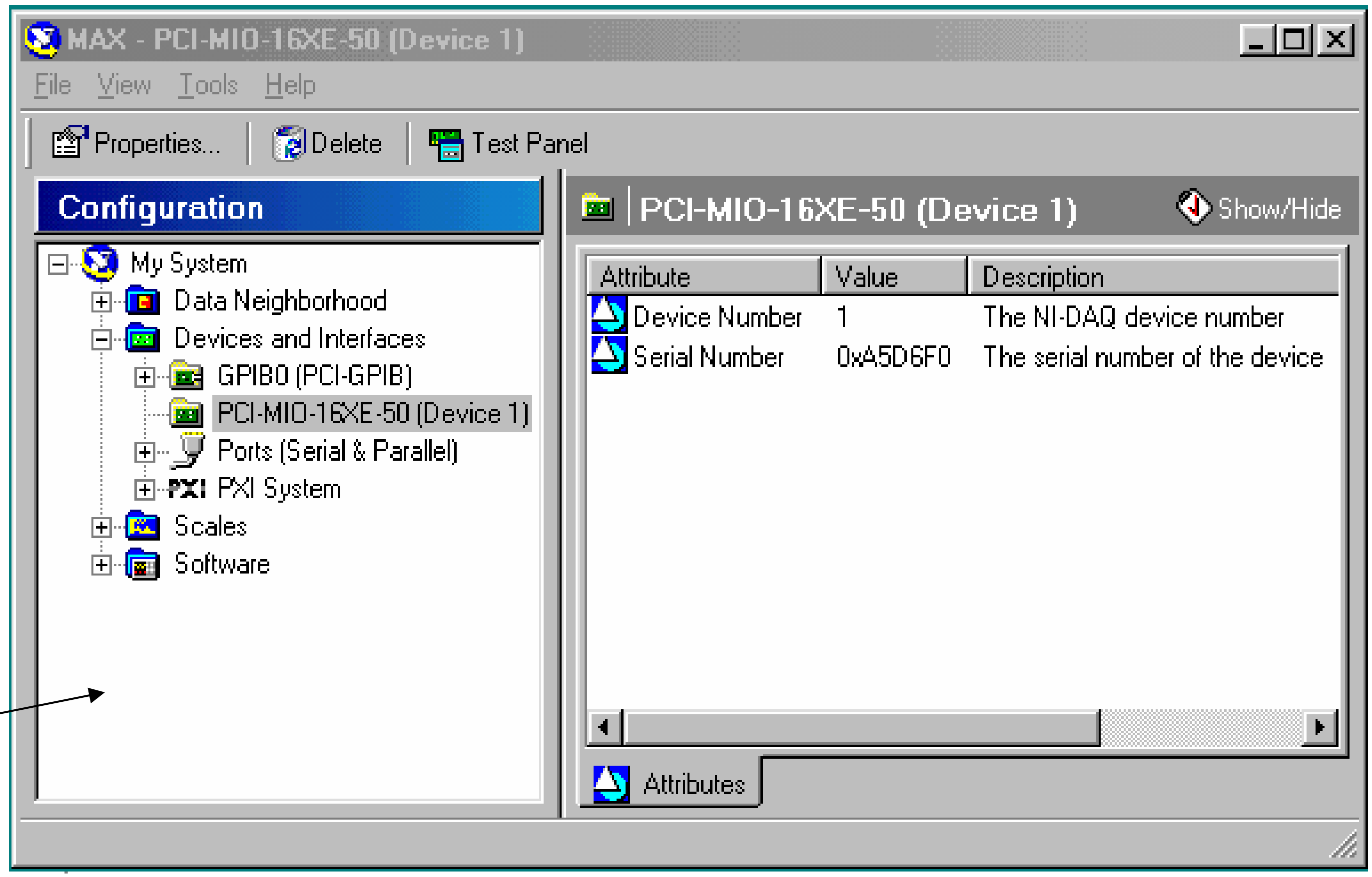
- Finding the hardware on the PC
- Testing the hardware and its operation
- Connecting signals to the DAQ hardware
- Software approach

Checking your hardware

In a LabVIEW environment, the Measurement and Automation Explorer (MAX) allows easy check of hardware.



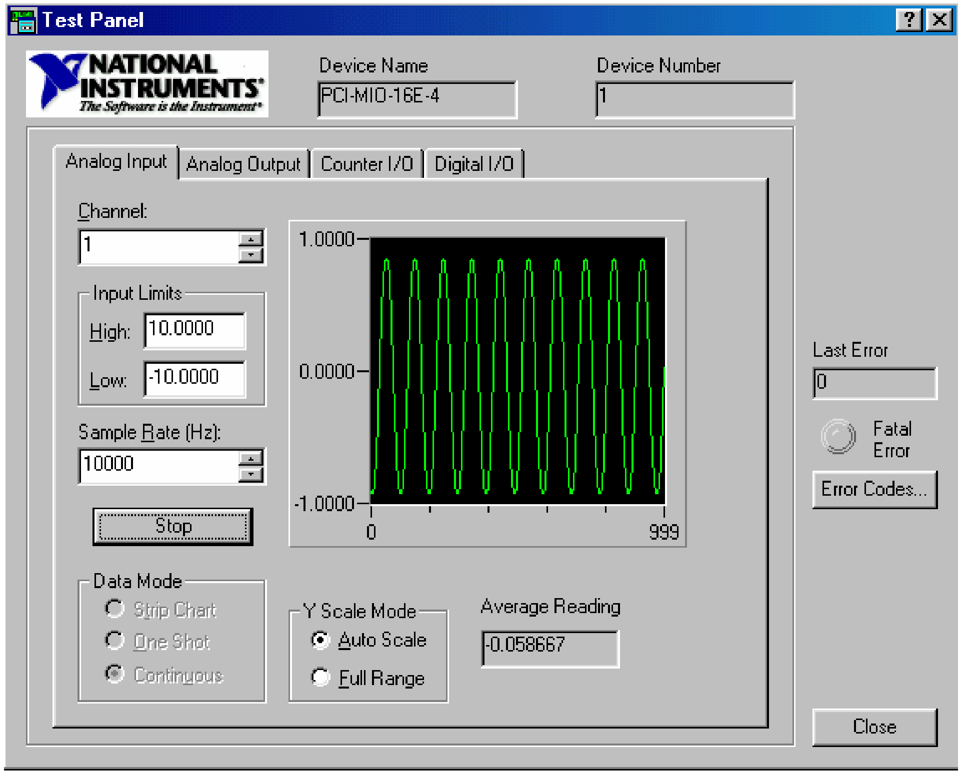
Desktop Icon



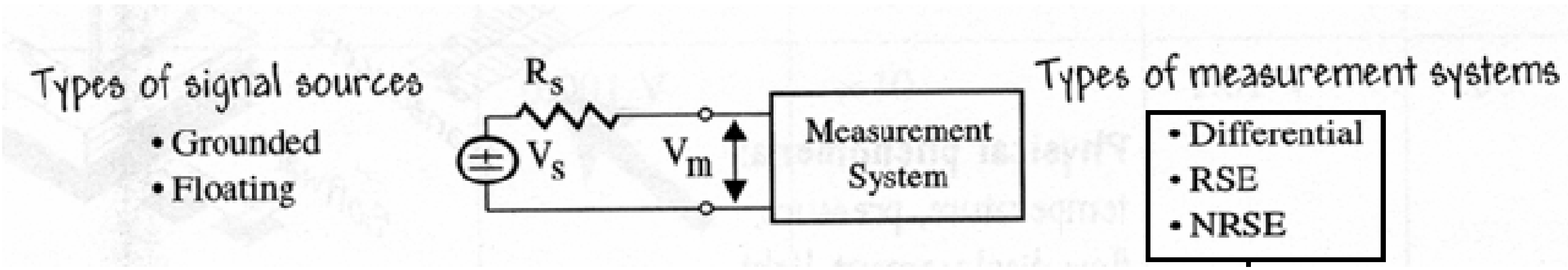
MAX Window

Test your hardware

From the MAX, you can test the hardware using a “Test Panel”. This makes it possible to determine if everything is running OK before you run a LabVIEW program.



Connecting Signals to a System



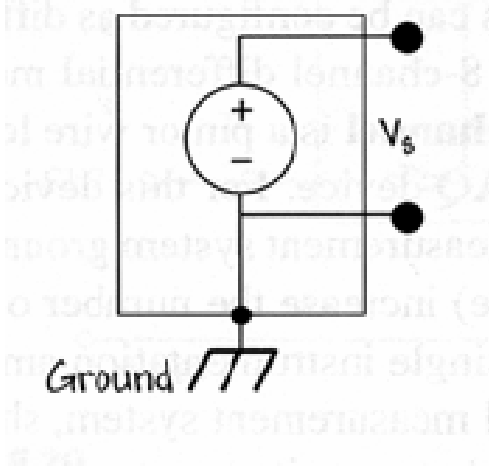
Types of Measurement Systems:

1. **Differential** measurement system
2. Referenced single-ended (**RSE**)
3. Non-referenced single-ended (**NRSE**)

You may see these **connection options** on DAQ hardware.

Types of Signal Sources

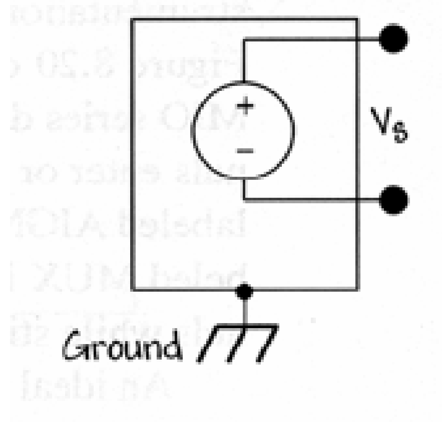
Grounded



(a) Grounded signal source

- Referenced to a system ground (e.g., earth, building)
- Signal generators, power supplies
- Share a common ground with a DAQ board, oscilloscope, etc.

Floating



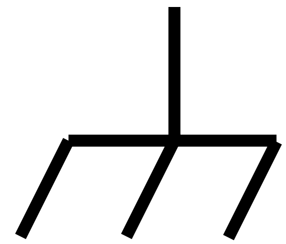
(b) Floating signal source

- Not connected to an absolute reference such as earth or building ground
- Batteries and battery-powered sources, many sensors such as thermocouples, etc.
- Neither terminal is connected to a ground

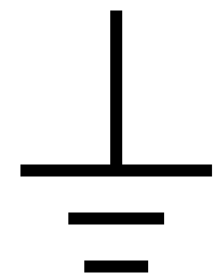
Commons and Grounds

"All grounds are not the same the world 'round."

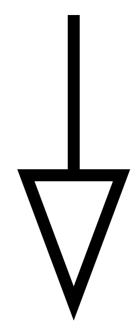
- Circuit or signal *common*



- Earth ground



- Chassis ground

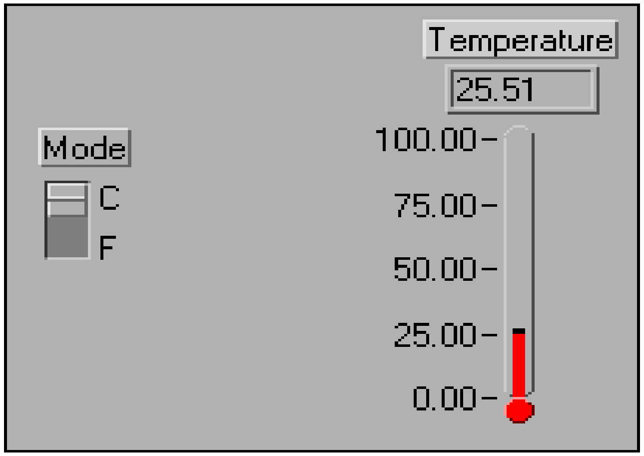


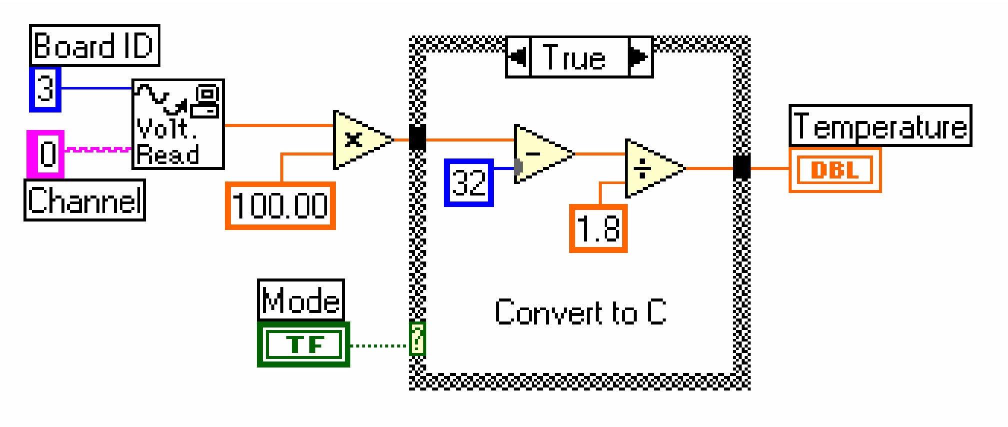
Software: Utilize LabVIEW

- **Virtual Instrument (VI)** – a LabVIEW program
- **Front Panel** – the user Interface of a LabVIEW program (gray background)
- **Block Diagram** – the code of a LabVIEW program (white background)
- **Icon/Connector** – the way to represent a VI within another VI
- **Controls Palette** – User Interface tools
- **Functions Palette** – Programming tools
- **Tools Palette** – Editing and debugging tools

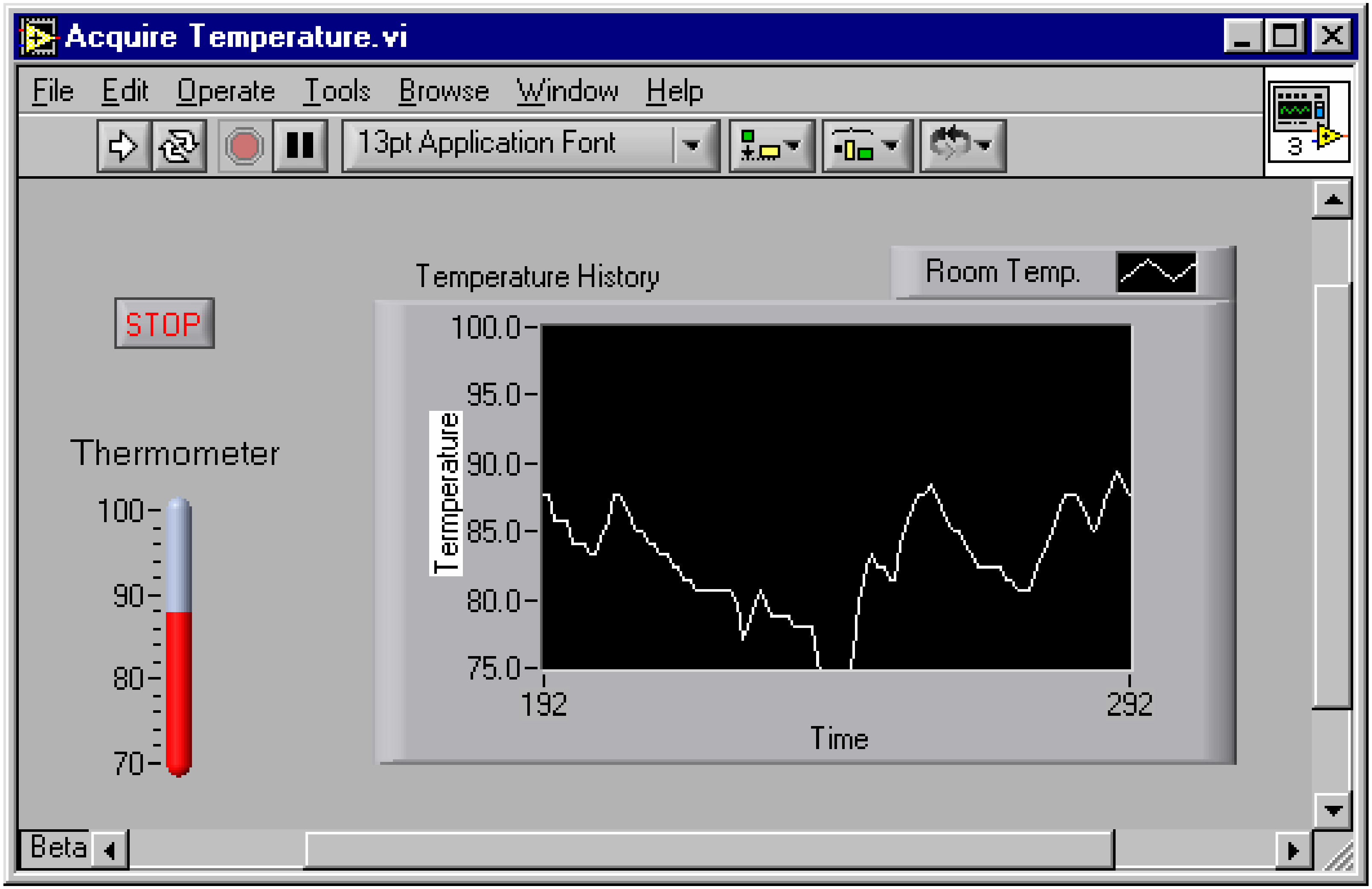
Virtual Instruments (VIs)

- •Front Panel
  - •Controls = Inputs
  - •Indicators = Outputs
- •Block Diagram
  - •Accompanying "program" for front panel
  - •Components "wired" together

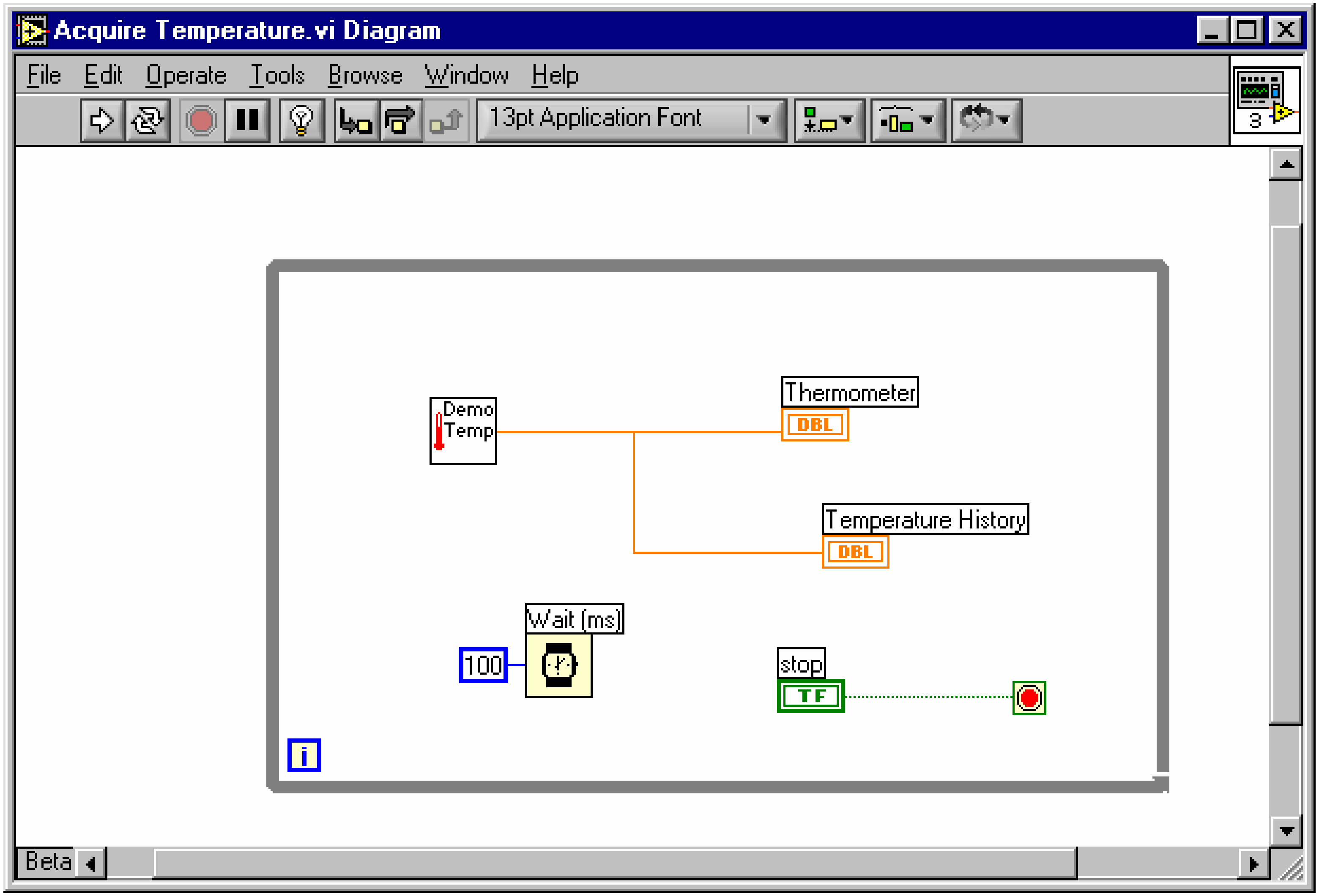




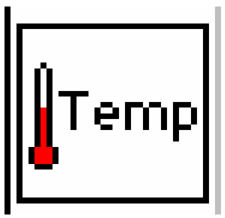
User Interface on Front Panel



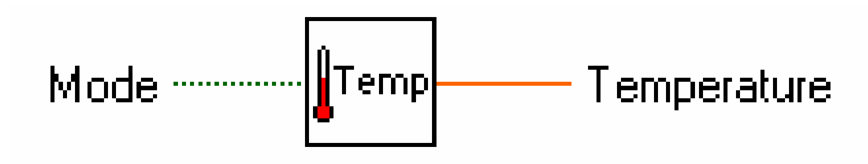
Function in the Block Diagram



Icons and Connectors

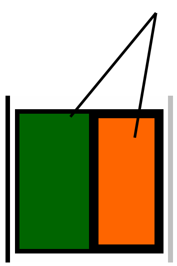


icon



An **icon** represents a **VI** in other block diagrams

terminals



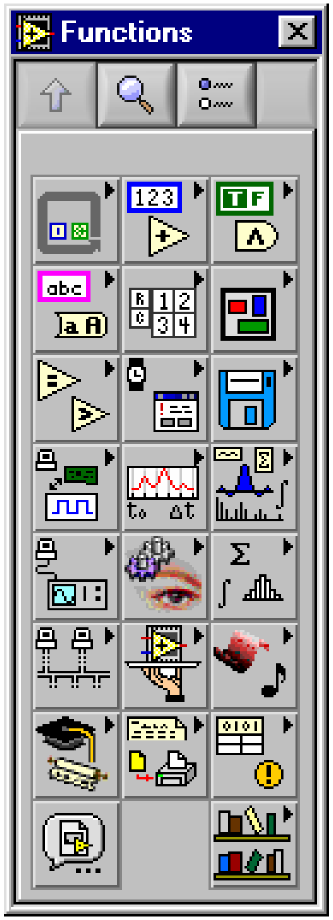
connector

A **connector** passes data to and receives data from a "subVI" through terminals

Control and Function Palettes

Controls Palette
(Panel Window)

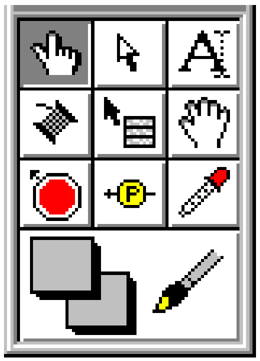
Functions Palette
(Diagram Window)



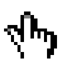
Graphical, floating palettes

Note: These can change in LV versions
Go to "All Functions" to see these menus.

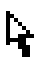
Tools



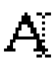
- **Editing and Debugging Tools**
- **Floating Palette**



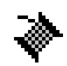
- **Operating Tool**



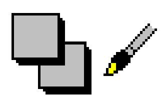
- **Positioning/Resizing Tool**



- **Labeling Tool**

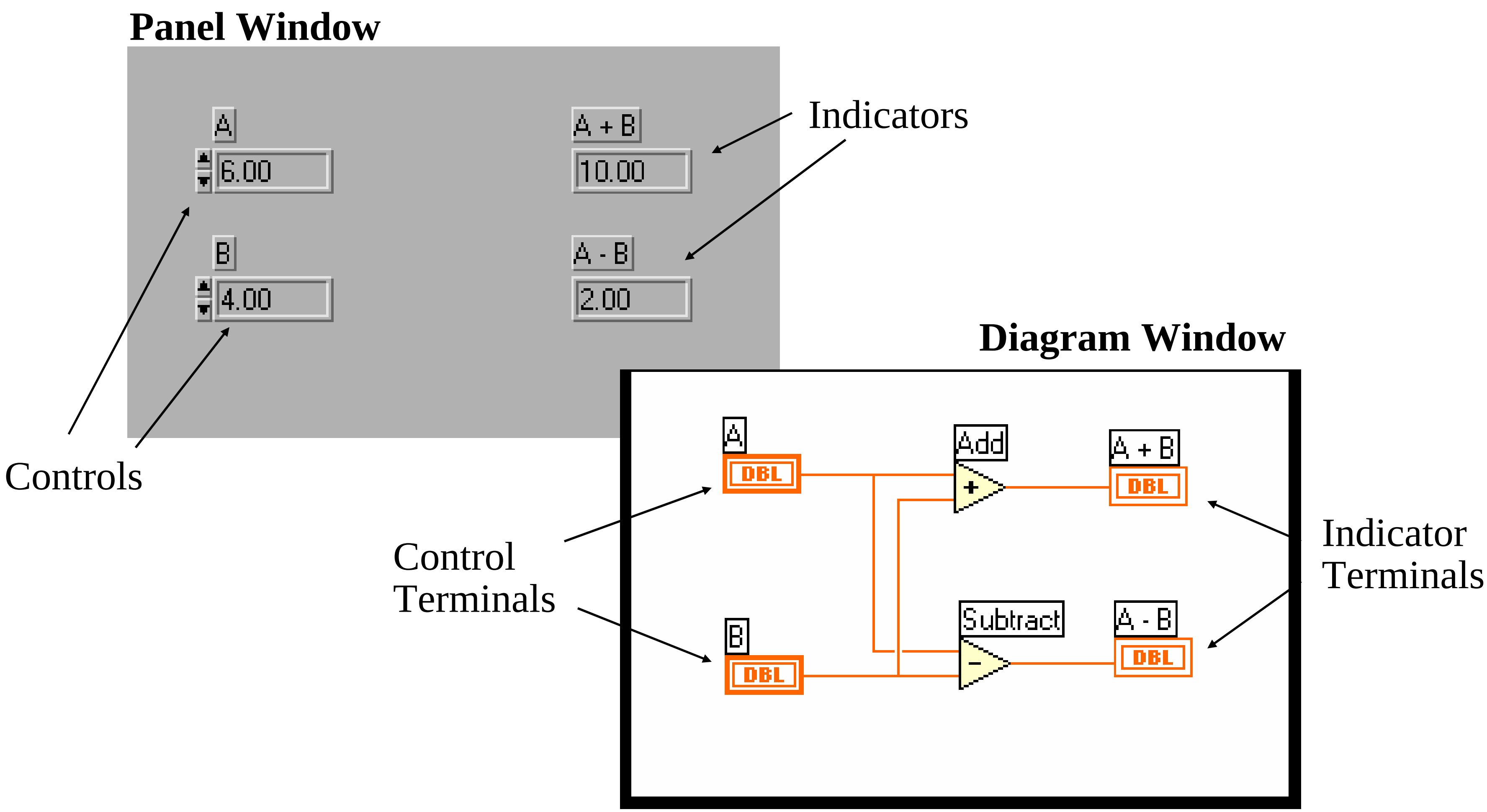


- **Wiring Tool**

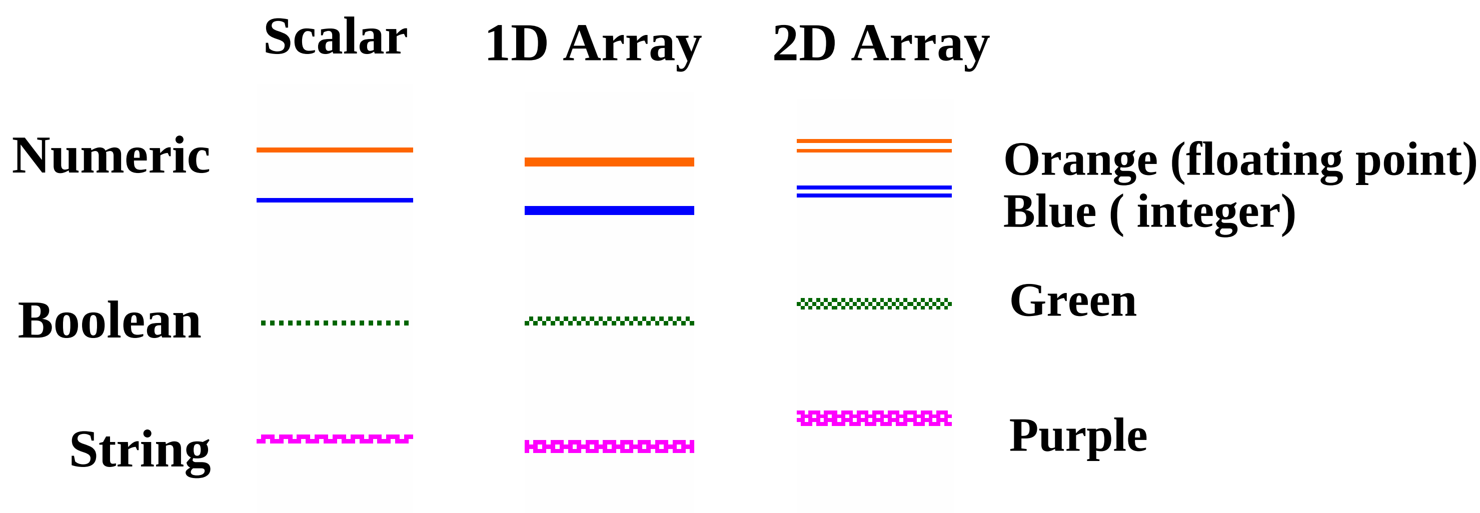


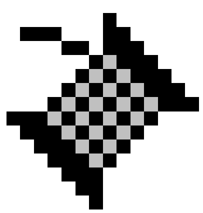
- **Coloring Tool**

The Front Panel and Diagram



Data types in LabVIEW

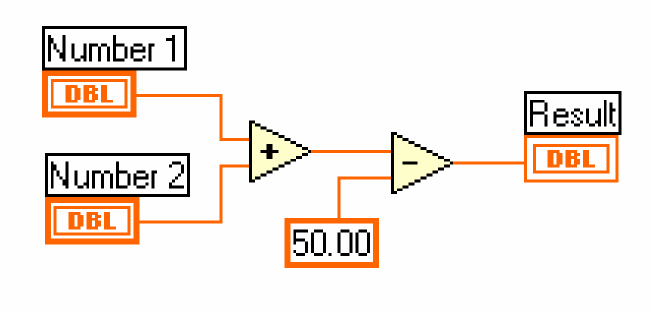


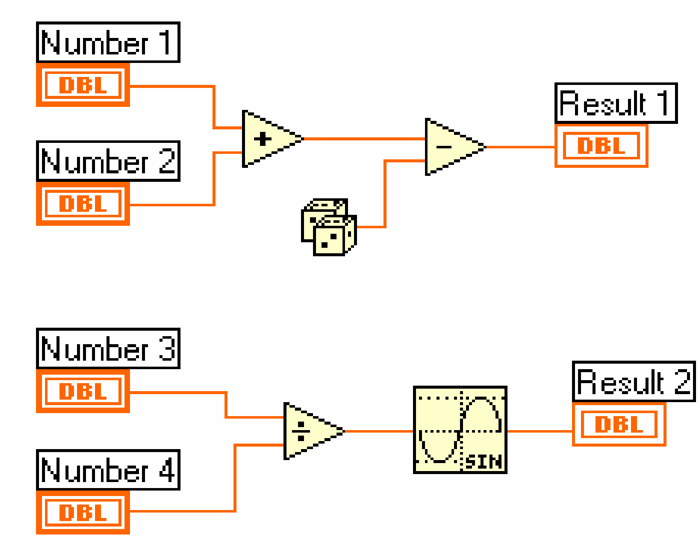


Use your Wiring Tool to wire Objects of your block diagram Together.

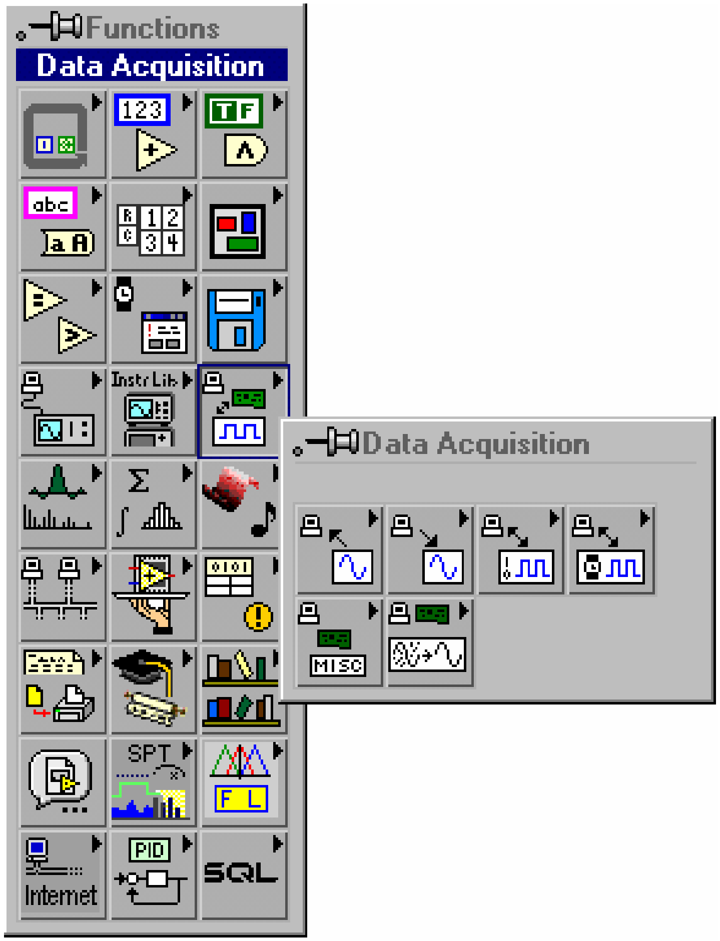
Dataflow Programming

- Block diagram does NOT execute left to right
- Node executes when data is available to ALL input terminals
- Nodes supply data to all output terminals when done



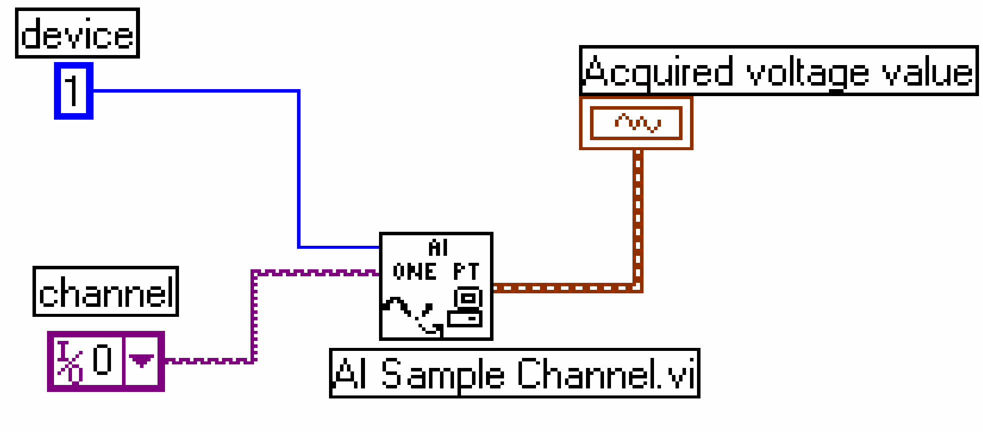


DAQ Functions Palette

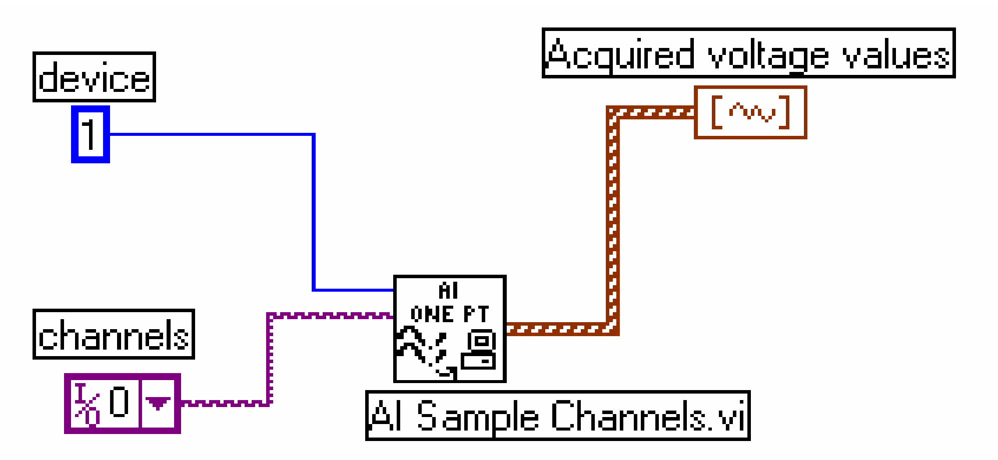


- The Data Acquisition sub-palette is where all the DAQ programming tools are located.
- The tools we will most be interested in using are the ***Analog Input*** tools.

Single value DC measurements

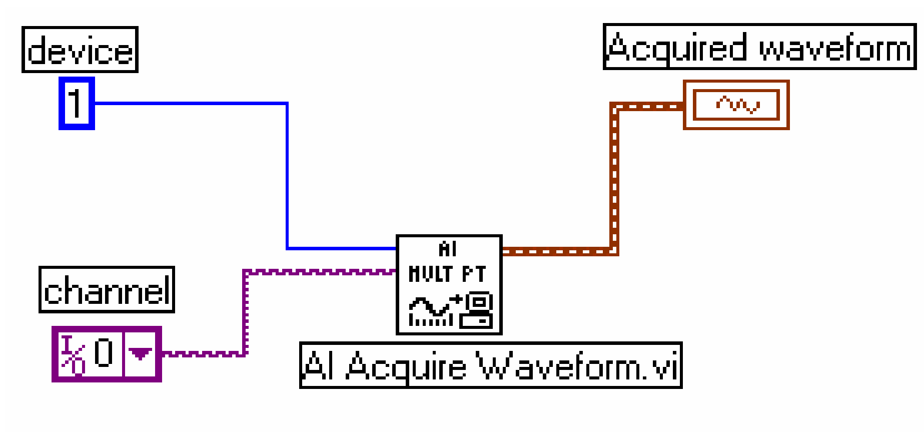


This program acquires one DC voltage value from one channel.

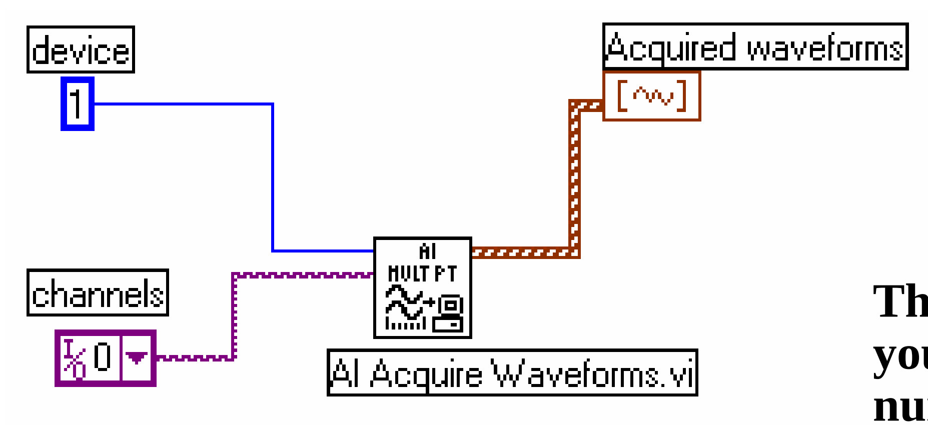


This program acquires one DC voltage value each from multiple channels.

Multiple (Waveform) Acquisition



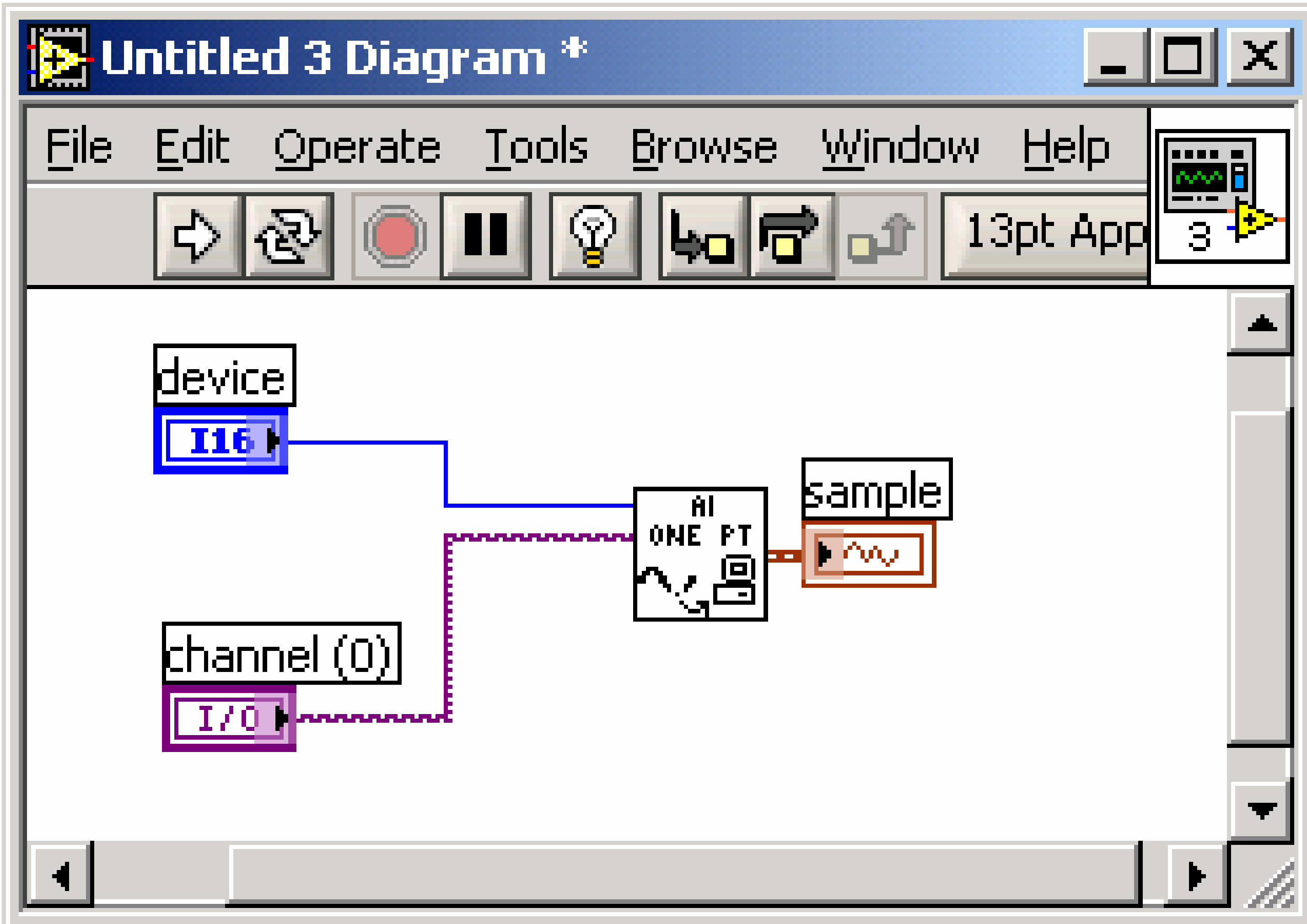
This program acquires one waveform from one channel.



This program acquires one waveform each from multiple channels.

There are inputs to these VIs that allow you to change the sampling rate, number of samples, etc.

Single-point measurements



Waveform measurements