SAND2007-7127P

EXPERIMENTAL MECHANICS (ESP 500)
Session 2
10/23/2007

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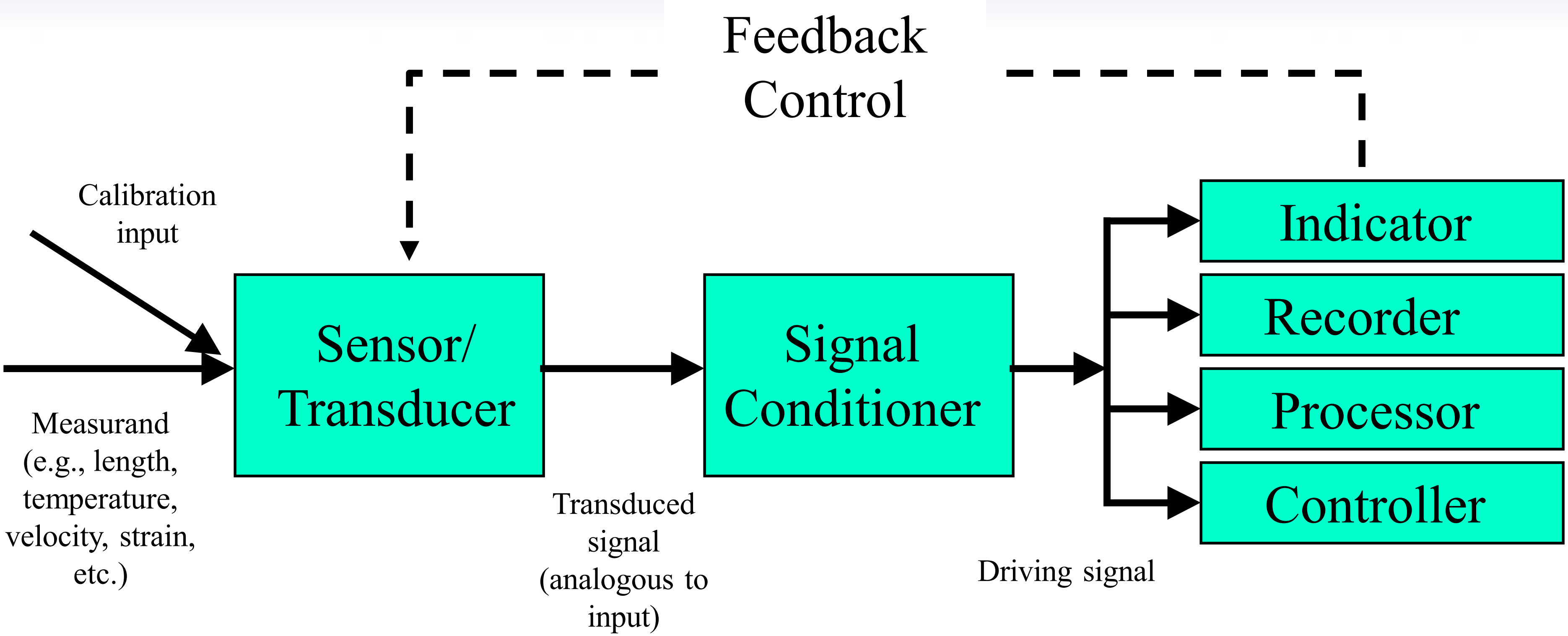
Outline

- Questions from last session?
- Data acquisition

References

- Books listed in Session 1 and:
- Omega Transactions: http://www.omega.com/literature/transactions/volume2/trantocvol2.htmlData acquisition
- National Instruments: http://www.ni.com/dataacquisition/

General Measuring System



- Based loosely on Beckwith and Marangoni, Mechanical Measurements, Fourth Edition, Figure 1.2

Analog signals

- Most measurands originate in analog form
  - Vary smoothly in time, without discontinuity
  - e.g., amplitude, phase, frequency, etc.
- We will discuss analog-to-digital (A/D) and digital-to-analog (D/A) conversion, but not much about measuring digital signals

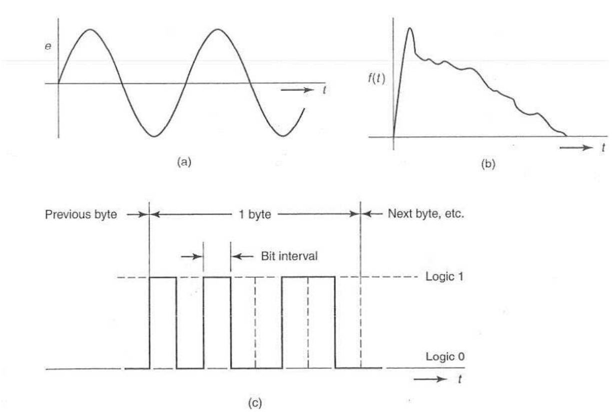


FIGURE 8.1: Examples of voltage–time relationships for analog signals (a) and (b), and a digital signal (c).

← Analog signals continuous in both amplitude and time

← Digital signal with only 2 logic states, discontinuous in both amplitude and time

Analog signals

- What do you want to measure, i.e., what do you need to know about the signal?
- Analog: Level (amplitude, intensity)
- Analog: Frequency – cannot be directly measured but determined by analyzing signal (often by using Fourier transform)

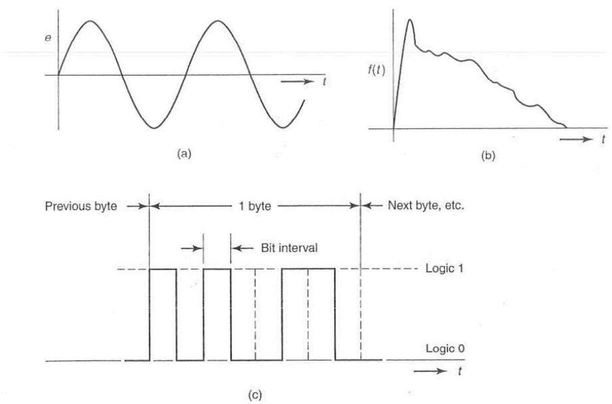
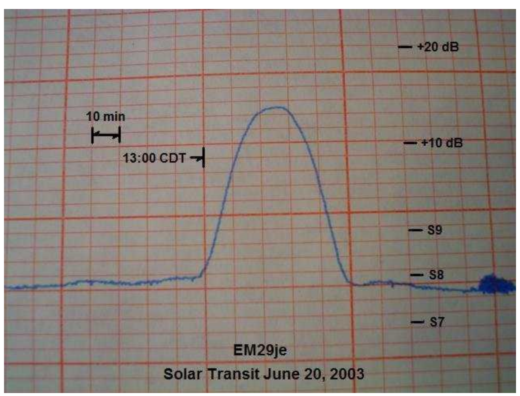


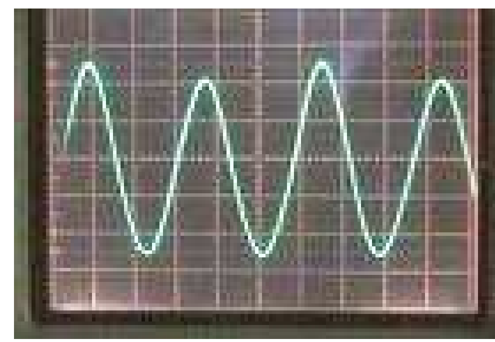
FIGURE 8.1: Examples of voltage–time relationships for analog signals (a) and (b), and a digital signal (c).

- Analog: Shape (important in vibrations, heartbeats, video signals, circuit responses, etc.)
- Digital: state and rate

Analog data acquisition

- Strip chart recorders
- Dials
- Oscilloscope traces (and photos of them)
- Data not ready for immediate processing, still need to be digitized





Digital data acquisition

- The low cost of integrated circuits has pretty much eliminated analog data acquisition
- Even fairly sophisticated instruments are relatively inexpensive
- Easy recording, storage, display, data transfer to colleagues, other computers, etc.
- Much data reduction now done “on the fly”
- Digital signals much more noise resistant. The information content of digital signals is not amplitude dependent. Unless the noise magnitude approaches the signal magnitude (often 5 V), the noise is ignored.
- This is especially important when signals need to be transmitted long distances (e.g., miles in a power plant) or via radio link

Digital data acquisition - example

- We need to measure the pressure in an inaccessible pipe location by using Bernoulli's equation to convert what we can measure to what we need

$$P_1 + \frac{1}{2}\rho u_1^2 = P_2 + \frac{1}{2}\rho u_2^2$$

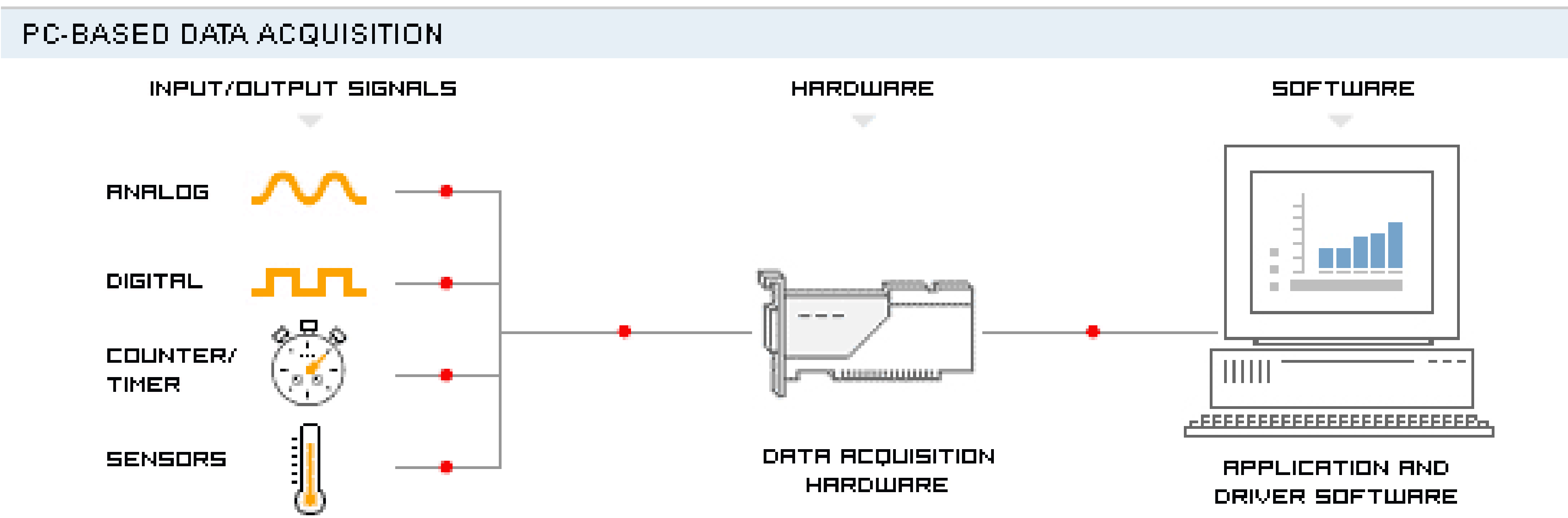
- Where P_1, P_2, u_1, and u_2 are the upstream and downstream pressures and velocities, respectively
- Old way: Record P_1, u_1, and P_2 and calculate u_2 later
- New way: Still record everything, but immediately calculate and display u_2 realtime – allows corrections

Data Acquisition Systems

- Introduction to data acquisition
  - Usually one needs to record data, not just write down a number from a meter or gauge
  - We learned last week that random error can be minimized by additional sampling – data acquisition makes this much easier to do and to control
  - This is true for all measurement applications, including process control where the measured signal is used for feedback control
  - The object of any data acquisition and processing system is to collect the data, process them in the desired fashion, and record the results in a form suitable for storage, presentation, or additional subsequent processing.
  - Data "logging" typically, but not necessarily, indicates slower speed system for long-term data acquisition

Data Acquisition Systems

- National Instruments
- Omega Instruments
- Lots of others



What's important in a data acquisition system (DAS)?

- Acquisition speed (sampling rate)
- Resolution (number of bits)
- Number of acquisition channels (dedicated or multiplexed)
- Settling time
- Output channels (analog or digital)
- Ease of use (software)
- Range
- Triggering
- Gain
- Cost
- etc

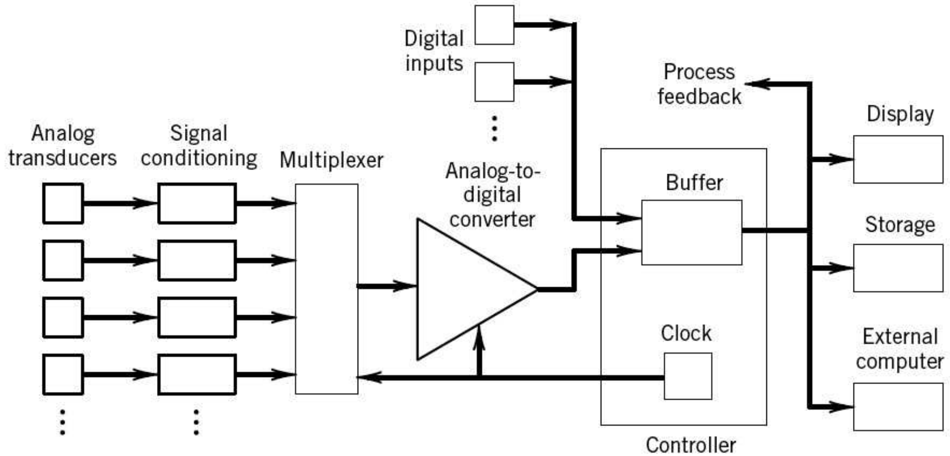


Figure 7.14 Signal flow scheme for an automated data-acquisition system.

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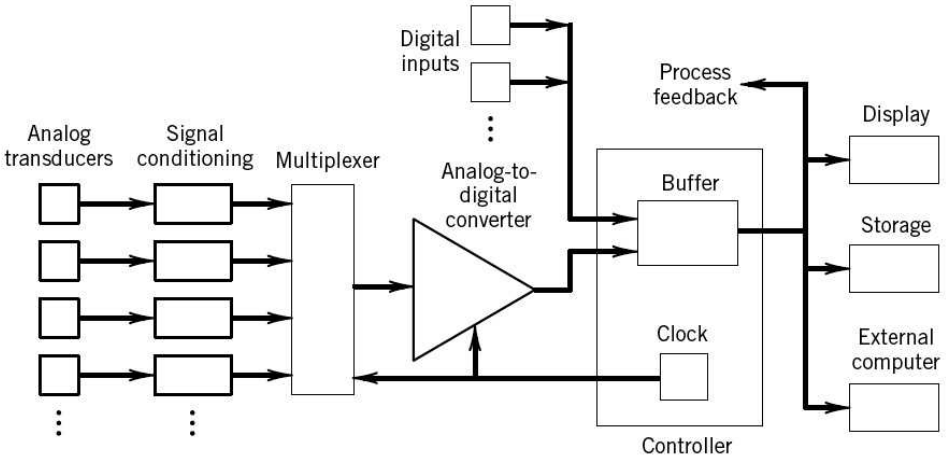
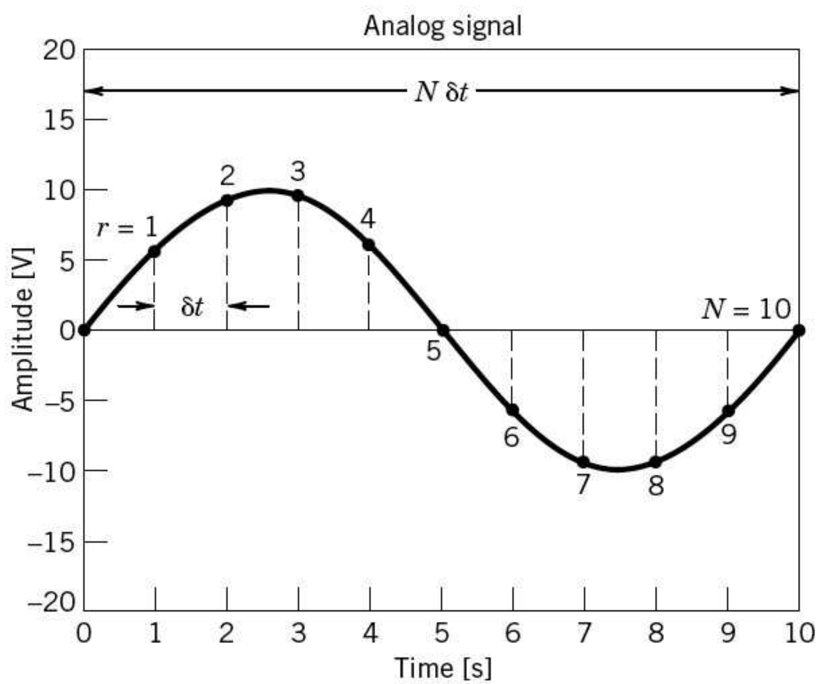


Figure 7.14 Signal flow scheme for an automated data-acquisition system.

Sampling

- Process by which continuous signals are made discrete

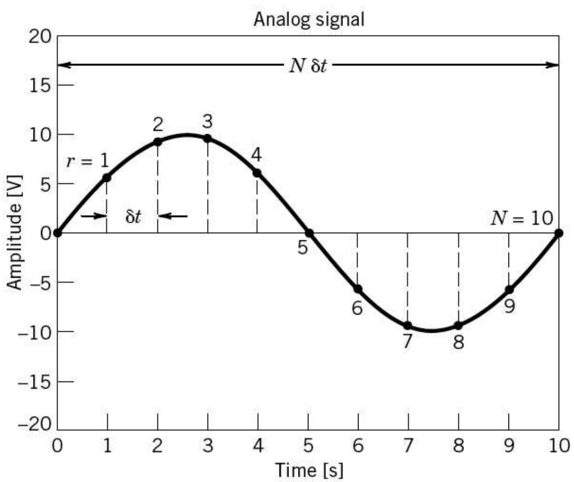


Discrete time signal	
{y(rδt)}	
r	Discrete data
0	0
1	5.9
2	9.5
3	9.5
4	5.9
5	0
6	–5.9
7	–9.5
8	–9.5
9	–5.9
10	0

Figure 7.1 Analog and discrete representations of a time-varying signal.

Sampling (2)

- The information content of the analog and digital signals appear quite different.
- However, important data on amplitude and frequency of signal can be well represented by the discrete series



Discrete time signal

$\{y(r\delta t)\}$

r	Discrete data
0	0
1	5.9
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5	0
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7	–9.5
8	–9.5
9	–5.9
10	0

Figure 7.1 Analog and discrete representations of a time-varying signal.

- Just how well depends on the frequency content of the analog signal, the sampling frequency (time period between discrete samples), and the total sampling period.

Sampling Rate

- Discretely sampled signals
- Varying sampling frequency gives very different perceptions of analog signal (10 Hz sine wave here)
- Nyquist sampling theorem states that in order to reconstruct the frequency content of a measured signal accurately, the sampling frequency must be more than twice the highest frequency contained in the measured signal
- $f_s > 2f$
- or $\delta t < 1/(2f)$

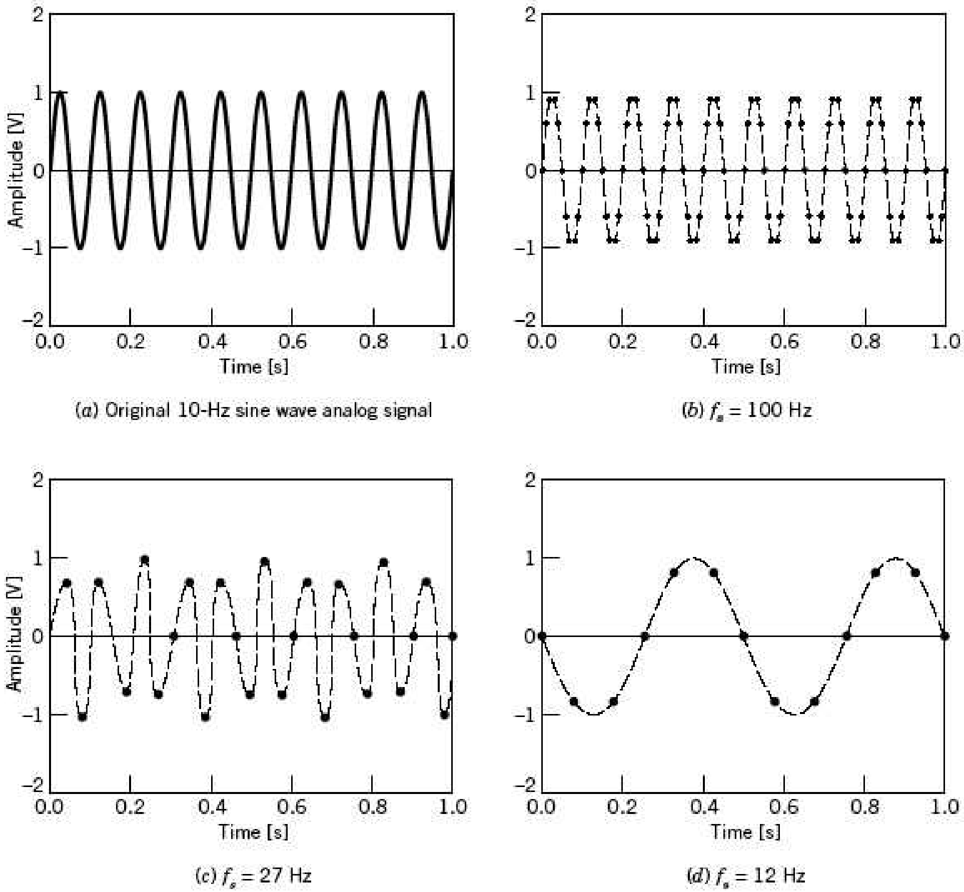
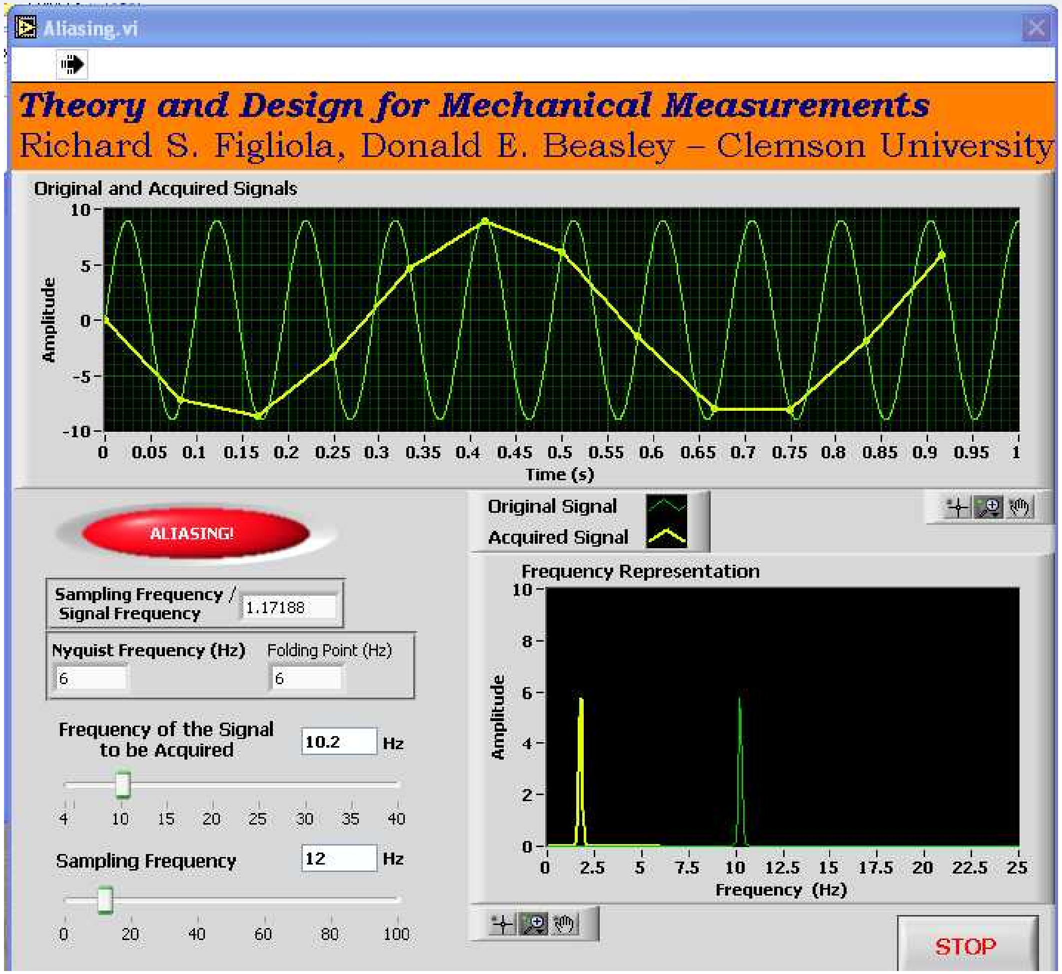


Figure 7.2 The effect of sample rate on signal frequency and amplitude interpretation.

Aliasing

- This is an important consideration in determining the maximum measurable frequency
- The Nyquist frequency is half of the sampling frequency, $f_{Nyq} = f_s/2$. Signals with frequencies greater than the Nyquist frequency f_{Nyq} appear as alias frequencies *less* than f_{Nyq} in the sampled signal.
- In other words, when $f_s \leq 2f$ the higher frequency content of the analog signal takes on a *false* appearance of a lower frequency in the discrete series, e.g., Figure 7.2d (previous slide) shows false alias frequency of 2 Hz
- Trade off: Higher sampling $f_s \rightarrow$ larger data files

Aliasing (Figliola vi)



Aliasing Gotcha

- What if you don't know the frequency content of the signal you are going to measure?
- Use a low pass filter set at the Nyquist frequency f_{Nyq} to remove the signal's frequency content at and above f_{Nyq} prior to sampling (anti-aliasing filter)
- Or sample so fast that the measured signal will not have any frequency content > f_{Nyq} (hard to guarantee that!)
- Be careful: Once aliasing occurs there is no way to distinguish between real and false frequency components.

Size of sample

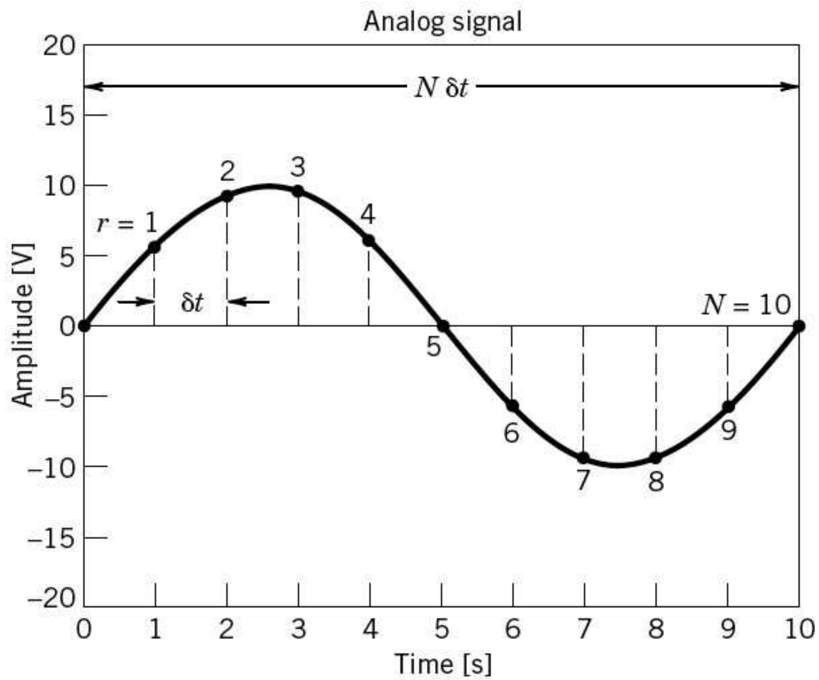
- Needed to determine the lowest measurable frequency
- If a waveform is to be resolved by discrete sampling, one or more full periods of the waveform must be present in the sampling period
- Since the period of sampling $T = N\Delta t = N/f_s$, where N is the number of points in the sample, the lowest resolved frequency is

$$f_{lowest} = \frac{1}{T} = \frac{1}{N\Delta t} = \frac{f_s}{N} \equiv \Delta f$$

- No lower frequency (other than $f = 0$) can be resolved
- Δf is also the frequency resolution, i.e., f changes less than Δf will not be measured in the discrete Fourier transform

Sampling

- Process by which continuous signals are made discrete



Discrete time signal

$\{y(r\delta t)\}$

r	Discrete data
0	0
1	5.9
2	9.5
3	9.5
4	5.9
5	0
6	–5.9
7	–9.5
8	–9.5
9	–5.9
10	0

Figure 7.1 Analog and discrete representations of a time-varying signal.

Size of sample

- How to use this in the lab?
- After the sample rate f_s is determined, estimate the lowest frequency of interest in the signal or estimate the frequency resolution needed to accurately resolve the frequency components in the signal. Then choose the number of points in the sample, N, to give the desired $\Delta f = f_s/N$

Size of sample

- Example:
  - If you need a 200 Hz sampling frequency to resolve the highest expected frequency in the signal (or if the anti-aliasing filter is set at 100 Hz), then:

N	$\Delta f = f_s/N$*
2	100 Hz
10	20 Hz
100	2 Hz
200	1 Hz
2000	0.1 Hz

*Lowest detectable frequency *and* frequency resolution of DAQ

What's important in a data acquisition system (DAS)?

- Acquisition speed (sampling rate)
- **Resolution (number of bits)**
- Number of acquisition channels (dedicated or multiplexed)
- Settling time
- Output channels (analog or digital)
- Ease of use (software)
- Range
- Triggering
- Gain
- Cost
- etc

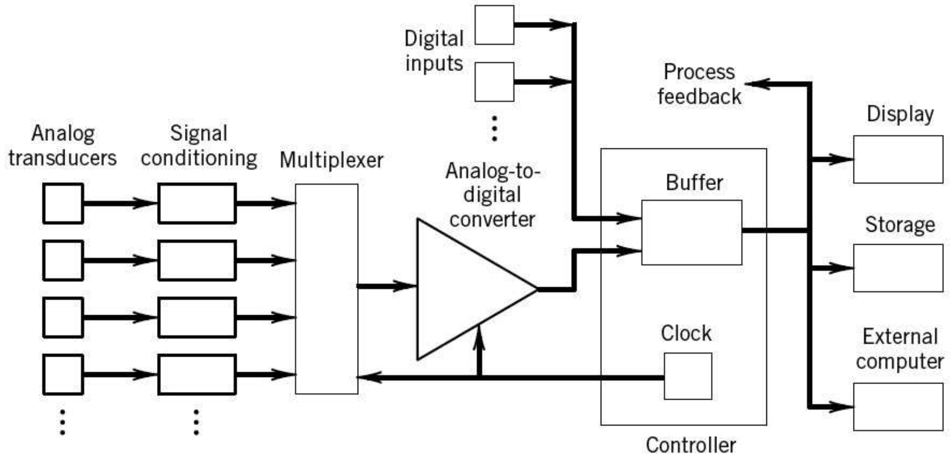


Figure 7.14 Signal flow scheme for an automated data-acquisition system.

A/D Resolution

- The raw analog signal is sampled into quantized (distinct, discontinuous) levels in the A/D process
- The size of each step (quantization level) depends on the bit resolution of the A/D system

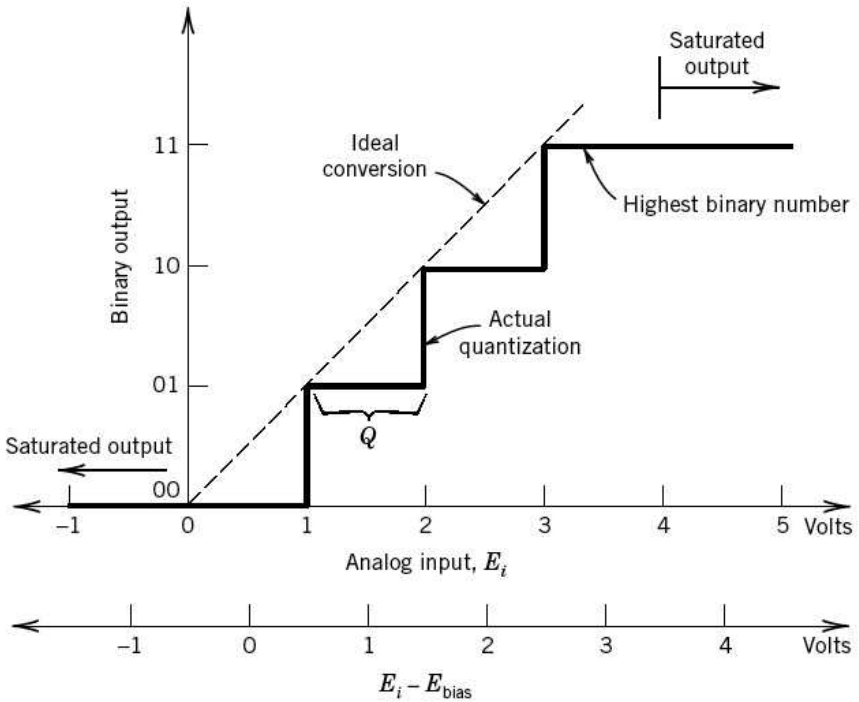


Figure 7.7 Binary quantization and saturation. (2-bit)

- The higher the number of bits the better the resolution, i.e., the smaller is the detectable voltage change
- Data are represented as an *n*-bit binary word, which can designate 2^n different levels

# bits	# levels (2^n)
2	$2^2 = 4$
8	$2^8 = 256$
12	$2^{12} = 4096$
16	$2^{16} = 65536$

A/D Conversion Considerations

- Resolution and Quantization Error
  - There is a smallest increment of input voltage change that can be resolved by the A/D converter
  - In general, the voltage resolution per bit, ε_V, depends on the full-scale voltage range and the number of bits of the converter

$$\varepsilon_V = \frac{\Delta V_{fs}}{2^n}$$

where ΔV_{fs} = the full-scale voltage range

n = the number of bits of the A/D converter

  - Typical A/D converters have 8, 12, or 16 bits, corresponding to dividing ΔV_{fs} into $2^8 = 256$, $2^{12} = 4096$, $2^{16} = 65{,}536$ increments
  - Now even $2^{24} = 16{,}777{,}216$ increments

A/D Conversion Considerations

- Resolution and Quantization Error (cont)
  - The finite resolution of the A/D converter introduces error into the recorded values, since the actual analog voltage usually lies between available bit levels
  - An estimate for the quantization uncertainty is $u_q = \varepsilon_V/2$ (95%)
  - Obviously, quantization error can be reduced by using an A/D with more bits

A/D Resolution Example

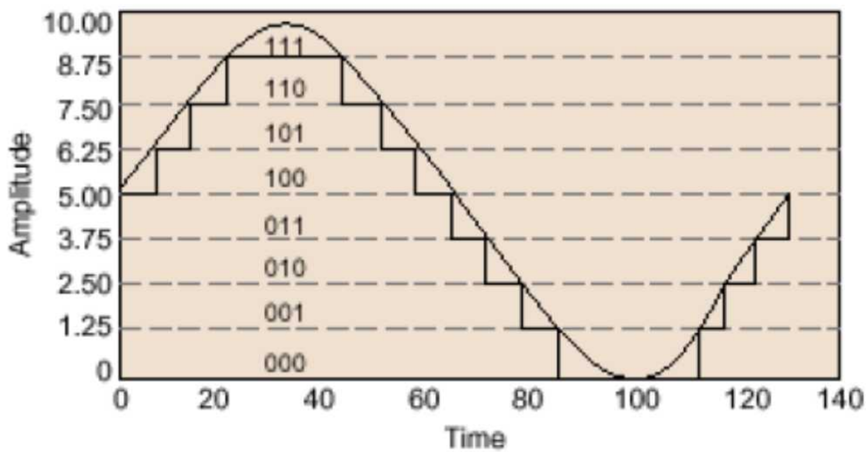


Figure 2. Digitized Sine Wave with a Resolution of Three Bits

2^3 = 8 levels

ΔV_{fs} = 10 V

Resolution ε_V = 10 V/8 = 1.25 V so as shown voltage changes of less than 1.25 V are not measured (i.e., signals of 0-1.24 V all register as 000 but 1.25-2.49 V all register as 001)

$u_q = \varepsilon_V/2$ = 1.25 V/2 = 0.625V (95%)

A/D Resolution Example

- Compute the relative effect of quantization error in the quantization of a 100 mV and a 1 V signal using 8-bit and 12-bit A/D converters, both having a full scale range of 10 V.
  - 8-bit: $\varepsilon_V = \Delta V_{fs} / 2^8 = 10/256 = 39$ mV
    $u_q = \varepsilon_V/2 = 19.5$ mV (95%)
  - 12-bit: $\varepsilon_V = \Delta V_{fs} / 2^{12} = 10/4096 = 2.4$ mV
    $u_q = \varepsilon_V/2 = 1.2$ mV (95%)

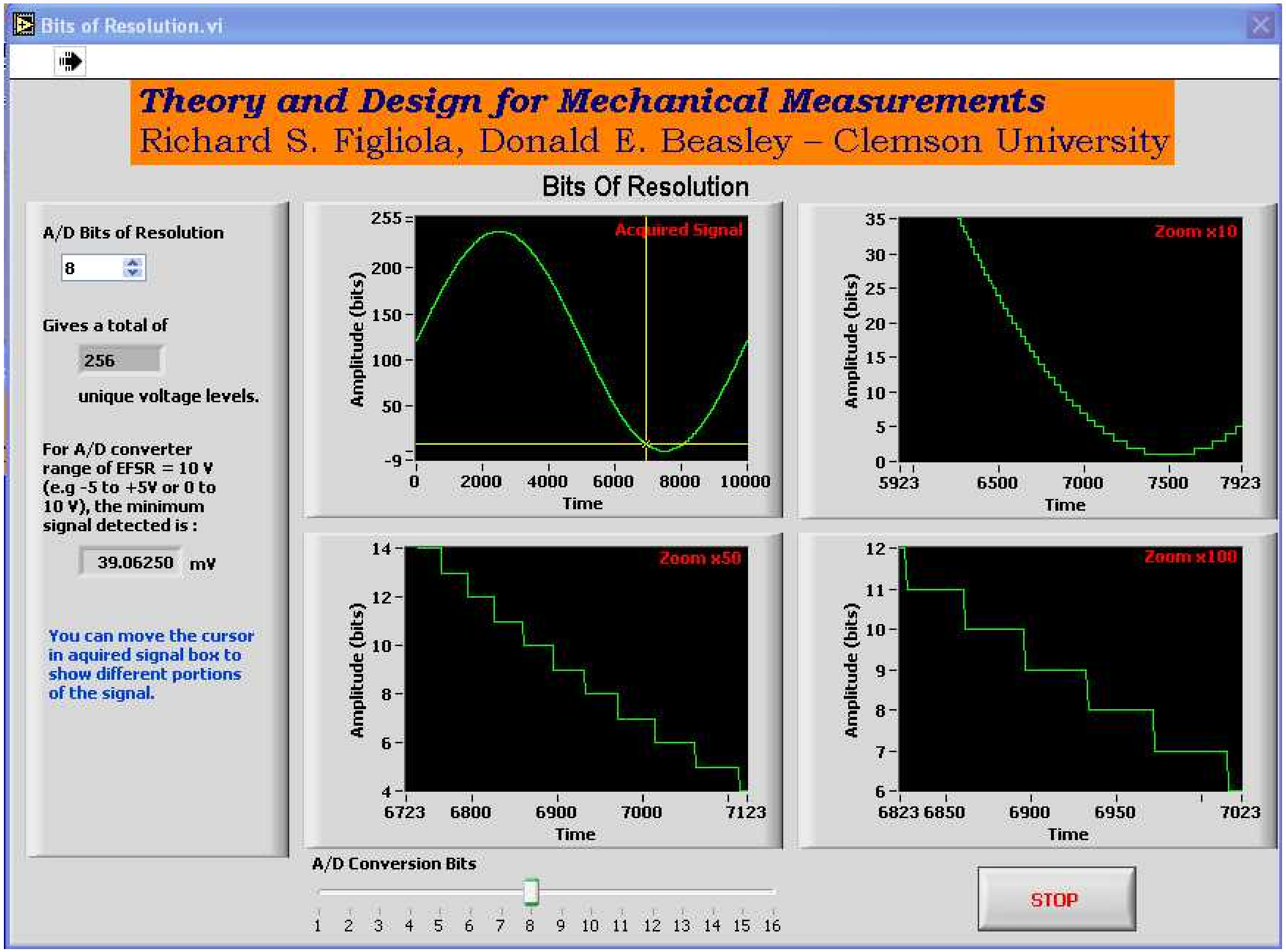
Determined purely by the full scale voltage range and the number of bits

- Consider % error:

Signal	N	u_q	% error
100 mV	8	±19.5 mV	19.5%
100 mV	12	±1.2 mV	1.2%
1 V	8	±19.5 mV	1.95%
1 V	12	±1.2 mV	0.12%

Relative error much greater at lower voltage levels. Generally want to amplify analog signal to use as much of full A/D range as possible.

Bits of Resolution (Figliola vi)



A/D Resolution

- Example: How many bits would you need to divide 10 V into .01 V intervals?
- Dividing 10 V into .01 V intervals gives 1000 intervals (10/0.01 = 1000)
- We then need a power of 2 that is larger than 1000.
  - The smallest power of 2 that is larger than 1000 is 2^{10} which is equal to 1024.
- That means that you need 10 bits in the converter, and the count in the counter/register will run from 0 to 1023.
- Real converters often go to 10.23 V, not 10 V because that gives perfect .01 V increments between resolvable voltages.
  - Another converter might run from -5.12 V to +5.11 V for the same reason.
- More is better when it comes to bits in an A/D. The indicated voltage will be closer to the actual value of the voltage being measured when there are more bits.
- More is pricier when it comes to bits in an A/D. It takes more parts, and they have to be made more accurately if there are more bits.

http://www.facstaff.bucknell.edu/mastascu/elessonshtml/Interfaces/ConvAD.html

Saturation Error

- The A/D converter has well-defined upper and lower limits of signal response, often 0 to 10 V or -10 V to +10 V.
- If the input signal exceeds the upper or lower limits the converter saturates and the recorded signal no longer varies with the input
- Can usually be prevented by appropriate signal conditioning prior to sampling

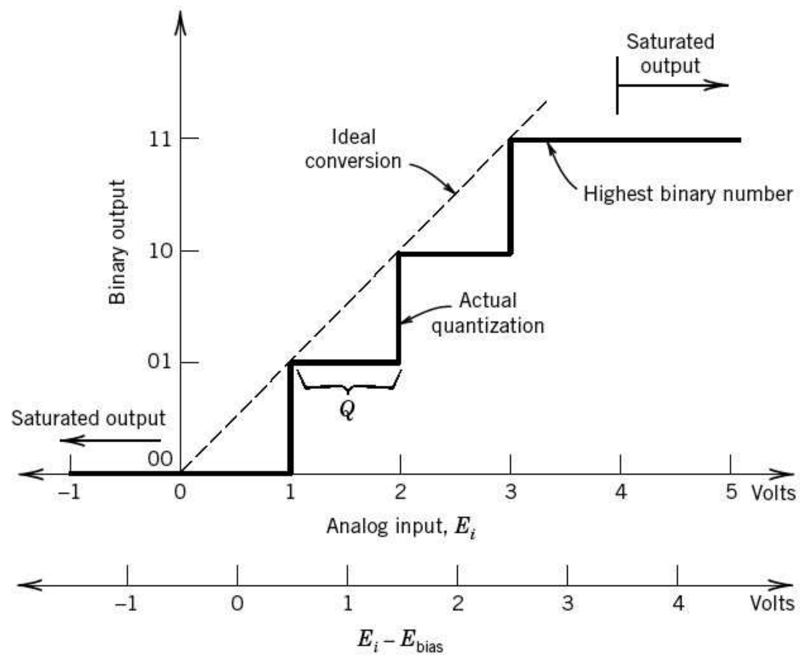
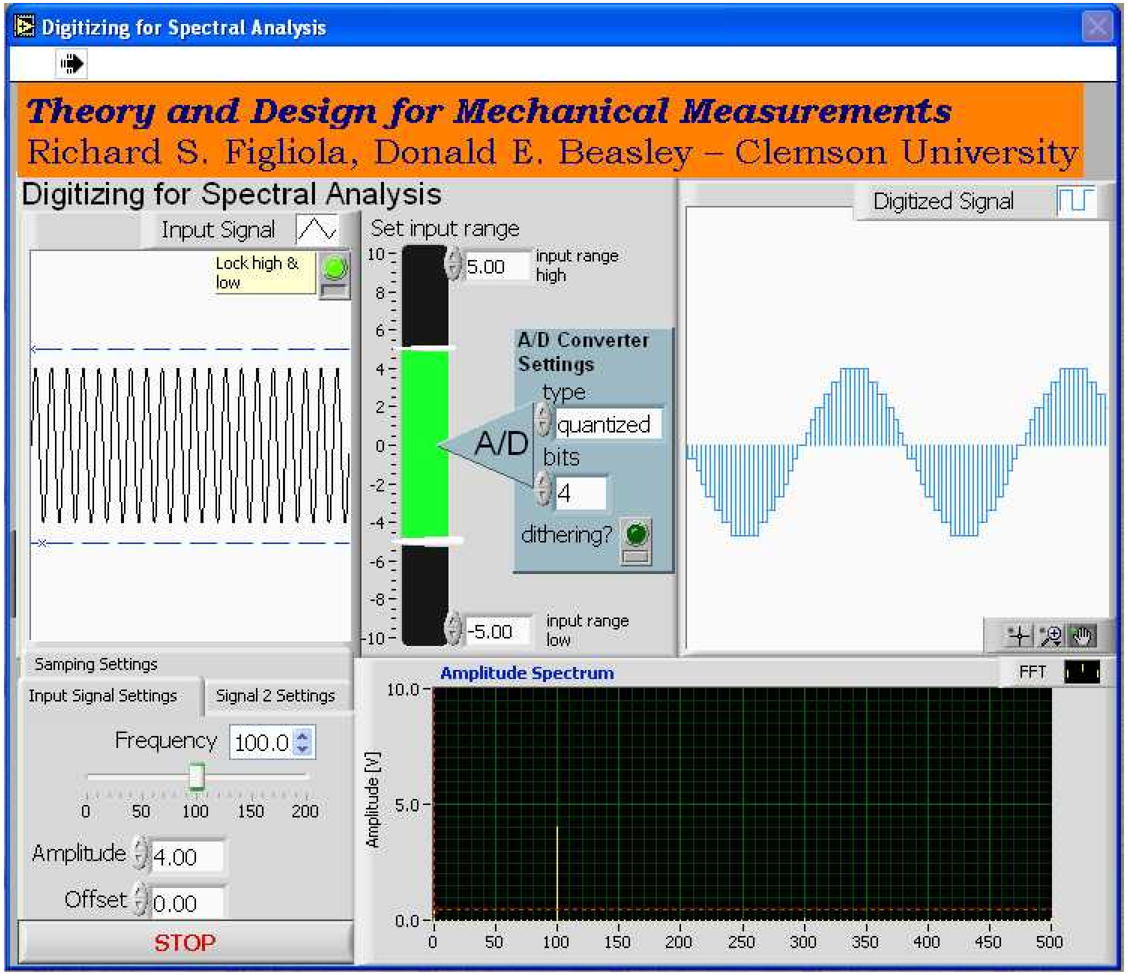


Figure 7.7 Binary quantization and saturation.

Digitizing for Spectral Analysis (Figliola vi)



What's important in a data acquisition system (DAS)?

- Acquisition speed (sampling rate)
- Resolution (number of bits)
- **Number of acquisition channels (dedicated or multiplexed)**
- Settling time
- Output channels (analog or digital)
- Ease of use (software)
- Range
- Triggering
- Gain
- Cost
- etc

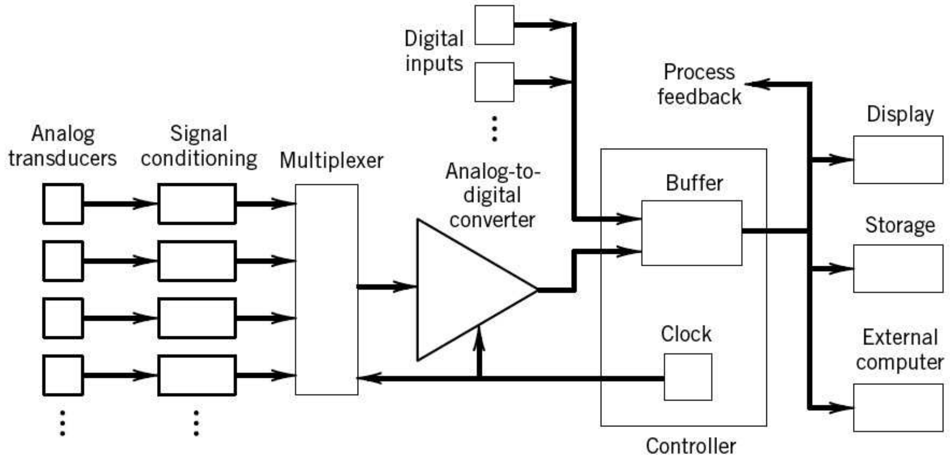


Figure 7.14 Signal flow scheme for an automated data-acquisition system.

Number of channels

- Usually specify single-ended or differential
  - Single-ended inputs are all referenced to a common ground
  - Best used when:
    - Signals are strong (greater than 1 V)
    - Leads from signal source to analog input hardware are short (less than 15 ft)
    - All input signals share a common ground reference
  - If the above don't hold, use differential inputs
    - Each input has its own ground reference
    - Noise errors are reduced because the common-mode noise picked up by the leads is cancelled out

- Often the user can select, e.g., 4 differential or 8 single-ended inputs
- Does each channel have its own A/D converter or are they multiplexed (as shown)
- Multiplexer also called "scanner/programmer" since it usually can be programmed for scan sequence, rate, etc.

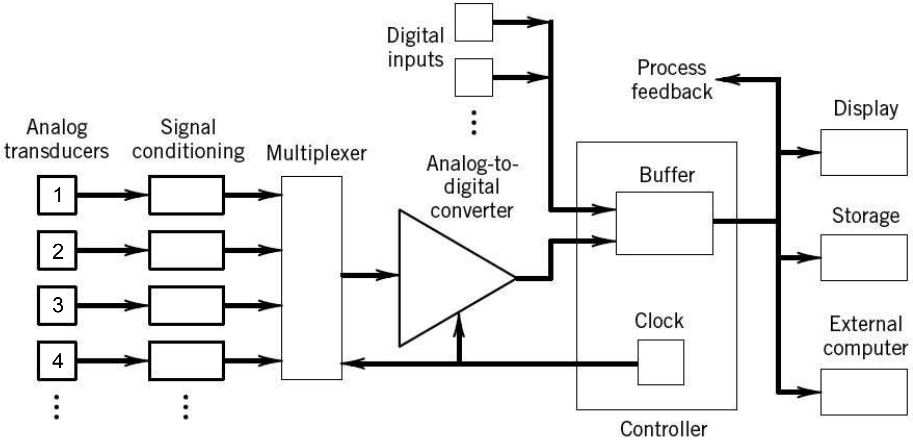
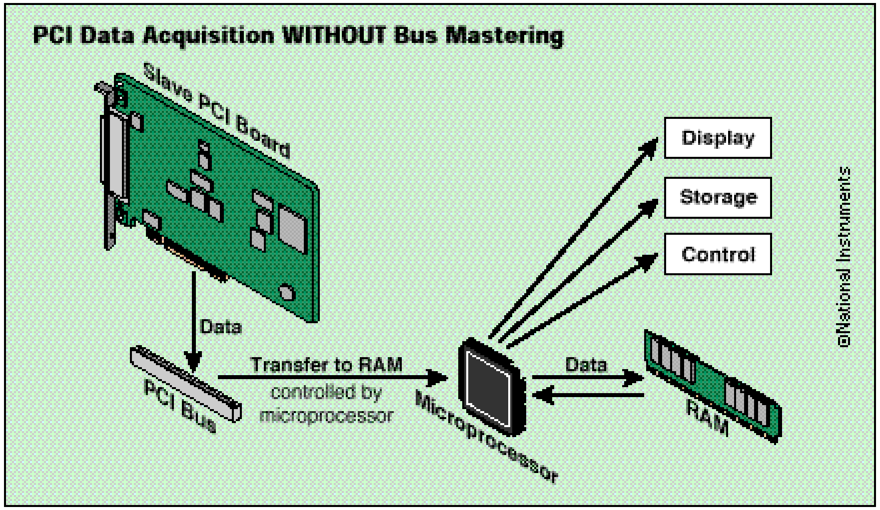


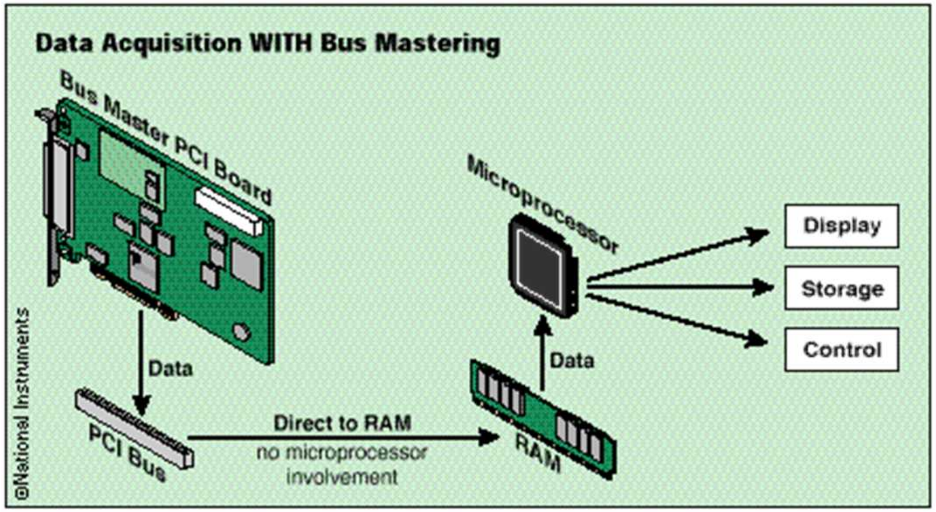
Figure 7.14 Signal flow scheme for an automated data-acquisition system.

Data transfer speed

- DAQ boards are usually installed in a PC on a high-speed bus like PCI
  - PCI allows 20 MHz to 40 MHz data transfer from microprocessor to RAM
- Bus mastering allows much faster, direct transfer to RAM
  - Higher cost



conventional



with bus mastering

A/D and D/A

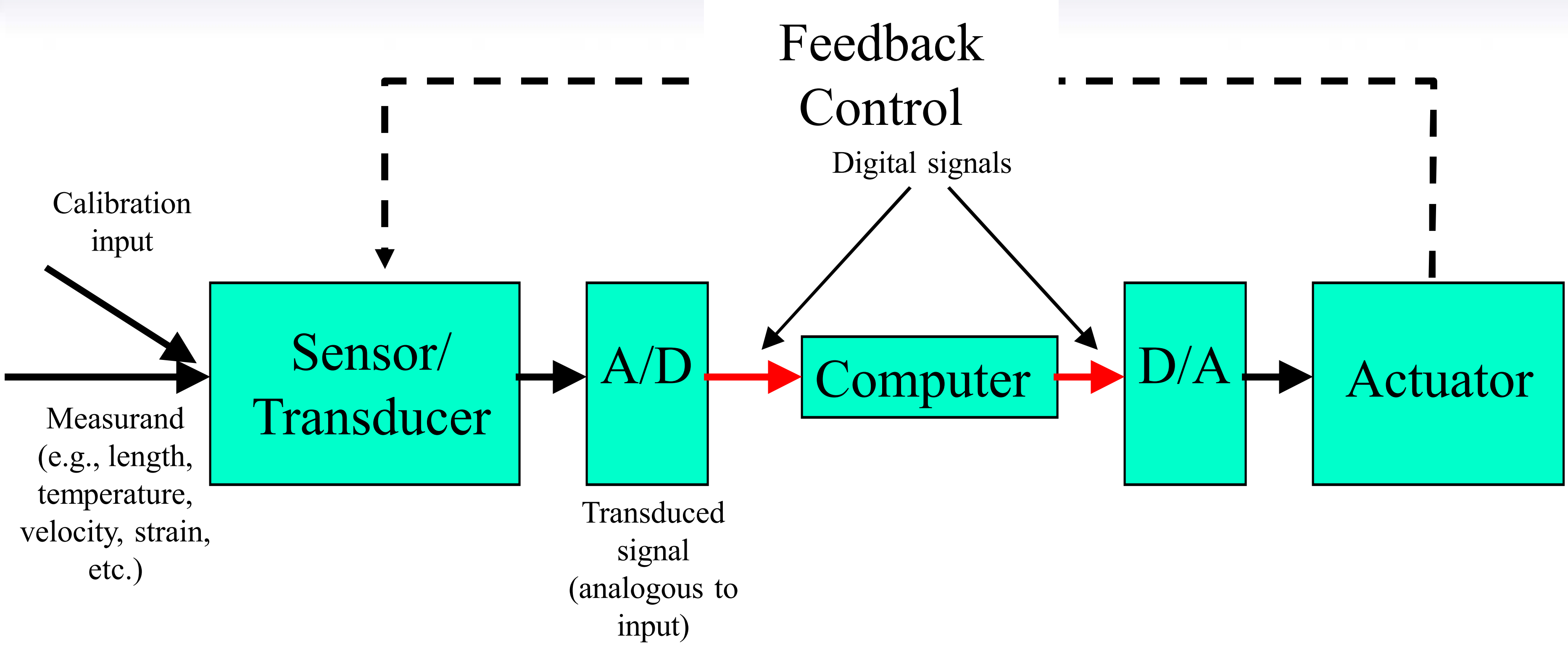
- Many A/D converters contain D/A converters within them, often embedded in places where you might not expect to find them.
- You may not think that you have ever used a D/A, but we will convince you that you have. We'll do that by having you use one you have used before.
- First, we need a source of digital signals that we can convert to analog signals. A common source is a music CD.
- The CD has tiny little pits on the surface. A low power laser lights the CD, and the reflectivity is different where there is a pit. That means that the reflected laser signal can be used to read the zeroes and ones on the CD.
- So, as the CD spins in the holder, a sequences of zeroes and ones is generated and sent on.
- That sequence of zeroes and ones is converted to an analog voltage that is amplified and fed to an earphone or a speaker.
- So, you have used D/A before - if you have ever used a CD player.

http://www.facstaff.bucknell.edu/mastascu/elessonshtml/Interfaces/ConvAD.html

A/D and D/A examples

- Telephones
- Satellite TV
- Satellite radio
- CDs
- DVDs
- ...

A/D and D/A in control system



A/D Conversion Considerations

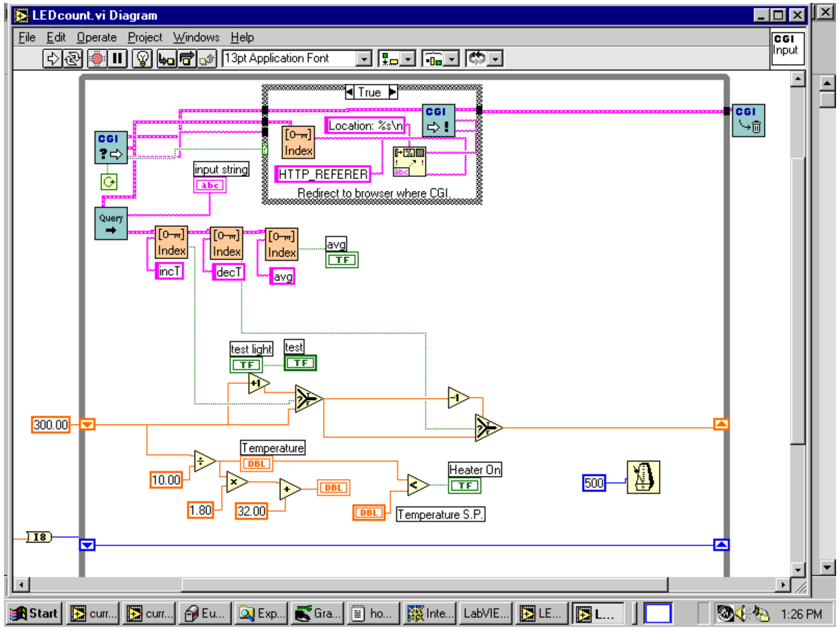
- Sample Rate
  - Be careful about multiplexed signals
    - Some A/D systems use a multiplexer so that the expensive components don't have to be duplicated for every channel
    - Make sure that you know the actual sampling frequency f_s for each channel (f_s for each channel = total f_s/# of channels)
- Signal conditioning for A/D conversion
  - Conditioning of the analog signal is often needed to
    - Prevent aliasing
      - By using a low pass, or antialiasing, filter to remove frequencies of $f_s/2$ or more from the analog signal.
    - Use as much of the A/D full range as possible
      - Amplify to minimize effect of quantization error
      - But be careful not to saturate

Current Specifications

- Constantly changing – check with manufacturers
  - 24-bit resolution
    - Sometimes noise knocks down usable bits (noise level exceeding bit resolution)
  - 60 Ms/sec
  - Increasing use of true simultaneous sampling on multiple channels rather than multiplexing
    - Potentially big speedup since no longer need to wait for A/D amplifier to settle down before multiplexing to next channel

DAQ Philosophy

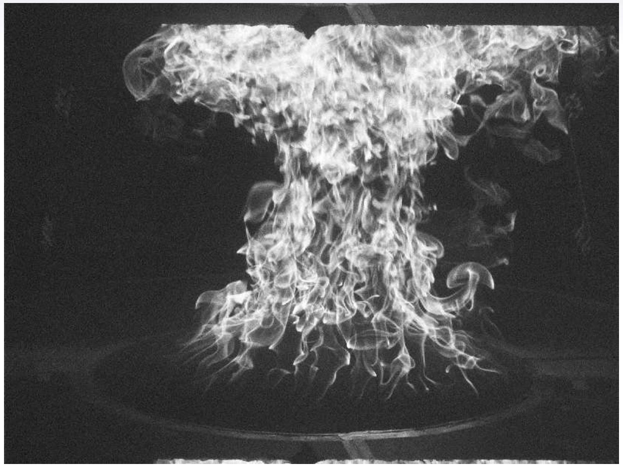
- Make sure data are useful after you have moved on
  - Characterize uncertainty
    - This will be much harder for someone else to figure out later
  - Save raw data in addition to processed data
  - Document DAQ procedure
  - Document data analysis procedures



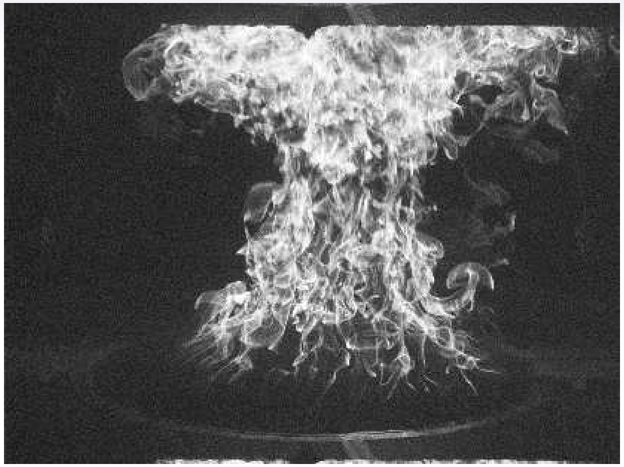
Digital Imaging

- Another type of digital data acquisition widely used in experimental mechanics
- CCD cameras (Charge Coupled Device)
  - Bit depth (here related to number of gray scales in image)
    - 8 bit (256 gray levels)
    - 12 bit (4096)
    - 16 bit (65,536)
  - Image is digitized into pixels - Pixel resolution
  - Acquisition speed (time to empty and clean shift register)
  - Interframe transfer for high-speed imaging
  - Digital video framing rates - stringent data transfer requirements
- CMOS (Complementary Metal Oxide Semiconductor) cameras

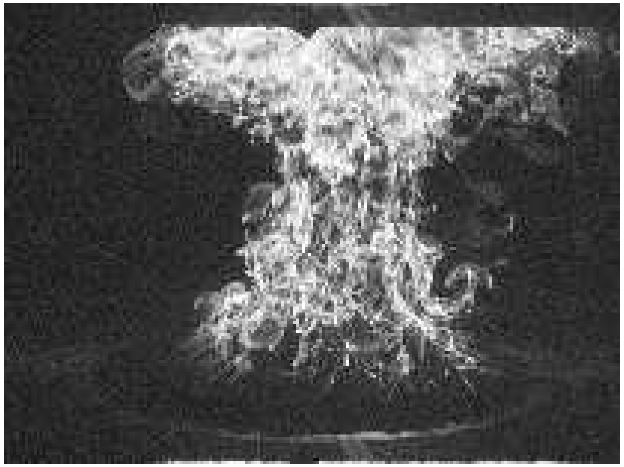
Digital Imaging



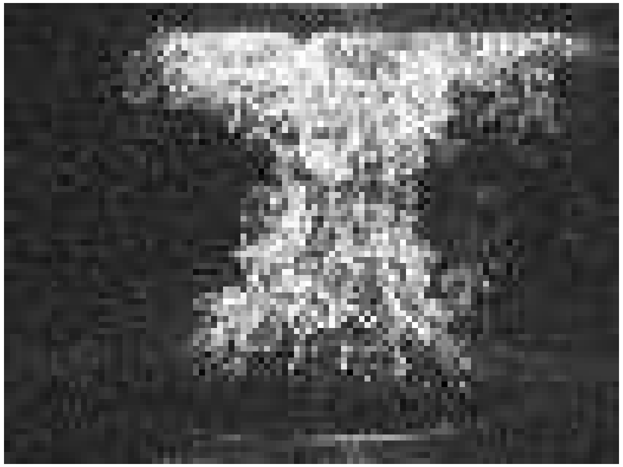
827 × 620 pixels, 8 bit, 503 KB



485 × 346 pixels, 8 bit, 166 KB



207 × 155 pixels, 8 bit, 33 KB



104 × 78 pixels, 8 bit, 9 KB

Digital Imaging

- Video framing rate:
  - 30 frames/second of standard video (640 × 480 pixels), 24-bit color (red, green, blue, each 8-bit), yields:

    $$30 \times 640 \times 480 \times 24 = \underline{221 \times 10^6 \text{ bits/second}}$$

  - Requiring fairly high speed computer connection (USB 2 or IEEE 1394 (FireWire) bus) – and this is a pretty simple camera
- For comparison, consider music CD:
  - Must reproduce full spectrum of human hearing, containing frequencies up to 20 kHz
  - It is sampled at 44.1 kHz (giving a Nyquist frequency f_{Nyq} = 22 kHz)
  - Each sample is 16-bit, and there are 2 channels for stereo:

    $$44.1 \times 10^3 \times 16 \times 2 = \underline{1.4 \times 10^6 \text{ bits/second}}$$

Software demo

- Goes with "Ease of Use" in earlier slide "What's important in a DAS"
- LabVIEW widely used graphical programming language
- Not a sales pitch – there are lots of other ways to program a DAQ system, but thought you might enjoy this demo:
- National Instruments LabVIEW tutorial: http://digital.ni.com/demo.nsf/websearch/6560D7CBFE70C58E86256C05006979A5?OpenDocument&node=1381_US