ME 3504

Process Monitoring and Control

College of Engineering
Arkansas State University

This Course …

- Background and Theory on Engineering Measurements
- Understand the principles and practice of designing of experiments
- Sensing, instrumentation, software
- Data acquisition, analysis, interpretation
- Role of Statistics, Data manipulation, etc.

- Lab – Design one or two experiments covering various aspects of the topics above. Design will be based on a problem statement given to you.

What is a Measurement ?

- Measurement: Comparison between a standard and what we want to measure (the measurand)
- What is the standard?
  - **Width of a man's thumb = 1 inch**
  - **Length of a man's foot = 1 foot**
  - **Length of a man's belt = 1 yard**
- But then, there is a need for an unchanging standard for physical parameters
  - **length (m), time (s), mass (kg), temperature (K), etc.**
- Other parameters can be defined in terms of these standard parameters (velocity = length/time)

Why do we make Measurements ?

- Establish a value or a trend
  - Directly related to the measuring device
- What do we expect out of a measurement device ?
  - Range
  - Sensitivity
  - Accuracy
  - Consistency

Units

SYSTEM OF UNITS
- SI
- US

- Primary Units
- Supplementary Units
- Derived Units

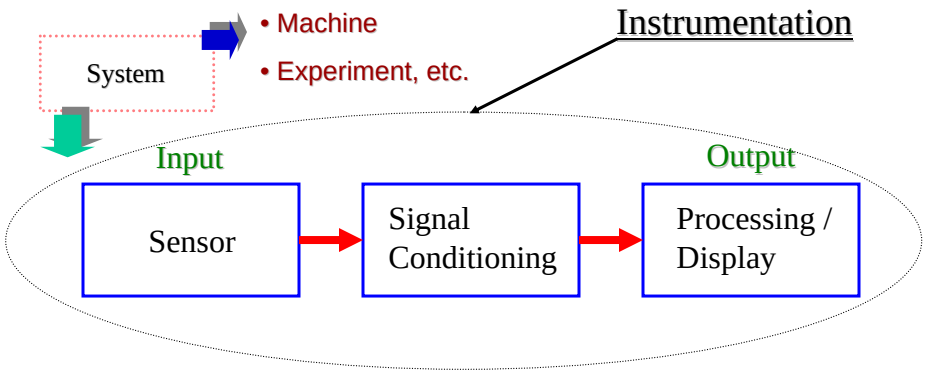
PRIMARY
- Length [m]
- Mass [kg]
- Time [sec]

SUPPLEMENTARY
- Temperature [K]
- Electrical Current [A]
- Voltage [V]

DERIVED
- Force [N]
- Energy [Joules]
- Velocity [m/sec]
- etc…

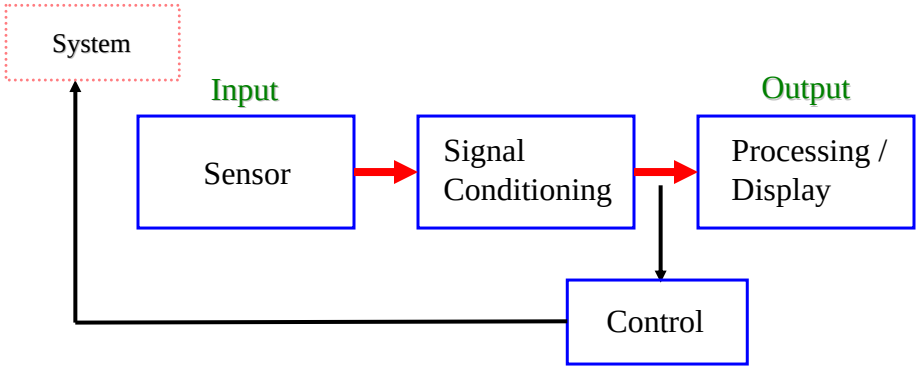
A General Measurement System: An Instrument, for example

- Process
- Machine
- Experiment, etc.



Functional Block Diagram

A General Measurement System: An Instrument, for example

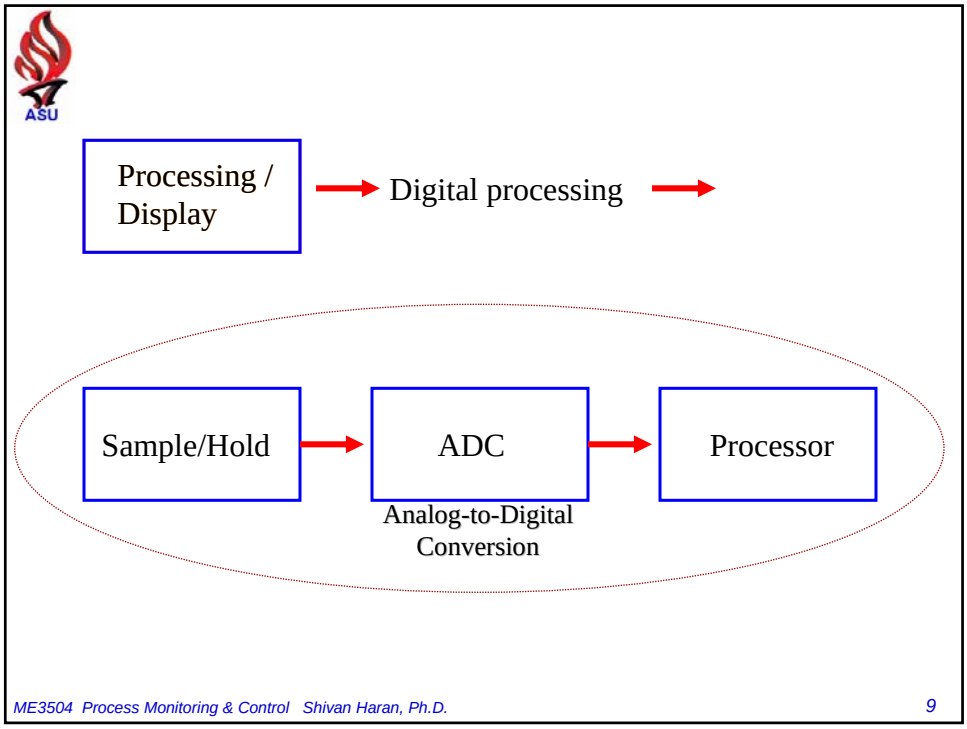


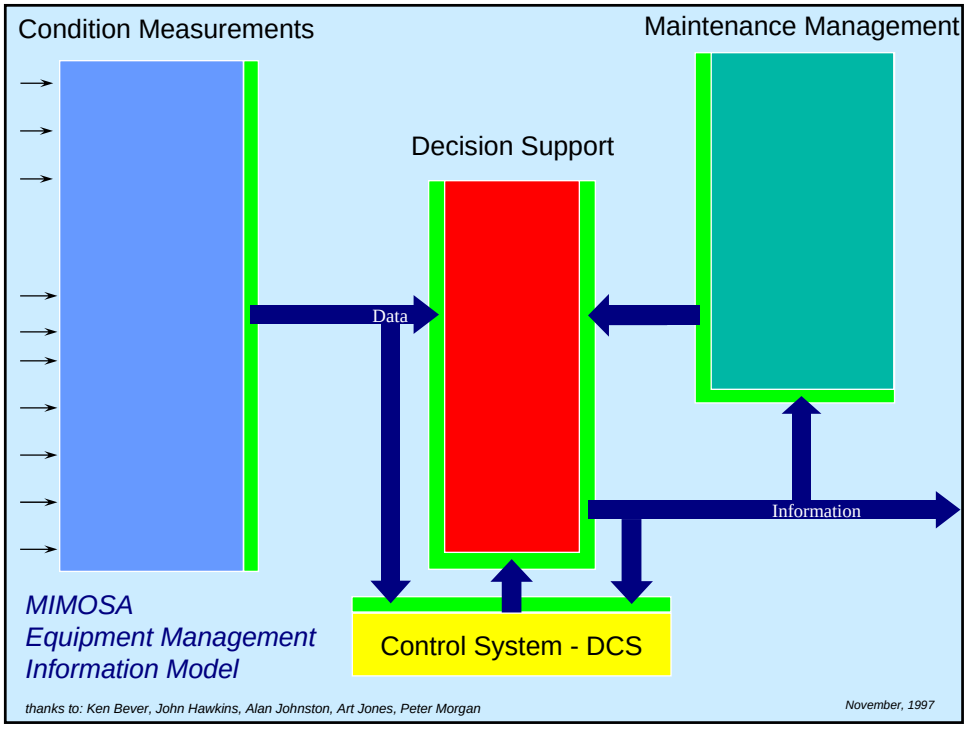
Functional Block Diagram

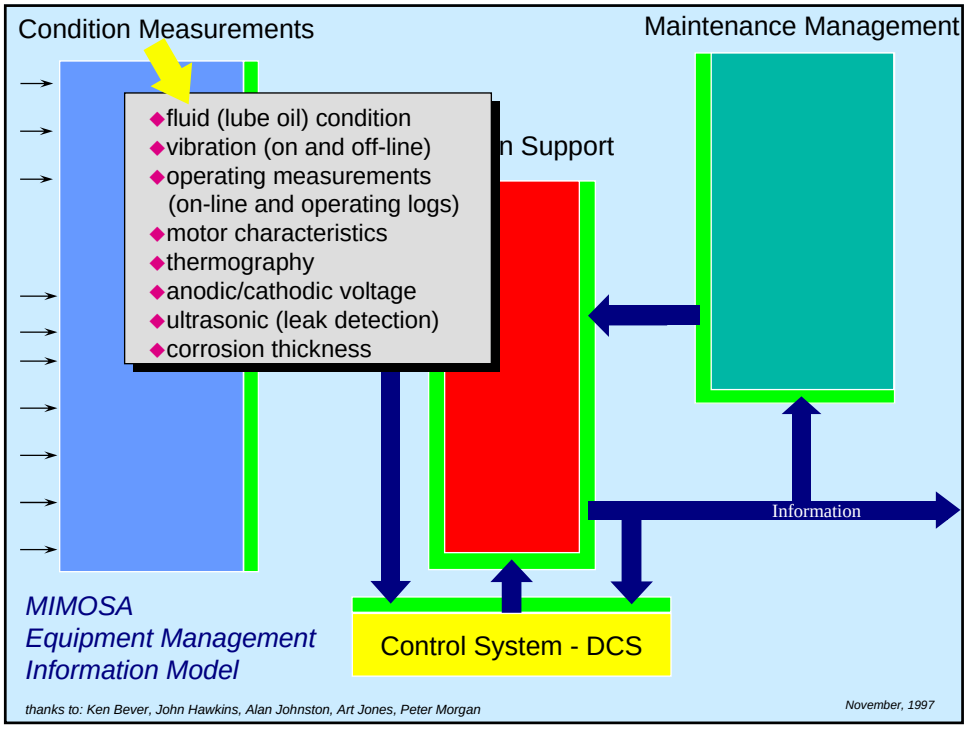
A General Measurement System: An Instrument, for example – contd…

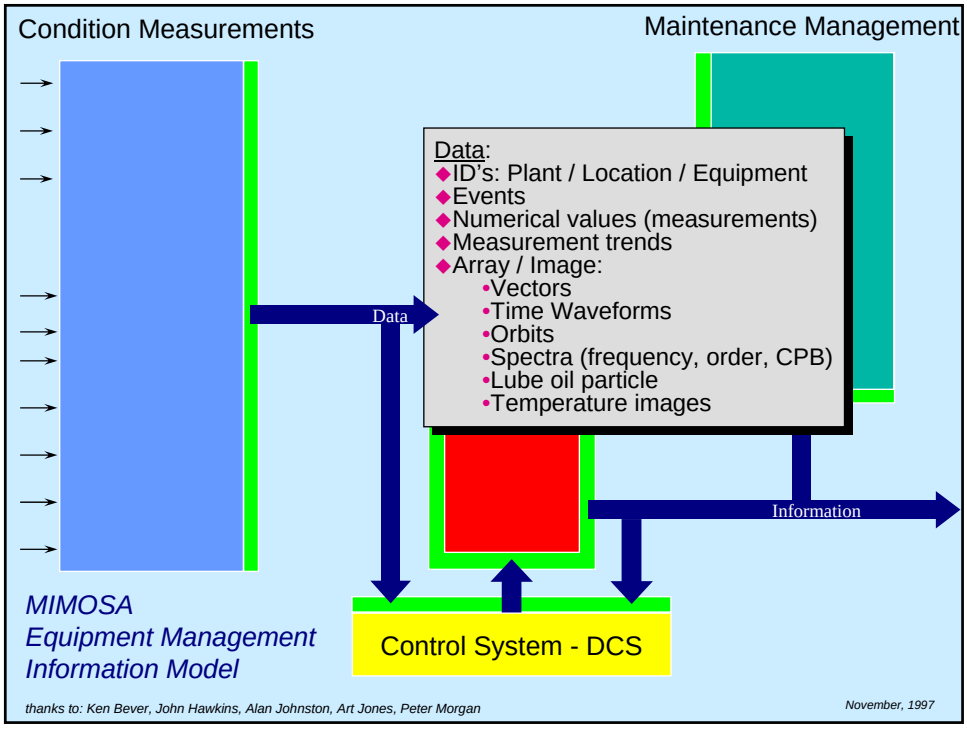
Processing / Display → Analog processing → Any device that accepts analog input

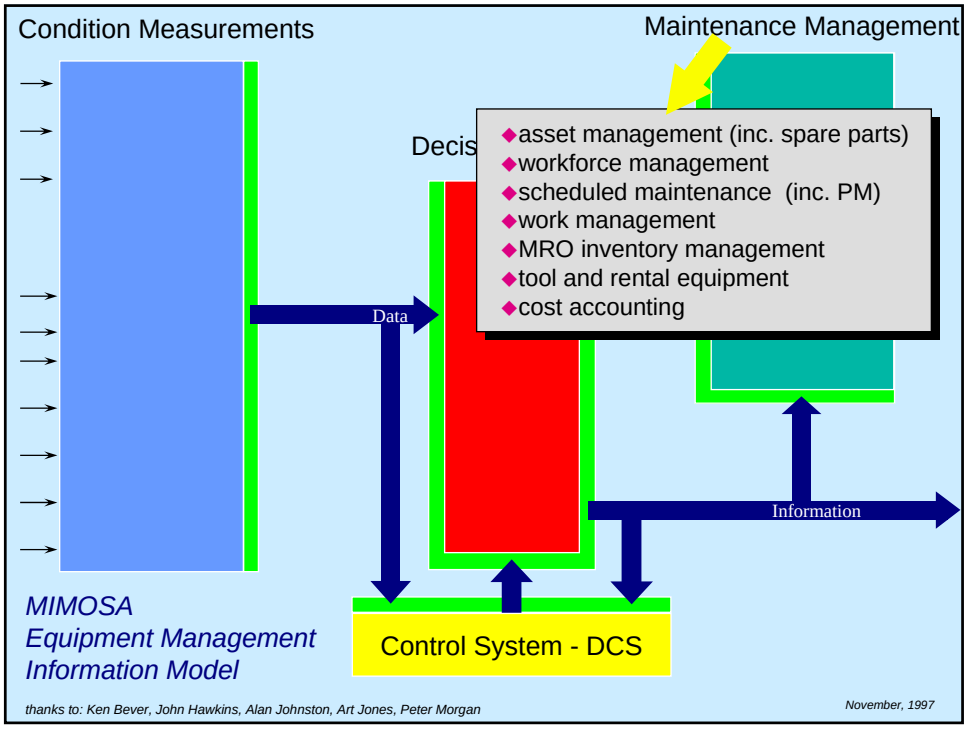
- Analog display (dial indicator, meter)
- Digital display
- Simple Alarm
- Shut off the system/machine
- Send it to another processing unit
- Strip chart recorder

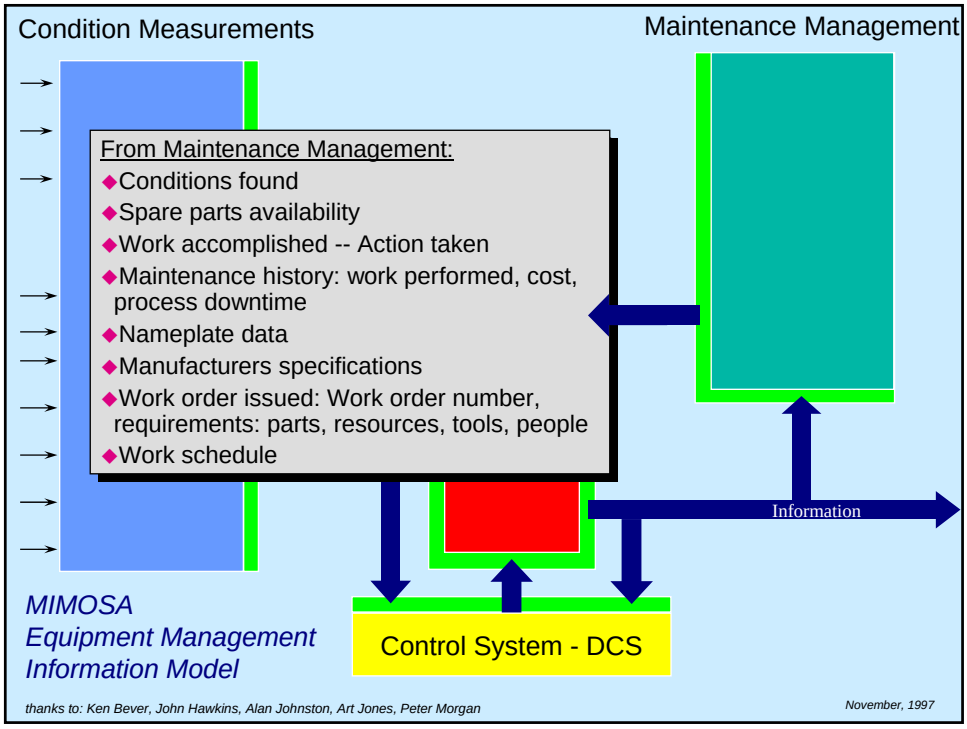

Processing / Display
Digital processing
Sample/Hold
ADC
Processor
Analog-to-Digital Conversion
ME3504 Process Monitoring & Control Shivan Haran, Ph.D.
9

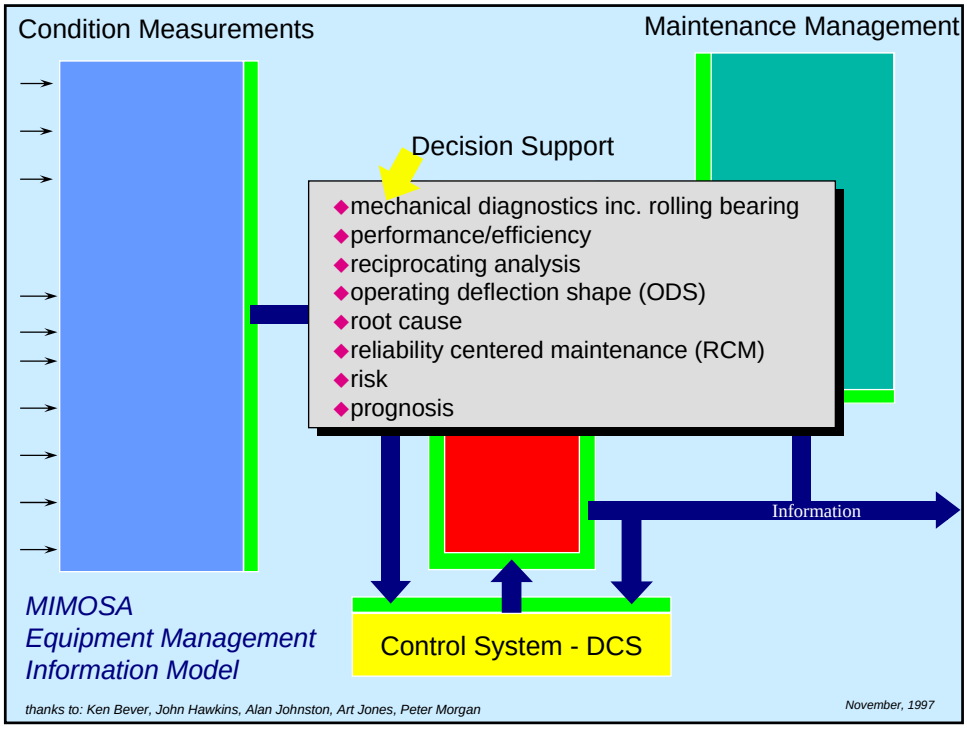

Condition Measurements
Maintenance Management
Decision Support
Data
Information
MIMOSA
Equipment Management
Information Model
Control System - DCS
thanks to: Ken Bever, John Hawkins, Alan Johnston, Art Jones, Peter Morgan
November, 1997

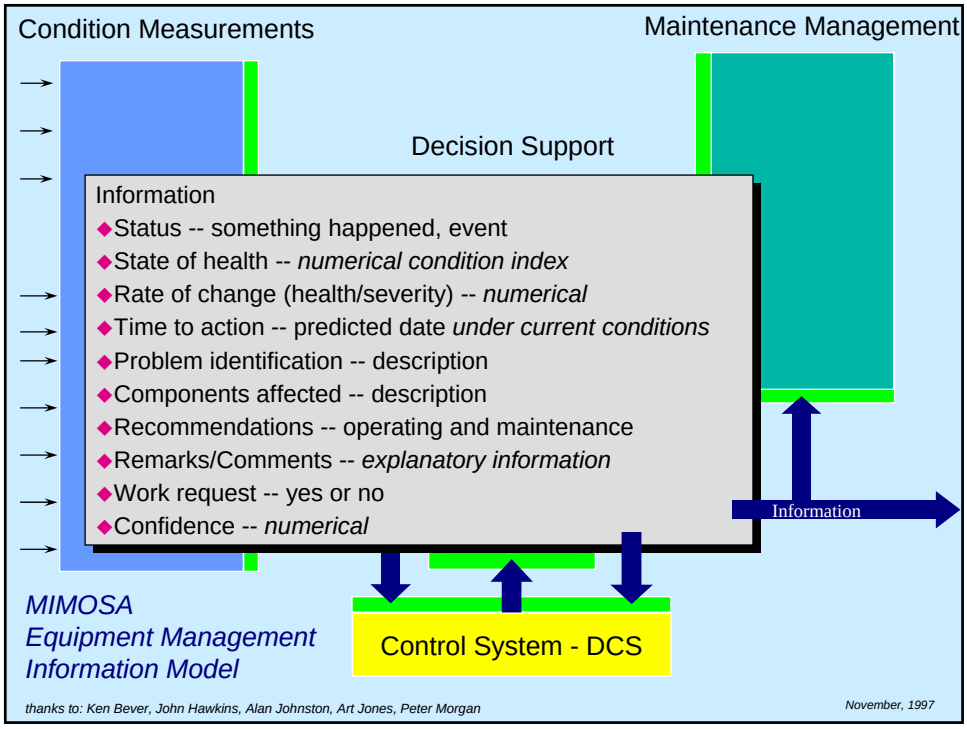

Condition Measurements
Maintenance Management
◆fluid (lube oil) condition
◆vibration (on and off-line)
◆operating measurements
(on-line and operating logs)
◆motor characteristics
◆thermography
◆anodic/cathodic voltage
◆ultrasonic (leak detection)
◆corrosion thickness
n Support
Information
MIMOSA
Equipment Management
Information Model
Control System - DCS
thanks to: Ken Bever, John Hawkins, Alan Johnston, Art Jones, Peter Morgan
November, 1997

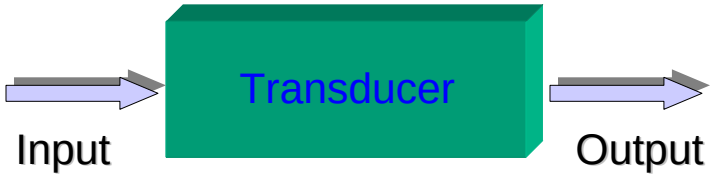

Condition Measurements
Maintenance Management
Data:
◆ID's: Plant / Location / Equipment
◆Events
◆Numerical values (measurements)
◆Measurement trends
◆Array / Image:
•Vectors
•Time Waveforms
•Orbits
•Spectra (frequency, order, CPB)
•Lube oil particle
•Temperature images
Data
Information
MIMOSA
Equipment Management
Information Model
Control System - DCS
thanks to: Ken Bever, John Hawkins, Alan Johnston, Art Jones, Peter Morgan
November, 1997


Condition Measurements
Maintenance Management
Decis
asset management (inc. spare parts)
workforce management
scheduled maintenance (inc. PM)
work management
MRO inventory management
tool and rental equipment
cost accounting
Data
Information
MIMOSA
Equipment Management
Information Model
Control System - DCS
thanks to: Ken Bever, John Hawkins, Alan Johnston, Art Jones, Peter Morgan
November, 1997


Condition Measurements
Maintenance Management
From Maintenance Management:
Conditions found
Spare parts availability
Work accomplished -- Action taken
Maintenance history: work performed, cost, process downtime
Nameplate data
Manufacturers specifications
Work order issued: Work order number, requirements: parts, resources, tools, people
Work schedule
Information
MIMOSA
Equipment Management
Information Model
Control System - DCS
thanks to: Ken Bever, John Hawkins, Alan Johnston, Art Jones, Peter Morgan
November, 1997


Condition Measurements
Maintenance Management
Decision Support
◆mechanical diagnostics inc. rolling bearing
◆performance/efficiency
◆reciprocating analysis
◆operating deflection shape (ODS)
◆root cause
◆reliability centered maintenance (RCM)
◆risk
◆prognosis
Information
Control System - DCS
MIMOSA
Equipment Management
Information Model
thanks to: Ken Bever, John Hawkins, Alan Johnston, Art Jones, Peter Morgan
November, 1997


Condition Measurements
Maintenance Management
Decision Support
Information
◆Status -- something happened, event
◆State of health -- *numerical condition index*
◆Rate of change (health/severity) -- *numerical*
◆Time to action -- predicted date *under current conditions*
◆Problem identification -- description
◆Components affected -- description
◆Recommendations -- operating and maintenance
◆Remarks/Comments -- *explanatory information*
◆Work request -- yes or no
◆Confidence -- *numerical*
Information
Control System - DCS
MIMOSA
Equipment Management
Information Model
thanks to: Ken Bever, John Hawkins, Alan Johnston, Art Jones, Peter Morgan
November, 1997



Example: Vibration
Pressure
Motion

Example: Charge
Voltage
Current

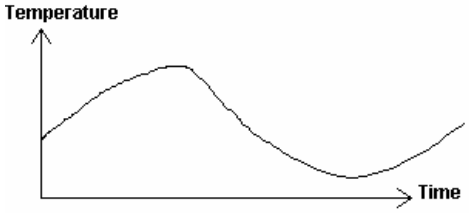
- Output is proportional to input in a given range
- Transducer selection is dictated by several parameters

The Signal

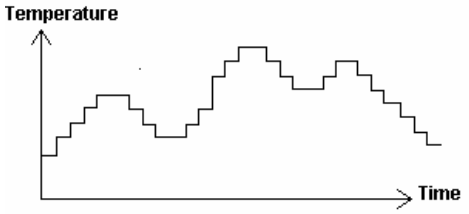
- Static signal
  - Constant with respect to time
  - Easily read with analog display
    - Glass thermometer used to measure the temperature in a room
    - Tire gage used to measure the air pressure in a tire
- Dynamic signal
  - Varies with respect to time
  - Typically read with a measuring system with recording capabilities or that shows a history of measured values
    - Heart monitor used in a hospital
    - Impact hammer used to study vibrations

How is a Signal Represented?

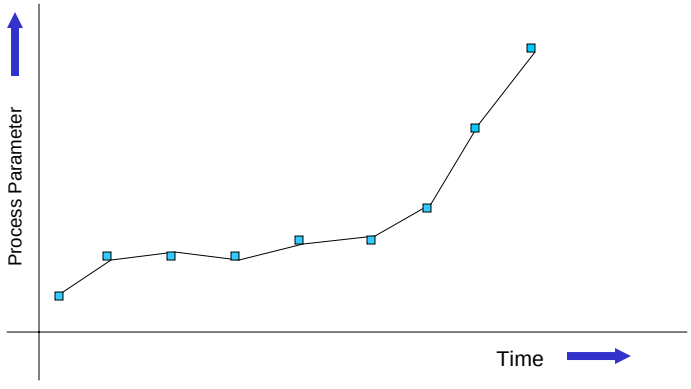
- Analog
  - Varies smoothly, continuous
  - Example: glass thermometer



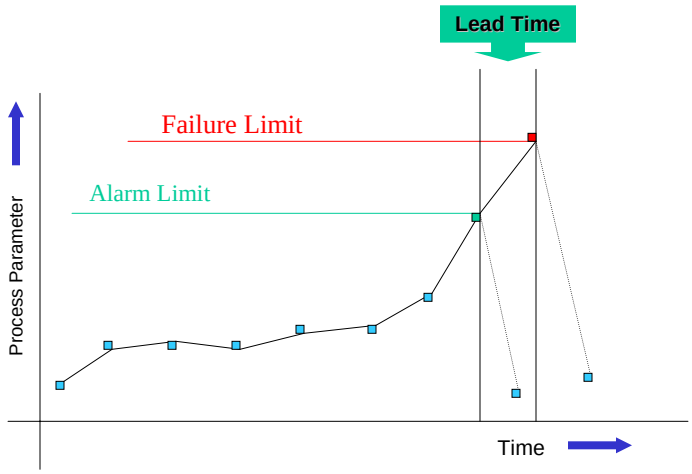
- Digital
  - Varies in a step-wise manner
  - Example: thermometer with digital display
  - 10011010=154



Trend Plot



Trend Plot – Monitoring a Process Parameter



Experimental Test Plan

- Identify pertinent process variables/parameters
  - based on test objectives
- Well thought out measurement plan for performing the tests
  - measurement techniques
  - equipment
  - procedure
- Selection of measurement technique/method
- Selection of instrumentation
  - sensors, supporting instruments, software
- Data analysis plan
  - analyze, present, how to use it

Sequential vs. Random Test

- Sequential test: Increase or Decrease input over the full input range
  - Hysteresis: difference between the upscale vs. downscale
- Random test: Random input over the range

Some Basic Definitions

- Data: Information obtained by experimental means
- A variable is the basic quantity being measured
  - Discrete – has discrete values (toss of a dice)
  - Continuous – has a continuous range of values (pressure temperature, vibration, etc.)
- Resolution: is the smallest increment of change that can be determined from the instrument readout

Variables

- Independent Variable: A variable that can be changed independently of other variables. It is not affected by change in the other variables
- Dependent Variable: A variable that IS affected by changes in one or more of the other variables
  - Control of a Variable: A variable is "controlled" if it can be held at a constant or prescribed value during an experiment
- Extraneous Variable: Variable that is not or cannot be controlled during a measurement but that affects the value of the output
  - pressure affects boiling pt.

Parameters

- A parameter is defined as a functional relationship between variables
  - A parameter that has an effect on the behavior of the measured variable is called a control parameter
  - A control parameter is completely controlled if it can be set and held at a constant value during a set of measurements
- example: fan flow coefficient C_1 given by:

$$C_1 = Q / nd^3$$

Q – flow rate
d – diameter of the fan
n – speed (rpm)

Noise and Interference

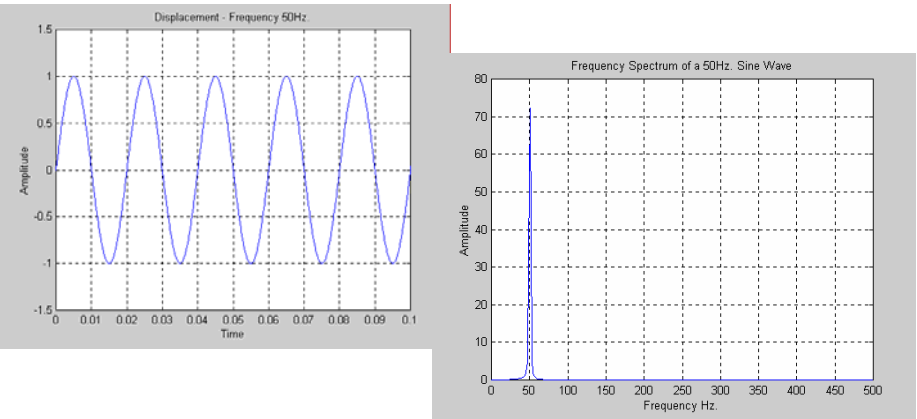
- Parameters are affected by extraneous variables
- Extraneous variables can be divided into Noise and Interference

  - Noise: is a random variation of the value of the measured output as a consequence of the variation of the extraneous variables (environmental influence, thermal, etc.)

  - Interference: produces undesirable deterministic trends on the measured value because of extraneous variables (EMI, RF, line frequency)

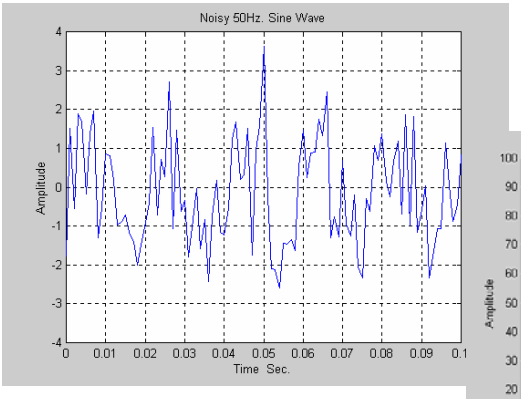
Noise

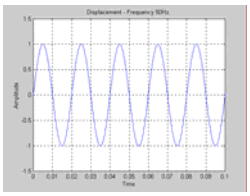
Frequency Spectrum of a 'clean' 50Hz. Sine Wave

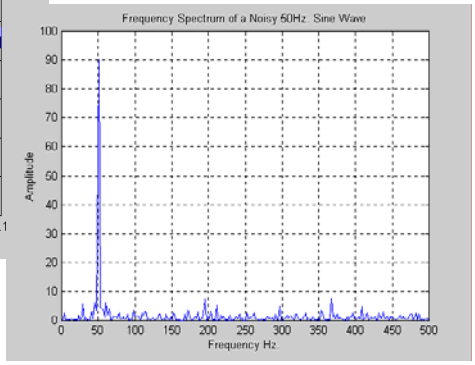


Noise

Frequency Spectrum of a 'noisy' 50Hz. Sine Wave







Replication & Repetition

- Repetitions: Repeated measurements made during any single test run or on a single batch
  - allows for quantifying the variation in a measured variable as it occurs during any one test or batch, while holding the operating conditions under normal control
    - e.g. – bearing diameter on a batch of 100 bearings

- Replication: An independent duplication of a set of measurements using similar operating conditions
  - allows for quantifying the variations in a measured variable as it occurs between tests, each test having the same nominal values of operating conditions

  (english meaning – duplication, imitation, copying)
    - e.g. – bearing diameter on a batch of 100 manufactured on a particular machine, on 10 consecutive days

Concomitant Methods
(occurring or existing concurrently)

- Obtaining two or more estimates for the results, each based on a different method
- Can be used as a check for agreement of results
  - finding volume using physical measurement, and also using the physical properties of the material
  - determining the results using two different theoretical approaches

Calibration

- What is Calibration ?

Calibration is the measurement of performance of an instrument or a sensor, which ensures the continued accuracy of measurements performed with the device

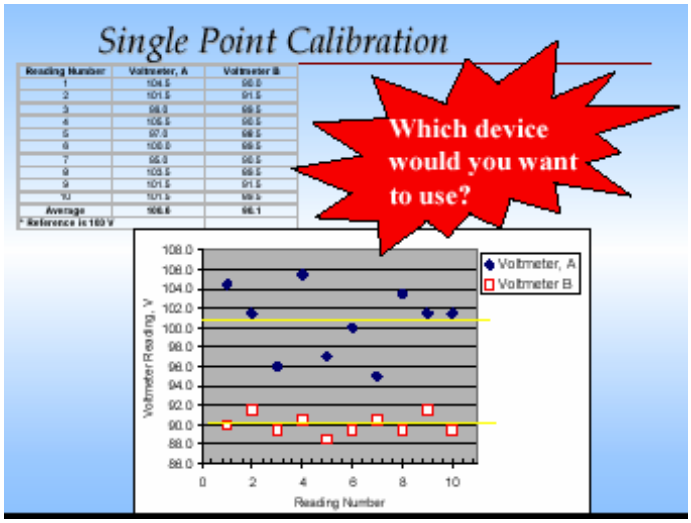
How do we Calibrate a System ?

- By applying a known value of input to a measurement system and observing the system's output
- Known value used for calibration is known as the "standard"
- Static Calibration: values of the variables involved remain constant ("static")
- Dynamic Calibration: when variables of interest are time dependant; input of known dynamic behavior is used and the output of the system is determined
  - e.g., using a sine wave input

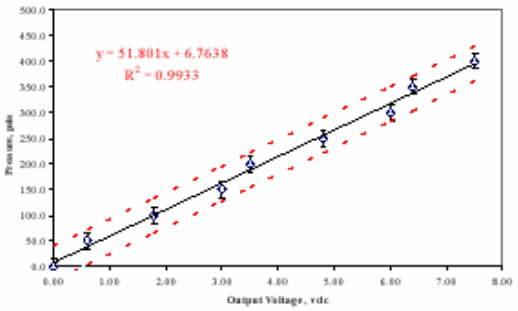
Calibration

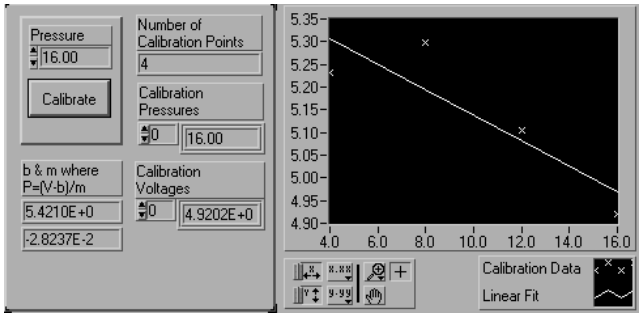
- Instrument calibration: is when known inputs are fed into the transducer and outputs of the instrument are observed
  - Single point: Output is proportional to the input
    Or – output = input x constant
  - Multi-point: several inputs are used
    - works when output is NOT proportional to input
    - significantly improves accuracy of calibration

Calibration



Example: Calibration Curve for a Pressure Transducer



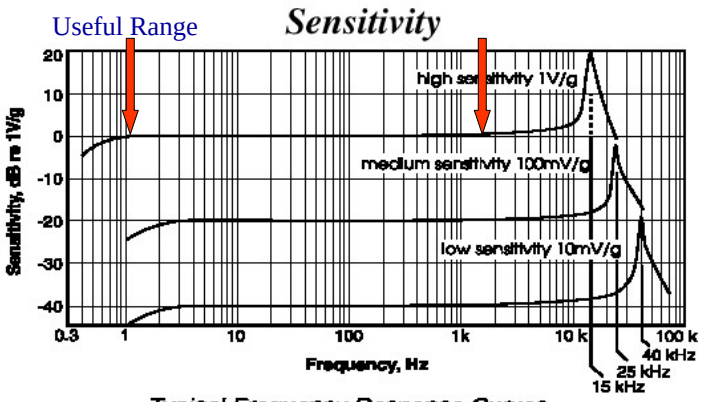


Sensitivity

- Sensitivity: is the change in the output per unit change in the input
- A calibration curve is obtained by plotting the output vs. the input (y vs. x)
- In the case of a linear calibration curve, the sensitivity is the slope of the (straight) line
  Also called Static Sensitivity
- The calibration curve also determines the useful range within which the instrument/sensor/system can be used
- Static Sensitivity: SLOPE of the calibration curve
- Input span: $x_{max} - x_{min}$.
- Output span: $y_{max} - y_{min}$ (or operating range)

Sensitivity

- Sensitivity: is the change in the output per unit change in the input
- Also determines the useful range



Typical Frequency Response Curves for Various Sensitivities

Accuracy and Precision

- Accuracy: is the closeness of a measurement (or a set of observations) to the true value
  - Higher the accuracy, lower the error
- Precision: is the closeness of multiple observations or repeatability of a measurement
  - Refers to how close a set of measurement are to each other
- Absolute Error = ε = (true – indicated value)
- % Accuracy = [1 – (|ε| / true value)] x 100

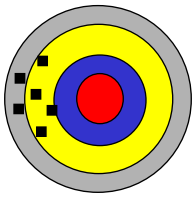
How Accurate is the Measurement ?

- There is always some uncertainty in measurements
  - Uncertainty: A likely bound on the error
- The application dictates the required accuracy:
  - Significant consequences
    - Core temperature of a nuclear reactor vs. outdoor temperature
  - Functionality
    - Measurement of lens curvature on eyeglasses vs. curvature of a wide-angle mirror

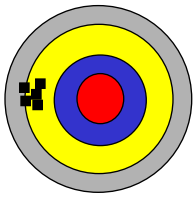
Accuracy versus Precision

(shooting at a target)

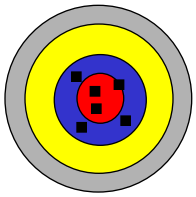
Not accurate or Precise



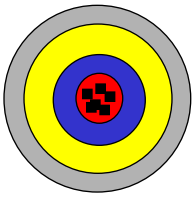
Precise but NOT accurate



Accurate and NOT Precise



Accurate AND Precise



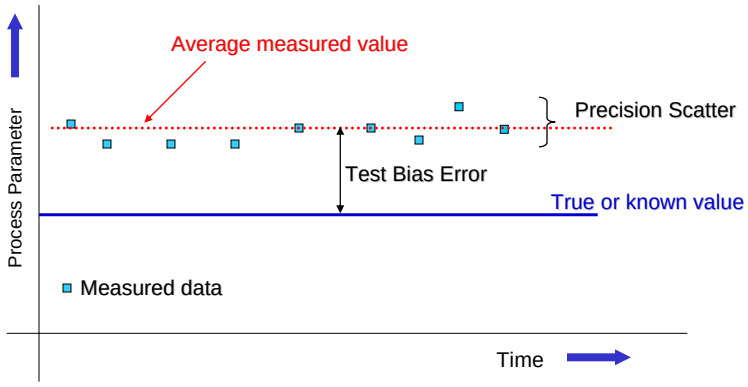
Precision Error

- Precision Error: is a measure of the random variation found during repeated measurements
- An estimate of a measurement system precision does not require calibration, per se
- A system that repeatedly indicates the same wrong value upon application of a particular input, would be considered very precise, regardless of its accuracy

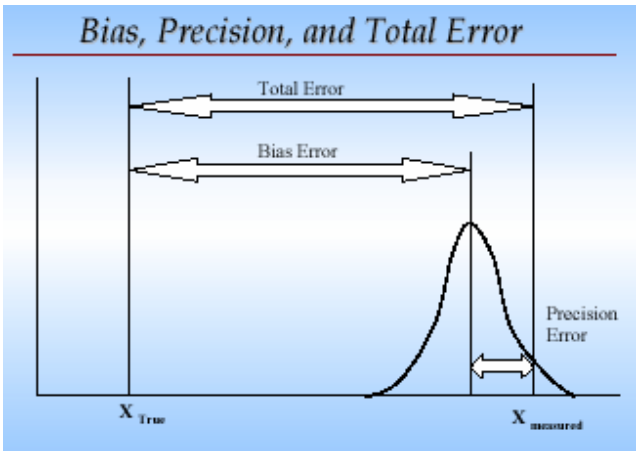
Bias Error

- Bias Error: is the difference between the average value and the true value
- To determine the bias error, one normally requires the average error to be determined by means of repeated measurements

Precision & Bias Error



Precision & Bias Error

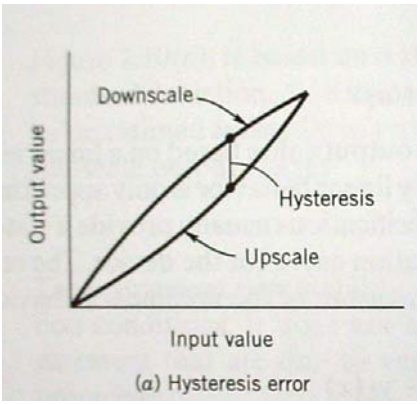


Hysteresis Error

Many sensors have the undesirable characteristic of giving a different value when the input is increasing than when it is decreasing. This is called hysteresis.

$$\%e_{h_{\max}} = \frac{e_{h_{\max}}}{r_o} \times 100$$

(output range = r_o)



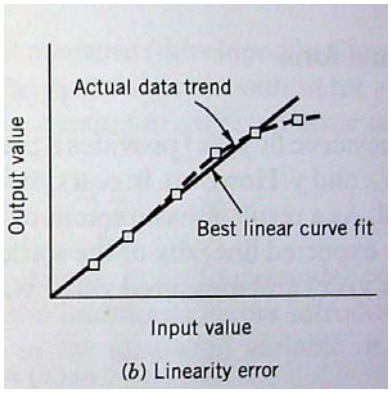
Linearity

Many types of sensors have linear input/output behavior, at least within a narrow range of inputs. The sensor thus follows an input/output relation like

$$y_L(x) = a_0 + a_1 x.$$

These will often be marketed as linear, and the only calibration data you get is the slope of the input/output relation (a_1) and the zero input value (a_0). For these types of sensors, the deviation from linear behavior should be reported in the specifications. This deviation can be calculated: $e_L(x) = y(x) - y_L(x)$.

The spec is usually the percentage error relative to full scale, or

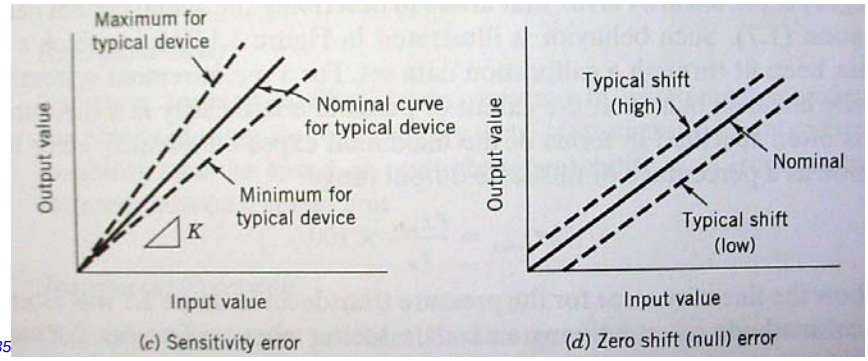


$$\%e_{L_{\max}} = \frac{e_{L_{\max}}}{r_o} \times 100$$

(output range = r_o)

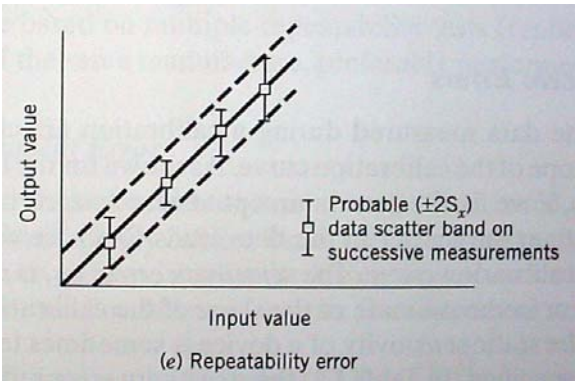
Zero and Sensitivity Errors

- Variations in the linearity parameters a_0 and a_1 are called zero errors and sensitivity errors, respectively.
- Zero errors are handled rather easily by measuring the zero input response before measurements are started.
- These two errors are often sensitive to temperature fluctuations in electronic equipment.



Instrument Repeatability

If a sensor is repeatedly calibrated under identical conditions, some variation in the result will occur. Repeatability is the measure of this variation and is normally described by the standard deviation S_x of the data.



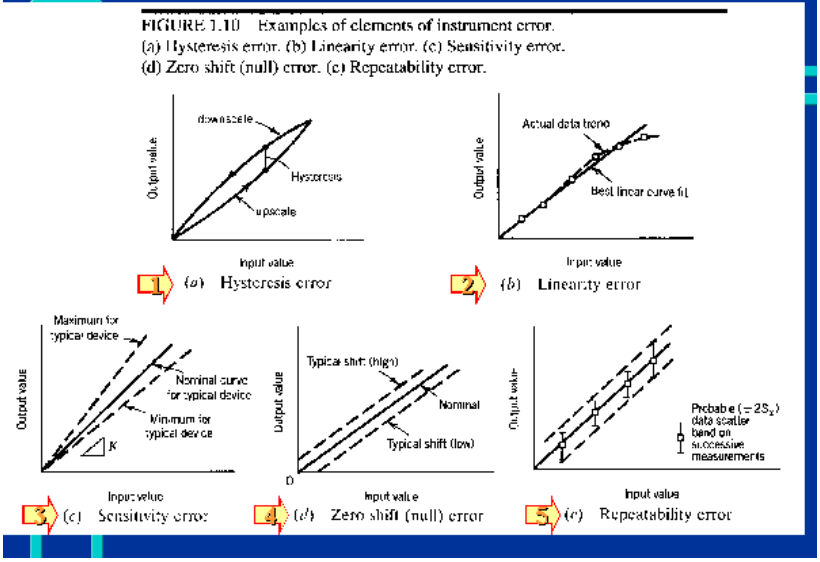
$$\%e_{R_{\max}} = \frac{e_{R_{\max}}}{r_o} \times 100$$

Types of Instrument Errors - a recap …

- Hysteresis Error
- Linearity Error
- Sensitivity Error
- Zero Shift (null) Error
- Repeatability Error

Types of Errors

Different Instrument Errors



Overall Instrument Error

- An estimate of the overall instrument error is made based on all known errors
- For *M* known errors, the instrument error e_c is given by

$$e_c = [e^2_1 + e^2_2 + e^2_3 + \ldots + e^2_M]^{1/2}$$

- For an instrument having known hysteresis, linearity, sensitivity and repeatability errors, the instrument error is estimated by

$$e_c = [e^2_h + e^2_L + e^2_K + e^2_R]^{1/2}$$

Basic Stages of a Measuring System

- Sensor/Transducer
  - Sensor: Uses some natural phenomenon to sense the variable being measured
  - Transducer: Converts the sensed information into a detectable signal
  - Loading: The measured quantity is always disturbed
- Signal Conditioning
  - Modifies (amplify, filter) the signal for the final stage
- Signal Processing
  - Processes the signal to covert it so that other parameters can be measured (Fourier transform)
- Output
  Indication or storing of the measured value
- Control/Feedback
  Use of the signal to control its future value

Bicycle Speedometer

- Sensor: A Magnet attached to one of the spokes
- Transducer: The Hall Effect device that produces an electrical pulse as the magnet passes
- Signal Conditioning: A circuit compares the pulses to a timer and determines the period. A correlation based on the measured period and wheel diameter is used to determine velocity.
- Output Stage: A digital signal is sent to the LCD displays and the velocity appears on the screen

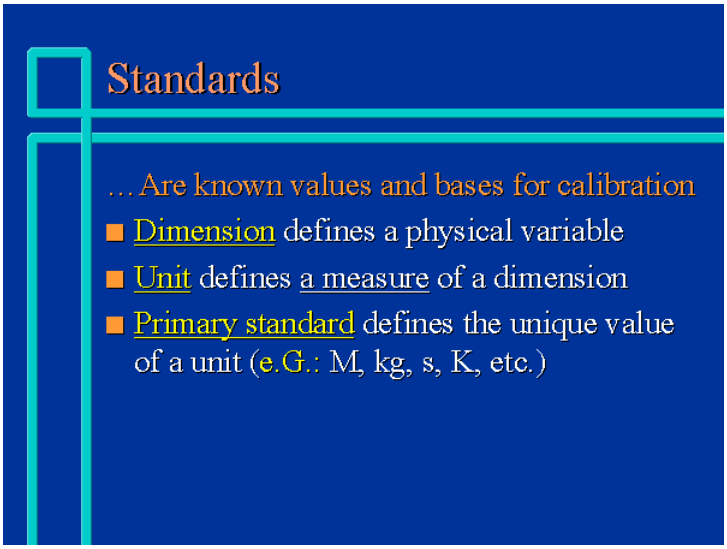
Standards

- Any time you measure anything, you are comparing it to something whose value you think you know. You assume your ruler is 1 ft long. But who says what a foot is?
- A combination of several international agencies are responsible for maintaining the primary standard measures of various quantities.
- The standard kilogram and the standard second are maintained by the French. Others are kept elsewhere. It extremely important that these standards do not change with time, even over hundreds of years.
- The National Institute of Standards and Technology (NIST) in Maryland is responsible for keeping standards for the US.

Hierarchy of Standards

- Primary Standard (NIST)
- Interlaboratory Transfer Standard (Secondary)
- Local Standard
- Working Instrument
- "Test Standards" – well documented test procedures technical terminology, methods to construct test specimens, test set-up, methods for data reduction, etc.
  - Maintained by professional societies such as ASME, ASTM, etc.

Standards



Presentation of Data

- Data presentation conveys significant information about the relationship between the variables
- Several types of plots available
  - Rectangular coordinates
  - Semi-log
  - Log-log

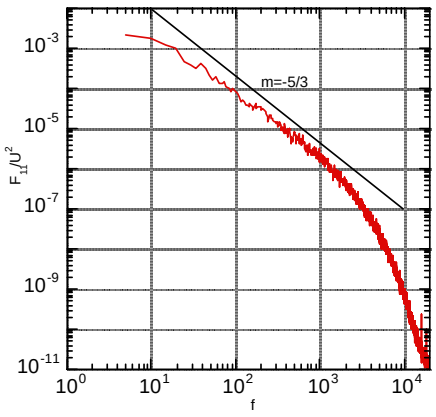
Presentation of Data

There are two basic reasons to plot something with a logarithmic scale:

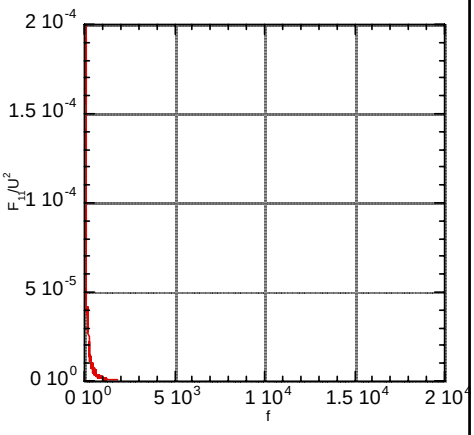
1) The variable spans several orders of magnitude, or
2) The relationship between the input variable *x* and the output variable *y* is, or may be, of the form $y = ax^n$ where *a* and *n* are constants. A log-log plot will reveal the value of *n* with little difficulty.

An example: Linear vs. Log-Log

log-log



linear



This Course …

- Grading considerations on the Lab Reports:
  - **Structure and presentation**
  - **Organization**
  - **Completeness**
  - **Presentation of Results (plots, numerical values, tables, etc.)**
  - **Numerical values – precision, units, etc.**
  - **Uncertainty analysis**
  - **Statistical analysis**
  - **Conclusions**
  - **Discussion on the experiment, results, analysis, etc.**

Technical Report – A Checklist

- Title
- Abstract
  - **Comes before the table of contents**
  - **About 100 – 150 words**
  - **Single paragraph**
  - **Objectives and scope of experiment**
  - **Key results**
  - **State main conclusions**

Technical Report – A Checklist

- Introduction
  - Motivation for present study
  - Purpose of the experiment
  - Literature review (optional)
  - Method of investigation
  - A preview of the report that follows
- Theoretical Analysis
  - Models or formulae that govern the study
  - Equations (number all equations)
  - Definition of terms (in equations)
  - Provide basic relationships
  - Long derivations belong in the Appendix

Technical Report – A Checklist

- Experimental Procedure
  - Description of Apparatus/Equipment
    - Use of illustrations and description in words
    - Include accuracy and range of all instruments
  - Description of Methods/Experimental Procedure
    - Organization
    - Text should flow well
    - Avoid narrative of successes and failures
- Results
  - Given in a logical order of significance
  - Graphs/tables used to demonstrate
  - Include accuracies, uncertainty in results

Technical Report – A Checklist

- Discussion
  - **Compare with theoretical expectations**
  - **Explain sources of experimental error and influence**
  - **Note important problems encountered in the study**
- Conclusions
  - **Summarizes results relevant to the study**
  - **Assess the study in terms of original objectives and purpose (given in the introduction)**
  - **Recommendations for future study (if applicable)**

Technical Report – A Checklist

- References
  - **Numbered list of references at the end**
    - **Choose standard format for references**
- Appendices
  - **Non-essential but important information (derivations, etc.)**
  - **Each appendix assigned by a letter and a descriptive title**

Questions on Experiments

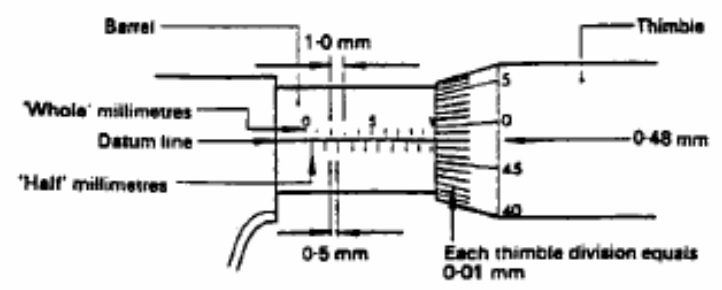
You can think about these when doing the labs !

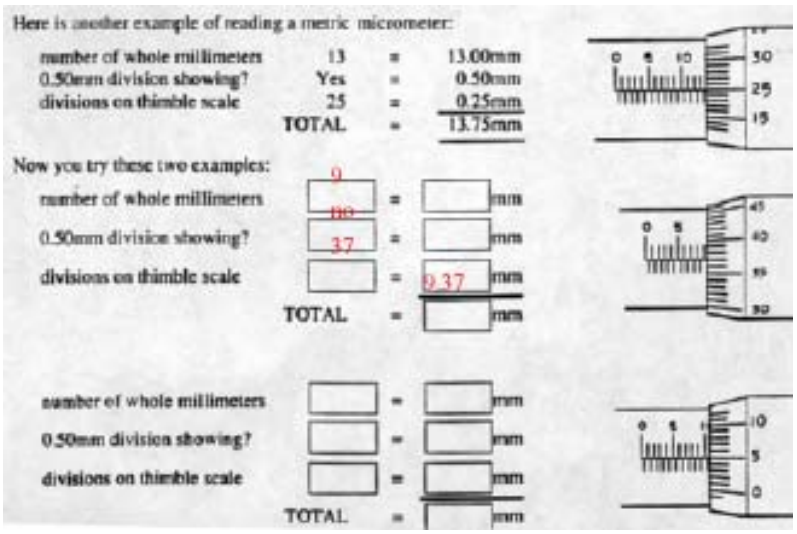
Some Sample questions …

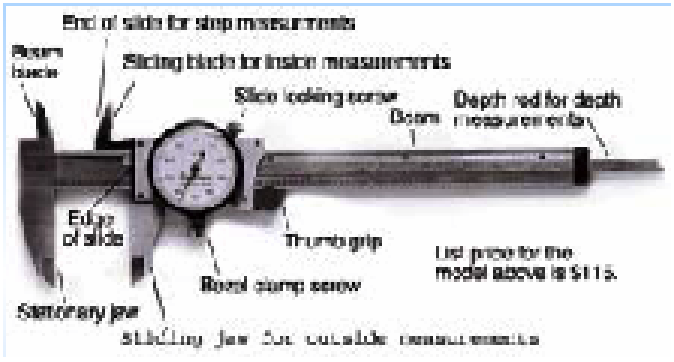
- What is the problem ? What questions are you trying to answer ?
- How accurately do you need to know the answers ? How is the answer to be used ?
- What are the physical principles involved ?
- What experiments or set of experiments might provide answers ?
- What variables must be controlled and How ?
- Quantities to be measured ? How accurately ?
- Instrumentation to be used? Information on the instruments
- How is data to be acquired, conditioned, stored ?

Some Sample questions …

- How much data is to be gathered ? Points of measurement ?
- Budgetary and time constraints
- Techniques of data analyses to be followed ?
- Effective and revealing way to present data
- Unanticipated questions raised by the data
- In what manner should data and results be reported ?




Here is another example of reading a metric micrometer:
number of whole millimeters 13 = 13.00mm
0.50mm division showing? Yes = 0.50mm
divisions on thimble scale 25 = 0.25mm
TOTAL = 13.75mm
Now you try these two examples:
number of whole millimeters = mm
0.50mm division showing? = mm
divisions on thimble scale = mm
TOTAL = mm
number of whole millimeters = mm
0.50mm division showing? = mm
divisions on thimble scale = mm
TOTAL = mm


Edge of slide
Thumb grip
Stationary jaw