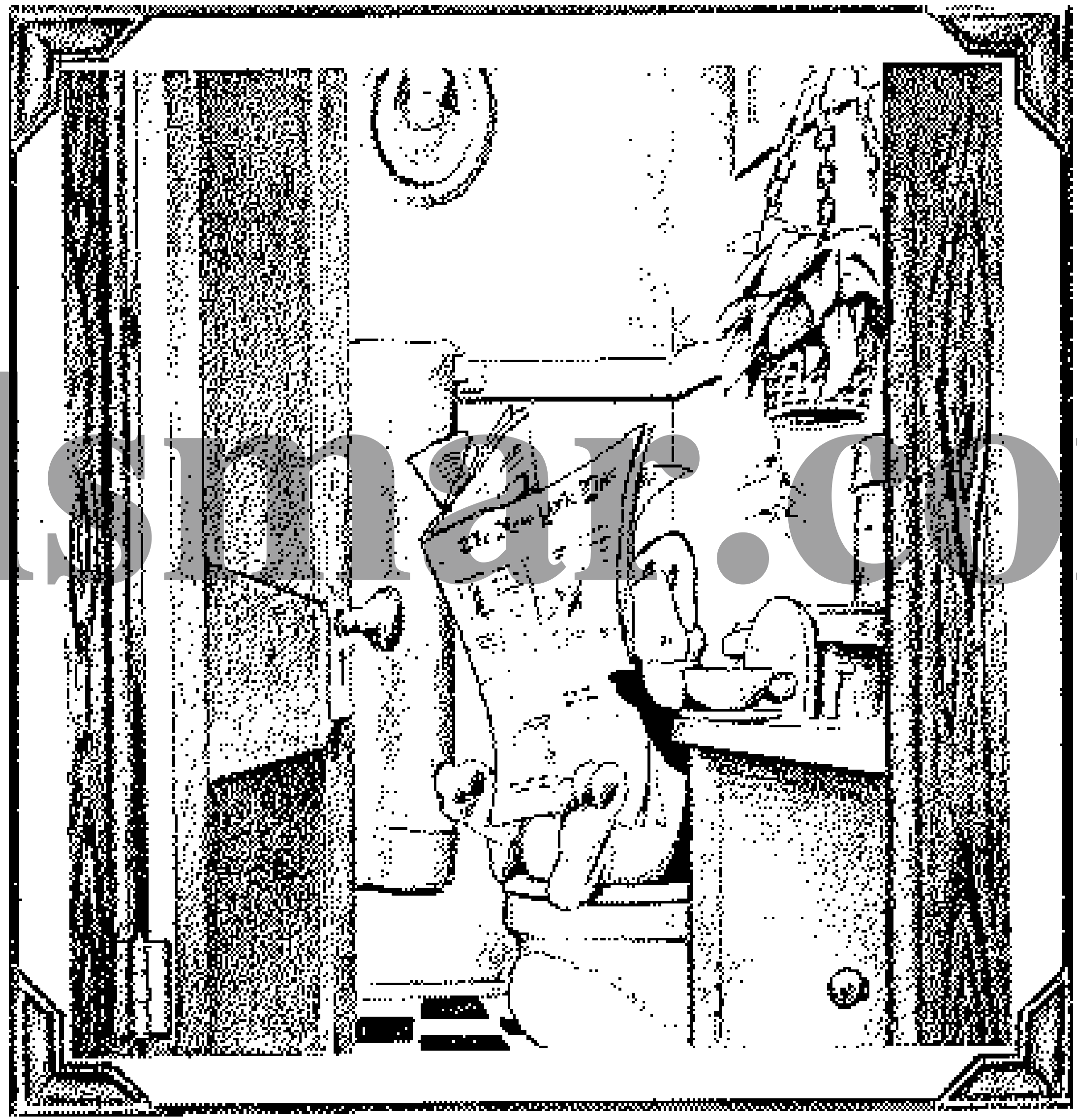
Measurement Systems Analysis

Don’t Let This Happen To YOU!



Variation

Think of Measurement as a Process

Definition

Measurement

The assignment of numbers to material things to represent the relationships among them with respect to particular properties.

C. Eisenhart (1963)

Measurement Systems Analysis

- Basic Concepts of Measurement Systems

  A Process

- Statistics and the Analysis of Measurement Systems
- Conducting a Measurement Systems Analysis
- ISO - TC 69 is the Statistics Group
- Ensures high ‘Data Quality’ (Think of Bias)

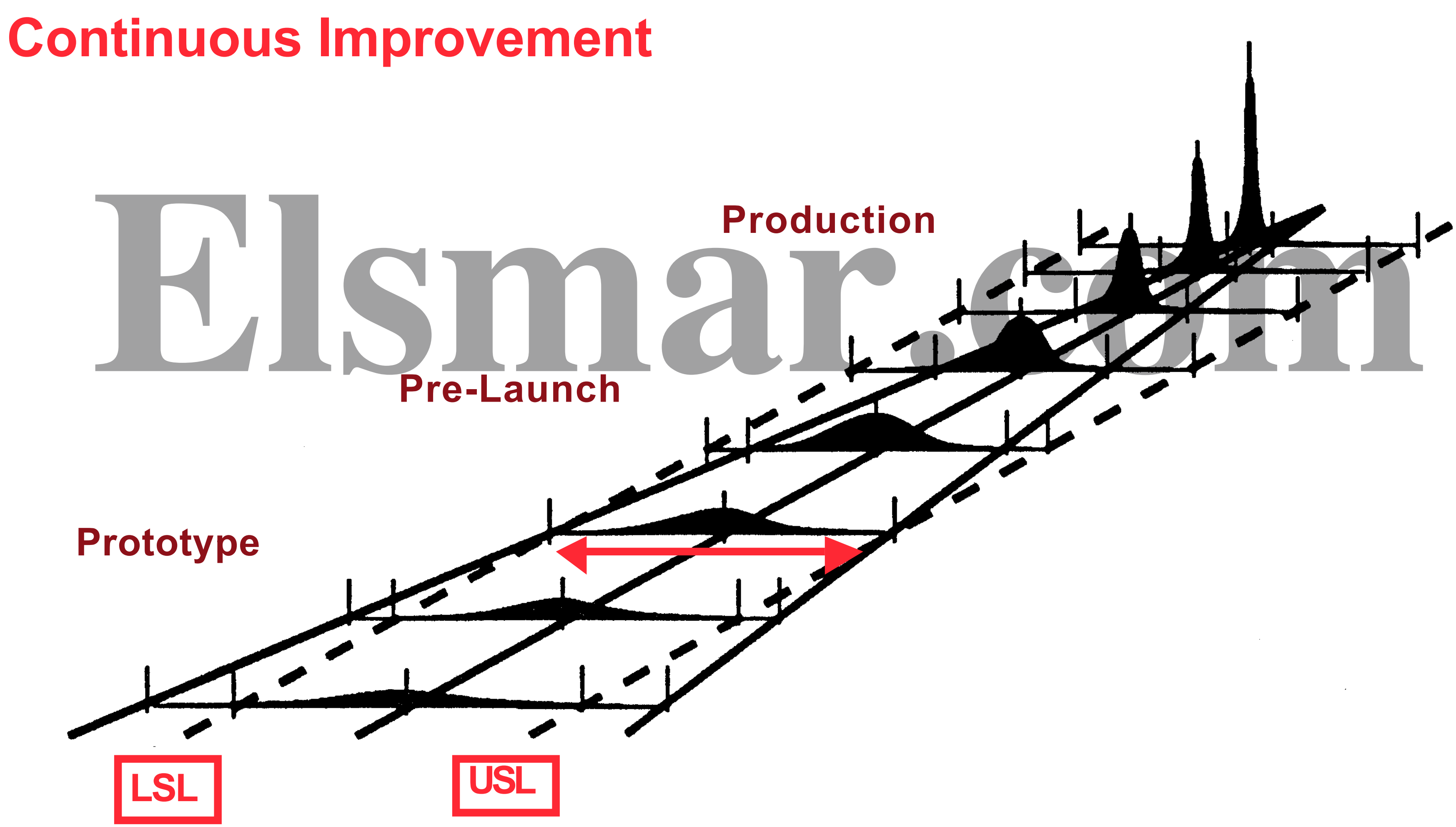
Course Focus & Flow

Measurement as a Process

- Mechanical Aspects (vs Destructive)
  - Piece part
  - Continuous (fabric)
- Features of a Measurement System
- Methods of Analysis
- Gauge R&R Studies
- Special Gauging Situations
  - Go/No-Go
  - Destructive Tests

Place Timeline Here

The Target & Goal



Key Words

- Discrimination

  Ability to tell things apart

- Bias [per AIAG] (Accuracy)
- Repeatability [per AIAG] (Precision)
- Reproducibility
- Linearity
- Stability

Measurement as a Process

Basic Concepts

- Components of the Measurement System
- Requirements of a Measurement System
- Factors Affecting a Measurement System
- Characteristics of a Measurement System

Features (Qualities) of a Measurement Number

- Units (Scale)
- Accuracy
- Precision (Consistency or Repeatability)
- Resolution (Reproducibility)

Measurement Related Systems

Typical Experiences with

Measurement Systems

Basic Concepts

- Every Process Produces a "Product"
- Every Product Possesses Qualities (Features)
- Every Quality Feature Can Be Measured
- Total Variation

  = Product Variation + Measurement Variation
- Some Variation Inherent in System Design
- Some Variation is Due to a Faulty Performance of the System(s)

The Measurement Process

What is the 'Product' of the Measurement Process?

What are the Features or Qualities of this Product?

How Can We Measure Those Features?

Measurement Systems Components

- Material to be Inspected
  - Piece
  - Continuous
- Characteristic to be Measured
- Collecting and Preparing Specimens
- Type and Scale of Measurement
- Instrument or Test Set
- Inspector or Technician
  - AIAG calls these 'Appraiser'
- Conditions of Use

Where Does It Start?

During the Design (APQP) Stage:

The engineer responsible for determining inspections and tests, and for specifying appropriate equipment should be well versed in measurement systems. The Calibration folks should be part of the process as a part of a cross-functional team.

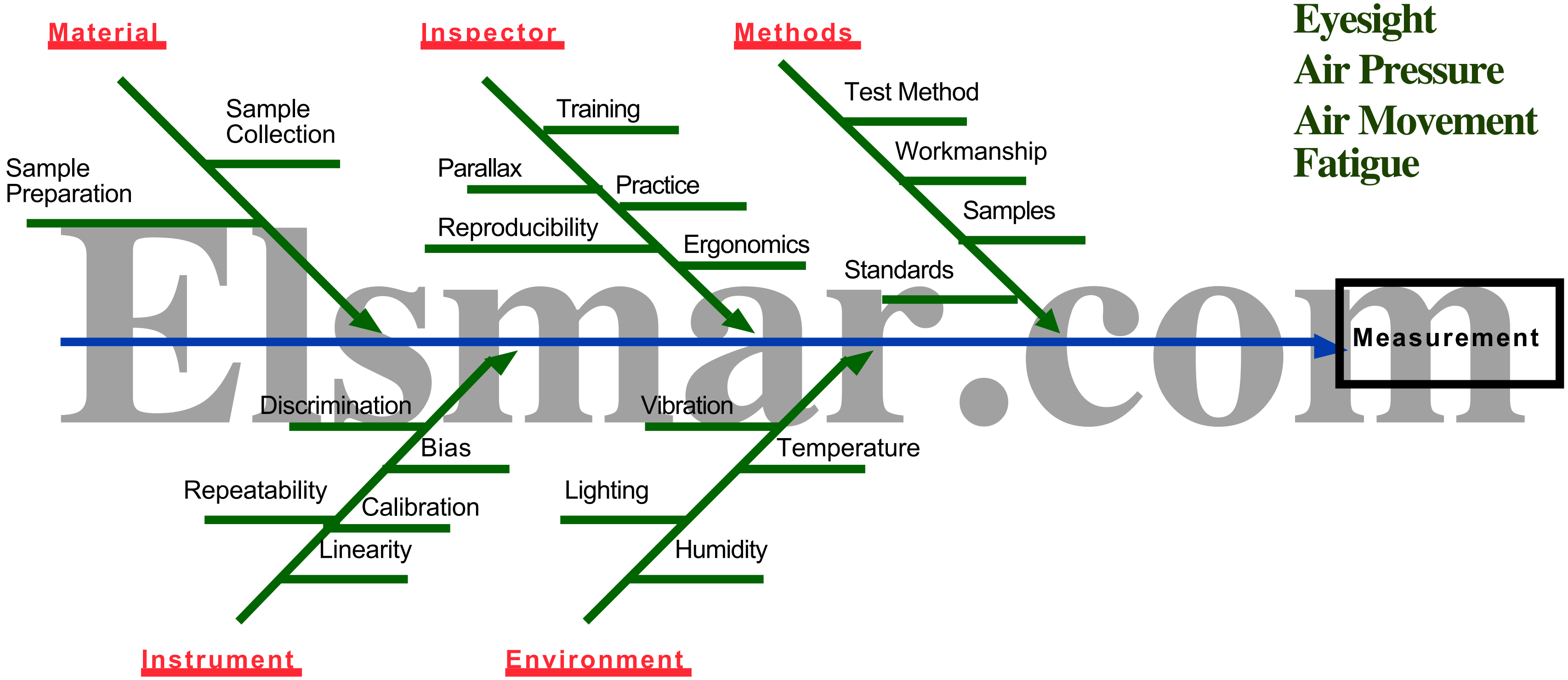
Variability chosen instrument must be small when compared with:

- Process Variability
- Specification Limits

Typical Progression

	Determine 'Critical' Characteristic	Product Engineer
How will the data be used?	Determine Required Resolution	Product Engineer
	Consideration of the Entire Measurement System for the Characteristic (Variables)	Cross-Functional
	Determine What Equipment is Already Available	Metrology

Measurement Systems Variables



Fixture
Eyesight
Air Pressure
Air Movement
Fatigue

These are *some* of the variables in a measurement system. What others can you think of?

Determining What To Measure

External Requirements

- Voice of the Customer

  You Must Convert to Technical Features

Convert To

- Technical Features
- Failure Modes Analysis

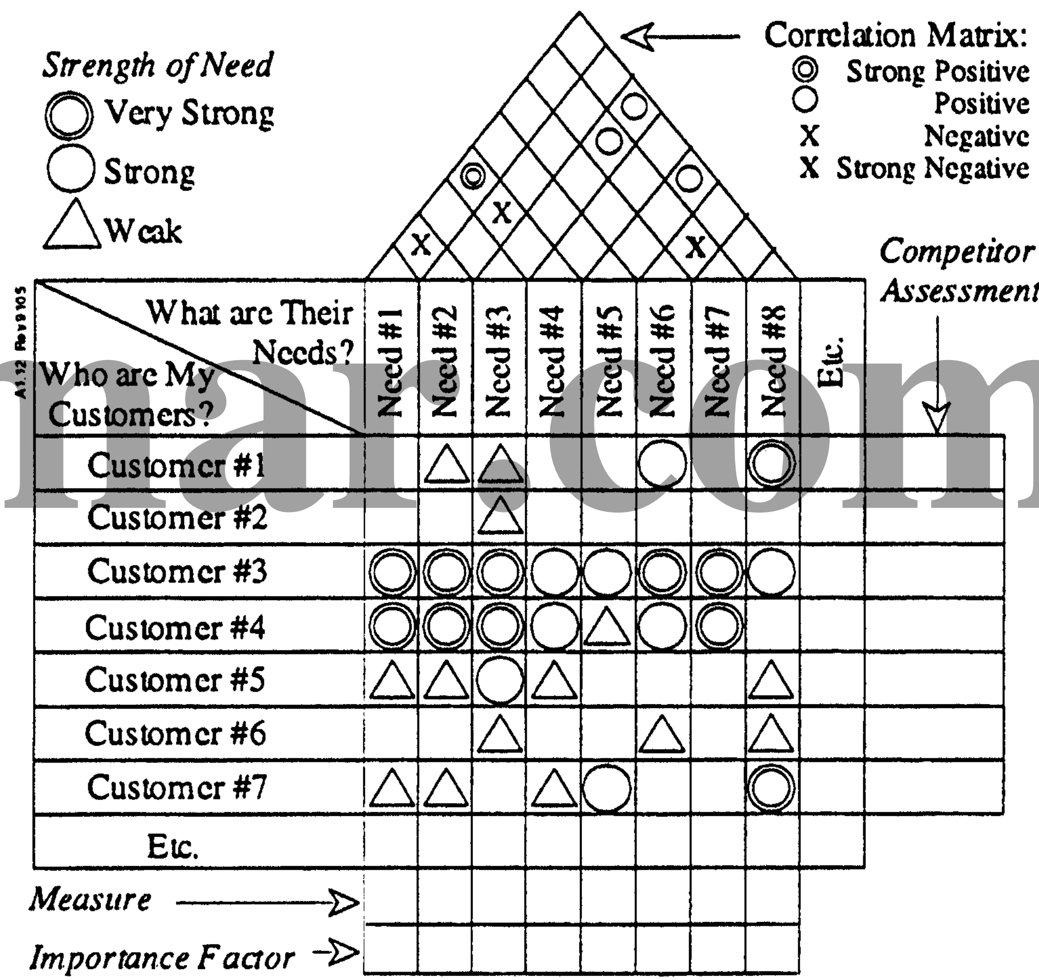
Internal Requirements

- Control Plan

Voice of the Customer

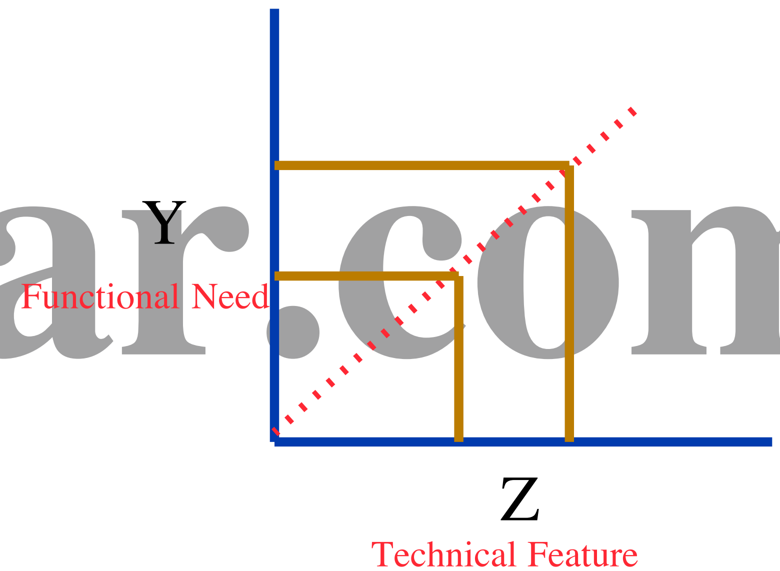
Customer may specify causes rather than output

- External and Internal Customers
- Stated vs Real and Perceived Needs
- Cultural Needs
- Unintended Uses
- Functional Needs vs. Technical Features



Convert to Technical Features

- Agreed upon Measure(s)
- Related to Functional Needs
- Understandable
- Uniform Interpretation
- Broad Application
- Economical
- Compatible
- Basis for Decisions



Failure Modes Analysis

Project No.: X101
System: Planetary Group
Analyst: Adam Apple
Date: 910228

Collateral Damage
Seriousness
Probability

CODES:	D	S	P
1.	very low	none	<1 in 10
2.	low	minor	≈3 in 10
3.	medium	significant	50-50
4.	high	high	≈7 in 10
5.	very high	catastrophic	>9 in 10

Component (Part #)	Potential Failure	Cause of Failure	Probability	Seriousness	Collateral Damage	Effect of Failure	Corrective Action
Gear, Hub Part # xxxxx	Grooved external spline teeth	Wear, case crunching	2	5	3	Will not transmit power	Heat treat splines
Plate, Reaction Part # xxxxx	Warped	Not made flat	3	4	2	Clutch slippage	Provide straightening
		Excessive heat, slippage	1	4	2	Clutch slippage	Increase engaging force
	Worn or smeared	Lack of lube	1	4	2	Clutch slippage	Increase lube oil
Disc Assembly Part # xxxxx	Warped	Excessive heat, slippage	1	5	3	Clutch slippage	Increase lube oil
	Loss of friction material	Bond failure	1	4	2	Clutch slippage	Develop better bonding
Spring Part # xxxxx	Broken	Fatigue	2	3	2	No plate separation	Design for lower stress
		Improper assembly	1	3	2	No plate separation	Provide assembly instructions

- Design FMEA
- Process FMEA
- Identify Key Features
- Identify Control Needs

Critical Features are Defined Here!

Automotive FMEA

Process Failure Mode And Effects Analysis

Low - High
1 - 10

Process: _
Primary Process Responsibility: ______________
Other Div. Or People Involved: ______________

Outside Suppliers Affected: ______________
Model Year/Vehicle(s): ______________
Scheduled Production Released: ______________

Engineer: ______________
Part Number: ______________
PFMEA Date: ________ Rev. ___

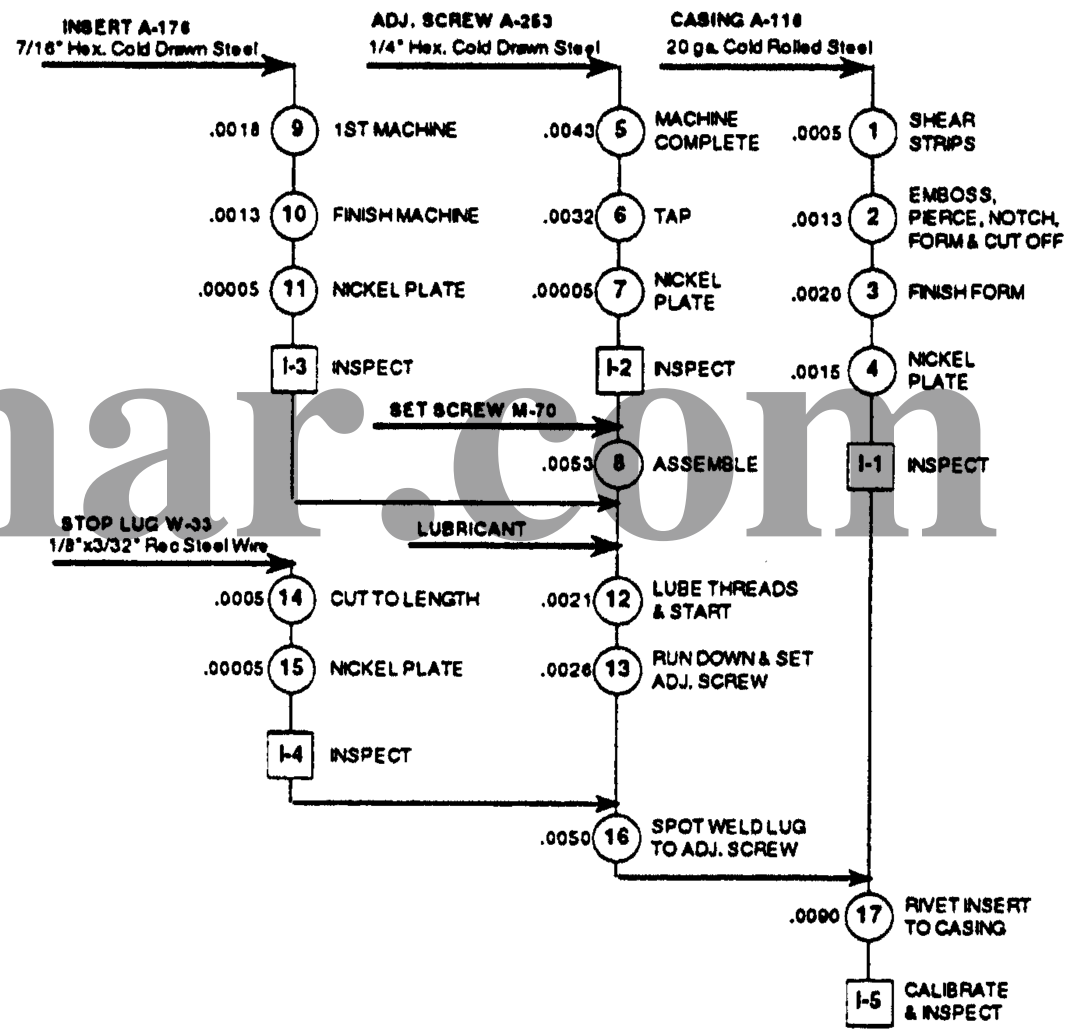
Approvals: Quality Assurance Manager ______________
Operations Manager ______________
Quality Assurance Engineer ______________
Senior Advisor ______________

Part Name Operation Number	Process Function	Potential Failure Mode	Potential Effects Of Failure	Potential Cause Of Failure	Current Controls	Occured	Severity	Detection	RPN	Recommended Actions And Status	Actions Taken	Occured	Severity	Detection	RPN	Responsible Activity
SIR Container 1	Take TPPE Material Held In Storage Area	Wrong Material	Fragmented Container Unpredictable Deployment	Insufficient Supplier Control Improper Handling Misidentified Material	Material Certification Required With Each Shipment Release Verification	1	9	2	18							
		Out Of Spec Material	Fragmented Container Unpredictable Deployment	Supplier Process Control	Periodic Audit Of Supplier Material	3	10	3	90							
		Contaminated Material	Fragmented Container Unpredictable Deployment	Open Boxes	Visual Inspection	1	9	7	63							
		Material Composition Change	Fragmented Container Unpredictable Deployment	Engineering Change Supplier Change	Release Verification Green "OK" Tag Customer Notification	1	10	7	70							
2	Move To Approved Storage	Unreleased	Fragmentation	Untrained LTO Untrained Personnel	Check For Green "OK" Tag At Press Trace Card Check List Training	5	10	1	50							

Leading to MSA. Critical features are determined by the FMEA (RPN indicators) and put into the Control Plan.

Control Plan / Flow Diagram

- Inspection Points
- Inspection Frequency
- Instrument
- Measurement Scale
- Sample Preparation
- Inspection/Test Method
- Inspector (who?)
- Method of Analysis

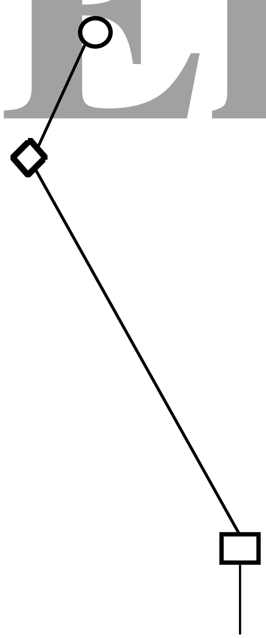


GM Process Flow Chart

Process Flow Diagram

Part Number: ______________________ Date: 4/5/93
Part Description: ______________________ Rev. : C
Prepared By: ______________________

Approved By:
QA Manager ______________________
Operations Manager ______________________
Senior Advisor ______________________
QA Engineer

Step	Fabrication	Move	Store	Inspect	Operation Description	Item #	Key Product Characteristic	Item #	Key Control Characteristic
1					Move "OK" Vinyl Material From Storage Area and Load Into Press.	1.0	Material Specs	1.0	Material Certification Tag
2					Auto Injection Mold Cover In Tool #	2.0	Tearstrip In Cover	2.1 2.2	Tool Setup Machine Setup
						3.0	Hole Diameter In Cover	2.1 2.2	Tool Setup Machine Setup
						4.0	Flange Thickness In Cover	2.1 2.2	Tool Setup Machine Setup
						5.0	Pressure Control Protrusions Height	2.1 2.2	Tool Setup Machine Setup
3					Visually Inspect Cover	6.0	Pressure Control Protrusions Filled Out	2.1 2.2	Tool Setup Machine Setup

Standard Control Plan Example

Control Plan Number	Key Contact / Phone	Date (Orig.)	Date (Rev.)
Part No./ Latest Change No.	Core Team	Customer Engineering Approval/Date	
Part Name/Description	Supplier/Plant Apoproval/Date	Customer Quality Approval/Date	
Supplier/Plant	Supplier Code	Other Approval/date (If Req'd)	Other Approval/date (If Req'd)

			Characteristics					Methods				
Part/ Process Number	Process Name/ Operation Description	Machine, Device, Jig, Tools for Mfg.	No.	Product	Process	Special Char. Class	Product/ Process Spec/ Tolerance	Evaluation Measurement Technique	Size	Frequ- ency	Control Method	Reaction Plan

Ford's Dimensional Control Plan (DCP)

Part Name Widget
Part Number 105E
Process Sheet Data 2 - 27
Department 5
Operation 2.6
Sheet 1 of 1
Last Revised Jan 99
Date Aug 99

ID	Description	Type	Importance Level	Control Factors Contributing	Capability Cp	Capability Cpk	Capability Date	Control Method	Sampling Frequency	Sampling Size	Gage Description	Gage R&R
OP05												
1	Outside Diameter	IP	3	C	4.0	3.5(L)	1-7-86	(At Supplier) $\bar{X}$ & R Charts	Every 2 Hrs.	2/S		
					(At Supplier)							
OP10												
2 Left	Inside Diameter	BP	2	T,M T-1	2.0	1.9(L)	4-10-86	Checksheet	At Tool Chg. & Every 150 pcs.	3/S	Micrometer (V)	20%
Right					3.1	2.4(L)	4-10-86					

Measurement as a System

- Choosing the Right Instrument
  - Instrument Calibration Needs
  - Standards or Masters Needed
  - Accuracy and Precision
- Measurement Practices
  - Where
  - How Many Places
- Reported Figures
  - **Significant Figures Rule**
    - **2 Action Figures**
    - **Rule of 10**
  - Individuals, Averages, High-Lows

Measurement Error

$$y = x + \varepsilon$$

Measured Value (y)

=

True Value (x) + Measurement Error ε

Deming says there is no such thing as a 'True' Value.

Consistent (linear)?

Sources of Measurement Error

- Sensitivity (Threshold)

  Chemical Indicators

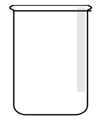
- Discrimination
- Precision (Repeatability)
- Accuracy (Bias)
- Damage
- Differences in use by Inspector (Reproducibility)

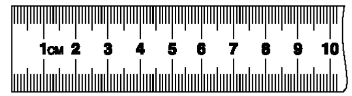
  Training Issues

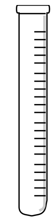
- Differences Among Instruments and Fixtures
- Differences Among Methods of Use
- Differences Due to Environment

Types of Measurement Scales

- **Variables**







  Can be measured on a continuous scale

  Defined, standard Units of Measurement

- **Attributes**

  No scale

  Derived 'Unit of Measurement'

  Can be observed or counted

  Either present or not

  Needs large sample size because of low information content

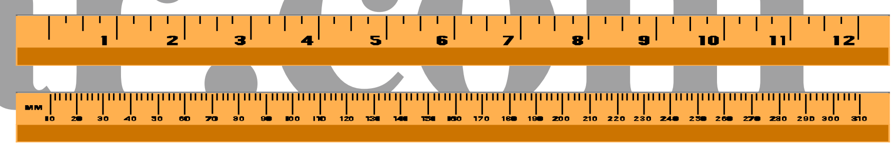
How We Get Data

- Inspection

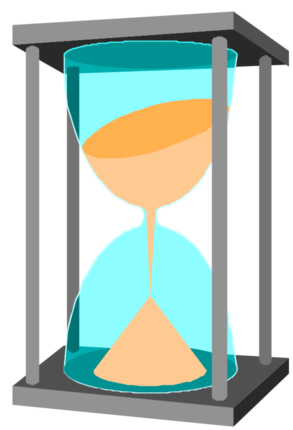
Includes Sensory (e.g..: Beer)

- Measurement

Magnitude of Quality

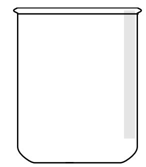


- Test

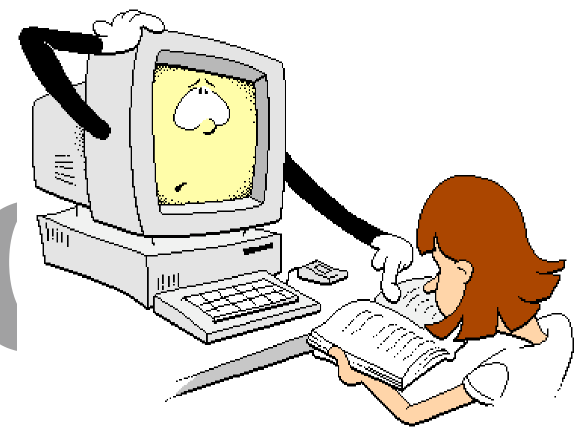


Operational Definitions

- Is the container **Round**?

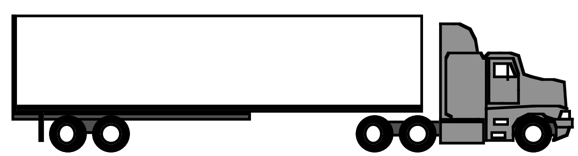


- Is your software **Accurate**?

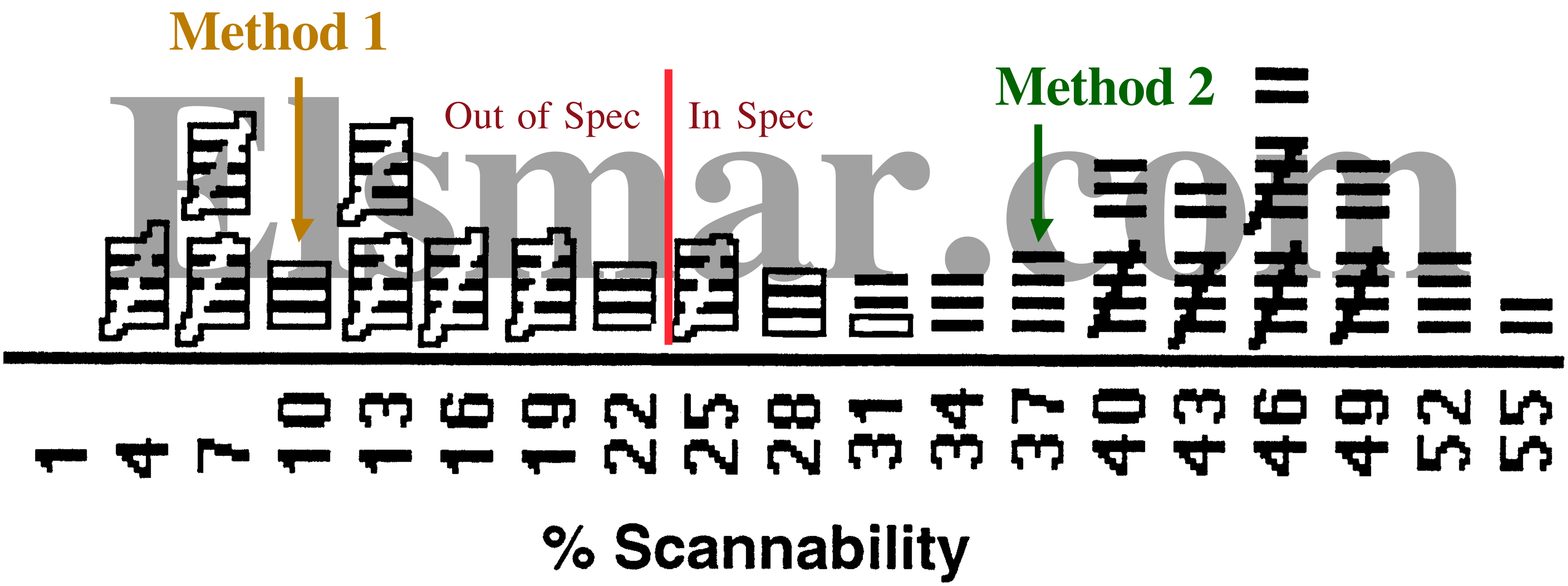


- Is the computer screen **Clean**?

- Is the truck **On Time**?



Different Method = Different Results



Measurement System Variability

- Small with respect to Process Variation
- Small with respect to Specified Requirements
- Must be in Statistical Control

  Measurement **IS** a **Process**!

  Free of Assignable Causes of variation

Studying the Measurement System

- Environmental Factors
- Human Factors
- System Features
- Measurement Studies

Standards

- **National**

  In the US - Kept or Tracked by NIST

- **Primary**

  Copied directly from National Standard using 'State-of-the-Art' Equipment

- **Secondary**

  Transferred from Primary Standard

- **Working**

  Used to calibrate laboratory and shop instruments

Environmental Factors

- Temperature
- Humidity
- Vibration
- Lighting
- Corrosion
- Wear
- Contaminants

  Oil & Grease

  Aerosols

Where is the study performed?

1. Lab?
2. Where used?
3. Both?

Human Factors

- Training
- Skills
- Fatigue
- Boredom
- Eyesight
- Comfort
- Complexity of Part
- Speed of Inspection (parts per hour)
- Misunderstood Instructions

Human Measurement Errors

- **Sources of Errors**

  Inadvertent Errors
  - **Attentiveness**
  - **Random**
  - **Good Mistake-Proofing Target**

Training Issue

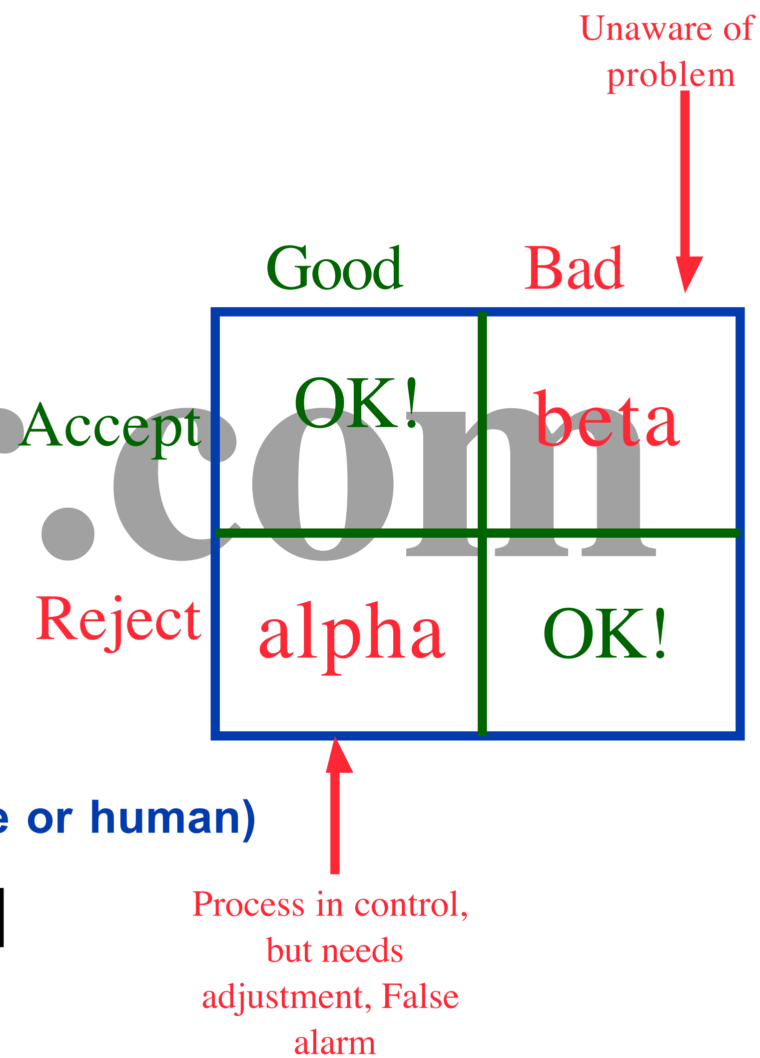
  Technique Errors
  - **Consistent**

  Wilful Errors (Bad mood)

- **Error Types (Can be machine or human)**

  Type I - Alpha Errors [α risk]

  Type II - Beta Errors [β risk]



Measurement System Features

- Discrimination

  Ability to tell things apart
- Bias [per AIAG] (Accuracy)
- Repeatability [per AIAG] (Precision)
- Reproducibility
- Linearity
- Stability

Discrimination

- Readable Increments of Scale
- If Unit of Measure is too course: Process variation will be lost in Rounding Off
- The “Rule of Ten”: Ten possible values between limits is ideal

  Five Possible Values: Marginally useful

  Four or Less: Inadequate Discrimination

Discrimination

Inadequate Discrimination Leads to Excessive Rounding

even — no round
odd — round up

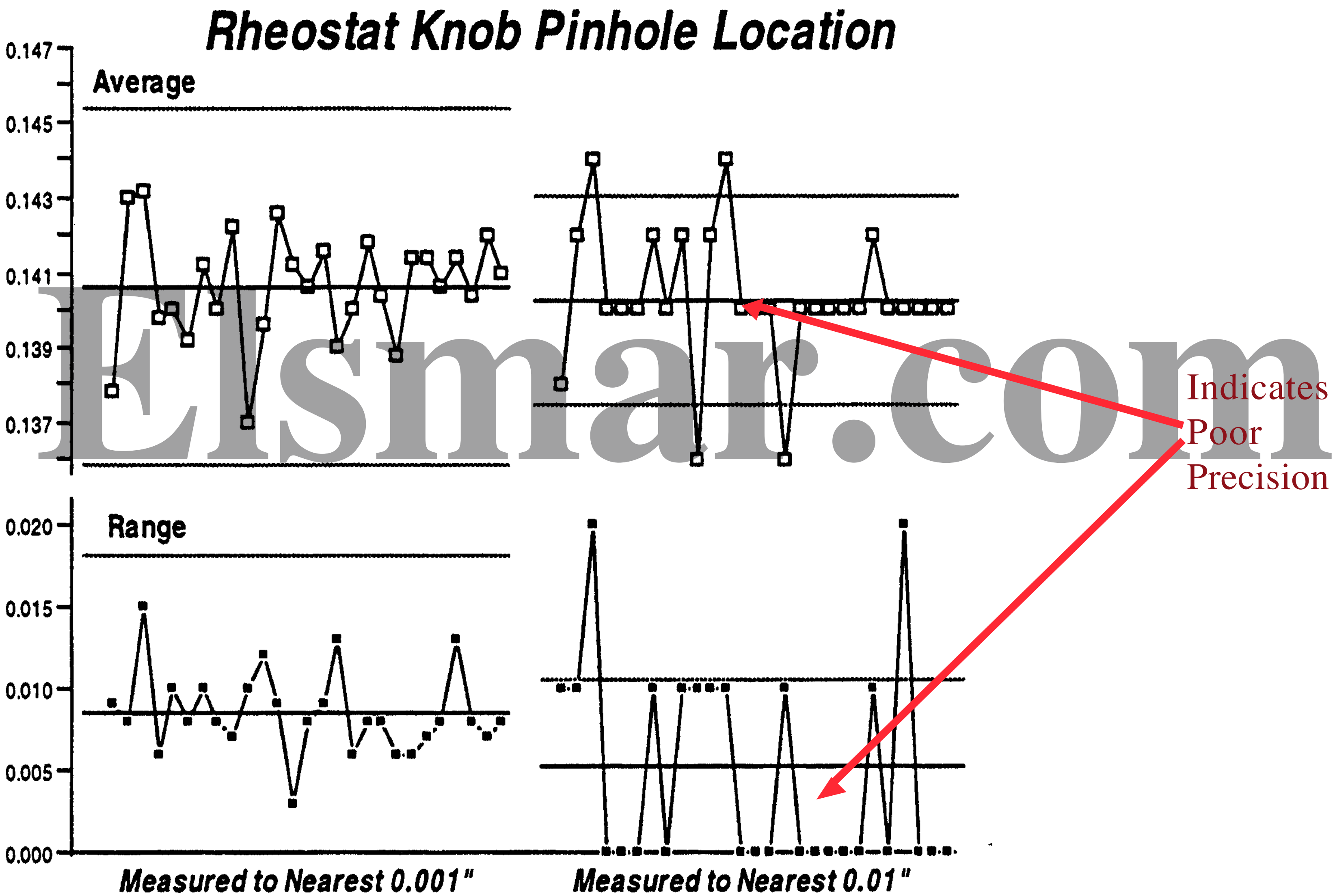
Rheostat Knob Data
To Nearest 0.001"

					Avg	R
140	143	137	134	135	137.8	9
138	143	143	145	145	143.0	9
139	133	147	148	149	143.2	15
143	141	137	138	140	139.8	6
142	142	145	135	136	140.0	10

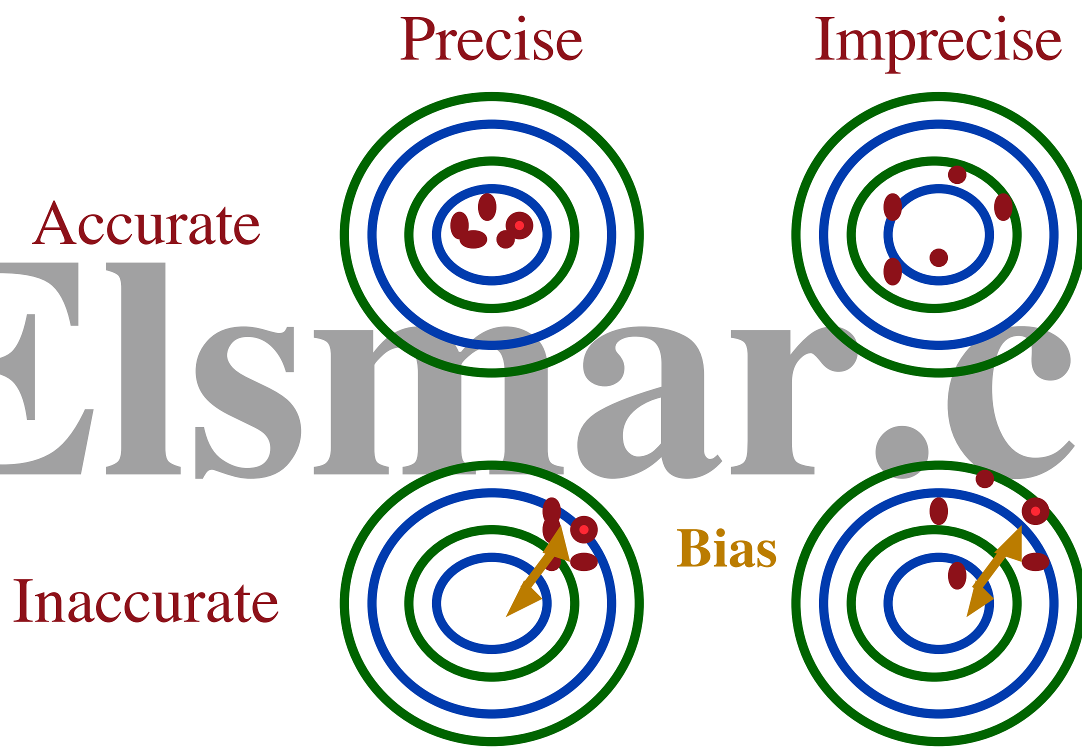
Rheostat Knob Data
To Nearest 0.01"

					Avg	R
14	14	14	13	14	13.8	1
14	14	14	14	15	14.2	1
14	13	15	15	15	14.4	2
14	14	14	14	14	14.0	0
14	14	14	14	14	14.0	0

Range Charts & Discrimination

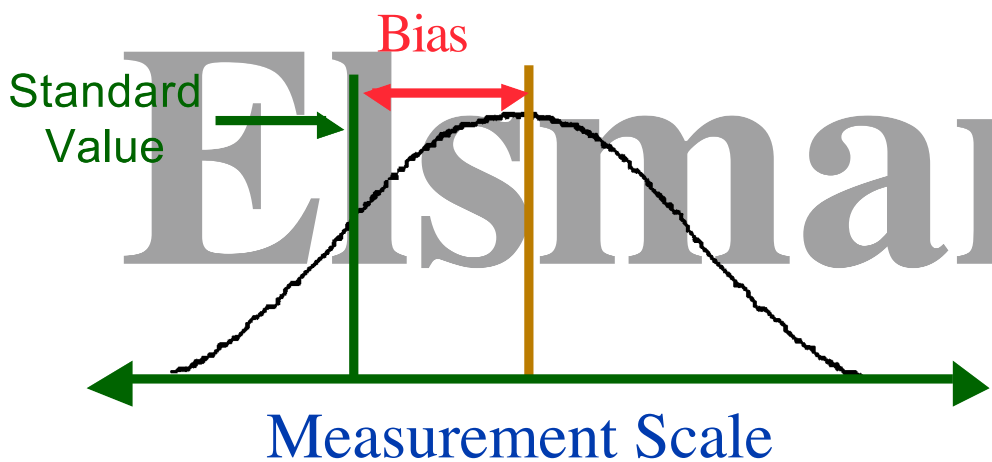


Bias and Repeatability



You can correct for Bias
You can NOT correct for Imprecision

Bias



- Difference between average of measurements and an Agreed Upon standard value
- Known as Accuracy
- Cannot be evaluated without a Standard
- Adds a Consistent "Bias Factor" to **ALL** measurements
- Affects all measurements in the same way

Causes of Bias

- Error in Master
- Worn components
- Instrument improperly calibrated
- Instrument damaged
- Instrument improperly used
- Instrument read incorrectly
- Part set incorrectly (wrong datum)

Bias and QS9000

BIAS - The difference between the observed Average of measurements and the master Average of the same parts using precision instruments. (MSA Manual Glossary)

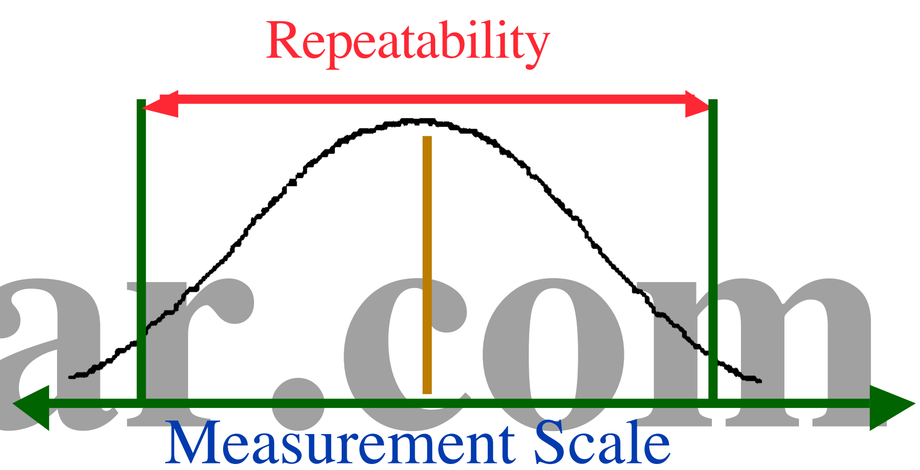
The auditor may want evidence that the concept of bias is understood. Remember that bias is nothing more than an offset from ‘zero’. Bias is linked to Stability in the sense that an instrument may be ‘zeroed’ during calibration verification. Knowing this we deduce that the bias changes with instrument use. This is in part the concept of Drift.

Bias

- I choose a caliper (resolution 0.01) for the measurement. I measure a set of parts and derive the average.
- I take the same parts and measure them with a micrometer (resolution 0.001). I then derive the average.
- I compare the two averages. The difference is the Bias.

Repeatability

- Variation among repeated measurements
- Known as Precision
- Standard NOT required
- May add or subtract from a given measurement
- Affects each measurement randomly



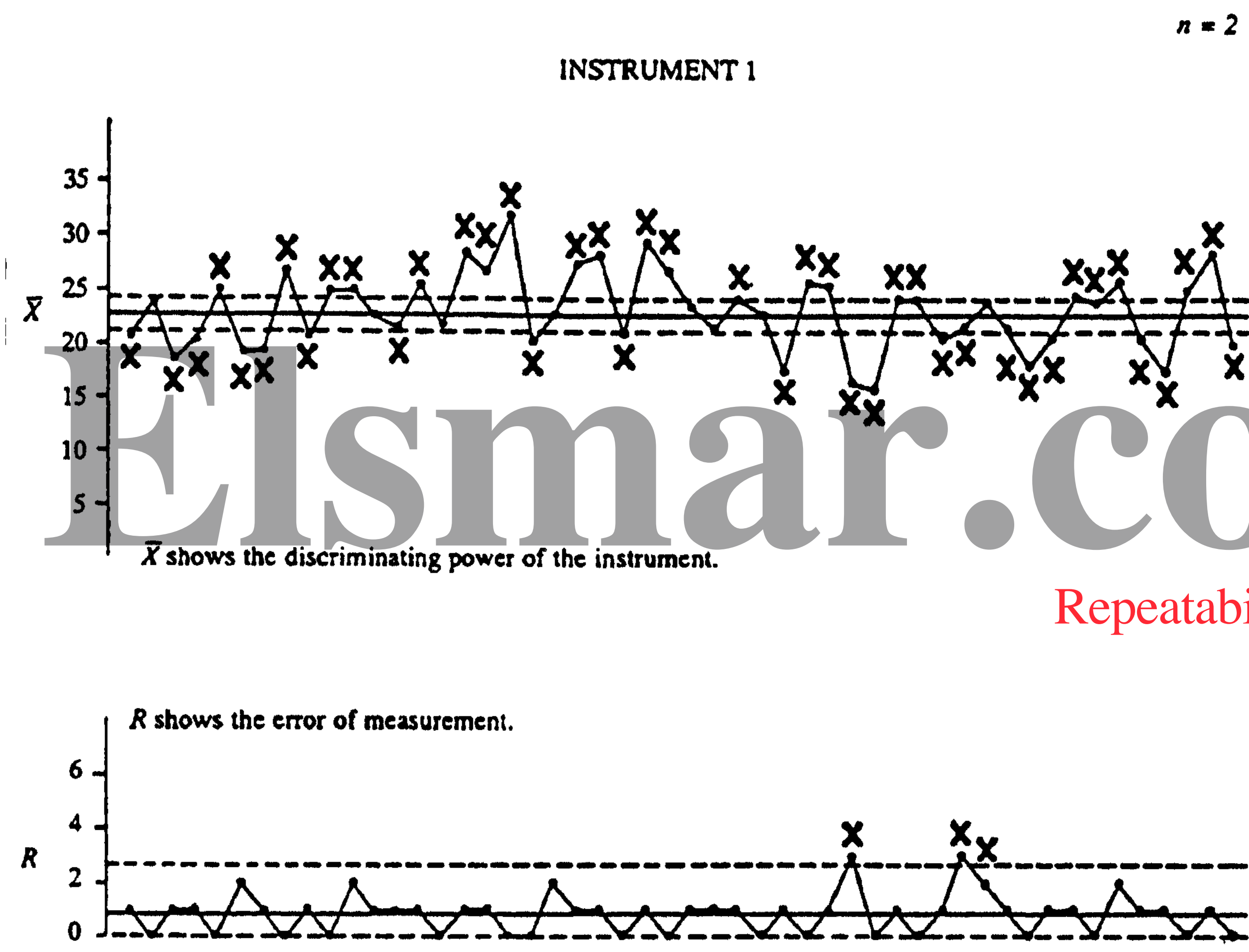
$5.15\sigma = 99\%$

Margin of Error
Doesn't address Bias

Repeatability Issues

- Measurement Steps
  - Sample preparation
  - Setting up the instrument
  - Locating on the part
- How much of the measurement process should we repeat?

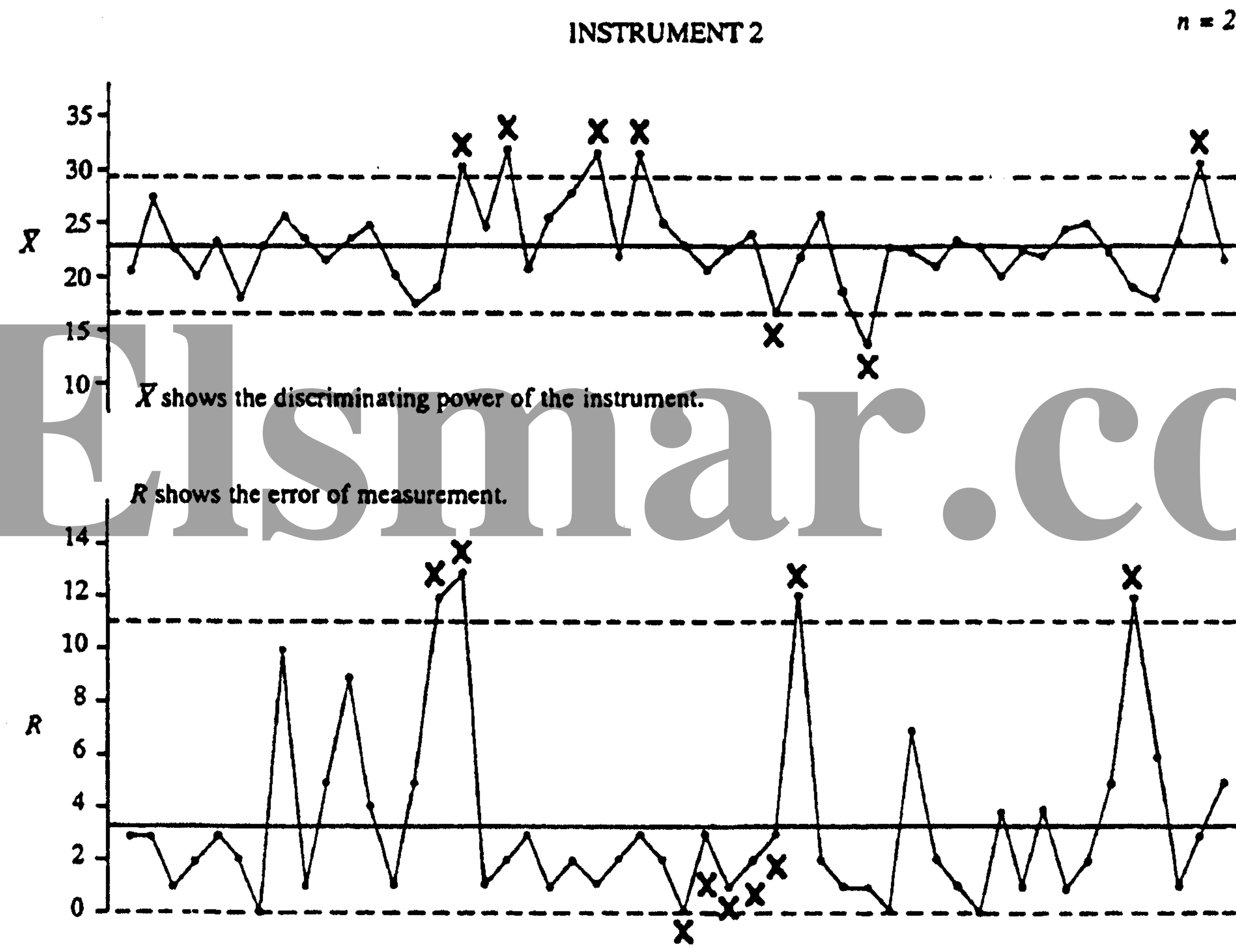
Using Shewhart Charts I



Repeatability

Source: AT&T SQC Handbook Pg. 87

Using Shewhart Charts II



Source: AT&T SQC Handbook Pg. 88

Evaluating Bias & Repeatability

- Same appraiser, Same part, Same instrument
- Multiple readings (n≥10 with 20 to 40 better)
- Analysis

True AIAG

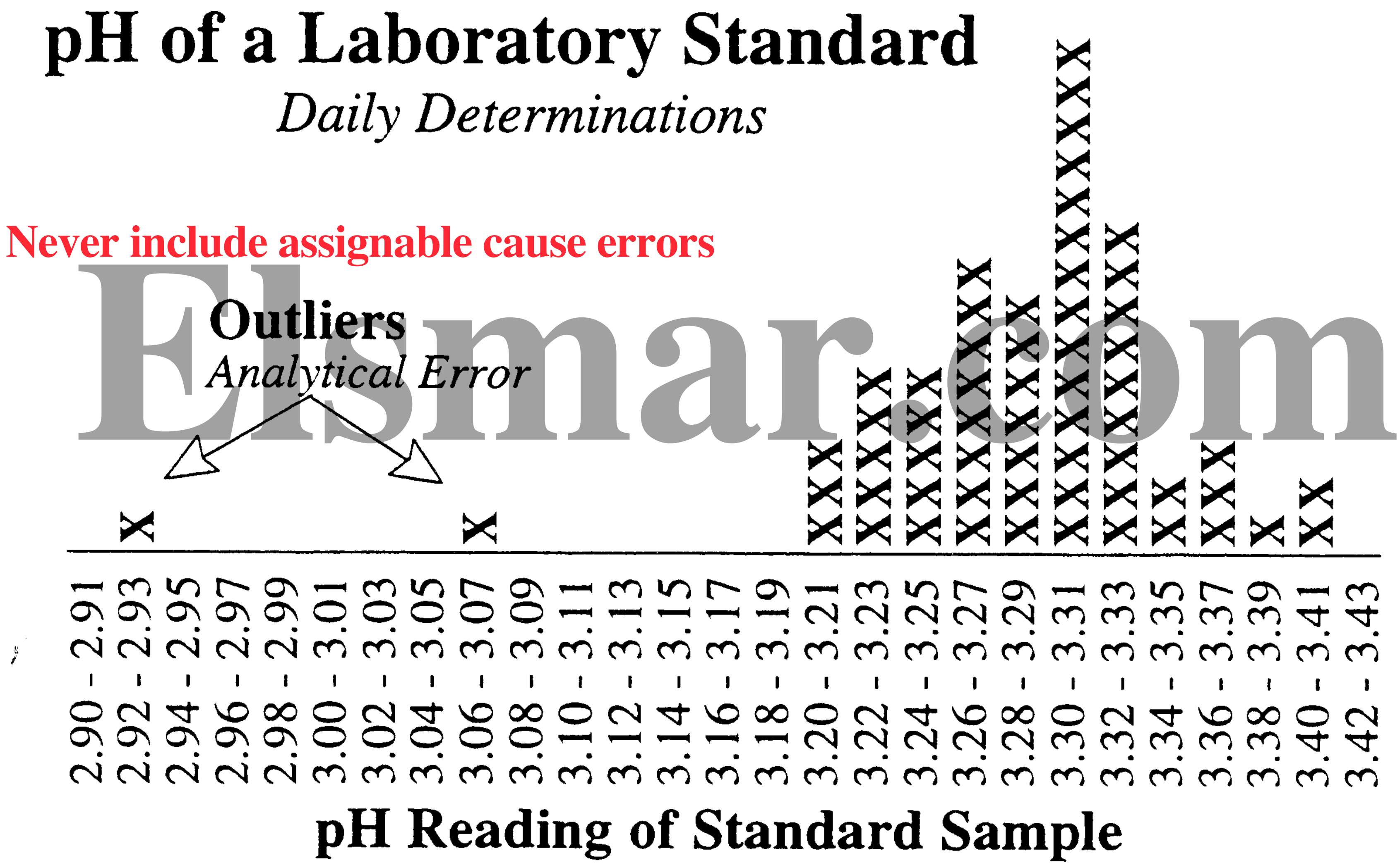
  - Average minus Standard Value = Bias
  - 5.15* Standard Deviation = Repeatability
  - or +/- 2.575 σ [99% repeatability]
  - or +/- 2 σ [95% repeatability]
- Histogram
- Probability

Repeatability Issues

- Making a measurement may involve numerous steps
    - **Sample preparation**
    - **Setting up the instrument**
    - **Locating the part, etc.**

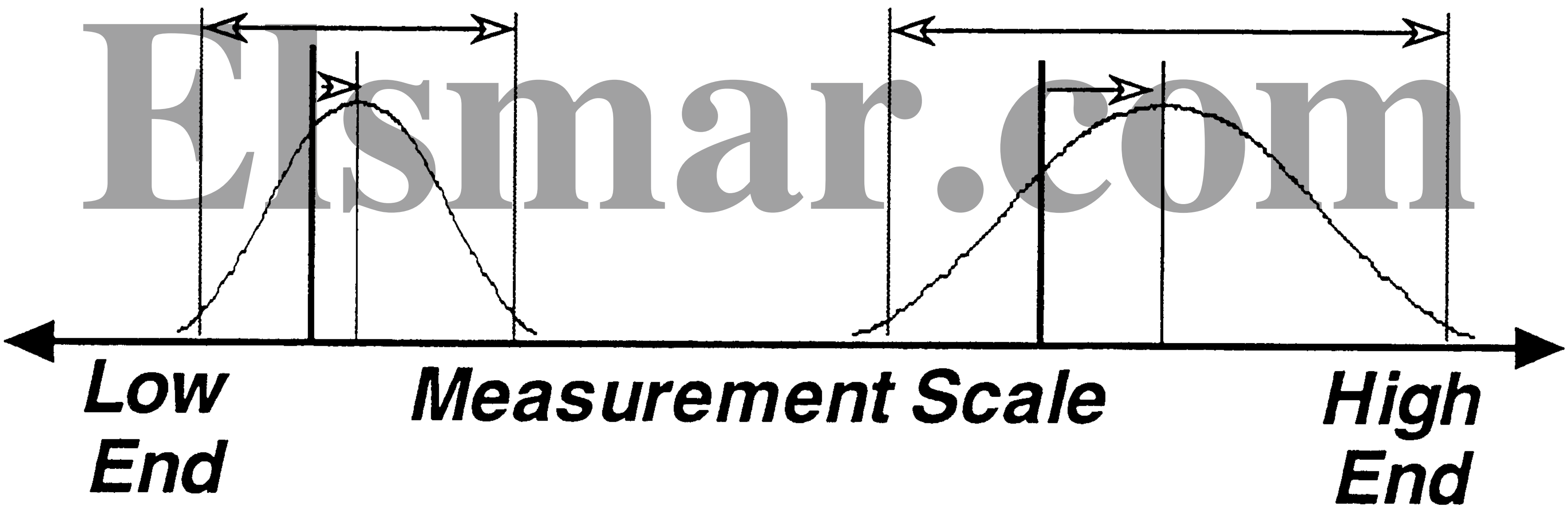
- How much of the measurement process should we repeat? How far do we go?

Bias & Repeatability Histogram

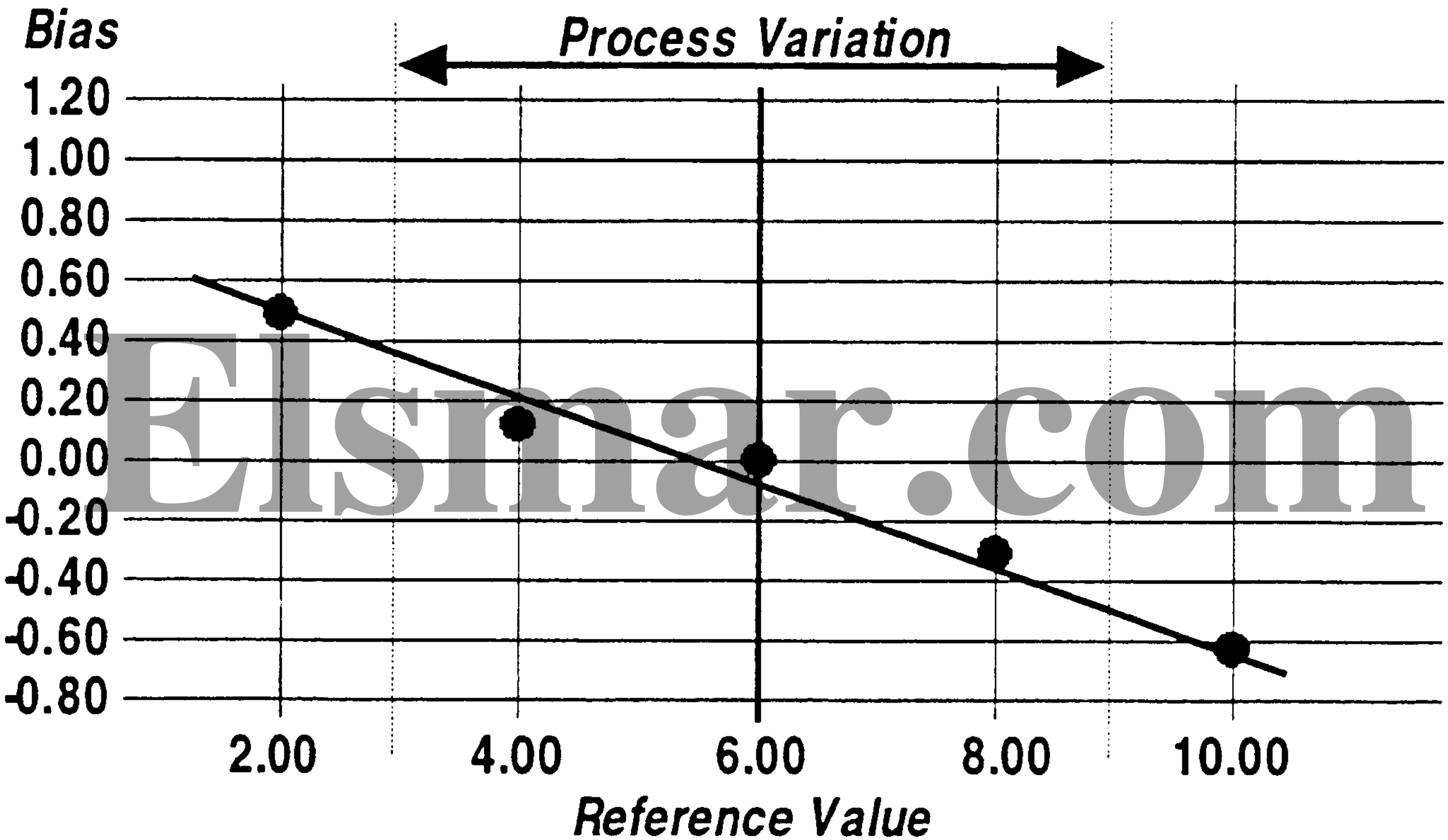


Linearity

- The difference in the Bias or Repeatability across the expected operating range of the instrument.



Plot Biases vs. Ref. Values



Linearity = |Slope| * Process Variation = 0.1317*6.00 = 0.79

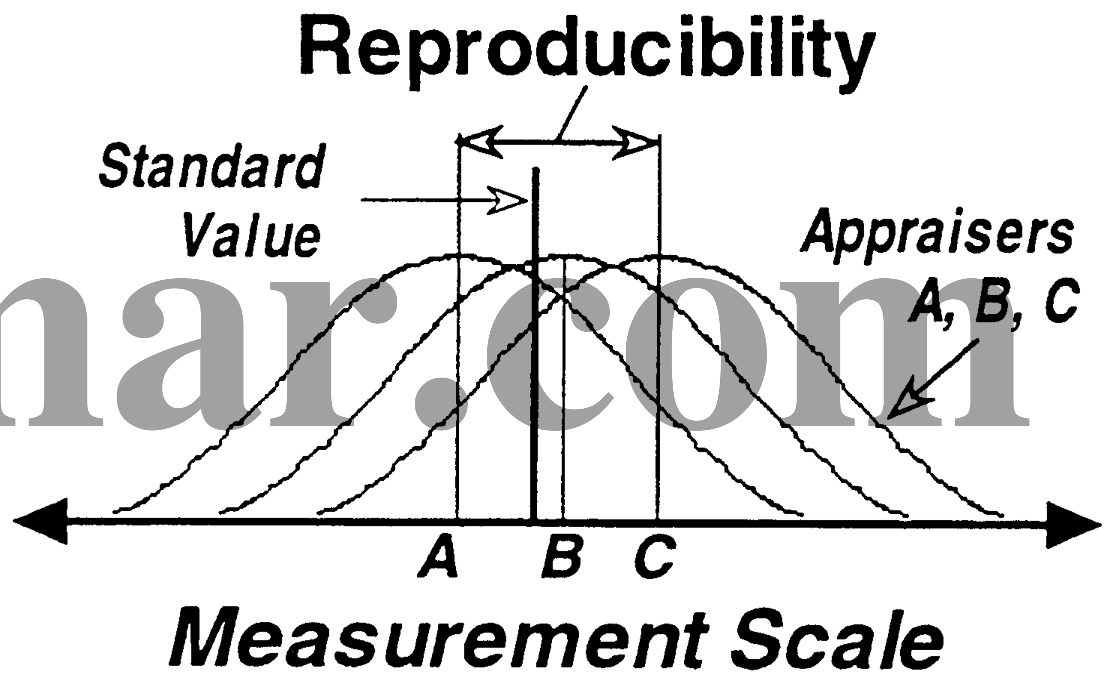
% Linearity = 100 * |Slope| = 13.17%

Causes of Poor Linearity

- Instrument not properly calibrated at both Upper and Lower extremes
- Error in the minimum or maximum Master
- Worn Instrument
- Instrument design characteristics

Reproducibility

- Variation in the averages among different appraisers repeatedly measuring the same part characteristic
- Concept can also apply to variation among different instruments



Includes **repeatability** which must be accounted for.

Reproducibility Example

	Appraiser X					Appraiser Y				
Trial:	1	2	3	Avg	R	1	2	3	Avg	R
Part A	217	216	216	**216.3**	1	216	219	220	**218.3**	4
Part B	220	216	218	**218.0**	4	216	216	220	**217.3**	4
Part C	217	216	216	**216.3**	1	216	215	216	**215.7**	1
Part D	214	212	212	**212.7**	2	216	212	212	**213.3**	4
Part E	216	219	220	**218.3**	4	220	220	220	**220.0**	0
				216.3					**216.9**	

First: Estimate Repeatability →

$$\overline{R} = 25/10 = 2.5$$

$$UCL_R = D_4\overline{R} = 2.575*2.5 = 6.4$$

$$\sigma = \overline{R}/d_2^* = 2.5/1.72 = 1.45$$

$$\textbf{Repeatability} = 5.15*\sigma = 7.5$$

Calculating Reproducibility (I)

- Find the range of the appraiser averages (R_0)
- Convert to Standard Deviation using d2*
  (m=# of appraisers; g=# of ranges used = 1)
- Multiply by 5.15
- Subtract the portion of this σ due to repeatability

Calculating Reproducibility

People variance

$$\text{Reproducibility (Raw)} = 5.15\frac{R_o}{d_2^*} = 5.15\frac{0.6}{1.41} = 2.2$$

$$\text{Reproducibility} = \sqrt{\left[5.15\frac{R_o}{d_2^*}\right]^2 - \frac{[5.15\sigma]^2}{nr}}$$

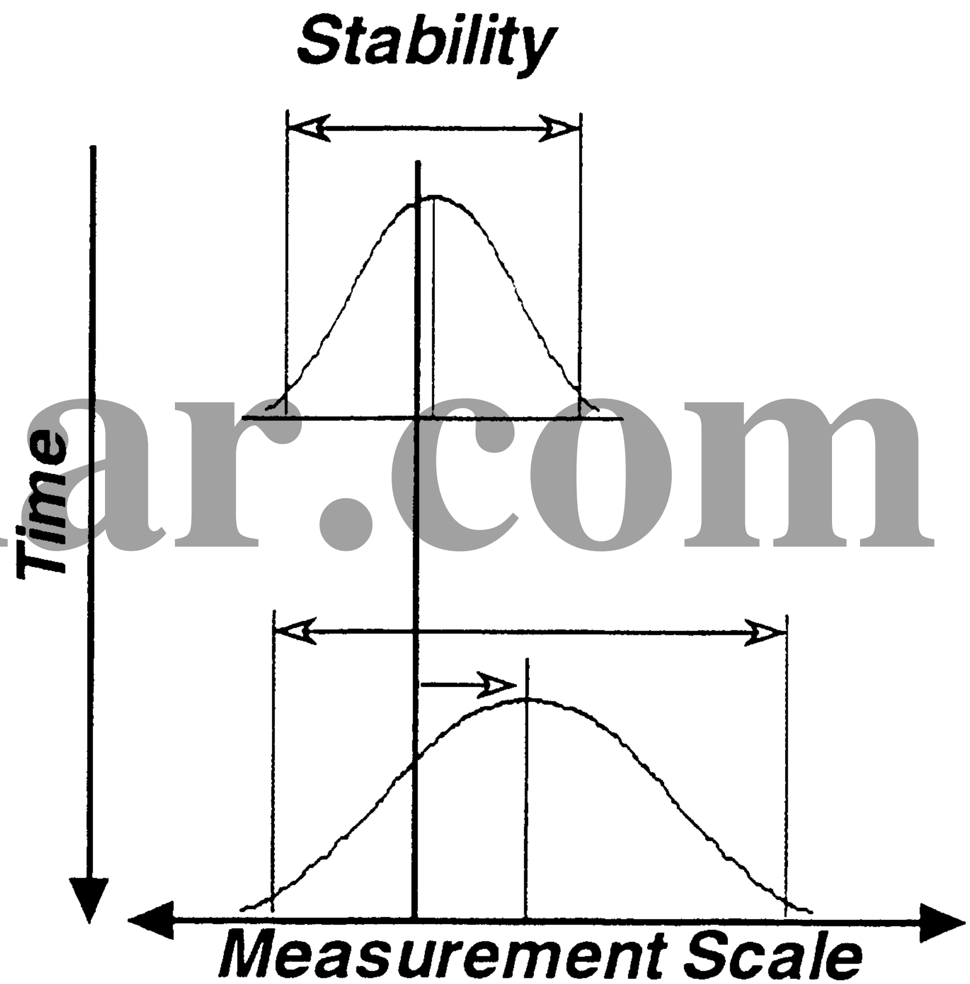
$$= \sqrt{(2.2)^2 - \left[\frac{(7.5)^2}{5 * 3}\right]} = 1.0$$

Times done

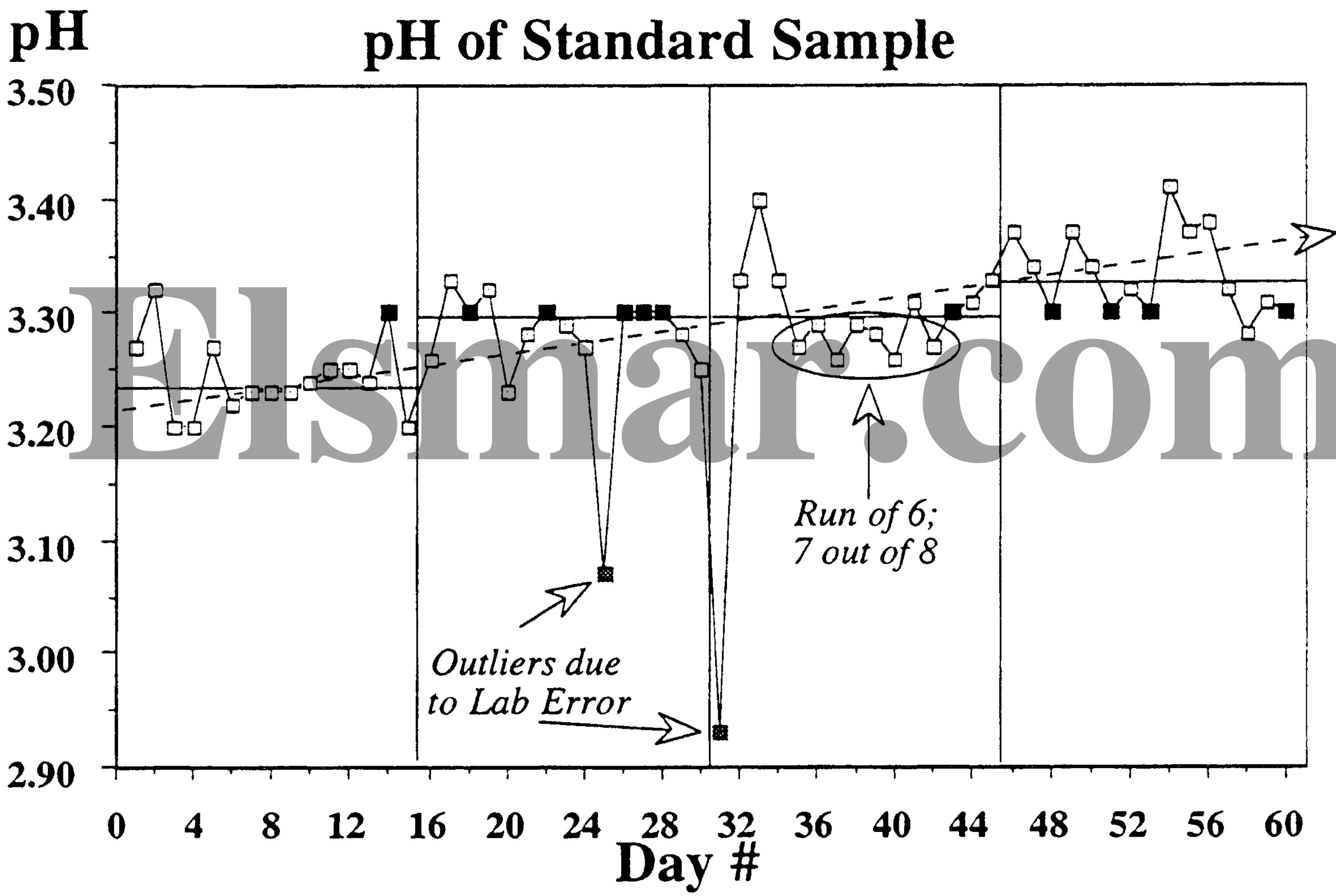
Trials

Stability

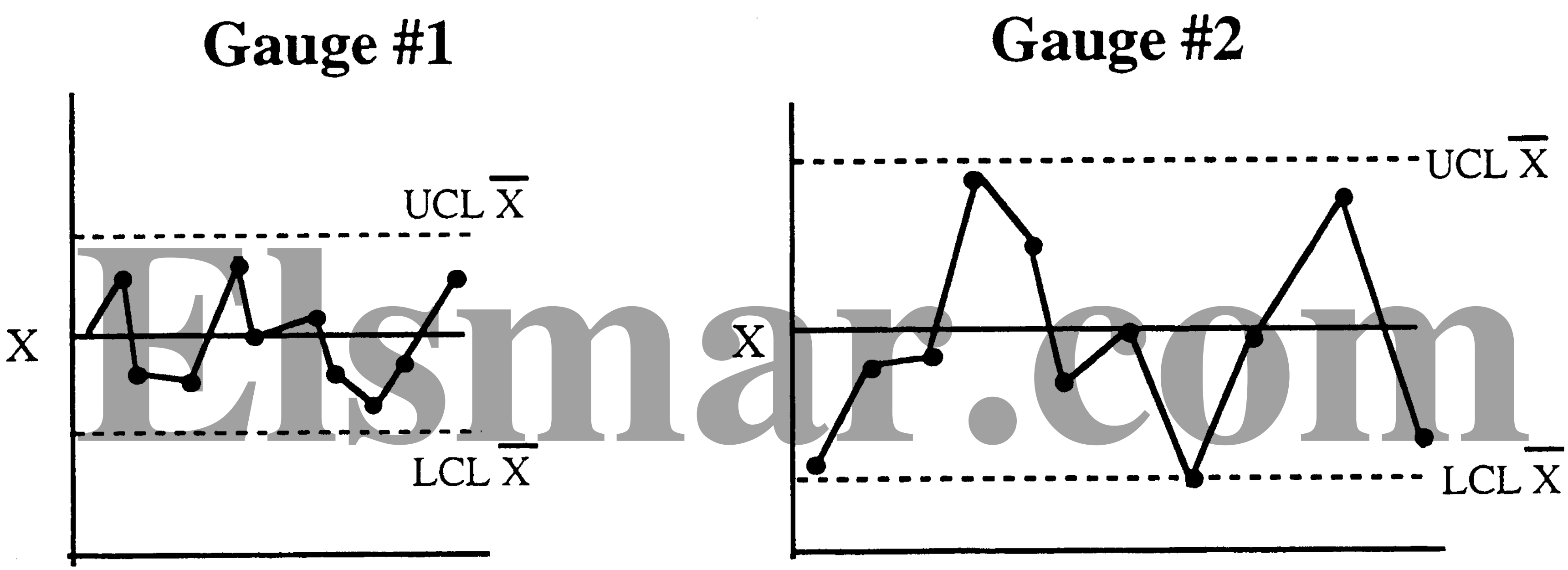
- Variation in measurements of a single characteristic
- On the same master
- Over an extended period of time
- Evaluate using Shewhart charts



Evaluate Stability with Run Charts



Stability



Both gages are stable, but.....

Importance of Stability

- Statistical stability, combined with subject-matter knowledge, allows predictions of process performance
- Action based on analysis of Unstable systems may increase Variation due to ‘Tampering’
- A statistically unstable measurement system cannot provide reliable data on the process

Methods of Analysis

Analysis Tools

- Calculations of Average and Standard Deviation
- Correlation Charts
- Multi-Vari Charts
- Box-and-Whisker Plots
- Run charts
- Shewhart charts

Average and Standard Deviation

- **Bias = Average - Reference Value [X-bar – X_0]**
- **The Bias is Real if the Reference Value Falls Outside the Interval: Average ± $2\sigma/\sqrt{n}$,**
- **Repeatability:** $\sigma_e = R_e/d_2^*$
- **Reproducibility:** $\sigma_o = \sqrt{[R_o/d_2^*]^2 - \frac{[\sigma_e]^2}{nr}}$

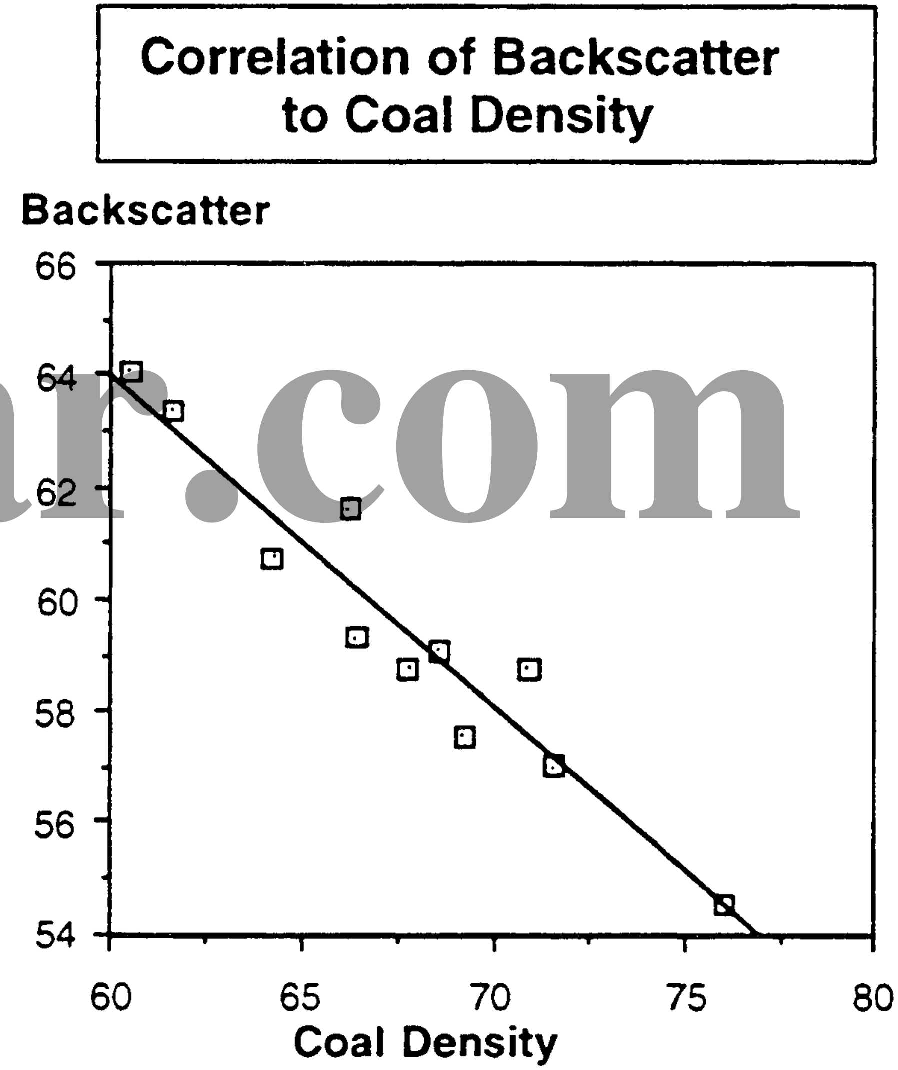
Correlation Charts

Describe Relationships

- Substitute measurement for desired measurement
- Actual measurement to reference value
- Inexpensive gaging method versus Expensive gaging method
- Appraiser A with appraiser B

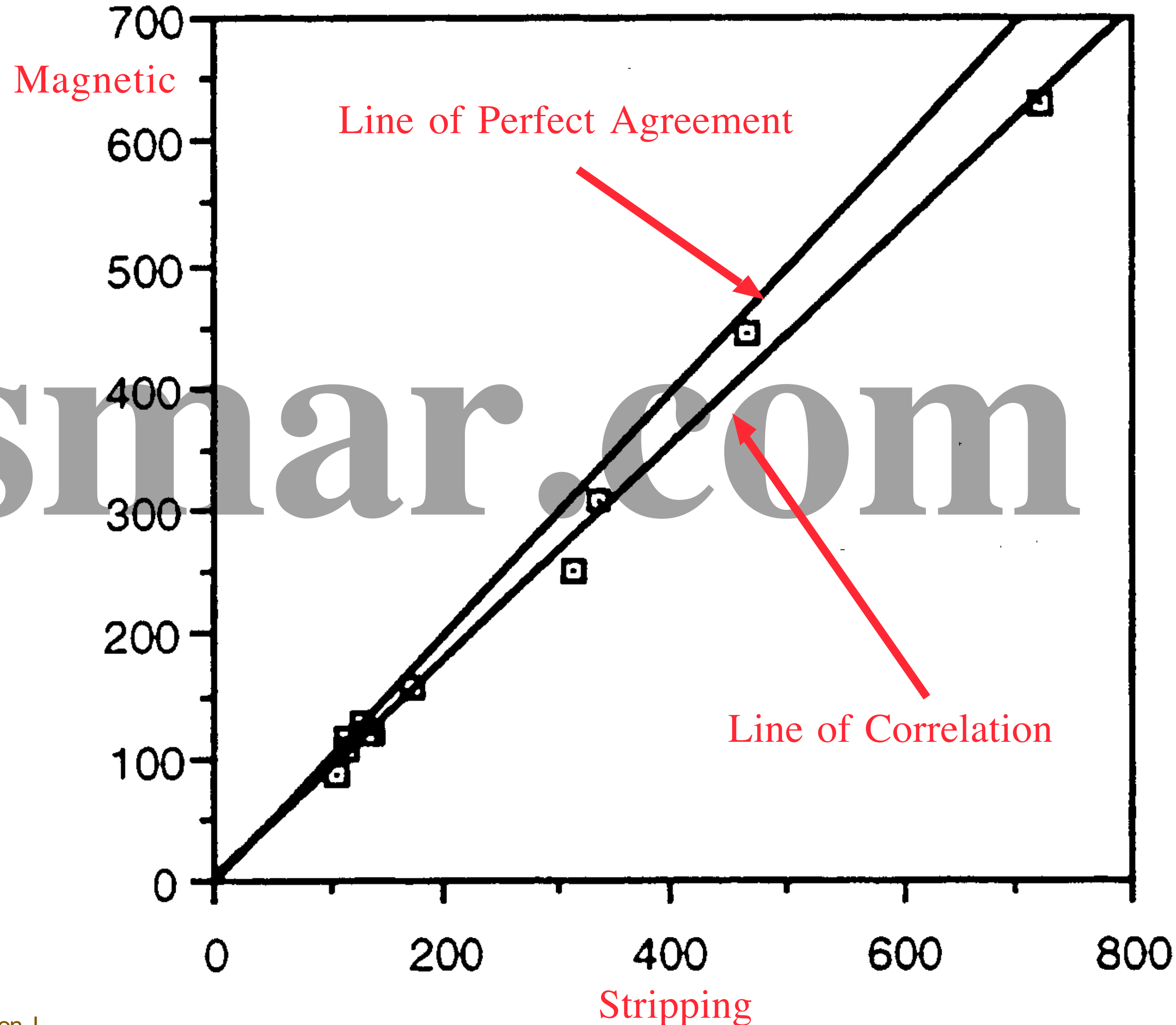
Substitute Measurements

- Cannot directly measure quality
- Correlate substitute measure
- Measure substitute
- Convert to desired quality



Comparing Two Methods

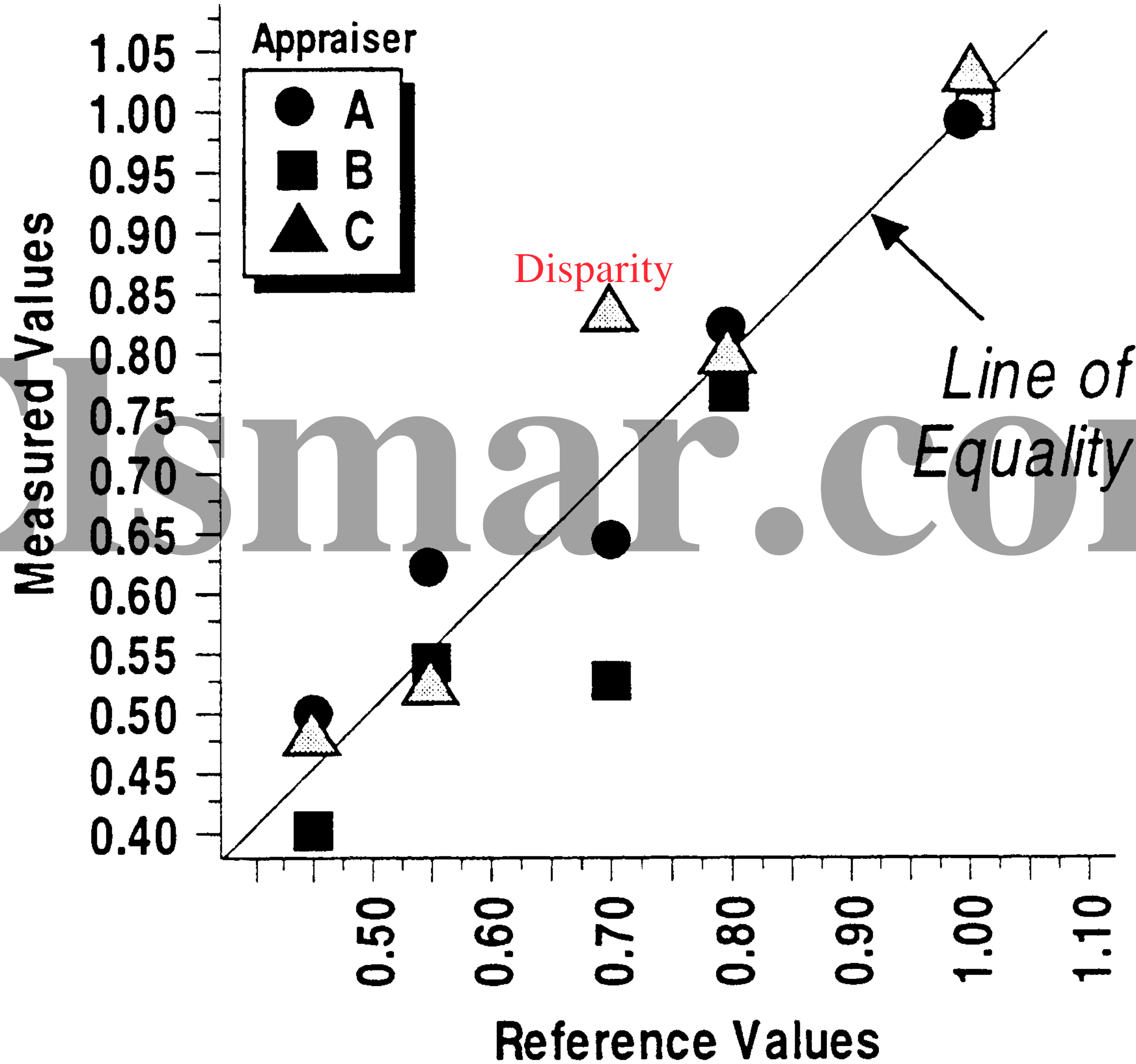
- Two methods
- Measure parts using both
- Correlate the two
- Compare to “Line of No Bias”
- Investigate differences



Measurements vs. Reference Data

	Part A	Part B	Part C	Part D	Part E
Adam	0.65	1.00	0.85	0.55	0.60
	0.60	1.00	0.80	0.45	0.70
	0.625	*1.000*	*0.825*	*0.500*	*0.650*
Betsy	0.55	1.05	0.80	0.40	0.55
	0.55	0.95	0.75	0.40	0.50
	0.550	*1.000*	*0.775*	*0.400*	*0.525*
Chuck	0.50	1.05	0.80	0.45	0.85
	0.55	1.00	0.80	0.50	0.80
	0.525	*1.025*	*0.800*	*0.475*	*0.825*
Ref. Val.	0.55	1.00	0.80	0.45	0.70

Measurements vs. Reference Correlation



Comparing Two Appraisers

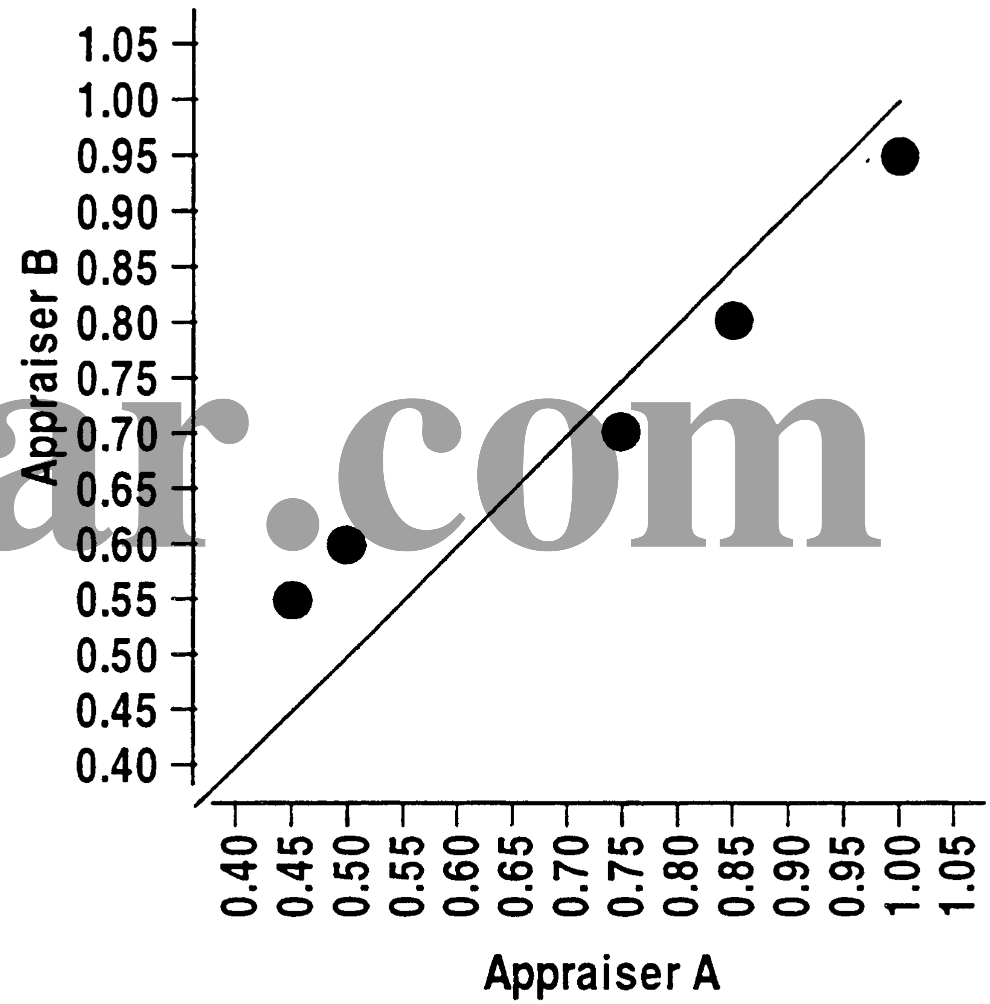
Part	Adam	Betsy	Range
1	0.85	0.80	0.05
2	0.75	0.70	0.05
3	1.00	0.95	0.05
4	0.45	0.55	0.10
5	0.50	0.60	0.10

R-bar = 0.07

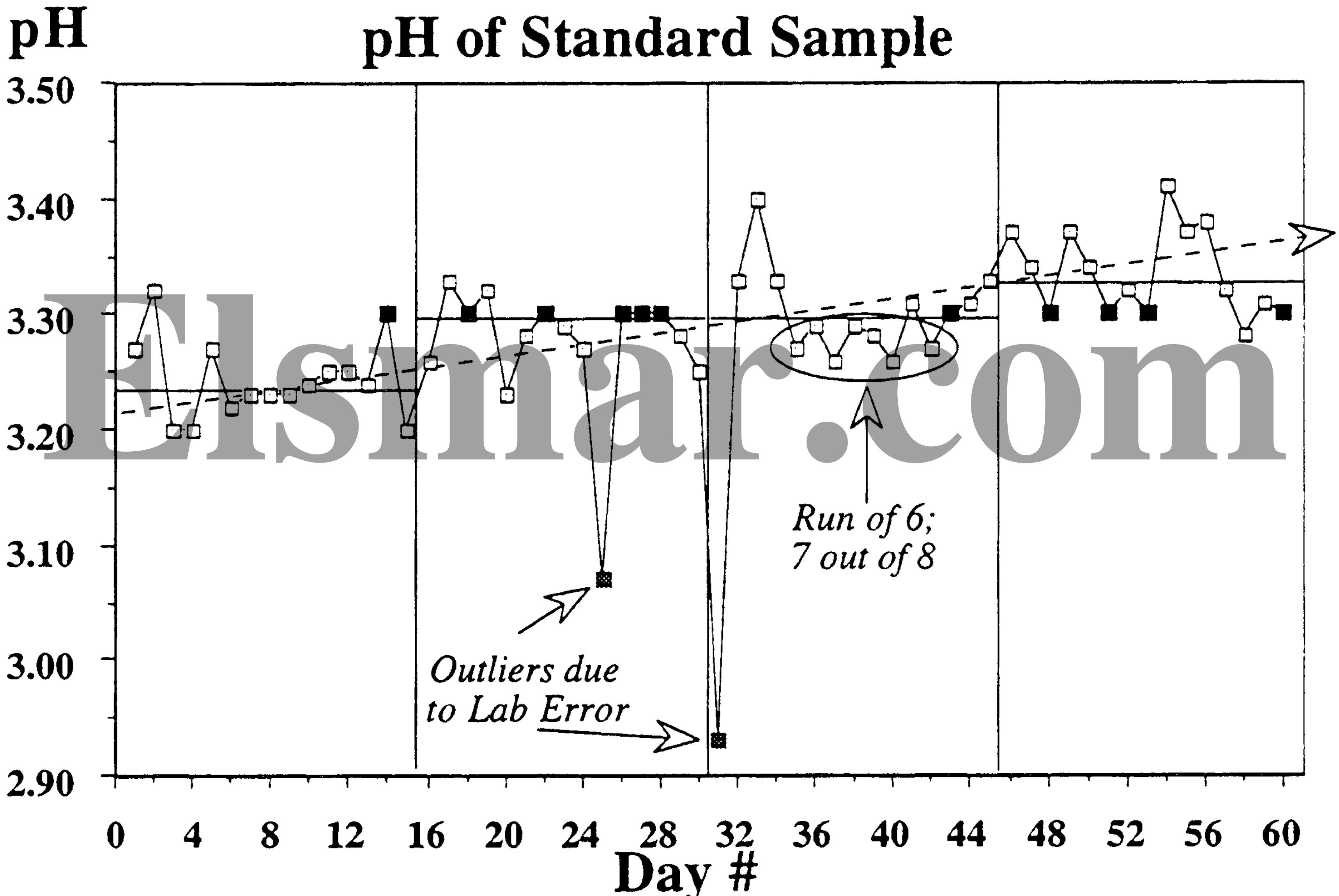
GR&R = 5.15*R-bar/d2*

= 5.15*0.07/1.19

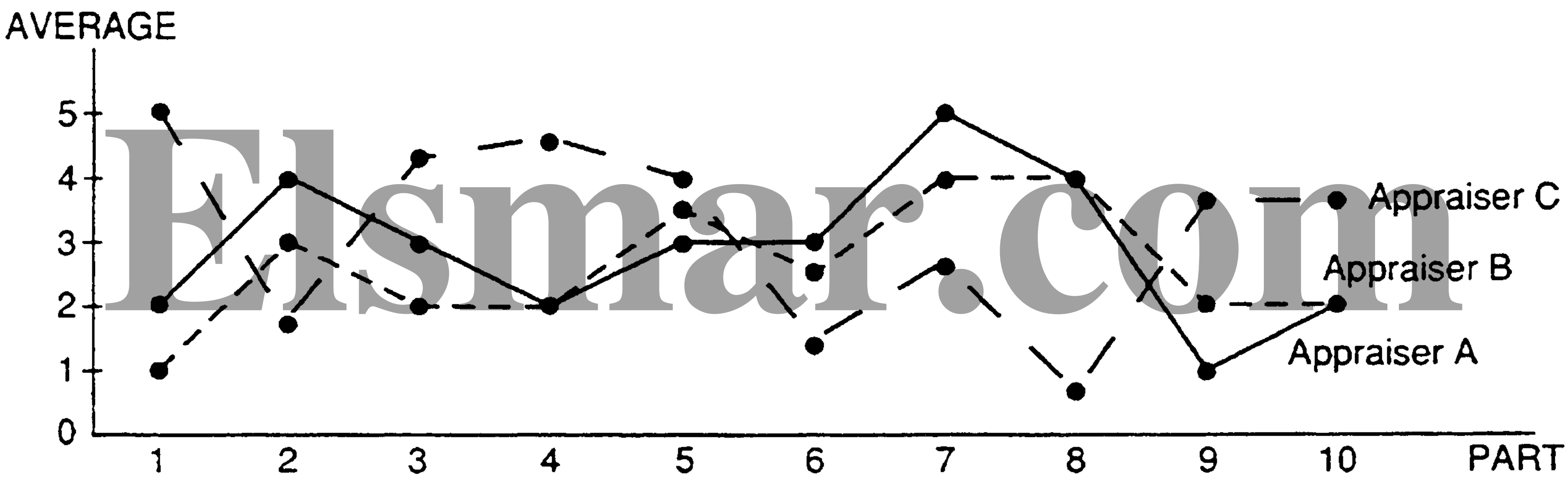
= 0.303



Run Charts Examine Stability



Multiple Run Charts



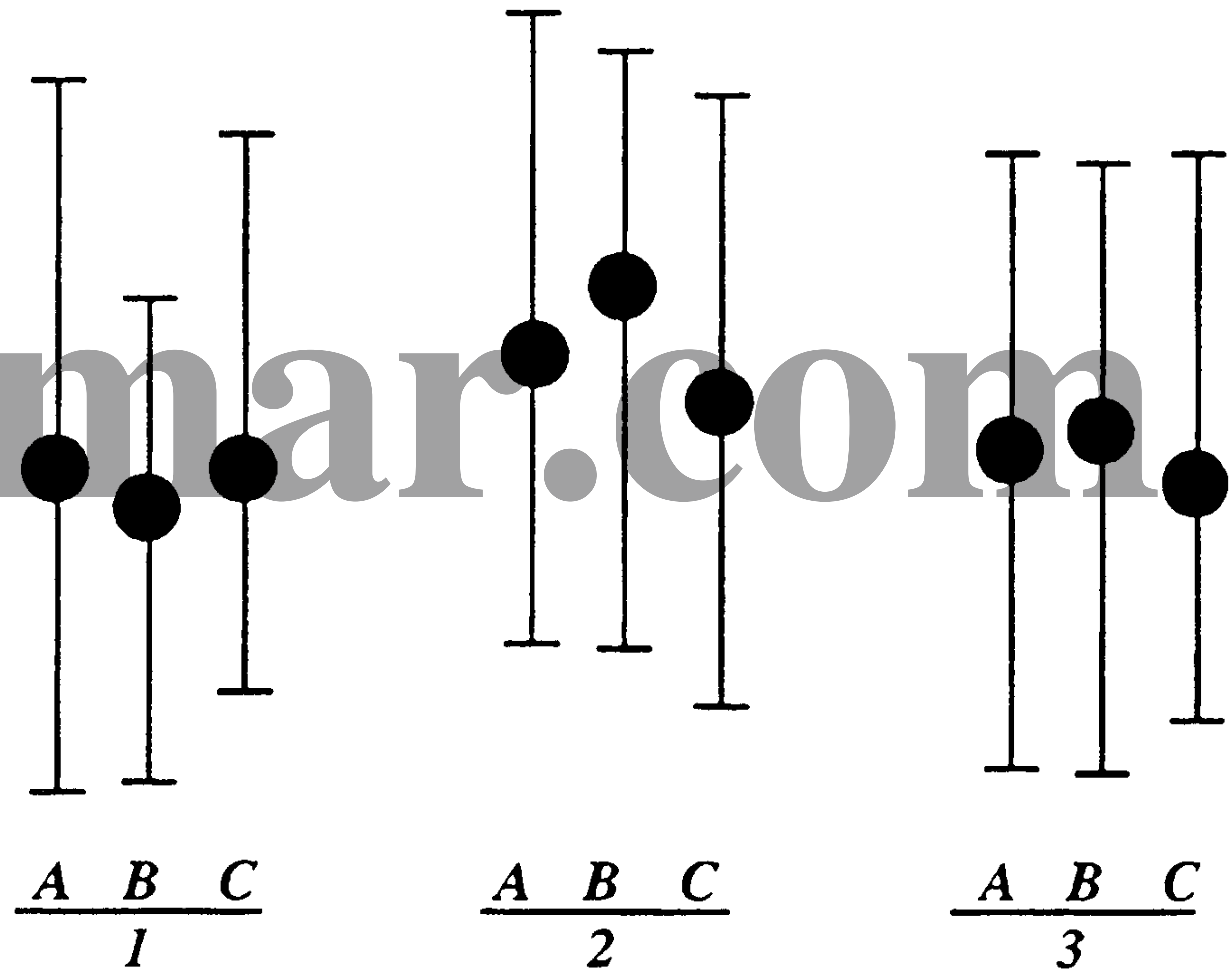
More than 3 appraisers confuses things...

Multi-Vari Charts

- Displays 3 points
- Length of bar; bar-to-bar; Bar cluster to cluster
- Plot High and Low readings as Length of bar
- Each appraiser on a separate bar
- Each piece in a separate bar cluster

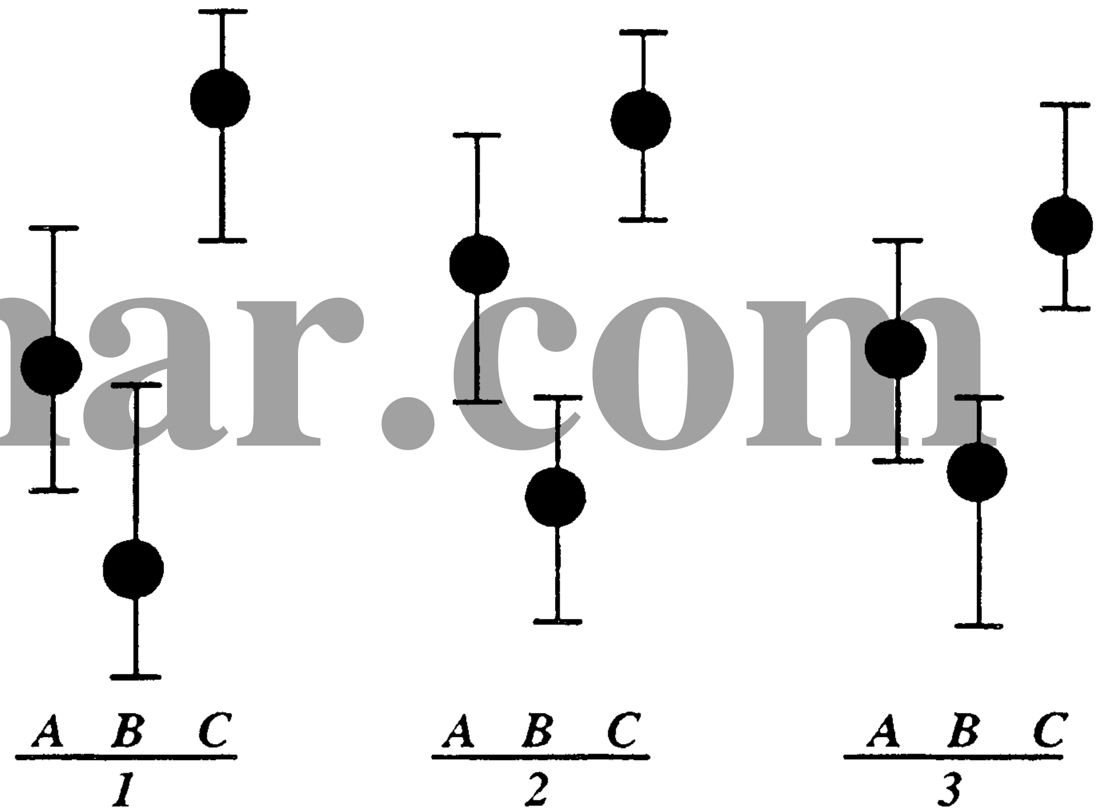
Multi-Vari Type I

- Bar lengths are long
- Appraiser differences small in comparison
- Piece-to-piece hard to detect
- Problem is repeatability



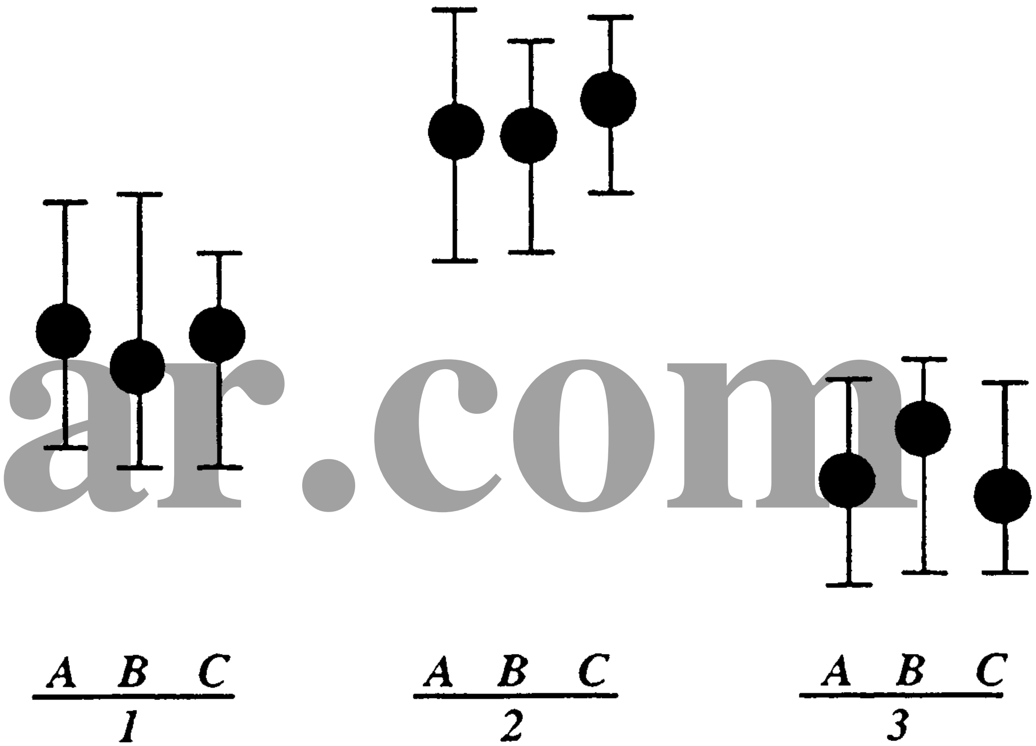
Multi-Vari Type II

- Appraiser differences are biggest source of variation
- Bar length is small in comparison
- Piece-to-piece hard to detect
- Problem is reproducibility

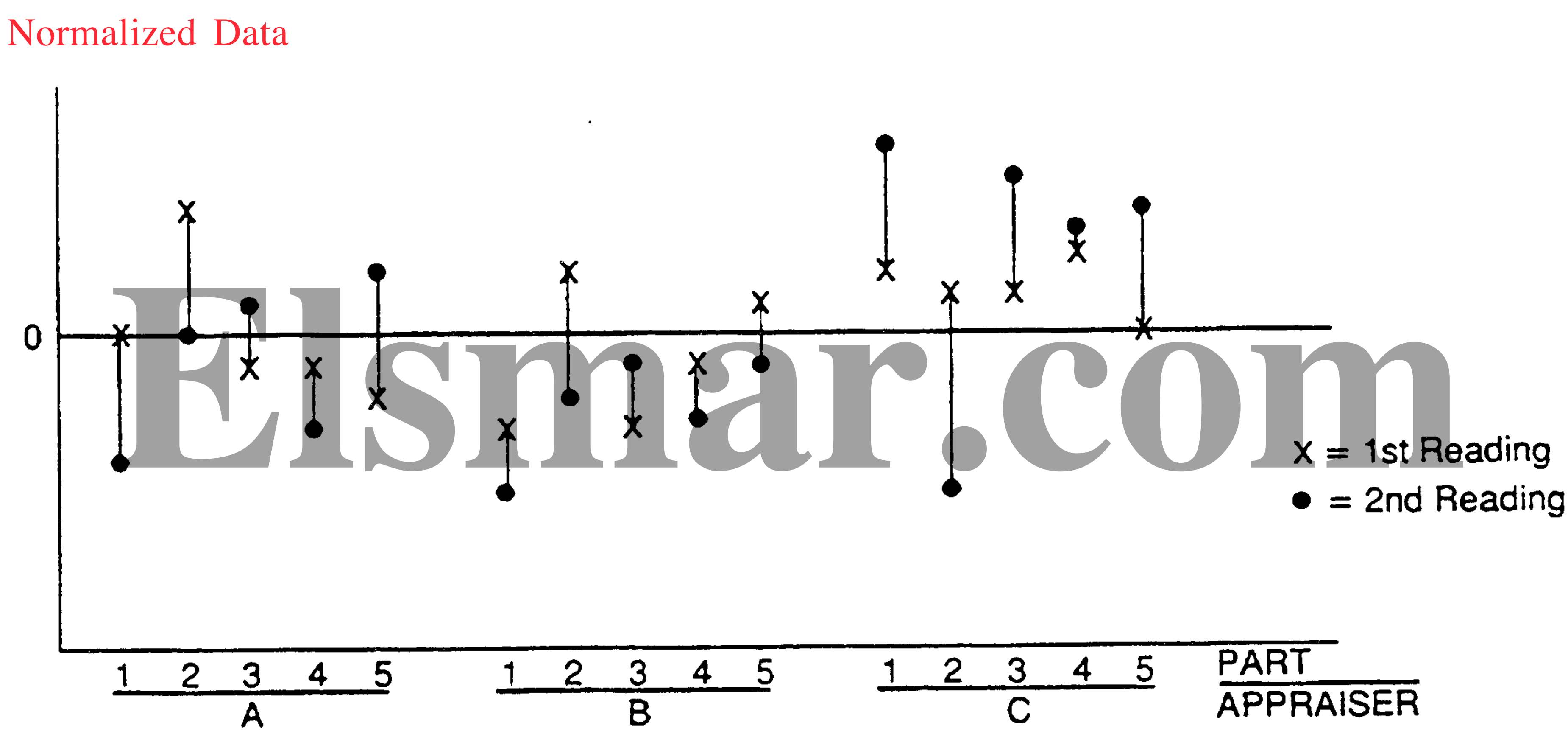


Multi-Vari Type III

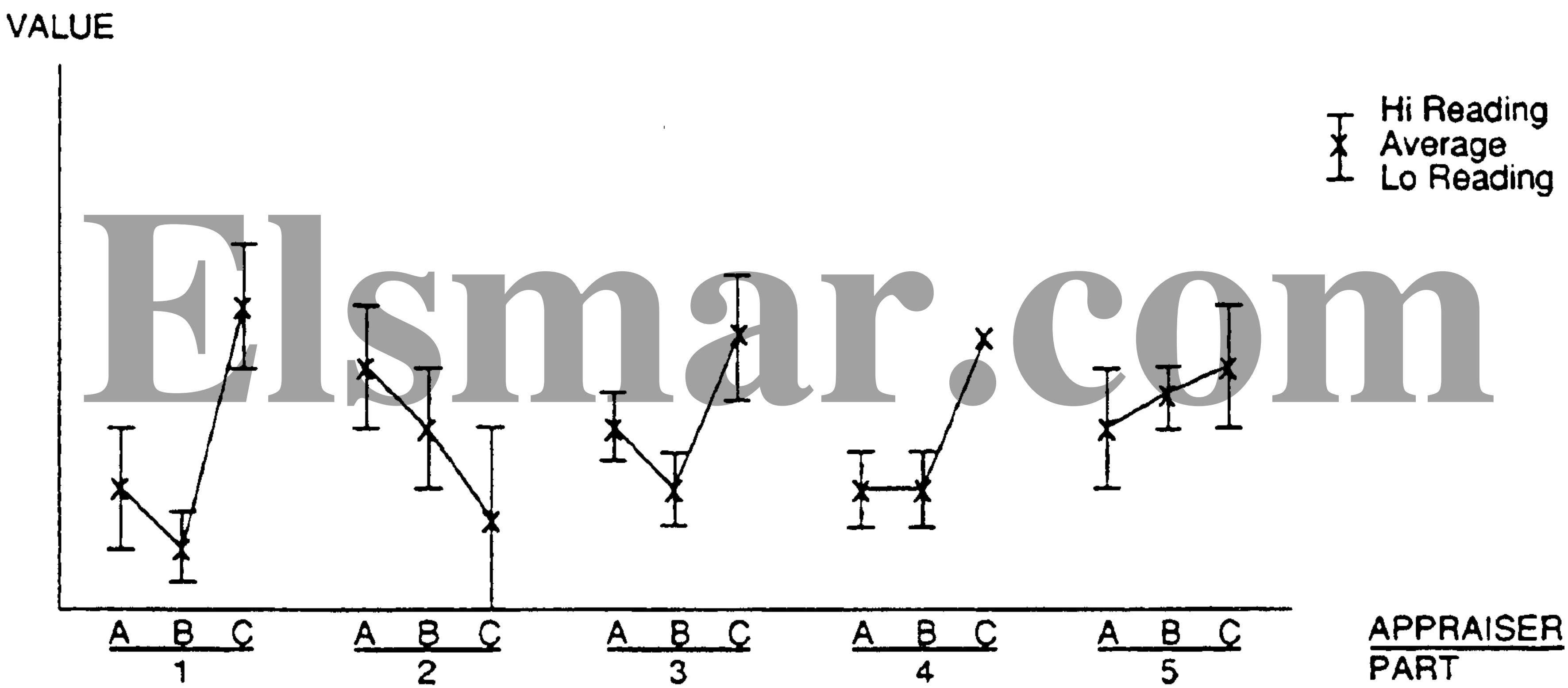
- Piece-to-piece variation is the biggest source of variation
- Bar length (repeatability) is small in comparison
- Appraiser differences (bar-to-bar) is small in comparison
- Ideal Pattern



Multi-Vari Chart Example



Multi-Vari Chart, Joined



Look for similar pattern

Using Shewhart Charts

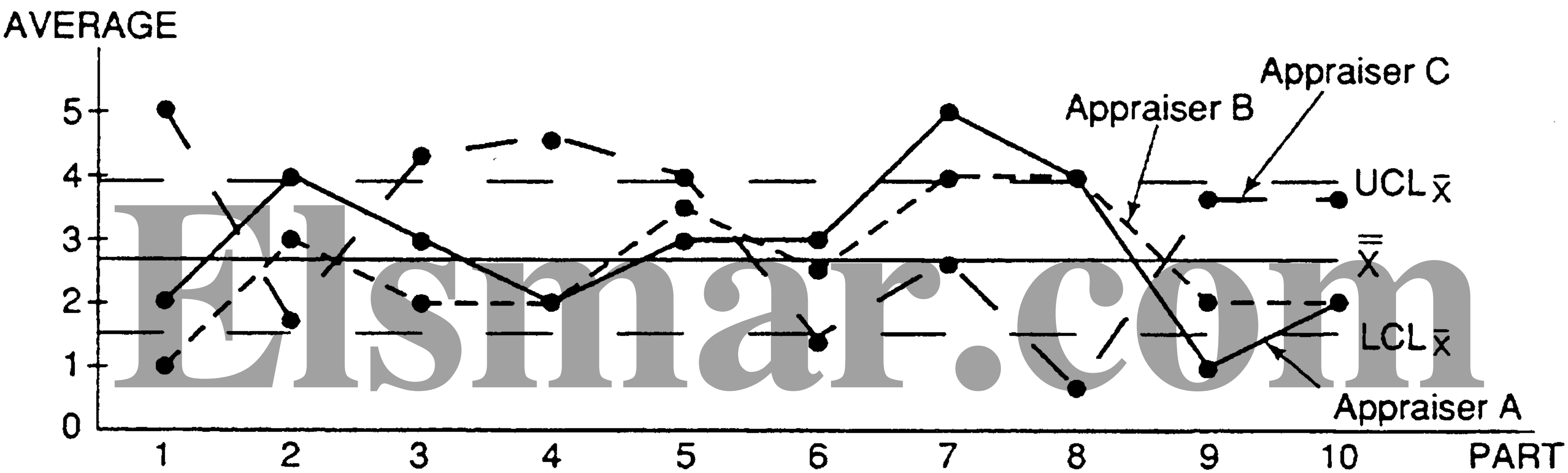
- Subgroup = Repeated measurements,, same piece
- Different Subgroups = Different pieces and/or appraisers
- Range chart shows precision (repeatability)
- Average chart "In Control" shows reproducibility

  If subgroups are different appraisers
- Average chart shows discriminating power

  If subgroups are different pieces

("In Control" is BAD!)

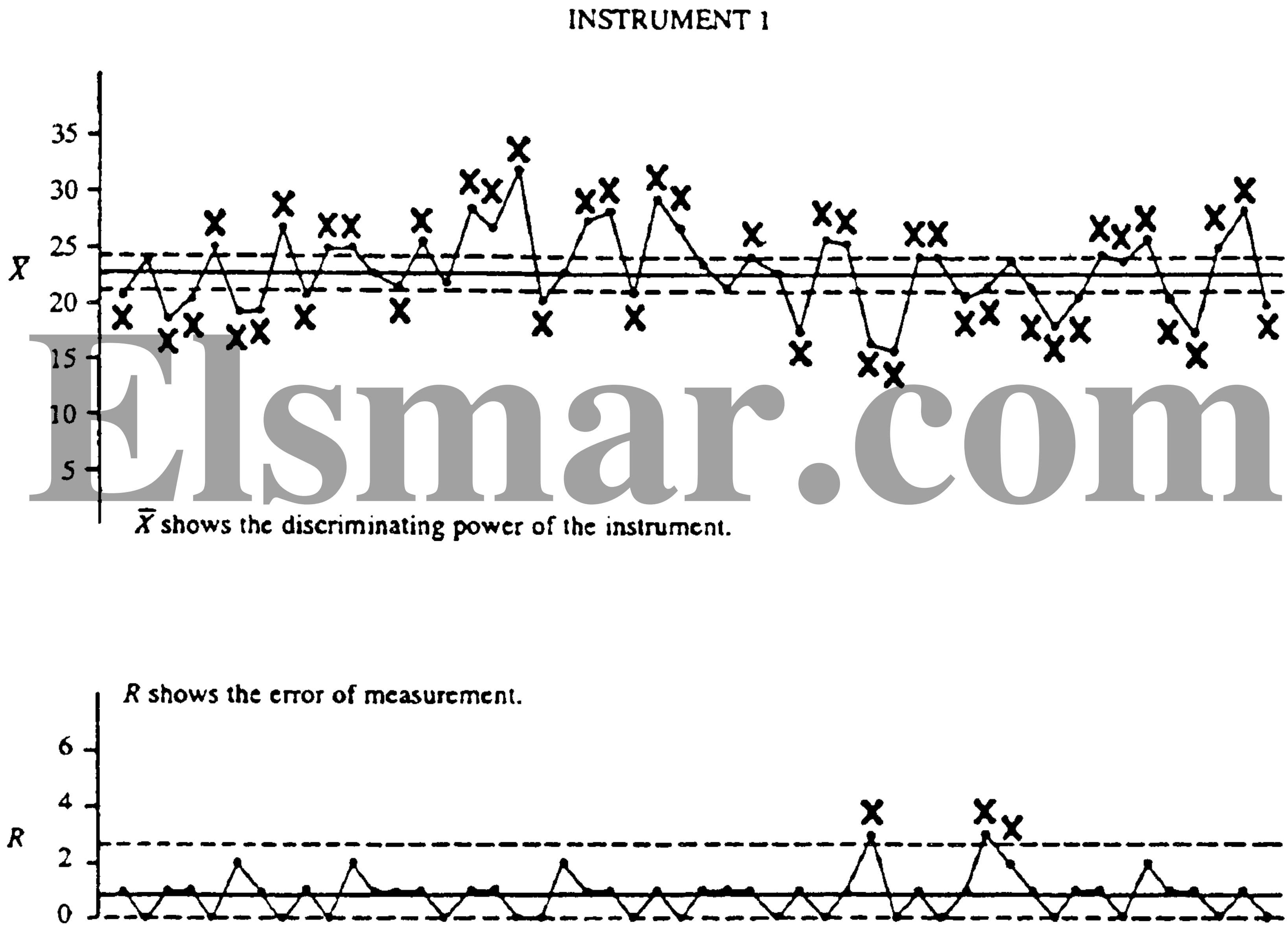
Shewhart Charts



This is not a good way to plot this data

Too many lines

Shewhart Chart of Instrument



Gage R&R Studies

Gauge R&R Studies

- Developed by Jack Gantt
- Originally plotted on probability paper
- Revived as purely numerical calculations
- Worksheets developed by AIAG
- Renewed awareness of Measurement Systems as ‘Part of the Process’

Consider Numerical vs. Graphical Data Evaluations

Terms Used in R&R (I)

- n = Number of Parts [2 to 10]

  Minimum of 5.
  2 to 10 To accommodate worksheet factors

  Parts represent total range of process variation

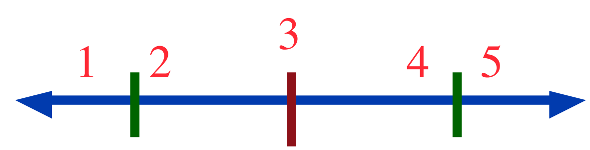
  Need not be "good" parts. Do NOT use consecutive pieces.

  Screen for size

- a = Number of Appraisers

  Each appraiser measures each part r times

  Study must be by those actually using



1 Outside Low/High
1 Inside Low/High
Target

- R - Number of trials
  - Also called "m" in AIAG manual
- g = r*a [Used to find d2* in table 2, p. 29 AIAG manual]

Terms Used in R&R (II)

- R-bar$_A$ = Average range for appraiser A, etc.
- R-double bar = Average of R-bar$_A$, R-bar$_B$
- R_p = Range of part averages   Process Variation
- X_{DIFF} = Difference between High & Low appraiser averages

  Also a range, but "R" is not used to avoid confusion

- EV = 5.15σ_e = Equipment variation (repeatability)
- EV = 5.15σ_o = Equipment variation (reproducibility)
- PV = Part variation
- TV = Total variation

R&R Calculations

- $EV = \overline{\overline{R}} * K_1$
  - K_1 depends on r, the number of *trials*
- $AV = \sqrt{(\overline{X}_{DIFF} * K_2)^2 - (EV^2/nr)}$

Left over Repeatability

  - K_2 depends on a, the number of *appraisers*
  - n = Parts; r = trials
- $R\&R = \sqrt{EV^2 + AV^2}$

Remember - Nonconsecutive Pieces

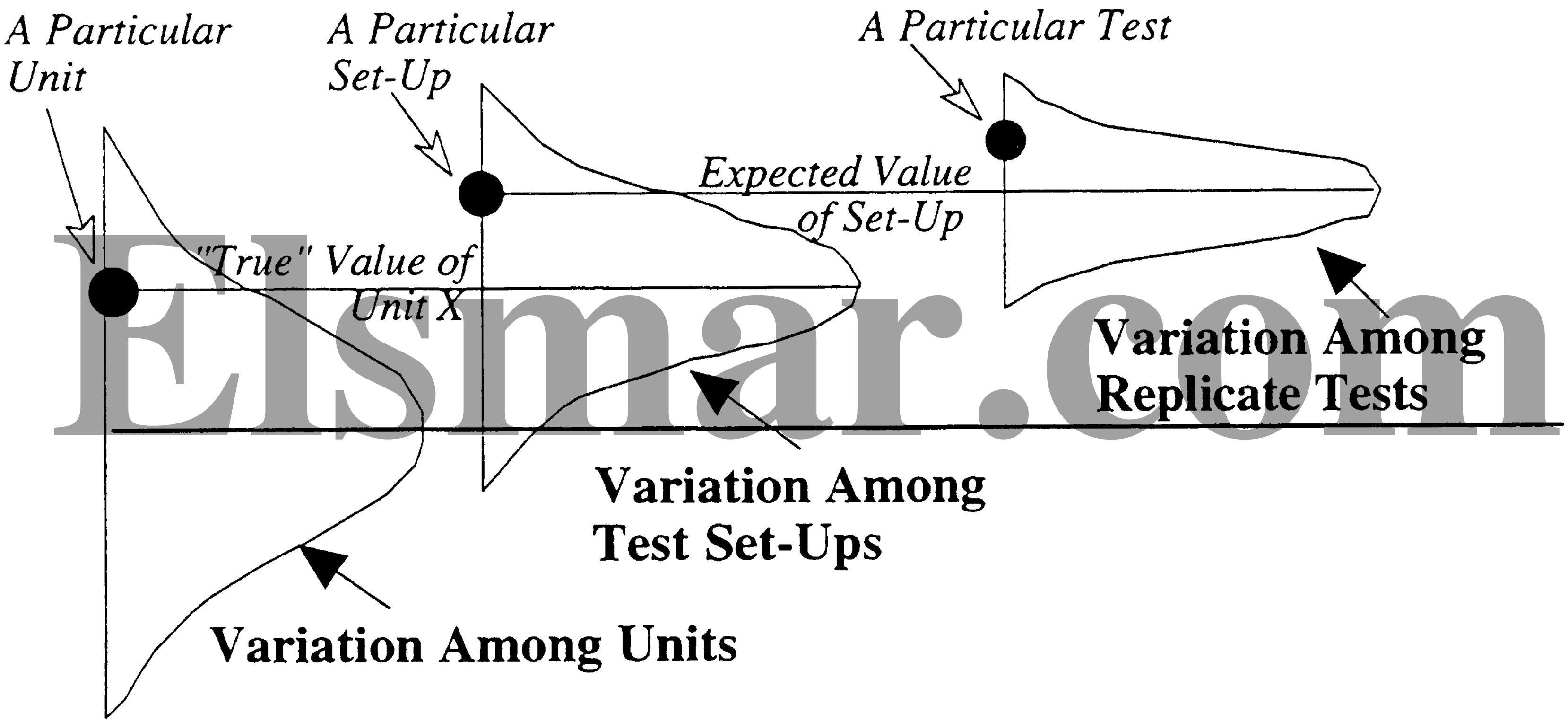
- $PV = R_P * K_3$
  - K_3 depends on n, the number of *parts*
- $TV = \sqrt{R\&R^2 + PV^2 - (EV^2/nr)}$

Left over Repeatability

Product Process Variation

Measurement System Variation

Accumulation of Variances



Evaluating R&R

- %R&R=100*[R&R/TV] (Process Control)
- %R&R=100*[R&R/Tolerance] (Inspection)
- **Under 10%:** Measurement System Acceptable
- **10% to 30%:** Possibly acceptable, depending upon use, cost, etc.
- Over 30%: Needs serious improvement

Analysis of Variance I

- Mean squares and Sums of squares
- Ratio of variances versus expected F-ratio
- Advantages

  Any experimental layout

  Estimate interaction effects
- Disadvantages

  Must use computer

  Non-intuitive interpretation

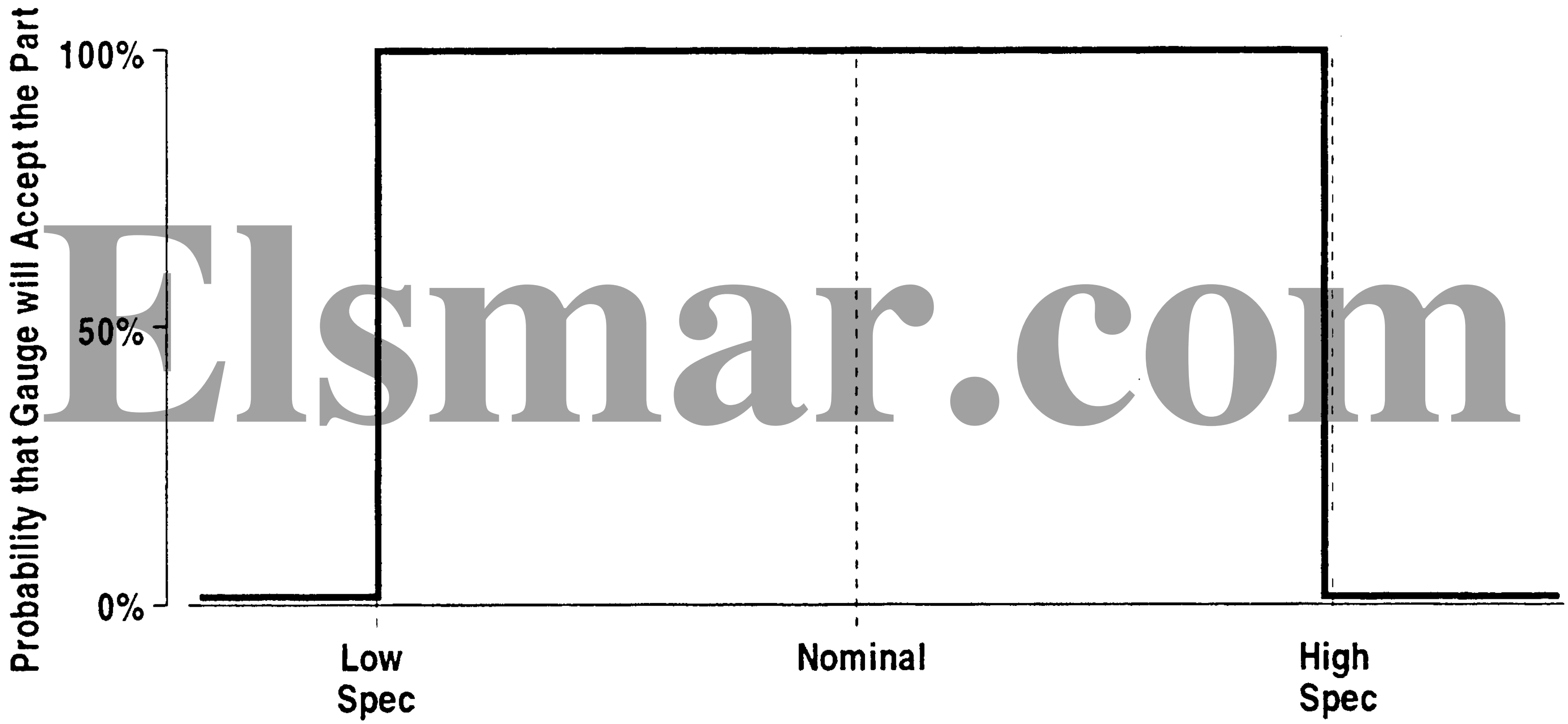
Analysis of Variance II

- The n*r measurements must be done in random sequence [a good idea anyway]
- Assumes that EV [repeatability] is normal and that EV is not proportional to measurement [normally a fairly good assumption]
- Details beyond scope of this course

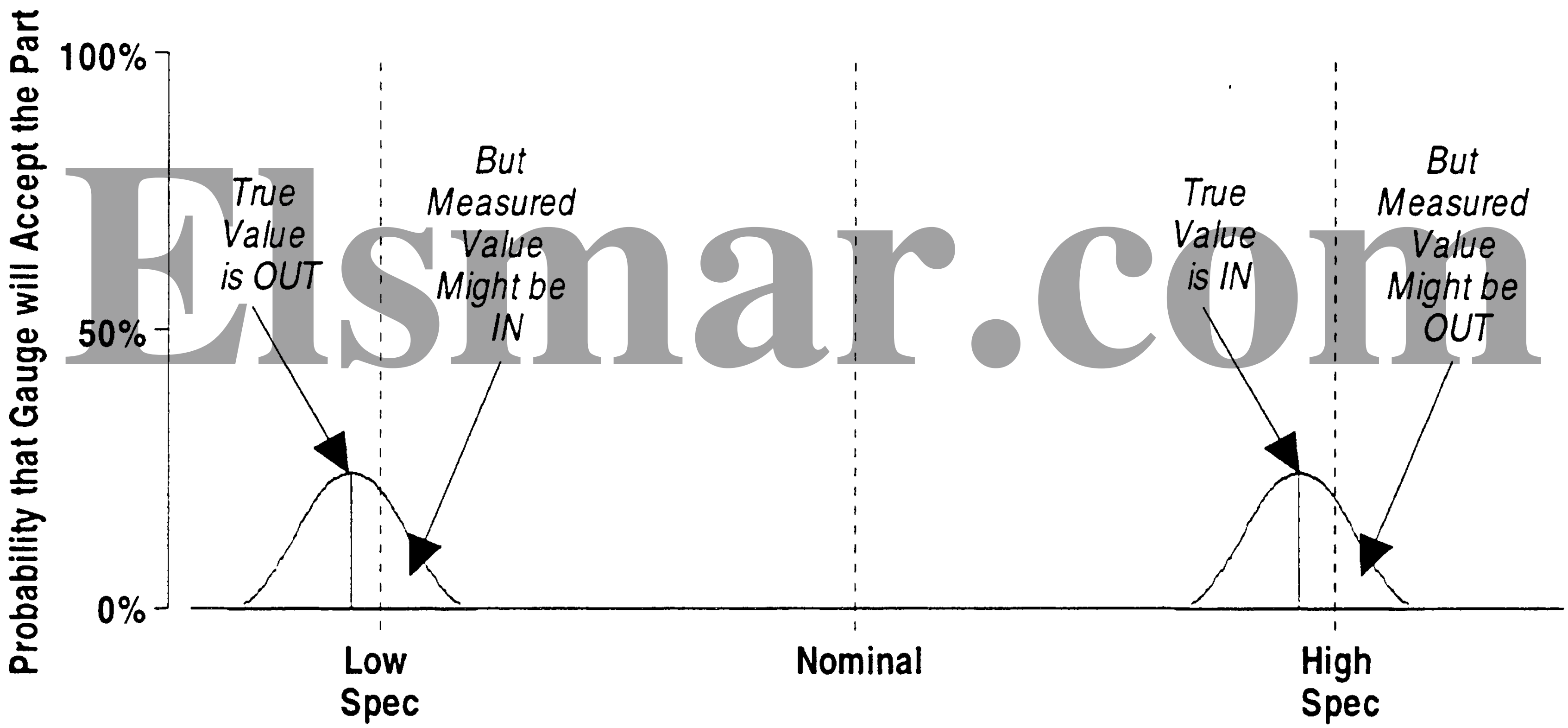
Special Gauging Situations

- Go/No-Go
- Destructive Testing

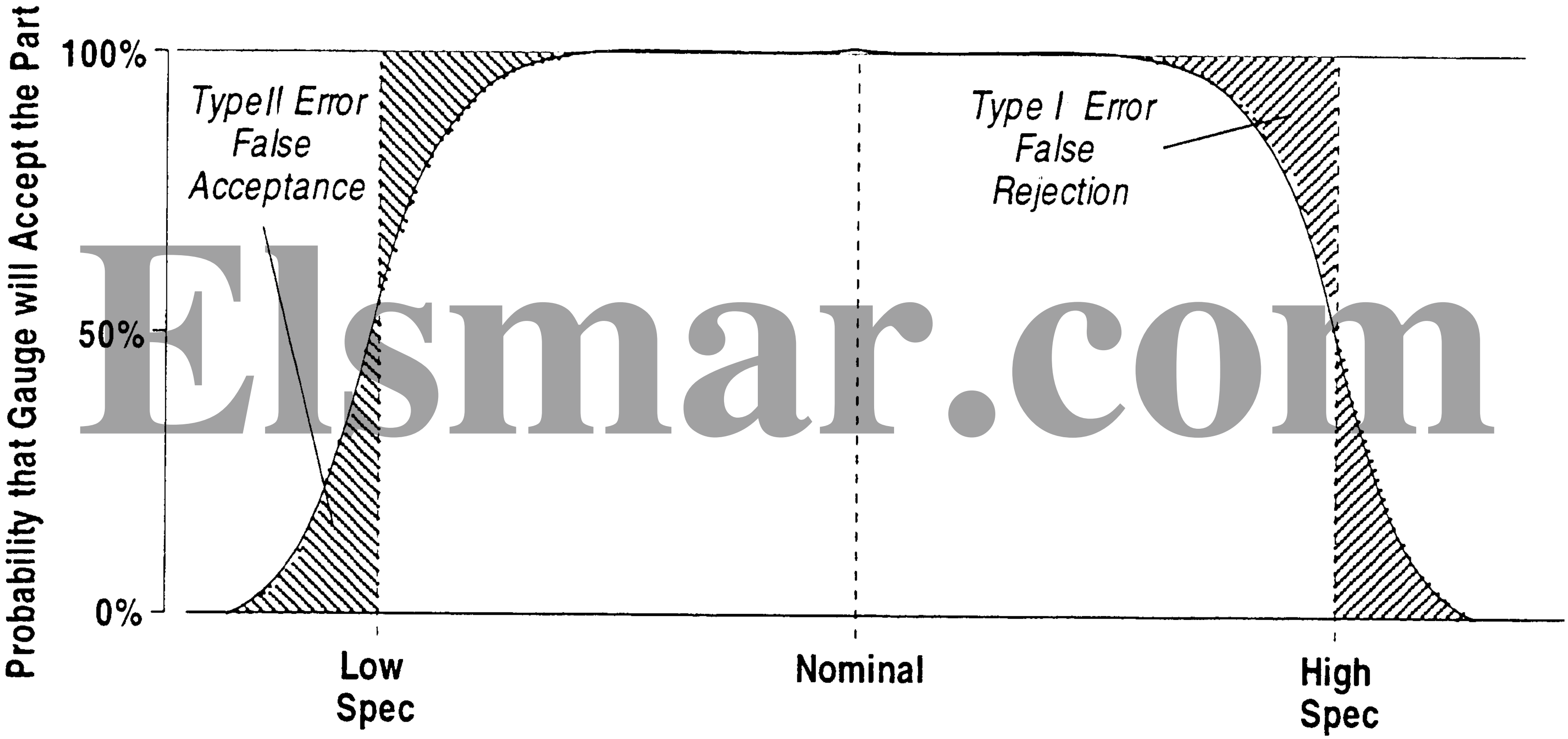
If Gauges were Perfect



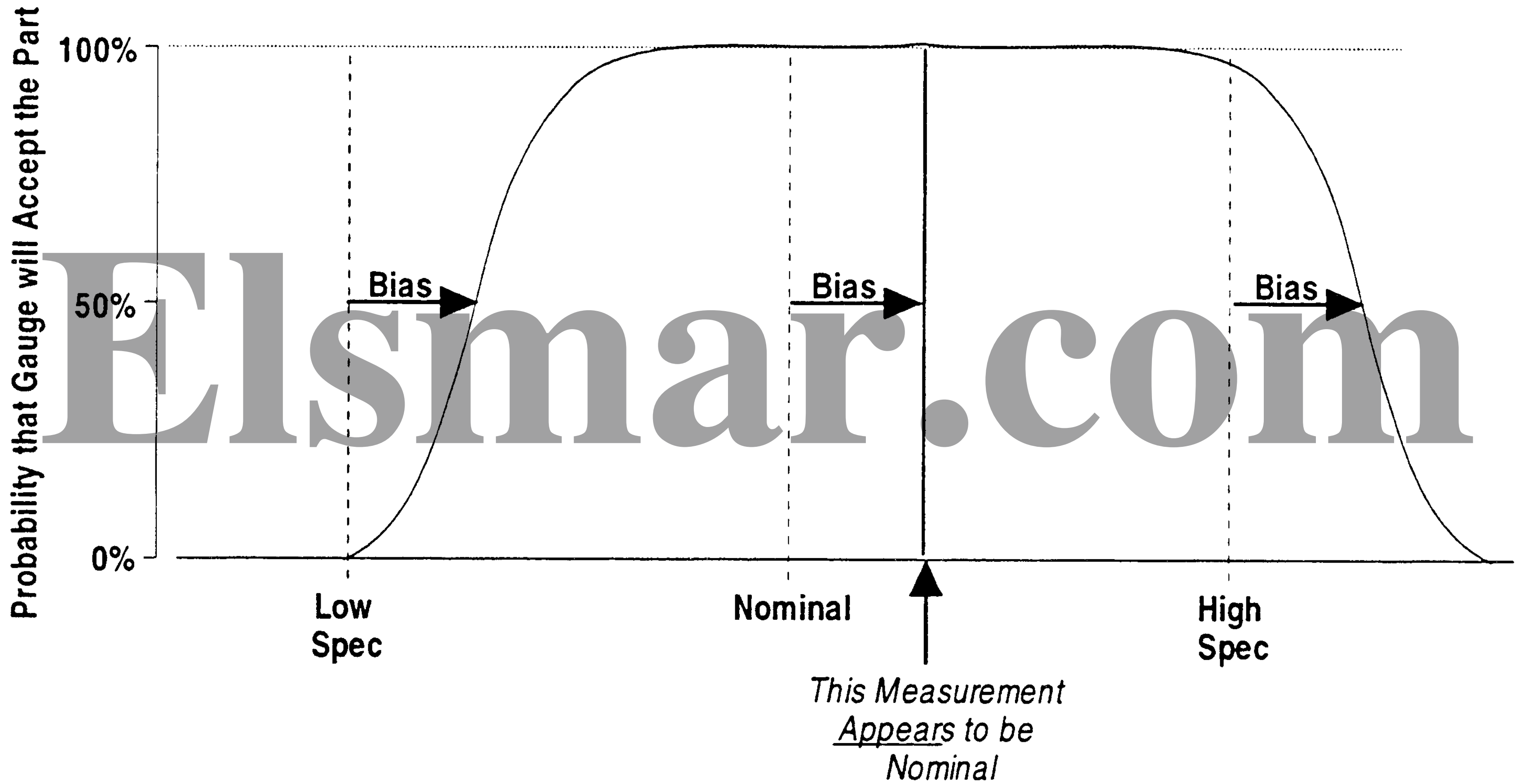
But Repeatability Means We Never Know The Precise Value



So - Actual Part Acceptance Will Look Like This:



The Effect of Bias on Part Acceptance



Go/No-Go gauges

- Treat variables like attributes
- Provide less information on the process, but...
- Are fast and inexpensive
- Cannot use for Process Control
- Can be used for Sorting purposes

“Short” Go/No-Go Study

- Collect 20 parts covering the entire process range
- Use two inspectors
- Gage each part twice
- Accept gauge if there is agreement on each of the 20 parts

* May reject a good measuring system

Destructive Tests

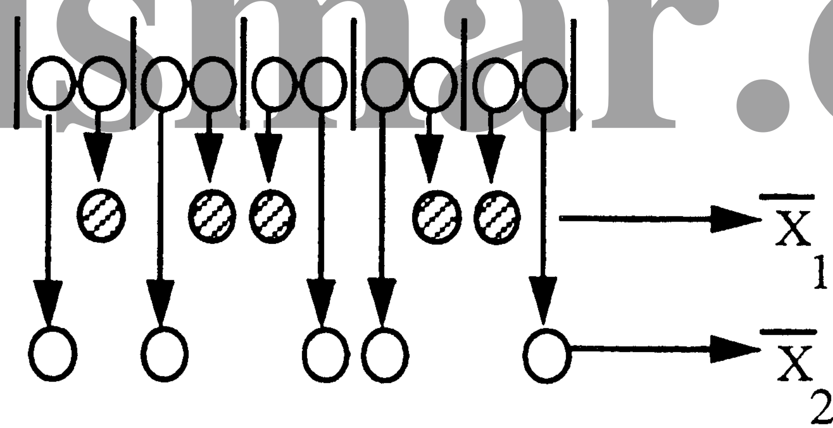
- Cannot make true duplicate tests
- Use interpenetrating samples
- Compare 3 averages
- Adjust using $\sqrt{n}$

Destructive Tests: Interpreting Samples

- Consecutive pieces

AIAG does not address

- Blocks of two
- Assign at random to replicate 1 or replicate 2



- Evaluate repeatability, as usual
- Multiply $\sqrt{n}\ \sigma_{x\text{-bar}}$ to get σ

Summary

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Measurement Variation

- Observed variation is a combination of the production process PLUS the measurement process
- The contribution of the measurement system is often overlooked

Types of Measurement Variation

- Bias (Inaccuracy)
- Repeatability (Imprecision)
- Discrimination
- Linearity
- Stability

Measurement Systems

- Material
- Characteristic
- Sampling and Preparation
- Operational Definition of Measurement
- Instrument
- Appraiser
- Environment and Ergonomics

Measurement Systems Evaluation Tools

- Histograms
- Probability paper
- Run Charts
- Scatter diagrams
- Multi-Vari Charts
- Gantt “R&R” analysis
- Analysis of Variance (ANOVA)
- Shewhart “Control” Charts

Shewhart Charts

- Range chart shows repeatability
- X-bar limits show discriminating power
- X-double bar shows bias

  (if a known standard exists)
- Average chart shows stability

  (sub-groups overtime)
- Average chart shows reproducibility

  (sub-groups over technicians/instruments)

Conclusion

- Rule of Ten
- Operating Characteristic Curve
- Special Problems
  - Go/No-Go Gages
  - Attribute Inspection
  - Destructive Testing