Measurement Systems Analysis (MSA)

including ANOVA, Non-Replicable Studies and Attribute MSA

QUALITY

with Minitab support (optional)

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Omnex provides training, consulting and software solutions to the international market with offices in the USA, Canada, Mexico, China (PRC), Germany, India, the Middle East, and SE Asia. Omnex offers over 400 standard and customized training courses in business, quality, environmental, food safety, laboratory and health & safety management systems worldwide.

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Course Objectives

- Explain bias, linearity, stability, repeatability and reproducibility.
- Identify the type of MSA study that is appropriate for the situations.
- Explain discrimination and number of distinct categories.
- Identify all important aspects of setting up a study.
- Explain how to use Minitab© to support MSA studies. **(optional)**
- Explain the acceptance criteria for Gage R&R studies.
- Explain ANOVA and apply it to GRR Analysis.
- Analyze automated and non-replicable measurement systems.
- Analyze attribute measurement systems.
- Develop an approach to measurement systems planning.

Agenda

- Course Overview and Introductions
- Chapter 1 – What is a Measurement System?
- Chapter 2 – Statistical Properties of Measurement Systems
- Chapter 3 – Discrimination & Uncertainty
- Chapter 4 – Bias, Linearity and Stability
  - **Breakout Exercise 1: Bias**
  - **Breakout Exercise 2: Bias & Linearity**
  - **Breakout Exercise 3: Stability**
- Chapter 5 – GRR Studies
  - **Breakout Exercise 4: Graphing GR&R**
  - **Breakout Exercise 5: Calculating GR&R**

Agenda

- Chapter 6 – Advanced Analysis (ANOVA)
- Chapter 7 – Automated Systems
  - **Non-Replicable Case Study**
- Chapter 8 – Attribute MSA
  - **Breakout Exercise 6: Attribute Analysis**
  - **Breakout Exercise 7: Calculating Attribute Analysis**
- Chapter 9 – Measurement Planning

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A BRIEF INTRODUCTION TO OMNEX

Omnex Introduction

- International consulting, training and software development organization founded in 1985.
- Specialties:
  - Integrated management system solutions.
  - Elevating the performance of client organizations.
  - Consulting and training services in:
    - Quality Management Systems, e.g., ISO 9001, IATF 16949, AS9100, QOS
    - Environmental Management Systems, e.g., ISO 14001
    - Health and Safety Management Systems, e.g., ISO 45001
- Leader in Lean, Six Sigma and other breakthrough systems and performance enhancement.
  - Provider of Lean Six Sigma services to Automotive Industry via AIAG alliance.

About Omnex

- Headquartered in Ann Arbor, Michigan with offices in major global markets.
- In 1995-97 provided global roll out supplier training and development for Ford Motor Company.
- Trained more than 100,000 individuals in over 30 countries.
- Workforce of over 700 professionals, speaking over a dozen languages.
- Former Delegation Leader of the International Automotive Task Force (IATF) responsible for
  ISO/TS 16949.
- Served on committees that wrote QOS, ISO 9001, QS-9000, ISO/TS 16949 and its Semiconductor Supplement, and ISO IWA 1 (ISO 9000 for healthcare).
- Former member of AIAG manual writing committees for FMEA, SPC, MSA, Sub-tier Supplier Development, Error Proofing, and Effective Problem Solving (EPS).

Key Omnex Global Offices

Employees From 20+ Nationalities

Working in Over 30 Countries

24x7 for 30 Years & Counting

Serving 35,000 Clients

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UAE - Dubai
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MALAYSIA - Kuala Lumpur (Rep)

Rules of the Classroom

- ✓ Start and end on time
- ✓ Return from breaks and lunch on time
- ✓ All questions welcome — Your input is valuable and is encouraged
- ✓ Don't interrupt others — One meeting at a time . OMNEX
- ✓ Listen – and respect others' ideas
- ✓ No "buts" – keep an open mind
- ✓ Phones in Do Not Disturb (silent) mode
- ✓ No e-mails, texting or tweeting during class
- ✓ If you are attending this course through the virtual classroom, your webcam must be on the entire time

If you must take a phone call or answer a text please leave the session for as short a period as possible

Icebreaker

- Instructor Information:
  - Name
  - Background
- Student Introductions:
  - Name
  - Position / Responsibilities
  - What is your involvement in measurement and testing processes?
  - What are your experiences with MSA?
  - What do you expect to take away from this class?
  - Please share something unique and/or interesting about yourself.

Chapter 1

What is a Measurement System?

Chapter 1: What is a Measurement System? – What We Will Cover

Learning Objectives

At the end of this chapter, you will be able to:

- Describe and explain the elements of a measurement system
- Explain the effects of measurement systems variation on decisions
- Discuss measurement systems analysis and its purpose

Chapter Agenda

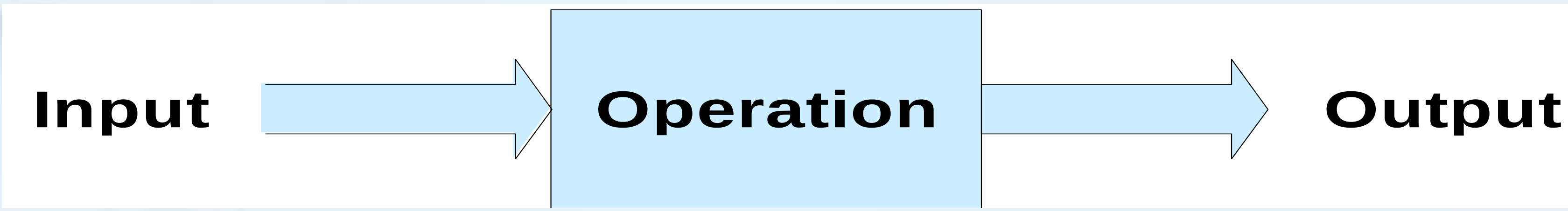
- What is a Measurement System
- Foundations of Measurement Systems Analysis
- Effects of measurement systems variation on process decisions

What is a Measurement System?

A measurement system is the collection of instruments or gages, standards, operations, methods, fixtures, software, personnel, environment and assumptions used to quantify a unit of measure or fix assessment to the feature characteristic being measured.

What is a Measurement System?

A Measurement System is a Process



- Key Process Output Variable

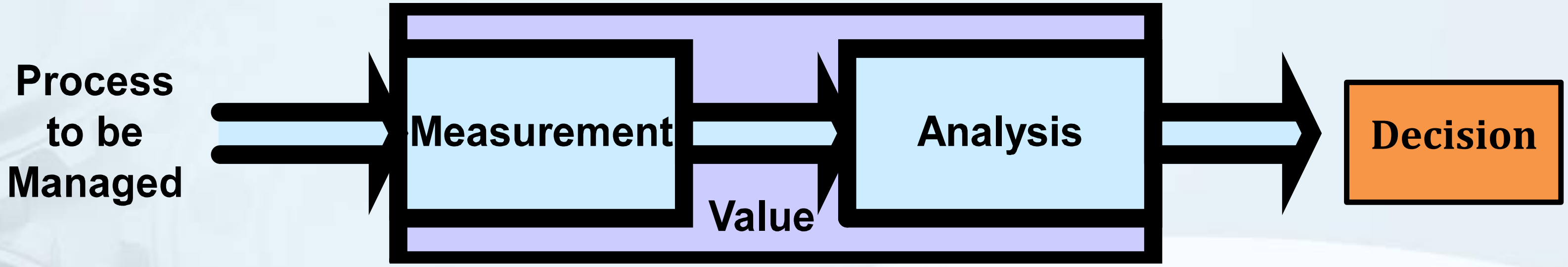
  KPOV (deliverable) = a decision on a product, process, or service

  – via a number assigned to a characteristic of a product, process, or service.

- The first step in assessing a system is to understand this process and determine if it will satisfy our requirements.

What is a Measurement System?

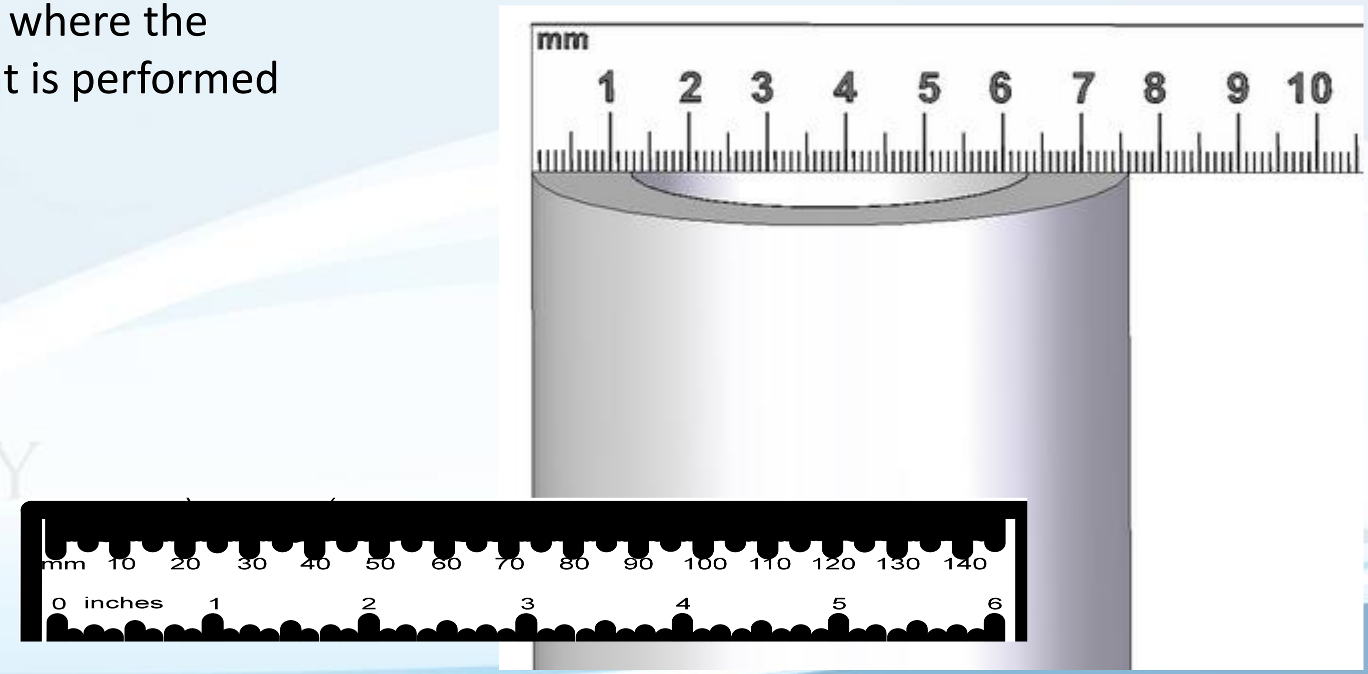
- From this definition, it follows that a measurement process may be viewed as a manufacturing process that produces decisions via numbers (data) for its output.



- Viewing a measurement system this way is useful because it allows us to bring to bear all the concepts, philosophy and tools that have already demonstrated their usefulness in the area of statistical process control.

Measurement System Example

- To measure the outside diameter of a tube, we use a system that includes:
  - item of interest
  - personnel
  - method to use the equipment
  - environment where the measurement is performed
- As a result of the activity, we make a decision based on a value that represents the diameter.



Measurement Knowledge to be Obtained

- How big is the measurement variation?
  - Is the measurement system capable for this study?
  - Is the measurement system stable over time?
- What are the sources of measurement variation?
- How do we improve the measurement system?

What is MSA?

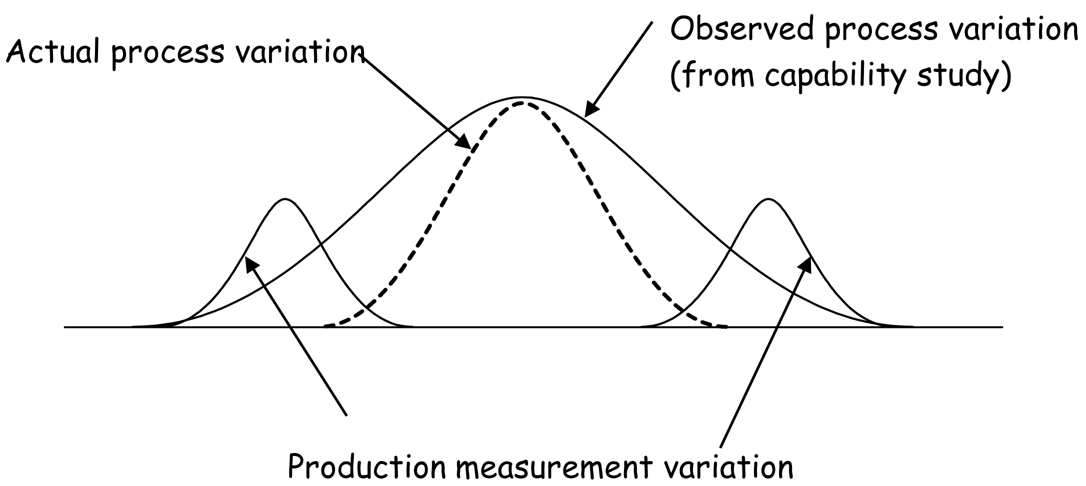
Measurement System Analysis (MSA)

- MSA primarily deals with analyzing the effect of the measurement system on the measured value.
- The objective of MSA is to assess the quality of the measurement system. o.m.n.ex

We test the system to determine its statistical properties, and use them in comparison with accepted standards, our needs and customer requirements.

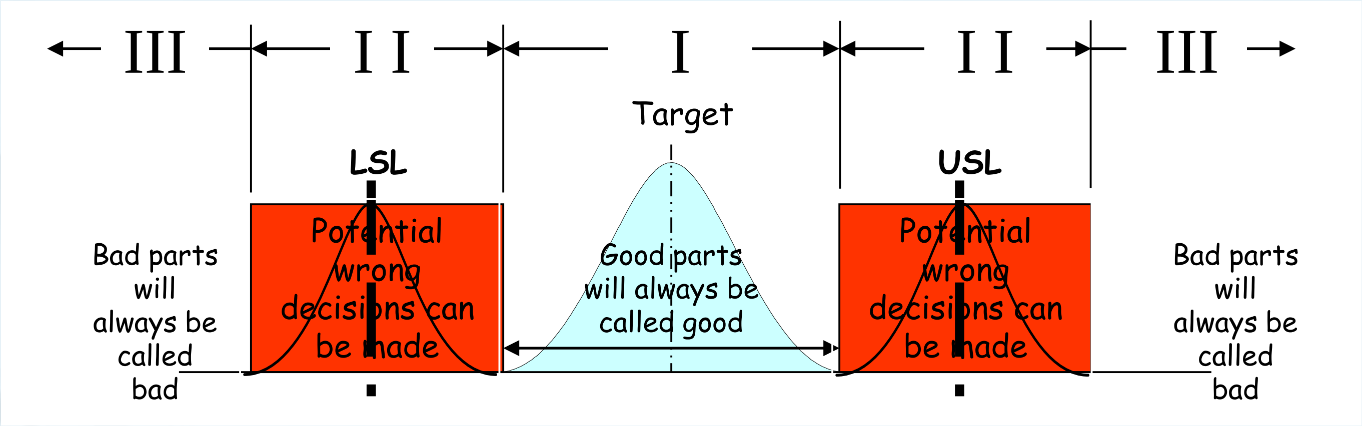
MSA – Control of Gauges and Fixtures

- The proper qualification of gauging and test equipment requires the use of statistical procedures to analyze the inherent variability observed in the use of these instruments.
- Additionally, before a capability study can be performed on a machine or a process, **the measurement system must be qualified** for its accuracy, repeatability and reproducibility to effectively judge the process or machine performance.



Observed process variation = Actual Process variation + *Measurement* variation

Effects on Product Decisions

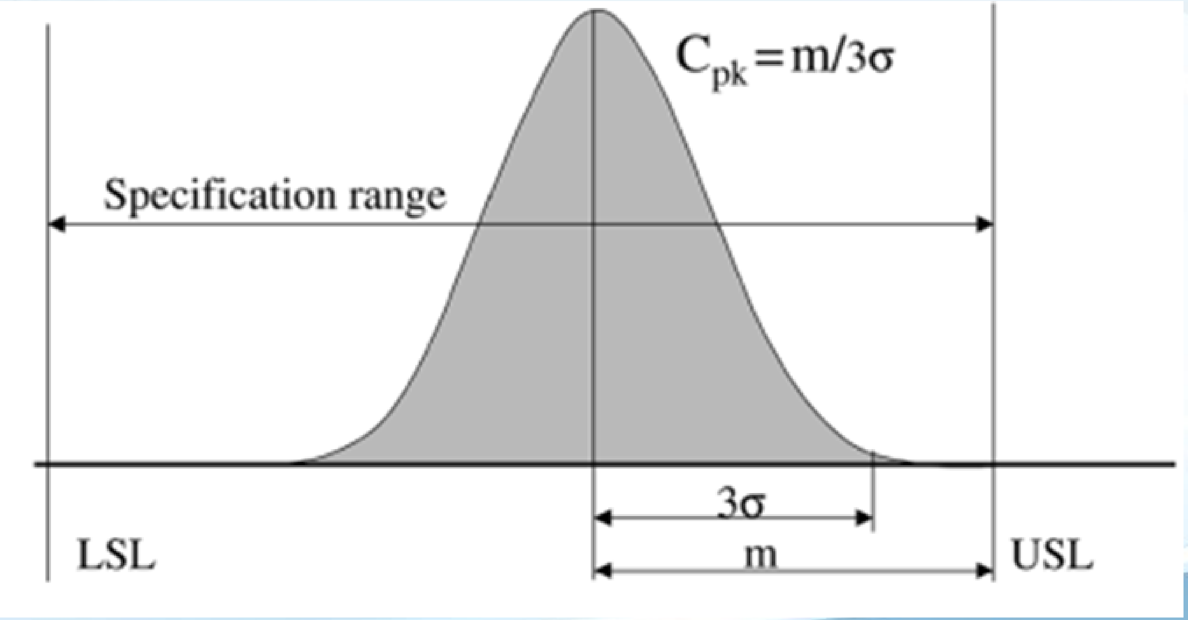


Two options exist to maximize making a ‘correct’ decision, they are:

1. **Improve the production process:** reduce variability of the process so that no parts will be produced in the type “II” areas above.
2. **Improve the measurement system:** reduce the measurement system error by reducing the size of the type “II” areas above so all parts will fall in the type “I” area above to minimize risk of a wrong decision.

Best-in-Class Approach

- Determinations on these fundamental issues are most meaningful if made relative to ***process variation***.
- **Reporting measurement variation as only a percent of tolerance** is generally inadequate for the worldwide market where emphasis is on continual process improvement.



Chapter 1: What is a Measurement System? – What We Covered

Learning Objectives

You should now be able to:

- Describe and explain the elements of a measurement system
- Explain the effects of measurement systems variation on decisions
- Discuss measurement systems analysis and its purpose

Chapter Agenda

- What is a Measurement System
- Foundations of Measurement Systems Analysis
- Effects of measurement systems variation on process decisions

Chapter 2

Statistical Properties of Measurement Systems

Chapter 2: Statistical Properties of Measurement Systems – What We Will Cover

Learning Objectives

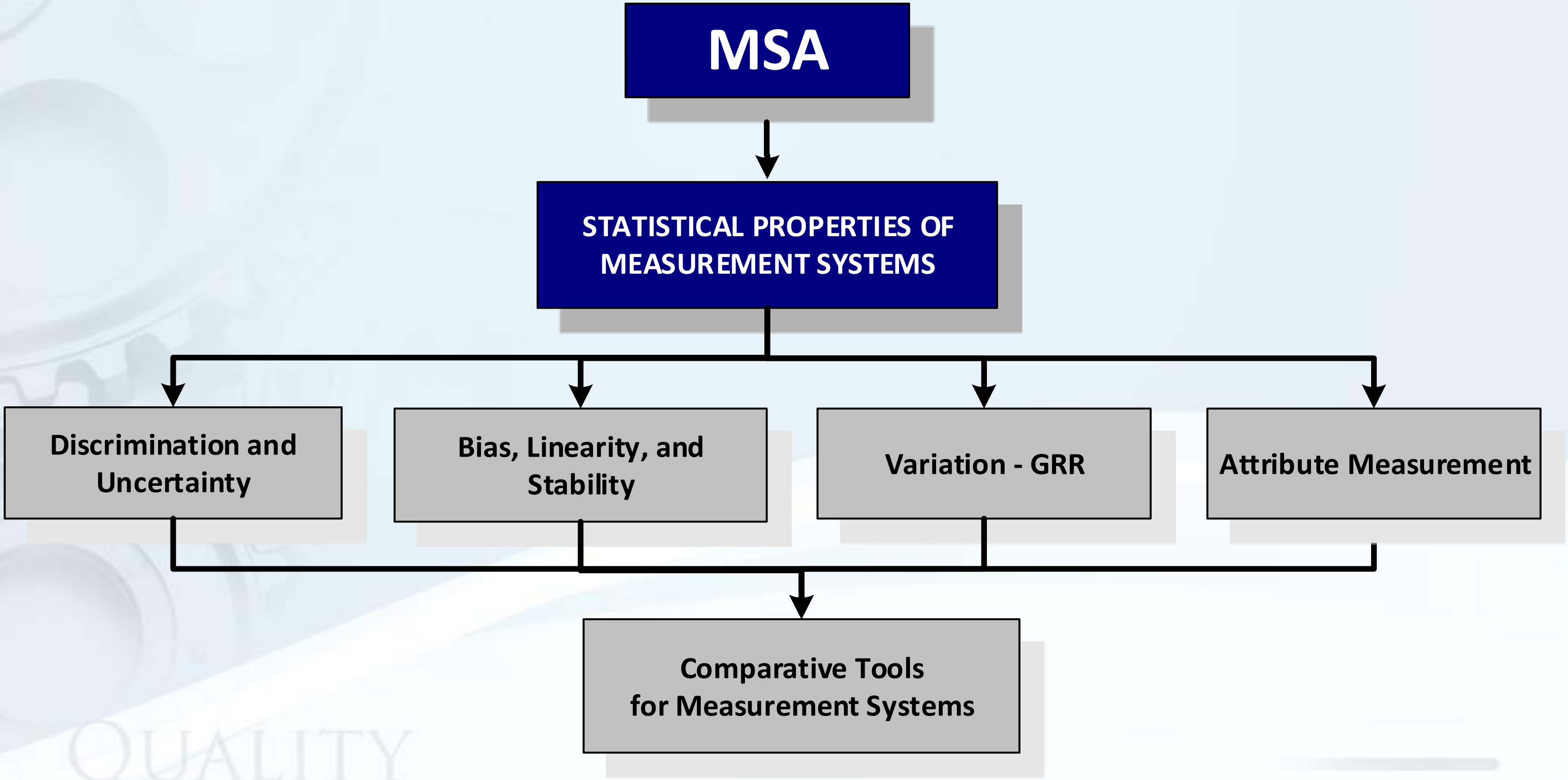
At the end of this chapter, you will be able to:

- Describe and explain the statistical properties of a measurement system
- Illustrate these properties
- Explain the effect of measurement systems variation on capability indices

Chapter Agenda

- The Statistical Properties of a Measurement System
  - Discrimination
  - Bias
  - Linearity
  - Stability
  - Repeatability
  - Reproducibility
- Sources of Measurement Systems Variability
- Effects of Measurement Systems Variation on Capability Indices

Application of MSA



Monitoring and Measuring – IATF 16949

The following clauses from IATF 16949:2016 reference monitoring and measuring resources:

- 7.1.5 Monitoring and Measuring Resources
- 7.1.5.1 General
- 7.1.5.1.1 Measurement Systems Analysis
- 7.1.5.2 Measurement Traceability
- 7.1.5.2.1 Calibration/Verification Resources
- 7.1.5.3 Laboratory Requirements
- 7.1.5.3.1 Internal Laboratory
- 7.1.5.3.2 External Laboratory

Measurement is Not Always Exact

- Measurement system variation affects individual measurements and decisions based on data.

- Measurement system errors are classified as:
  - Discrimination
  - Location
    - Bias
    - Linearity
    - Stability
  - Variation
    - Repeatability
    - Reproducibility

Discrimination or Resolution

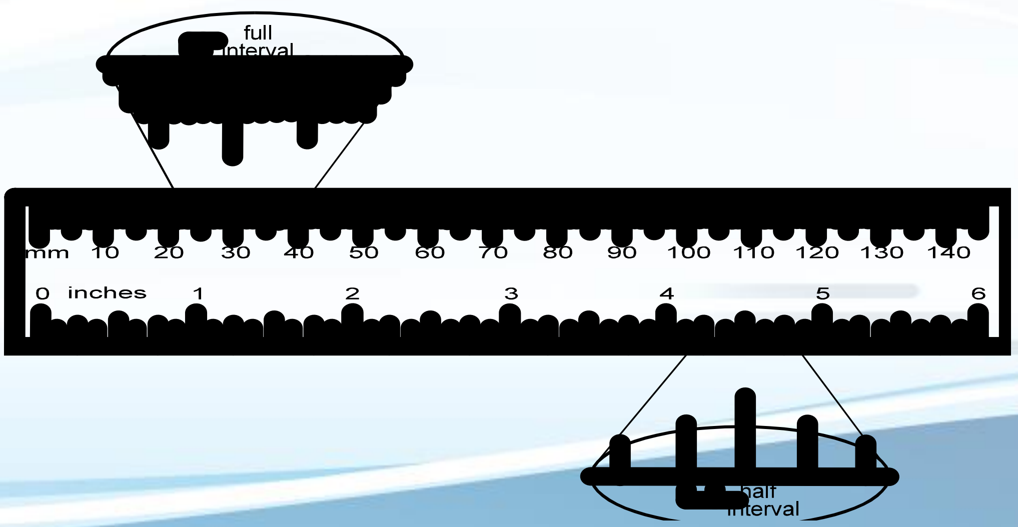
- Discrimination or resolution of a gage is its ability to detect small changes in the characteristic being measured.
- As a general rule, the measurement system should be able to read to (the smaller of)
  - ${}^{1}/_{10}$ the tolerance on a part for product decisions and
  - ${}^{1}/_{10}$ the expected process variation for process decisions.

Example:

If tolerance of part is

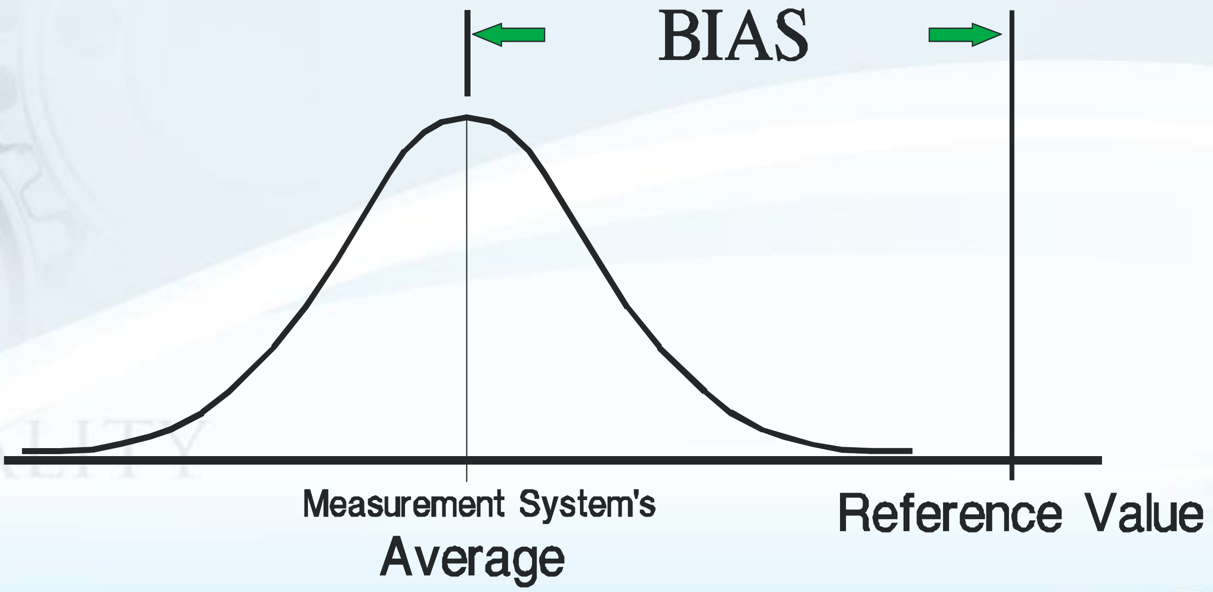
USL – LSL = 0.05

The least count (LC) on the measuring instrument should less than 0.005



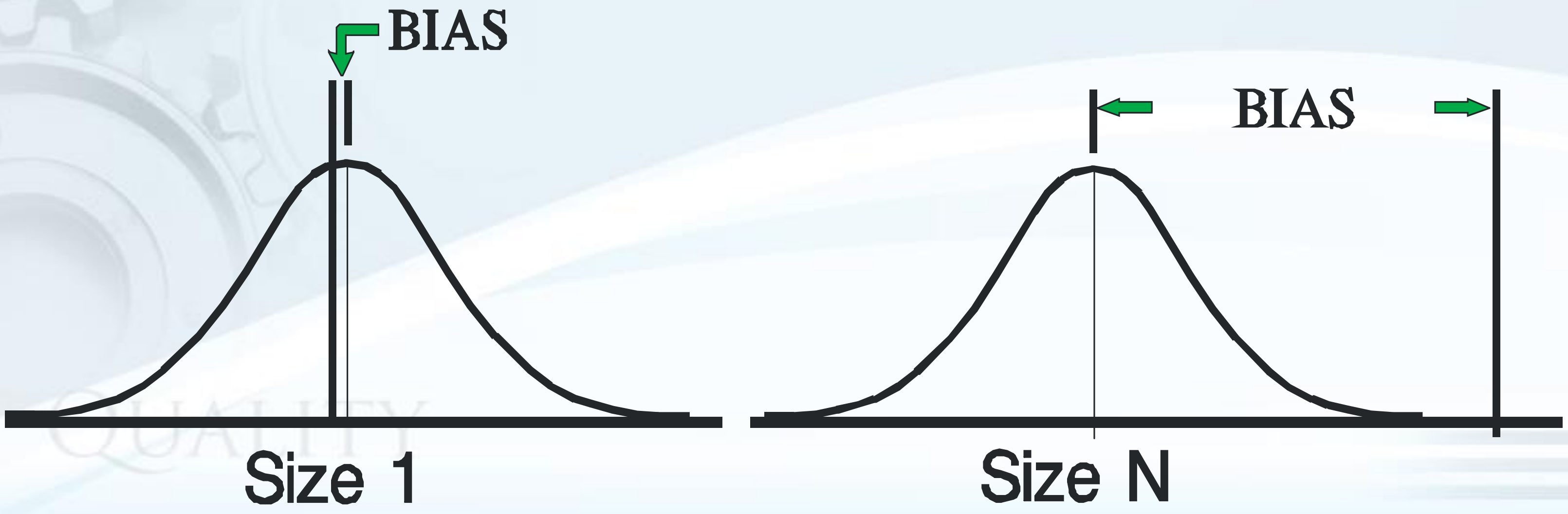
Measurement is Not Always Exact

- **Bias**
  - Difference between the observed average of measurements and the reference value
  - A systematic error component of the measurement system



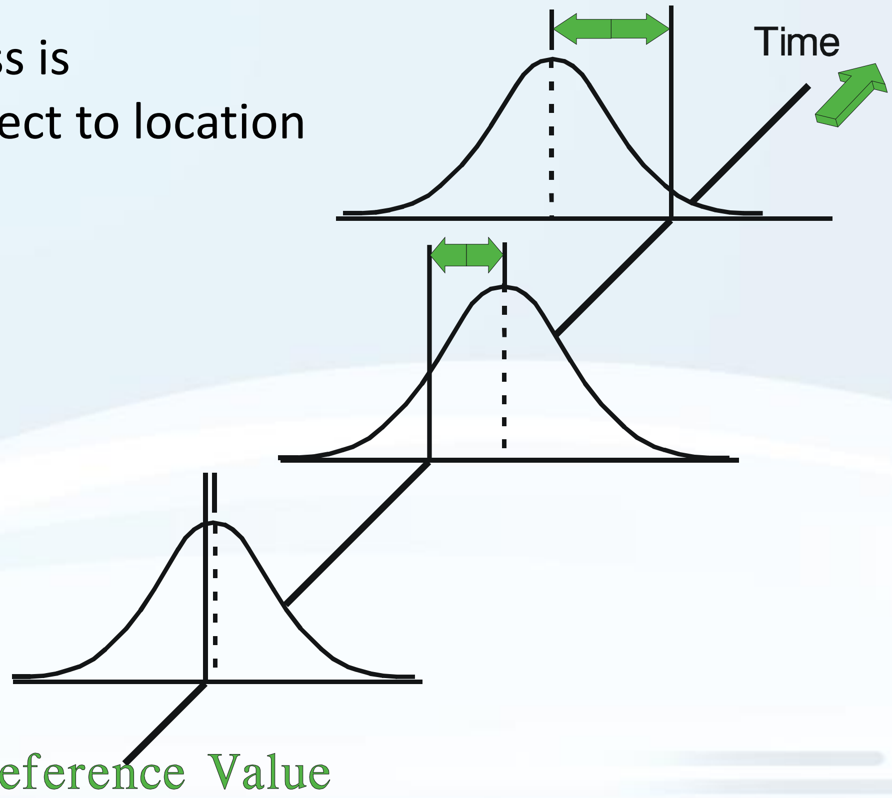
Measurement is Not Always Exact

- **Linearity**
  - The change in bias over the normal operating range
  - The correlation of multiple and independent bias errors over the operating range
  - A systematic error component of the measurement system



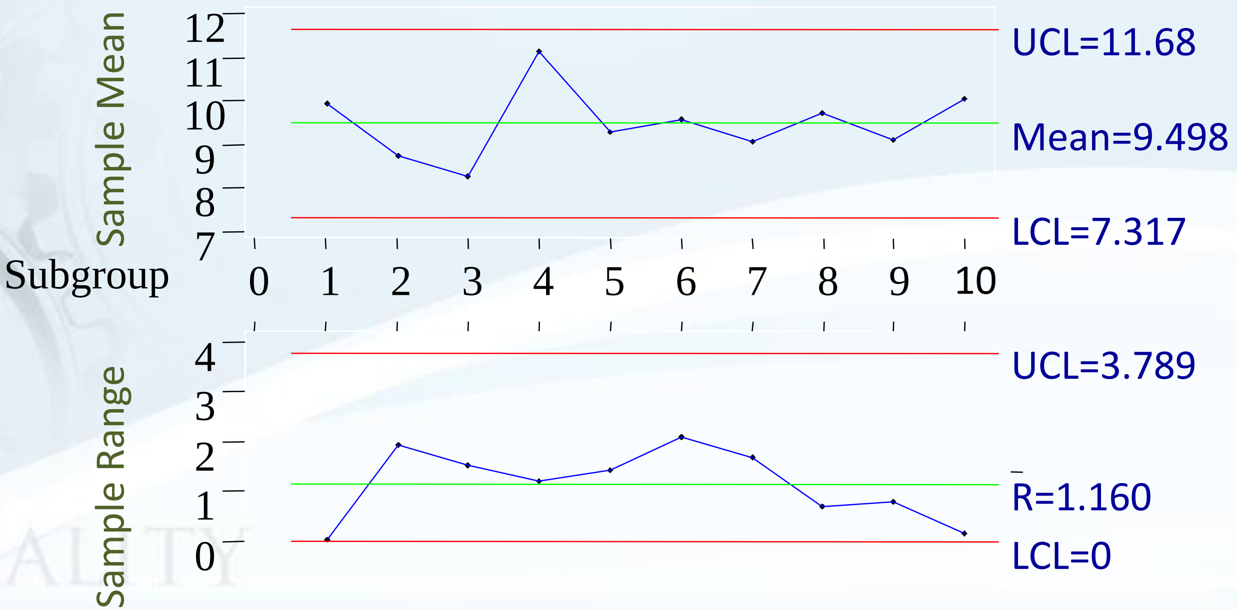
Measurement is Not Always Exact

- **Stability**
  - The change in bias over time
  - A stable measurement process is in statistical control with respect to location
  - Alias: Drift



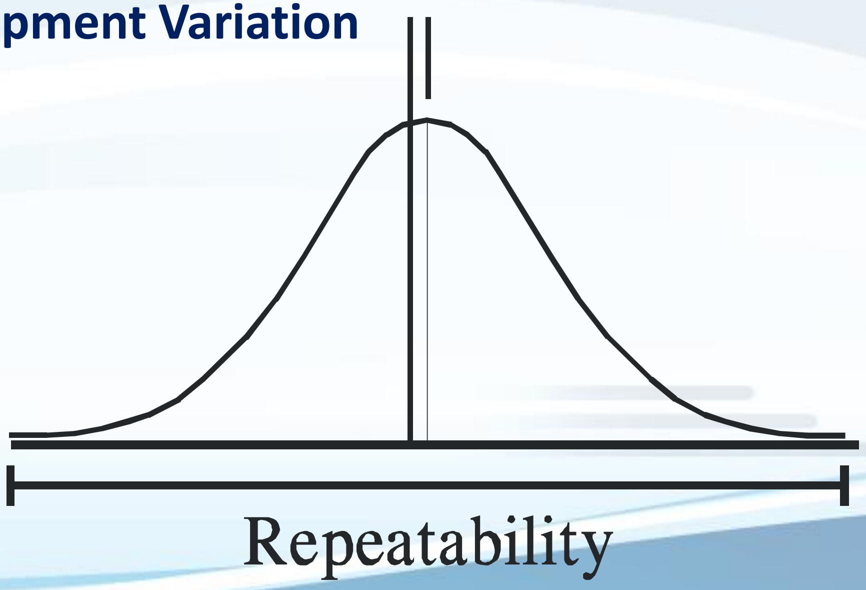
Stability

- If the readings are not within the limits, a designed experiment might have to be conducted to determine the cause of gage instability and correct it.

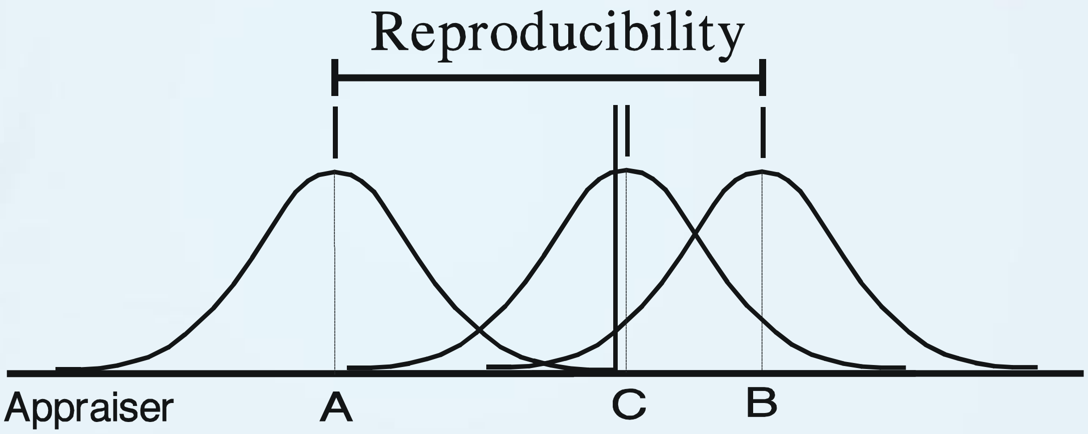


Measurement is Not Always Exact

- **Repeatability**
  - Variation in measurements obtained with one measuring instrument when used several times by an appraiser while measuring the identical characteristic on the same part
  - The variation in successive (short term) trials under fixed and defined conditions of measurement
  - Commonly referred to as E.V. – **Equipment Variation**
  - Instrument (gage) capability or potential
  - Within-system variation



Measurement is Not Always Exact



- **Reproducibility**
  - Variation in the average of the measurements made by different appraisers using the same gage when measuring a characteristic on one part
  - For product and process qualification, error may be appraiser, environment (time), or method
  - Commonly referred to as A.V. – **Appraiser Variation**
  - Between-system (conditions) variation
  - ASTM E456-96 includes repeatability, laboratory, and environmental effects as well as appraiser effects

Ideal Measurement Systems

- Produce correct measurements each time used and each measurement agrees with a master standard.

- Have statistical properties of:
  - zero variance
  - zero bias

And consequently:

  - zero probability of mis-classifying any product measured

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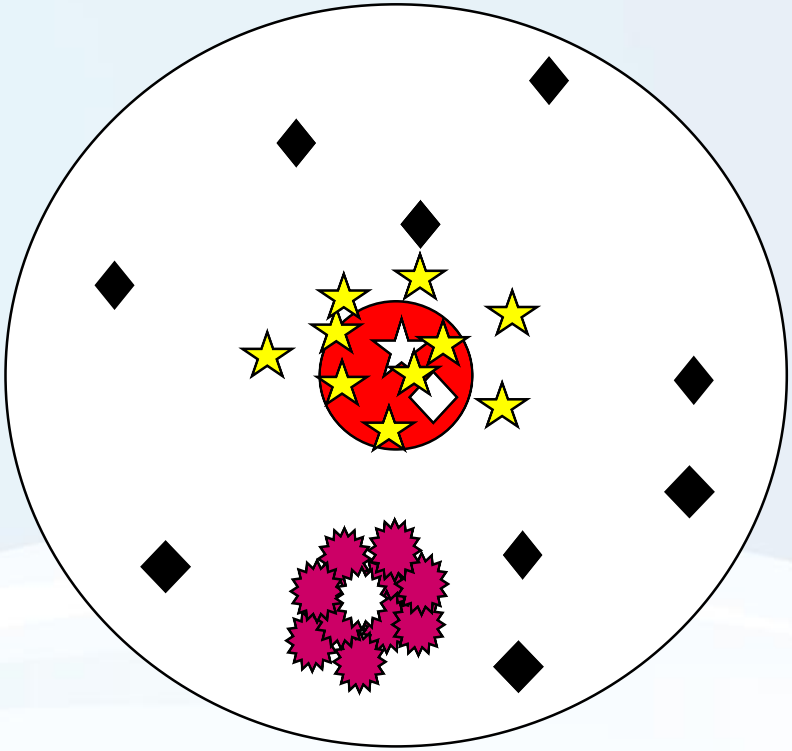
Accuracy vs. Precision Concepts

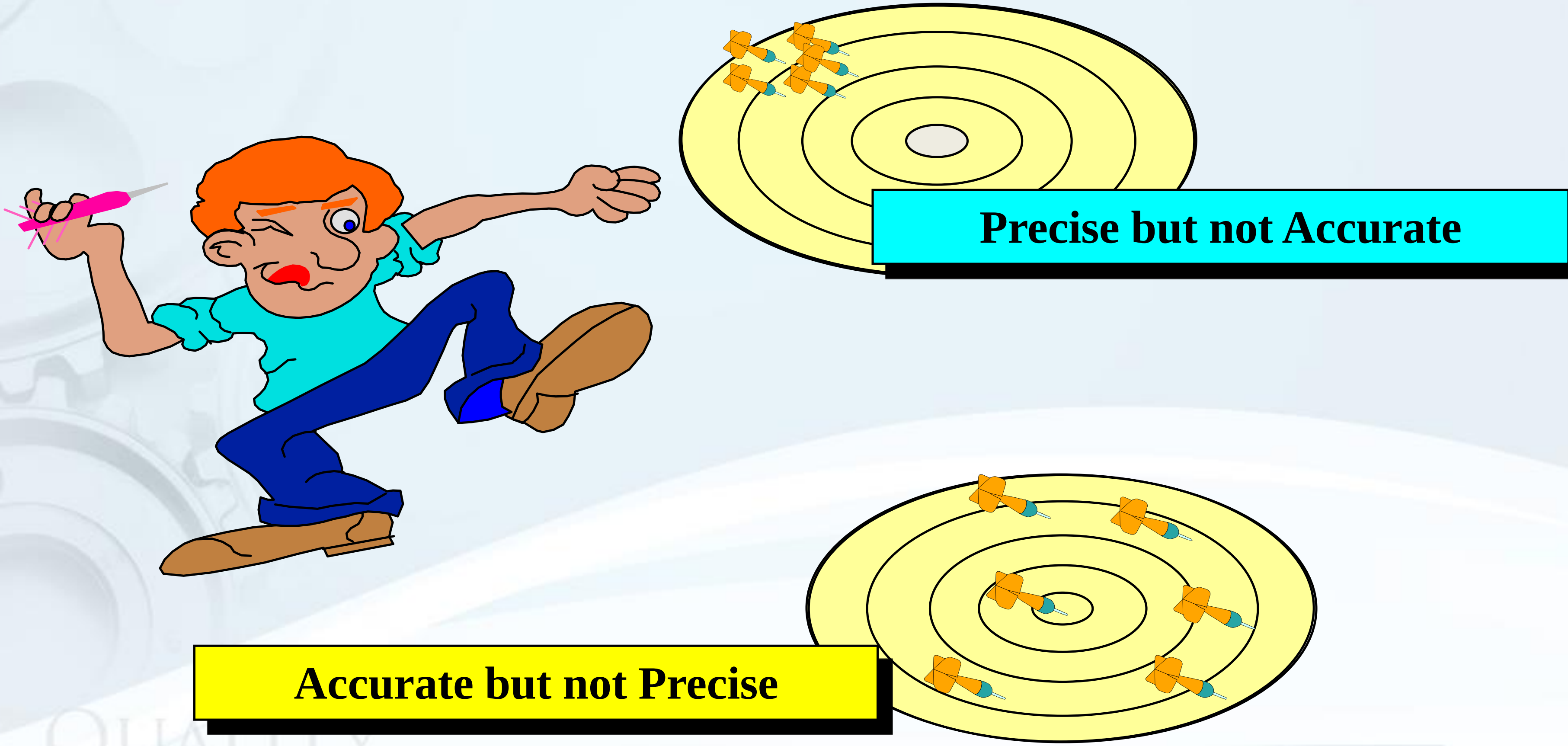
- ★ Contestant A
- ✸ Contestant B
- ◆ Contestant C
- ☆ Average for Contestant A
- ✸ Average for Contestant B
- ◇ Average for Contestant C



A has best Accuracy
B has best Precision
C has better Accuracy than B

Compare the performance of A & C

Accuracy vs. Precision Concepts



DEFINE: Accuracy and Precision

- **Accuracy**
  - "How close is the measured value to the reference value?"
  - ASTM includes the effect of location and width errors
  - **MSA evaluates bias instead of accuracy .** O-M-N-E-X
- **Precision**
  - "Closeness" of repeated readings to each other
  - **MSA evaluates repeatability and reproducibility**

Accuracy and precision are not calculated as part of an MSA analysis

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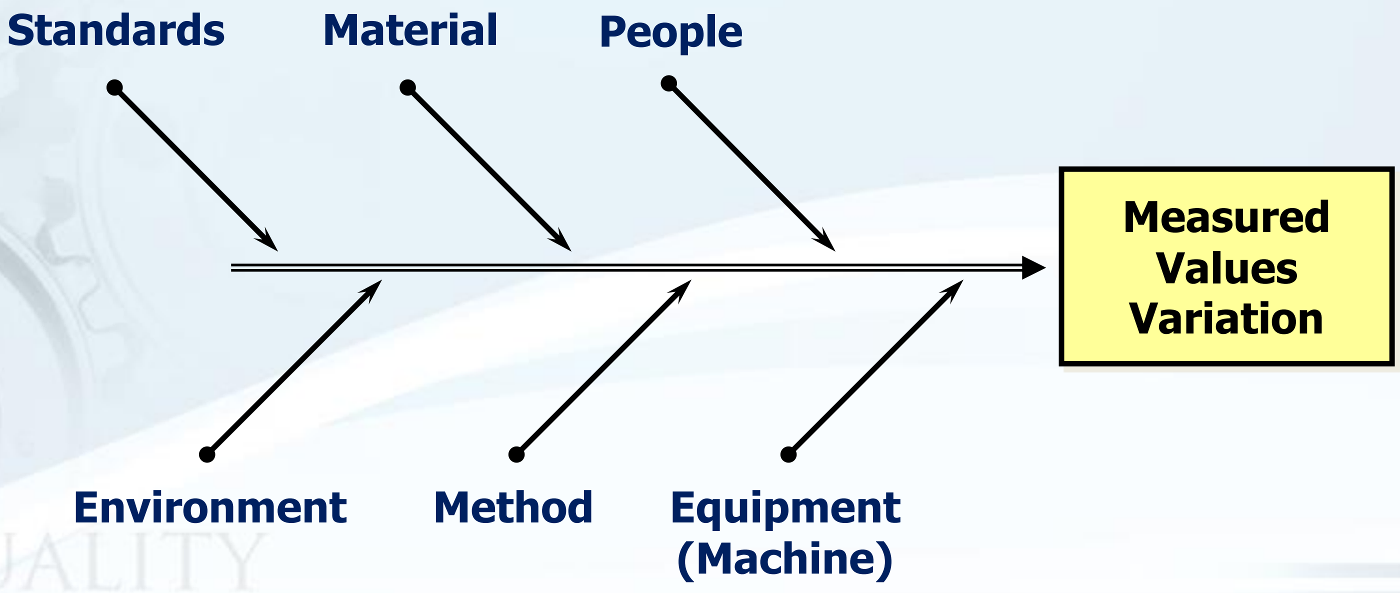
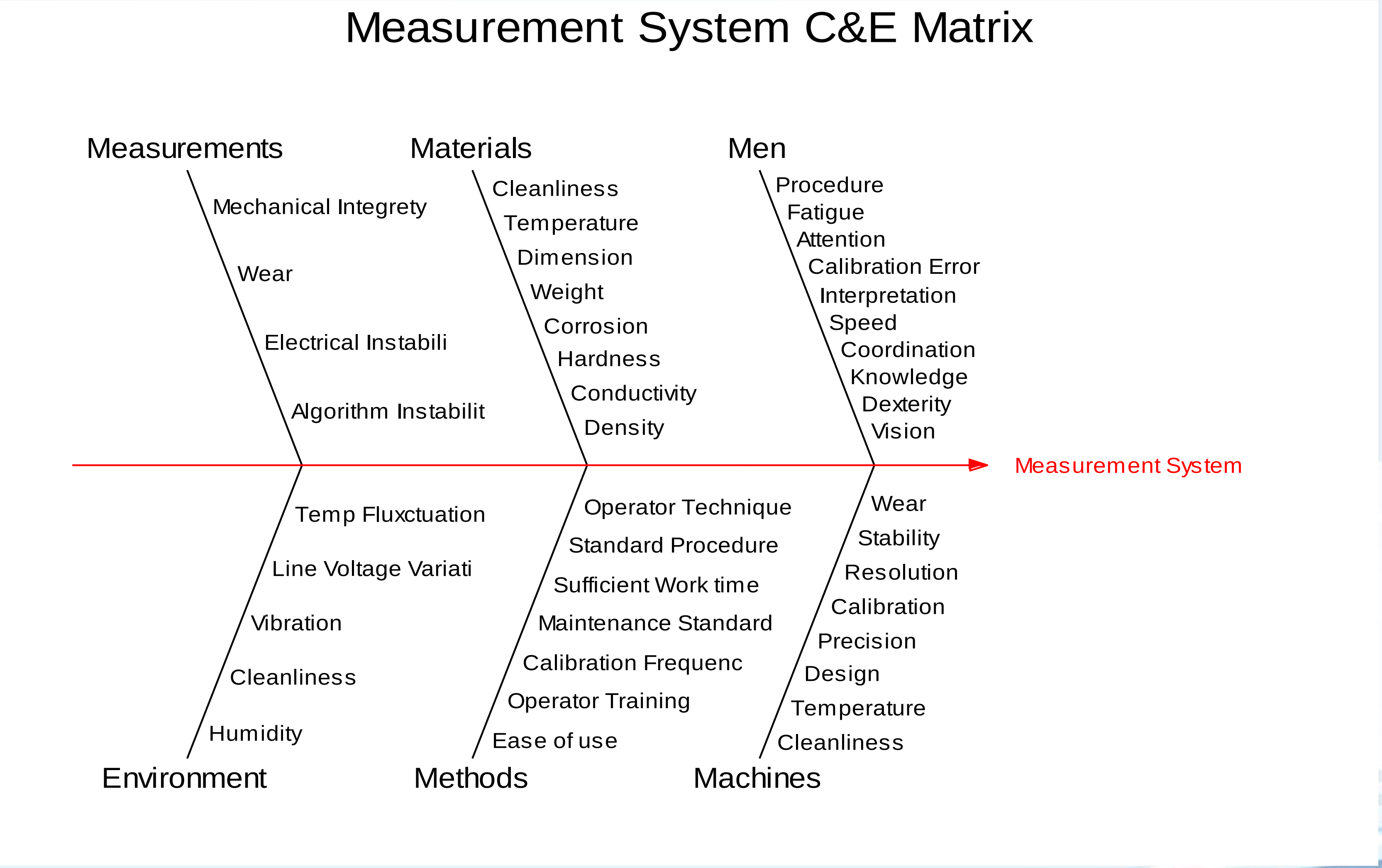
Measurement Systems Variation

- Measurement process components and their interactions contribute variation in outcome of data.



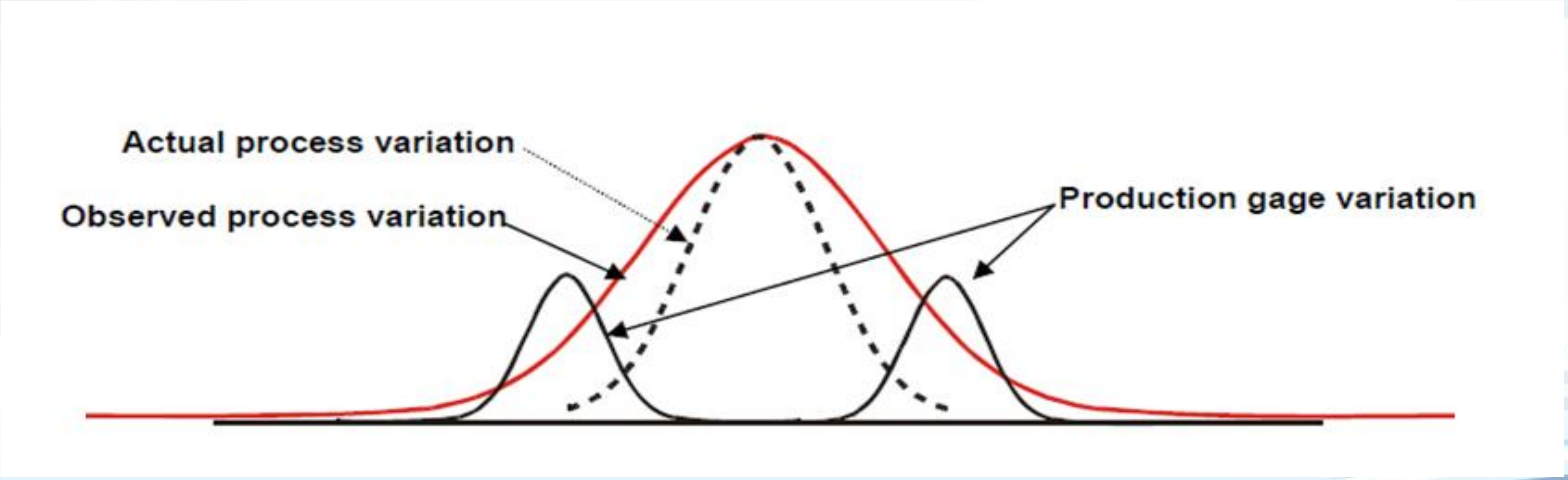
Sources of Measurement Variation



Mathematical Perspective

- Data collected for controlling a process contains variations from two different and independent sources:
  - Manufacturing Process Variation (MPV)
  - Measurement System Variation (MSV)

  - **The observed variation is the Total Variation (TV) which includes both MPV & MSV**



Effects of Measurement Error

Averages

$$\mu_{observed} = \mu_{product} + \mu_{measurement}$$

Measurement System Bias — Determined through "Bias Study"

Variability

$$\sigma^2_{observed} = \sigma^2_{product} + \sigma^2_{measurement}$$

Measurement System Variability — Determined through "R&R Study"

Measurement Error: Effect on Capability Index

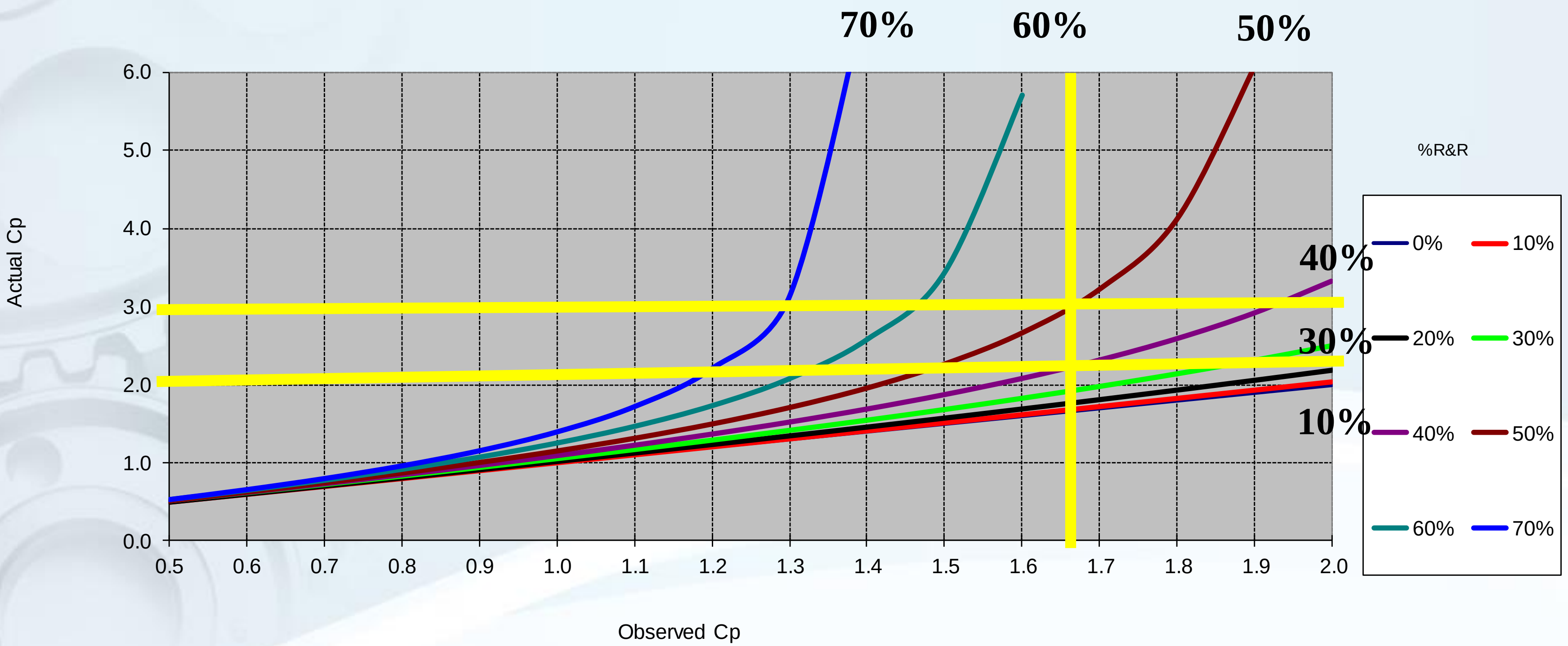
We know that

$$C_{pAct} = \frac{|USL - LSL|}{6\sigma_{Act}} \quad \textbf{where} \quad \sigma_{Act} = \sqrt{\sigma^2_{Obs} - \sigma^2_{MS}}$$

Therefore:

$$C_{pAct} = \frac{|USL - LSL|}{6\sqrt{\sigma^2_{Obs} - \sigma^2_{MS}}}$$

R&R Effect on Capability



* As % of tolerance

Chapter 2: Statistical Properties of Measurement Systems – What We Covered

Learning Objectives

You should now be able to:

- Describe and explain the statistical properties of a measurement system
- Illustrate these properties
- Explain the effect of measurement systems variation on capability indices

Chapter Agenda

- The Statistical Properties of a Measurement System
  - Discrimination
  - Bias
  - Linearity
  - Stability
  - Repeatability
  - reproducibility
- Sources of Measurement Systems Variability
- Effects of Measurement Systems Variation on Capability Indices

Chapter 3

Discrimination & Uncertainty

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Chapter 3: Discrimination & Uncertainty – What We Will Cover

Learning Objectives

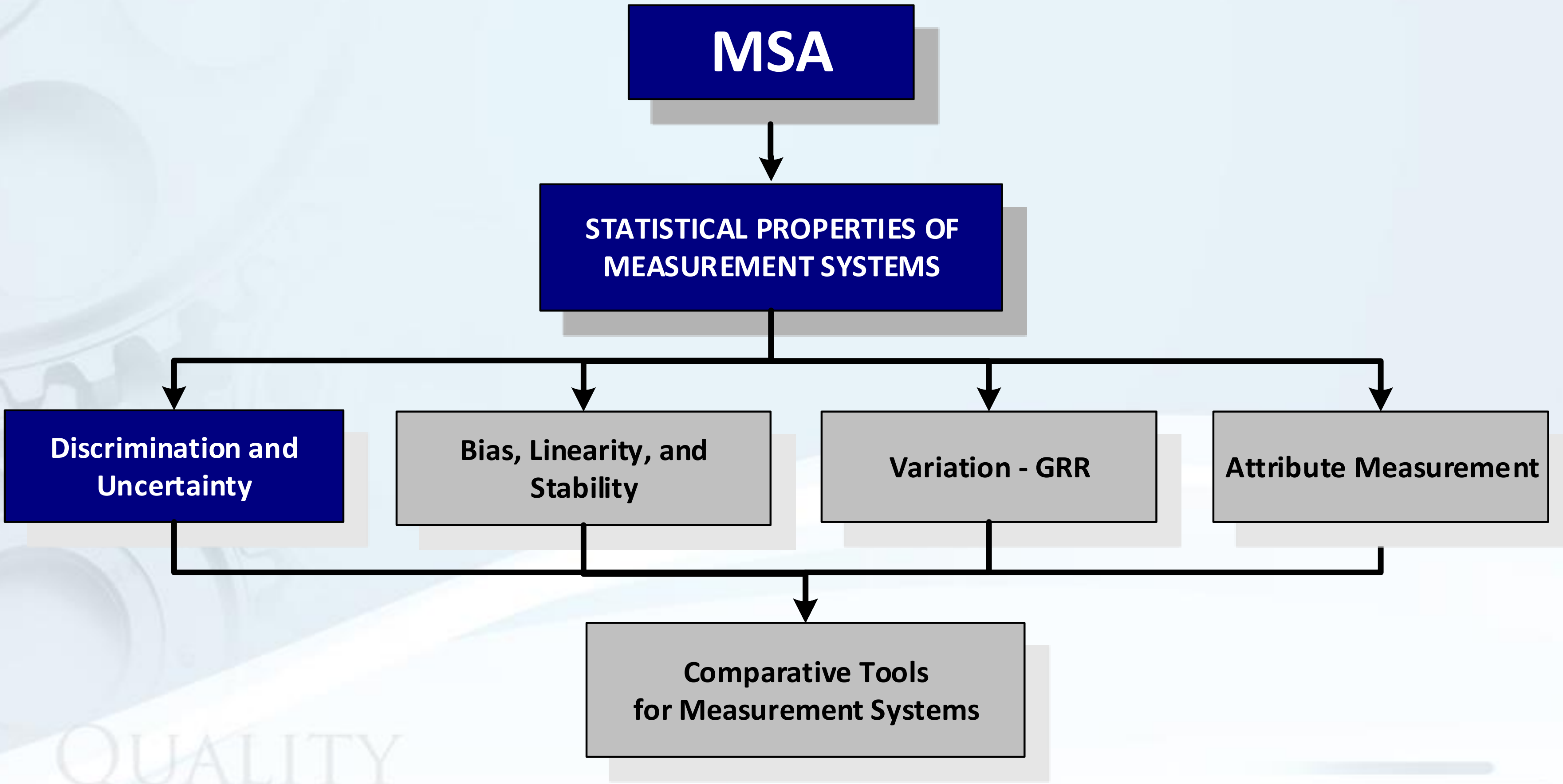
At the end of this chapter, you will be able to:

- Describe and explain the statistical properties of Discrimination & Uncertainty in a measurement system
- Illustrate these properties
- Explain the effect of Discrimination on control charts

Chapter Agenda

- Understanding Discrimination and Its Effects
- Understanding Uncertainty

Application of MSA

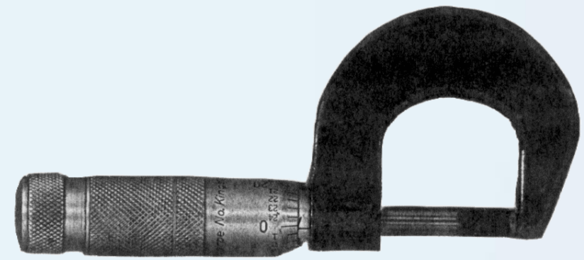


Discrimination

- Understand measurement system capability to provide information on process variability.
- Measurement system is unacceptable for analysis if it cannot detect process variation.
- Measurement system is unacceptable for controlling a process if it cannot detect special cause variation.

Understanding Discrimination

Discrimination: *"The ability of the system to detect and indicate even small changes of the measured characteristic; also known as resolution."*



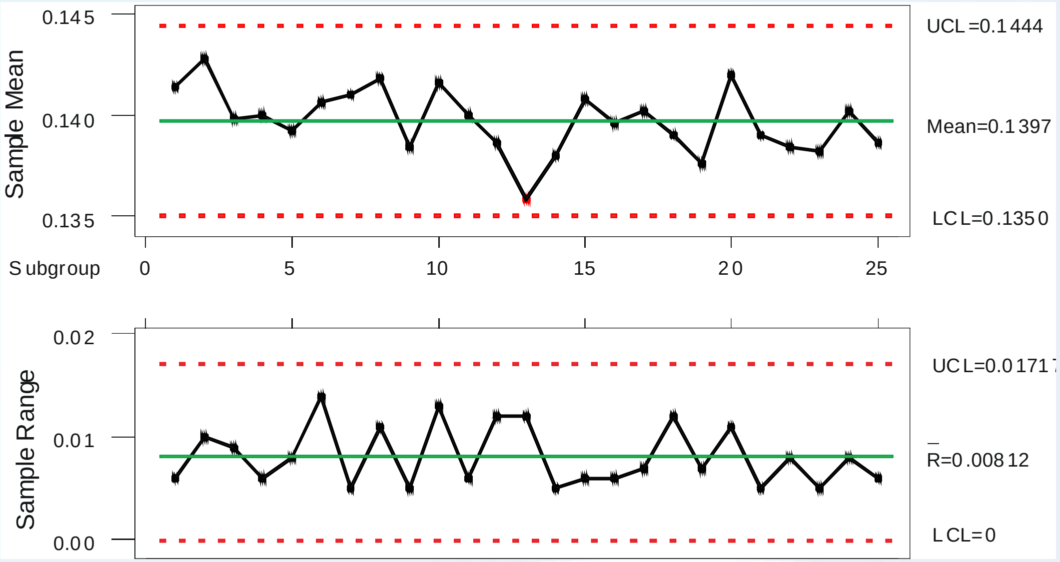
Measuring a Coin's Thickness

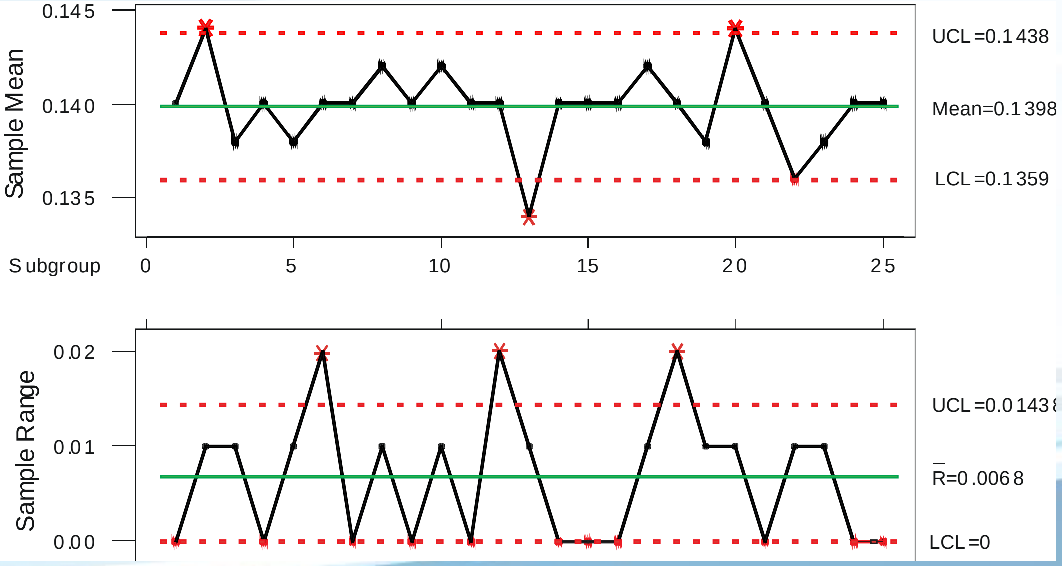
Which measurement system provides better information on the variation of the three coins?

Discrimination and the Control Chart

Example

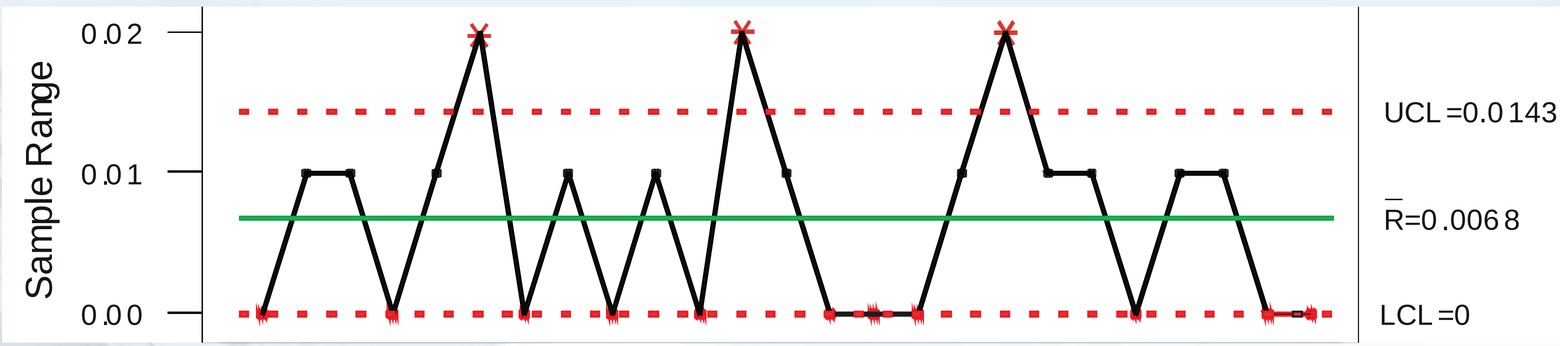
- This shows the measurement of same samples by two systems
- Observe contrast between measurement system with resolution of 0.001" and one with 0.01"





Inadequate Discrimination

- Inadequate discrimination of a measurement system is shown on Range Charts when:
  - only one, two or three values for ranges can be read;
  - more than 1/4 of ranges are zero.



- To correct inadequate discrimination, choose gages of resolution proportionally smaller than the specification or process variation.

Discrimination Decision Rules

- Resolution of 1/10th of tolerance or process spread.
- Study gage discrimination during APQP and test for adequacy before PPAP:
  - Evaluate range chart of manufacturing process or similar process, per previous page and examples.
  - For continual improvement, 1/10th tolerance may be inadequate.

MSA recommends 1/10th of Six Sigma (total) manufacturing standard deviation

Measurement Uncertainty

- Measurement uncertainty is the **sum of all the variations** assigned to the variables that make up the measurement system (all the way back to the basic reference standards from the international standards institutes).

- The total of those probabilities should be weighted and carry importance in proportion to the seriousness and criticality of the measurements being made.

Measurement Uncertainty and Calibration

- Uncertainty-traceability chain
  - The first measurement uncertainty associated with a measurement system is generated by the process of calibration.
  - Calibration permits the estimate of errors of the measurement instrument or system, or the assignment of values to marks on arbitrary scales.
  - The reference material itself, the calibration process, and the environment and personnel performing the activity actually contribute to the measurement uncertainty.
  - The reason for accredited and qualified calibration labs is to guarantee you get reliable data from the measuring systems you have calibrated.

$$u^2 = \sigma^2_{ms} + \sigma^2_{calchain}$$

$$U = \pm 2u \text{ (95\% conf band)}$$

Measurement Uncertainty

- Decisions resulting from measurement system analysis include:
  - Use the system as is, taking into account its uncertainty.
  - Improve the system to control the variation in the contributing factors.
  - Consider other measurement systems of higher levels of discrimination and capability (these will usually cost more, but your MSA data will help to identify and justify adequate resources).

Chapter 3: Discrimination & Uncertainty – What We Covered

Learning Objectives

You should now be able to:

- Describe and explain the statistical properties of Discrimination & Uncertainty in a measurement system
- Illustrate these properties
- Explain the effect of Discrimination on control charts

Chapter Agenda

- Understanding Discrimination and Its Effects
- Understanding Uncertainty

Chapter 4

Bias, Linearity and Stability

Chapter 4: Bias, Linearity and Stability – What We Will Cover

Learning Objectives

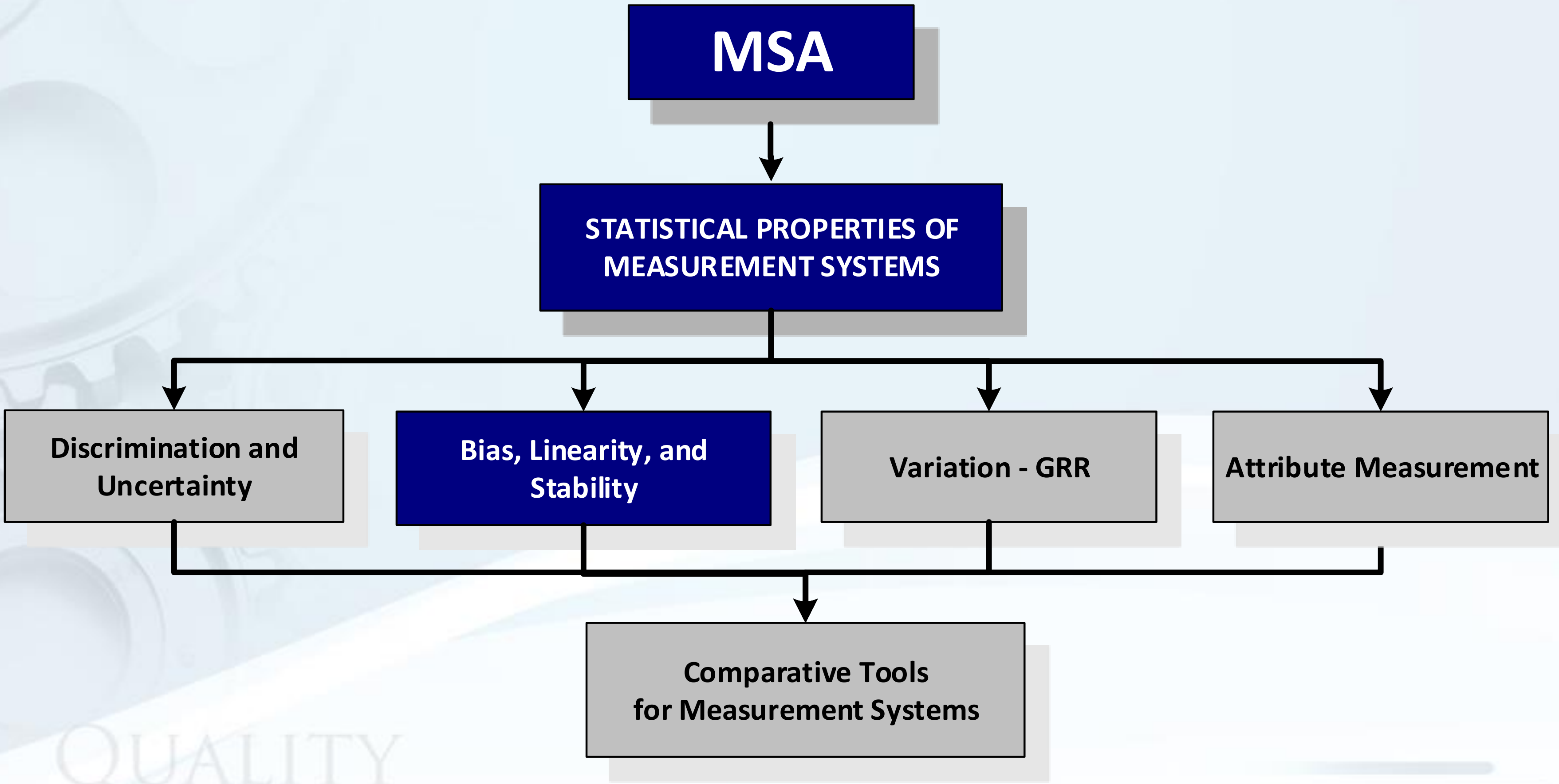
At the end of this chapter, you will be able to:

- Describe and explain the statistical properties of Bias, Linearity and Stability in a measurement system
- Illustrate these properties
- Determine the Bias, Linearity and Stability of a Measurement System

Chapter Agenda

- Define Reference Value
- Describe and Analyze a Measurement System's Bias
  - **Breakout Exercise #1**
- Describe and Analyze a Measurement System's Linearity
  - **Breakout Exercise #2**
- Describe and Analyze a Measurement System's Stability
  - **Breakout Exercise #3**

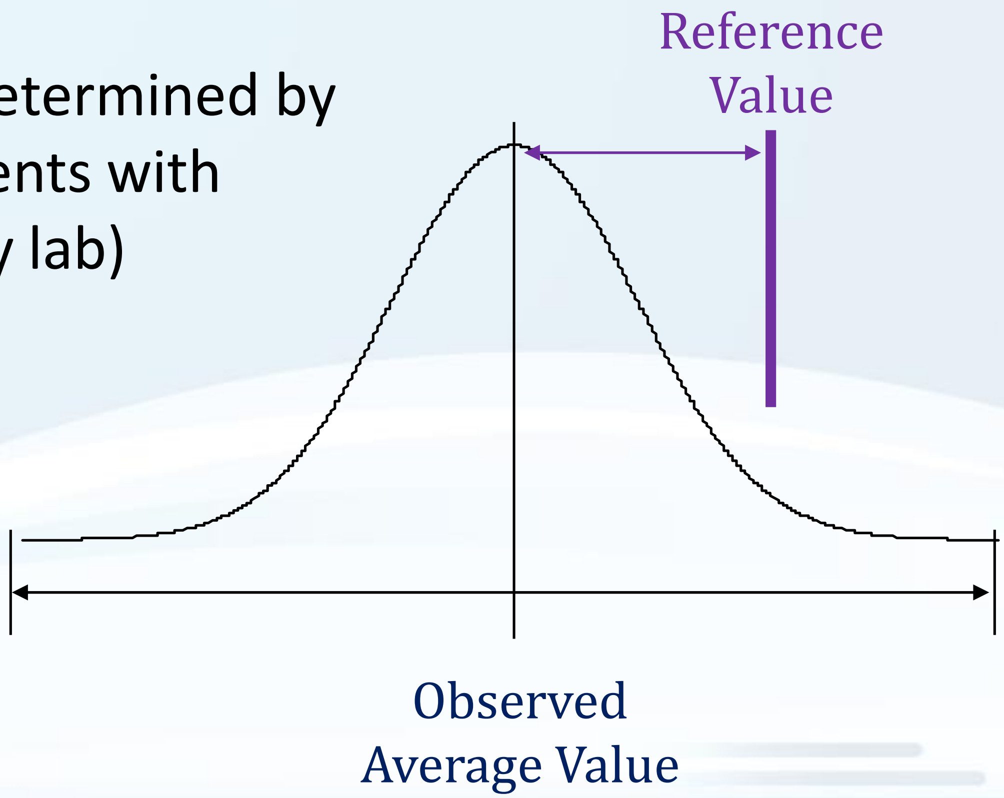
APPLICATION OF MSA



BIAS Definition

BIAS – The difference between the observed average of the measurement and the reference value.

The reference value can be determined by averaging several measurements with a higher level (e.g., metrology lab) of measuring equipment.



Terminology

- **True Value (?)**
  - Theoretically correct value – **unknown and unknowable**
  - Reference standards
  - Traceable to NIST standards

Reference Value

- **Bias**
  - Distance between average value of all measurements and **reference value**
  - Amount gage is consistently off target
  - Systematic error or offset

Reference Value

- A value that serves as an agreed upon reference for comparison.
  - A reference value can be determined by averaging several measurements with a higher level of measuring equipment

- Sometimes known as:
  - master value
  - accepted value
  - conventional value
  - assigned value
  - best estimate of the value
  - master measurement
  - measurement standard

Reference Material

- A material or substance with one or more properties which are sufficiently well-established to be used for the calibration of an apparatus, assessment of a measurement method, or for assigning values to materials.

National/International Measurement Standards

- A material measure, measuring instrument, reference material or system intended to define, realize, conserve or reproduce a unit, or one or more values of a quantity, in order to transmit them to other measuring instruments by comparison. O$M$$NEX
- These standards are recognized by an official national decision or by an international agreement to serve internationally, as the basis for fixing the value of all other standards of the quantity concerned.
- Some Examples:
  - Solution of cortisol in human serum as a standard of concentration
  - Iodine-Stabilized Helium
  - Neon Laser Length Standard
  - Weston Standard cell
  - Standard gage block
  - 100 Ω standard resistor
  - 1 kg mass
  - Caesium atomic frequency standard
  - Josephson Array Voltage Standard

Traceable Standard Limitations

- Difficult to use in destructive testing
- Some product characteristics and process results have no defined industry or national standards
- Some tests have no defined industry or national standards
- Discuss limitations during design and development, contract review and APQP – management responsibility issue

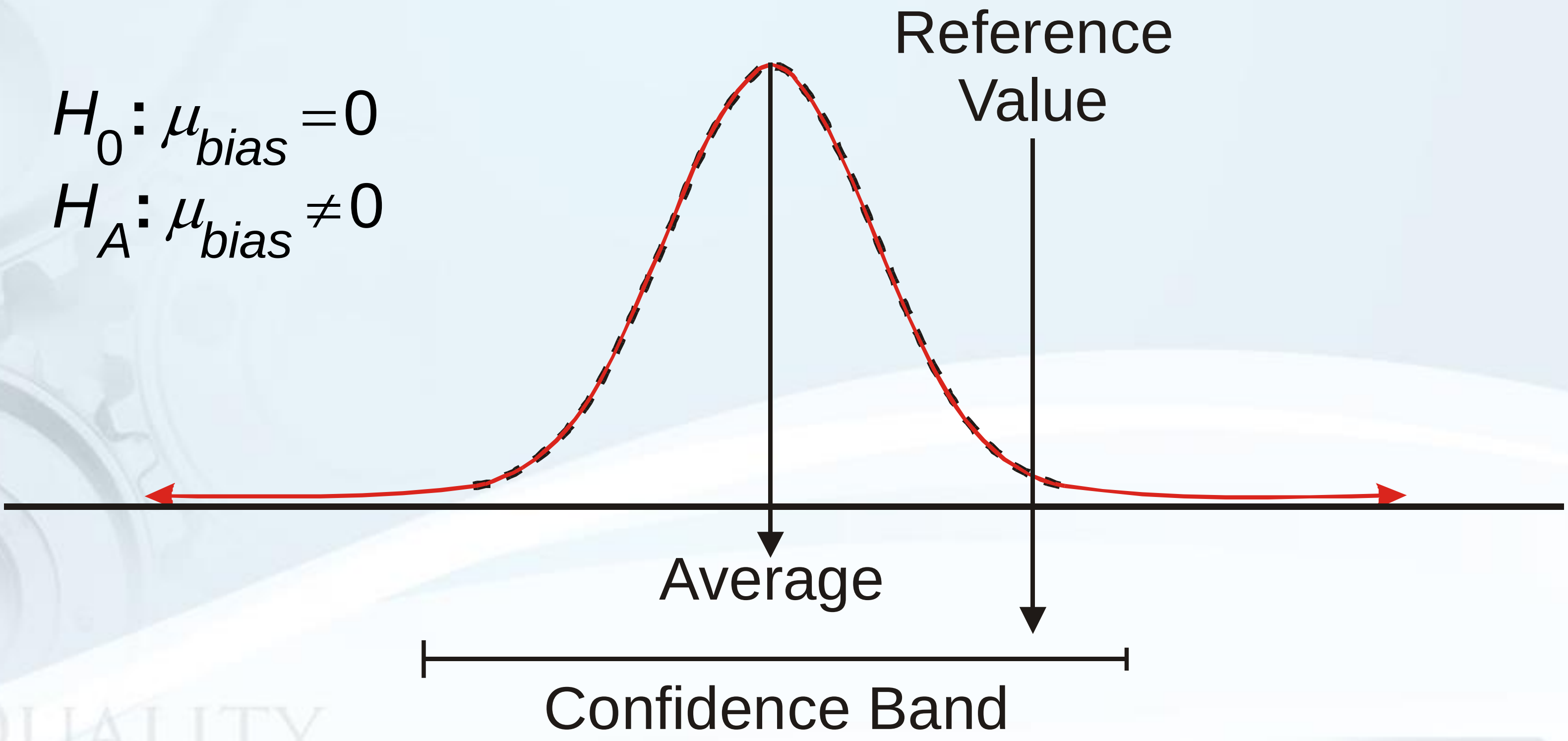
Why Do a Gage Bias Study?

- Because it is required
- To determine if the bias is acceptable (statistically zero)

Analysis of Bias

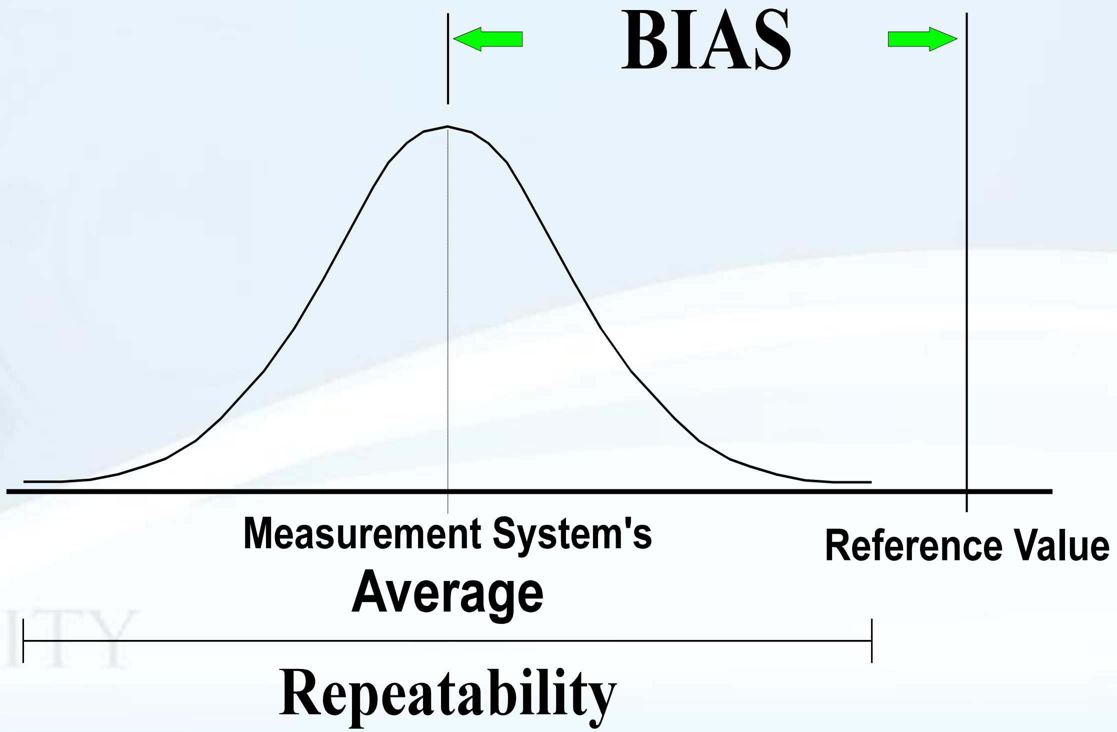
Test of Hypothesis Approach

$$H_0: \mu_{bias} = 0$$
$$H_A: \mu_{bias} \neq 0$$



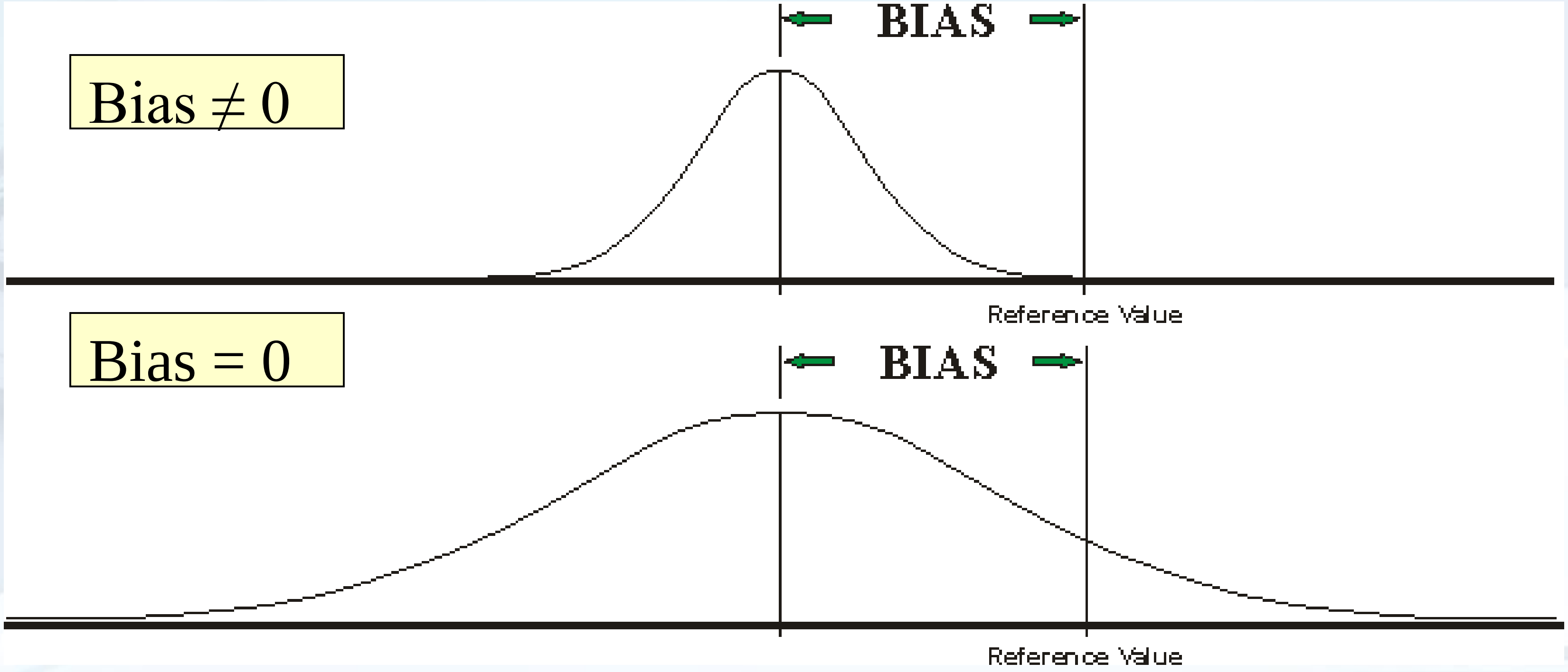
Bias

- The calculation of repeatability is part of the bias analysis

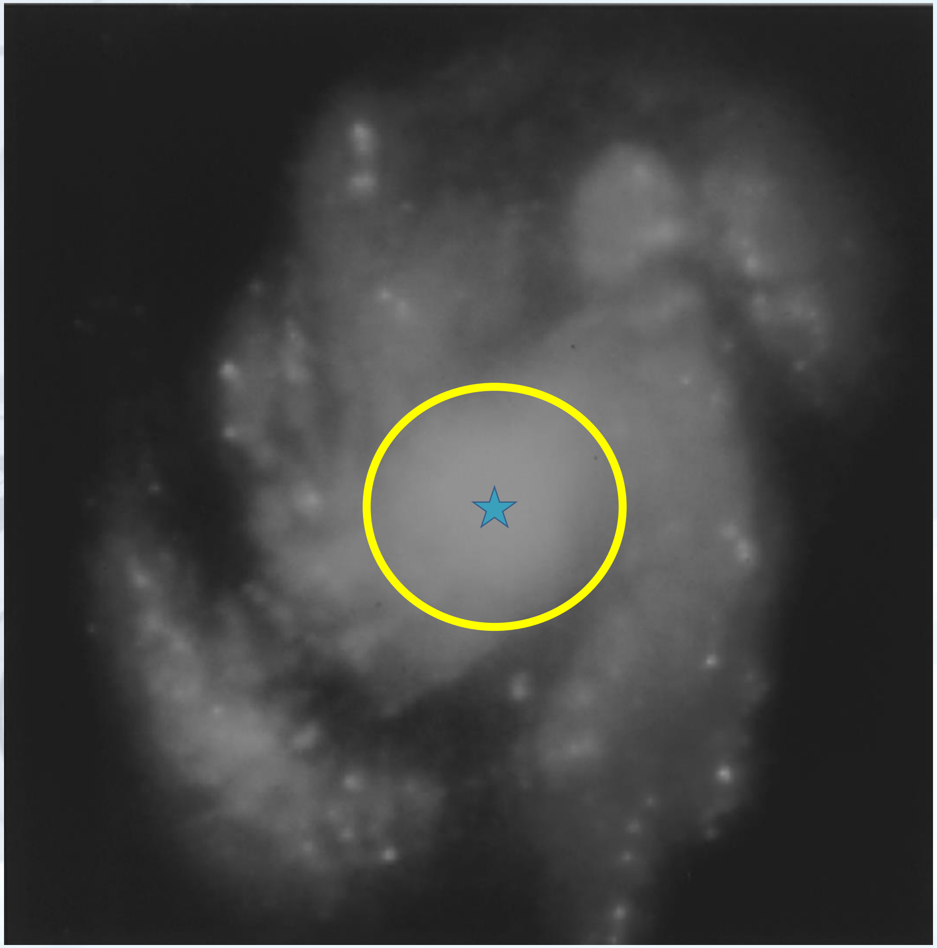


Bias

- Same bias – but the bottom one is statistically zero and the top is not



Measurement is Not Always Exact



Bias Study Instruction

1. Obtain accepted reference value using a master or measuring equipment of higher level, such as layout equipment to create a “golden unit” or “master part” to use as a reference value.

2. Measure same part by same appraiser a *minimum* of 10 times using the gage under evaluation.

Bias Study Instruction

- Analysis:
  - Calculate:
    - Bias = reading – reference value
  - Plot the histogram of all the bias readings
    - Determine if any special causes are present
  - Calculate:
    - sd(repeatability) = standard deviation of all the readings
    - sd(bias) = sd(repeatability) divided by the square root of the sample size
    - The t-statistic and/or confidence bounds
  - Determine if the average bias is statistically zero – i.e.,
    - Is the repeatability acceptable; i.e. is EV ≤ 10% ?
    - Is the t-statistic less than the critical value?
    - Is zero contained within the confidence bounds?

Bias Calculation – Example

Bias Calculation-Data sheet

	X^i	Reference Value=0.72650	Bias
	1	0.72660	0.00010
	2	0.72440	-0.00210
T	3	0.72535	-0.00115
R	4	0.72630	-0.00020
I	5	0.72710	0.00060
A	6	0.72745	0.00095
L	7	0.72630	-0.00020
S	8	0.72515	-0.00135
	9	0.72525	-0.00125
	10	0.72570	-0.00080

@msa e class data **Excel file; tab:** ***bias calc***

BIAS EXAMPLE

The outside diameter of a shaft is measured ten times by the same operator – the data is given below

The tolerance is 0.73 ± .03

The reference value is 0.72650

X i	**Reference Value=0.72650**	Bias
1	0.72660	0.00010
2	0.72440	-0.00210
3	0.72535	-0.00115
4	0.72630	-0.00020
5	0.72710	0.00060
6	0.72745	0.00095
7	0.72630	-0.00020
8	0.72515	-0.00135
9	0.72525	-0.00125
10	0.72570	-0.00080

Average ($\bar{X}$) = 0.72596

Avg Bias = Observed Average - Reference
= 0.72596 - 0.72650 = - 0.00054

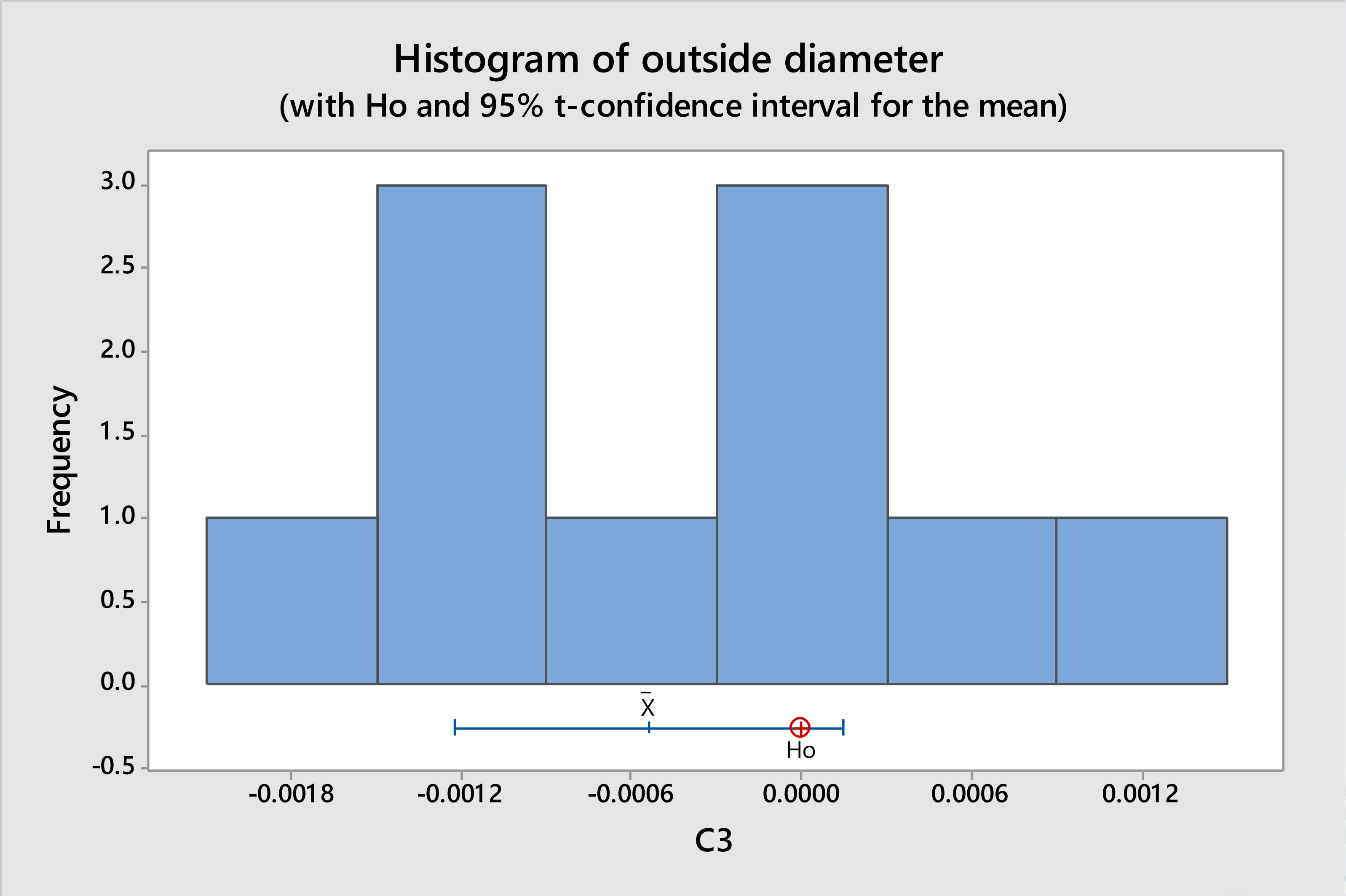
The observed measurements on the average will be 0.00054" smaller than the reference value

BIAS EXAMPLE

Average	= 0.72596
Bias	= - 0.00054
Overall StdDev	= 0.000954
%EV (tol)	= 100% * Overall StdDev / (Tolerance/6) = 9.54 %
StdDev Bias	= 0.000954/sqrt(10) = 0.000302
Confidence Bounds	= Average ± Critical *t* value * StDev Bias (-0.001223, 0.000143)
Critical *t* value = $t_{.025,df}$	= 2.26216 for df = 9 (from t table) for 95% confidence *excel function =T.INV(0.025,9)*
Calculated *t*	= abs(-0.00054)/0.000302 = 1.79

- **Analysis**
  - Since calculated *t* is less than the critical *t* value,
  - And zero (0) is contained within the Confidence Bounds (-0.001223, 0, 0.000143)
  - Therefore, accept the hypothesis that the bias is zero.
  - That is, the bias is statistically zero.

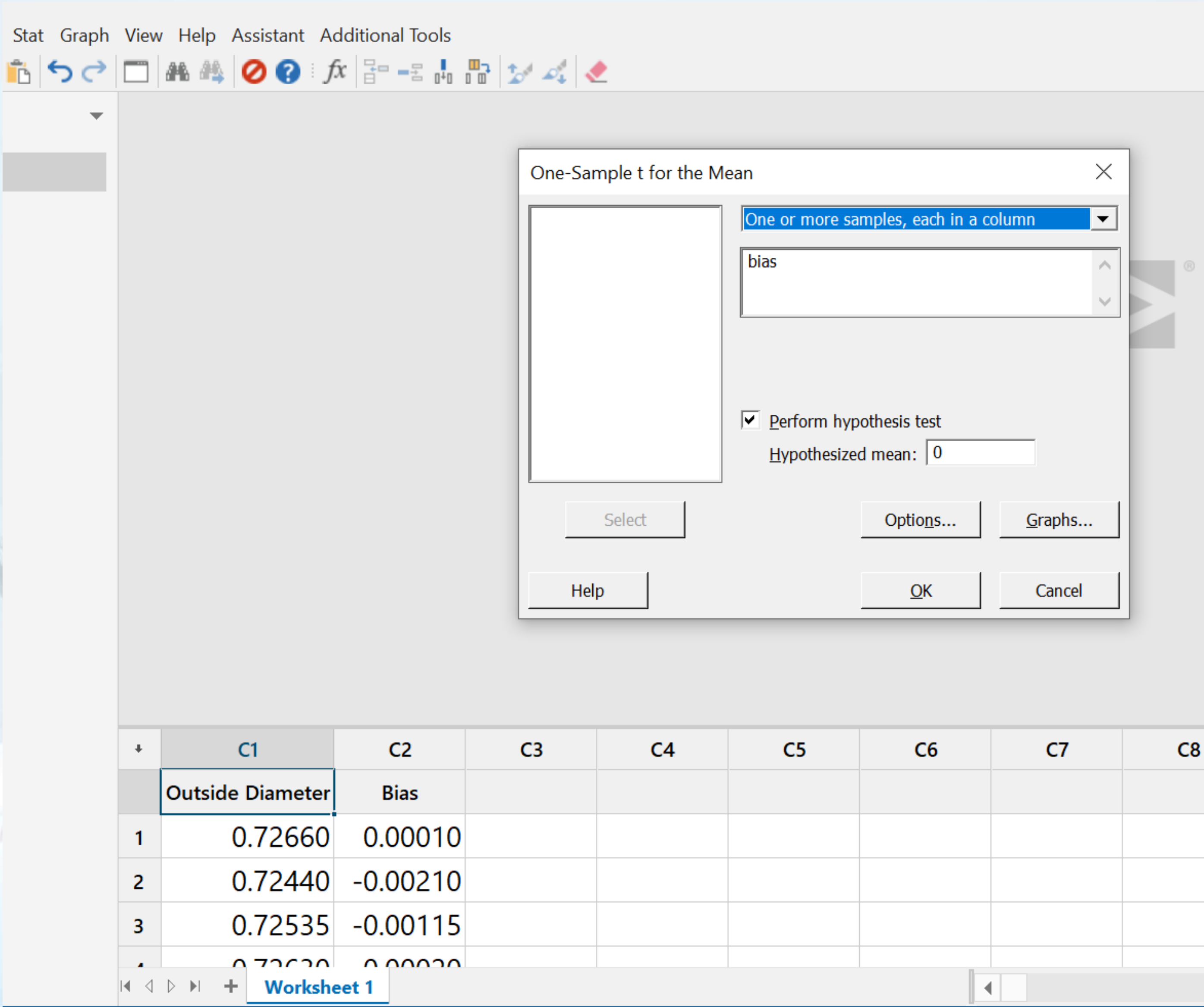
BIAS EXAMPLE



BIAS EXAMPLE using Minitab

1. Copy data into Minitab from ***@msa e class data*** Excel file
   - Highlight rows 3 –13 of columns D and E in the ***bias calc*** tab
   - Copy these data
   - In Minitab, click in the to cell (grey) of column 1 and paste the data
2. Stat > Basic Stat > one sample T for the mean
3. Select: One or more samples, each in a column
4. Select the column with the bias data
5. Select Perform Hypothesis Test with a hypothesized mean of zero (0)
6. In Graphs, select Histogram
7. Click OK

BIAS EXAMPLE using Minitab



BIAS EXAMPLE using Minitab

Descriptive Statistics

N	Mean	StDev	SE Mean	95% CI for μ
10	-0.000540	0.000954	0.000302	(-0.001223, 0.000143)

μ: population mean of Bias

Test

Null hypothesis H_0: μ = 0
Alternative hypothesis H_1: μ ≠ 0

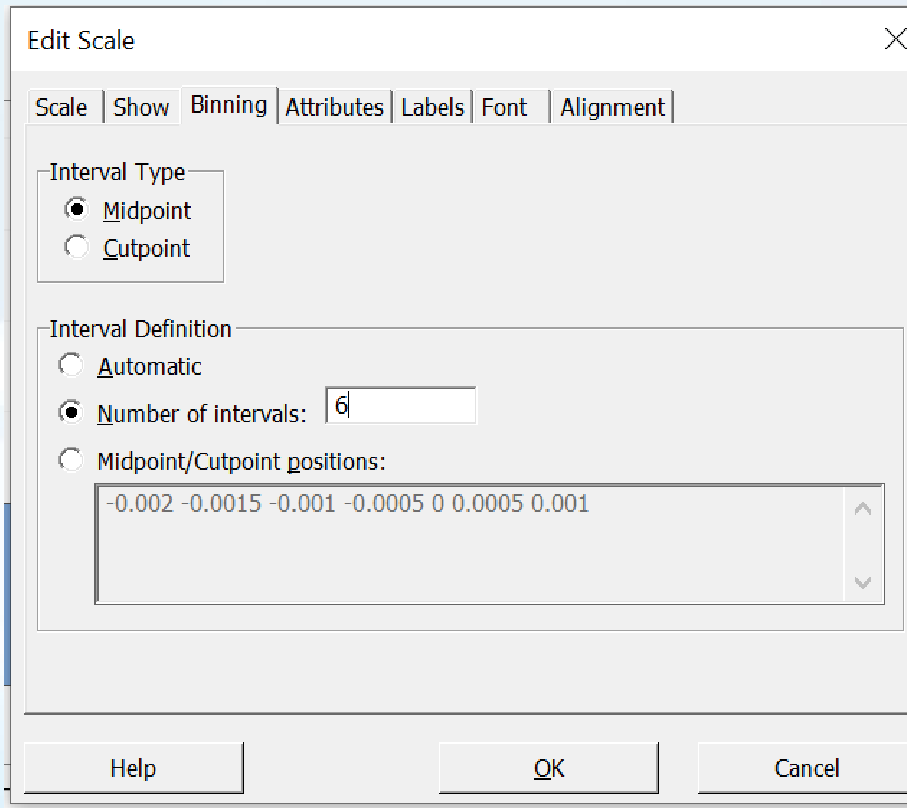
T-Value	P-Value
-1.79	0.107

BIAS EXAMPLE using Minitab

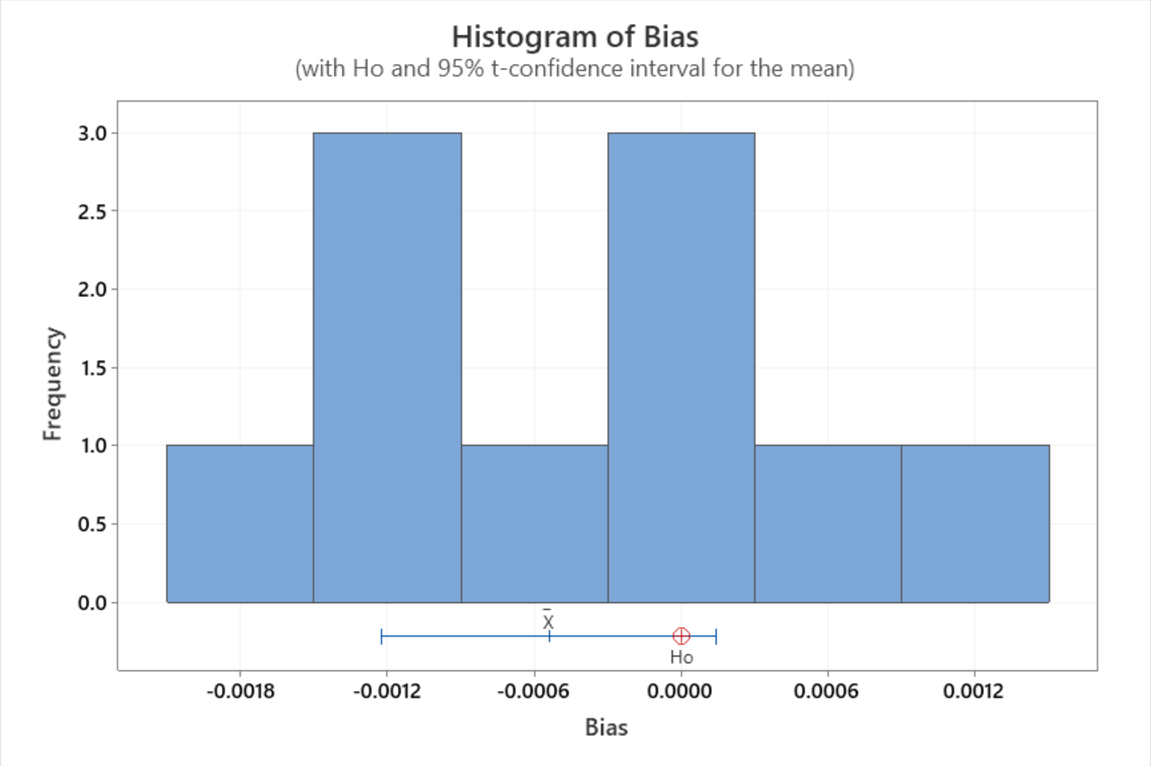
BIAS EXAMPLE using Minitab

To change histogram scaling:

1. Right-click on graph and select Edit Graph
2. On the new graphic, right-click on the x-scale and select Edit X Scale
3. Select Tab Binning
4. Change number of intervals to 6
5. Click OK



BIAS EXAMPLE using Minitab



Breakout Exercise 1

Calculating Bias

Breakout Exercise 1: Calculating Bias

Use the data in Breakout Workbook, Breakout Exercise 1 or *@msa e class data* Excel file; tab: *bias – brk #1*

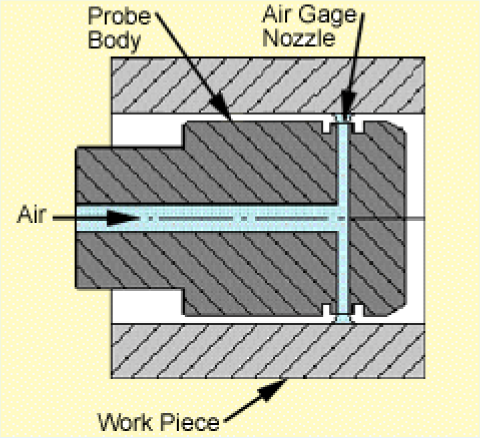
- Calculate the bias values
- Plot the bias Histogram
- Calculate the confidence bounds
- Determine if the bias is acceptable

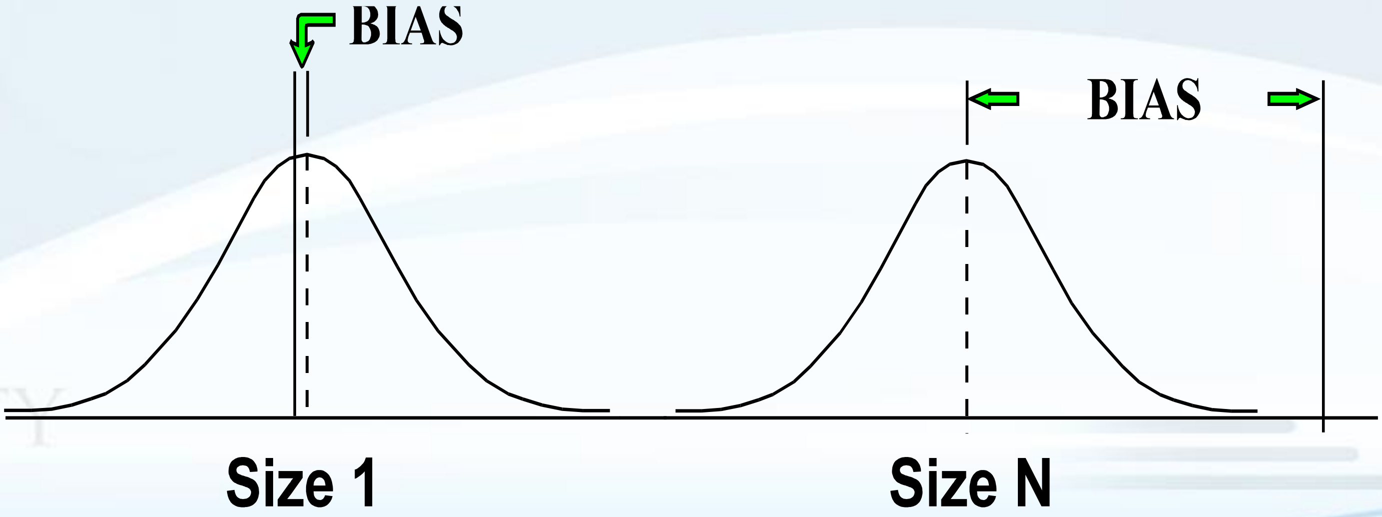
Cause of Unacceptable Bias

- Error in measuring instrument
- Instrument:
  - worn, dirty, broken
  - improper design
  - made to wrong dimension
  - improper discrimination
  - improper calibration
  - improper use by operator

Linearity

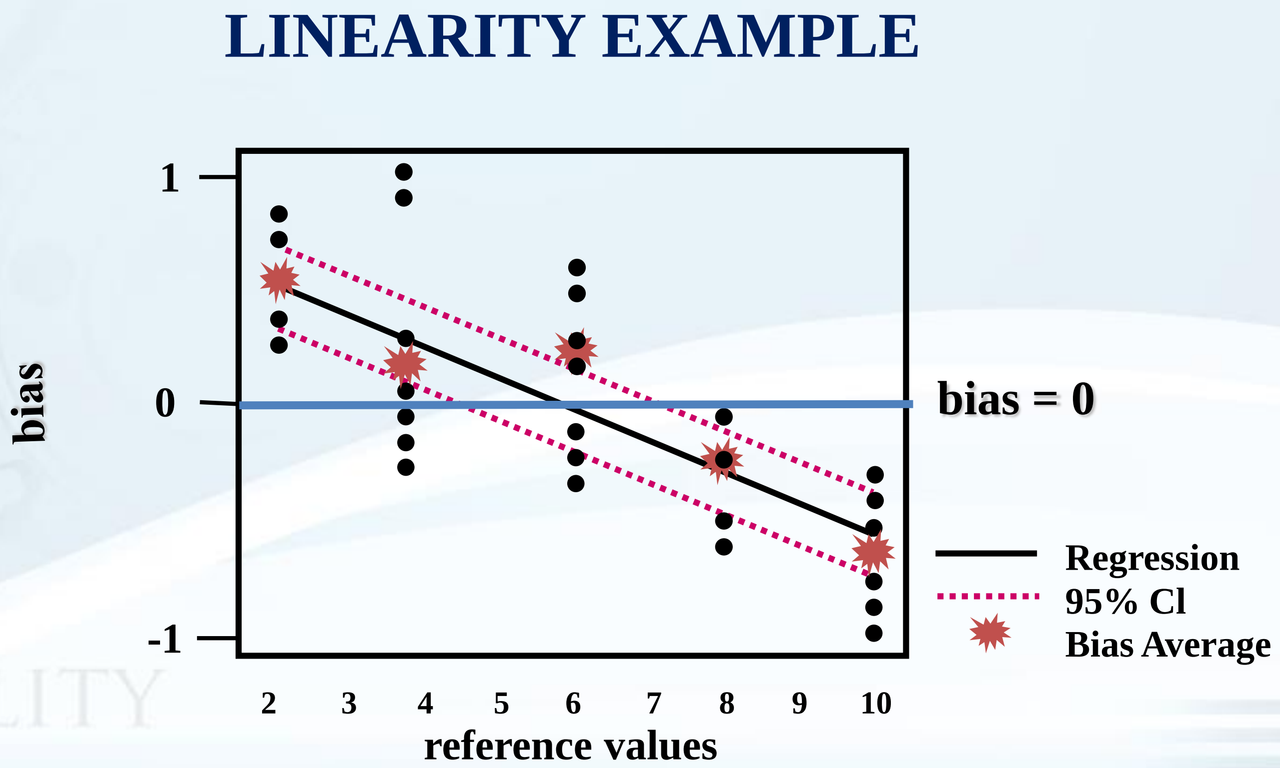
Test of Hypothesis Approach





Linearity

- Difference in the bias values of a measurement system through its expected operating range.

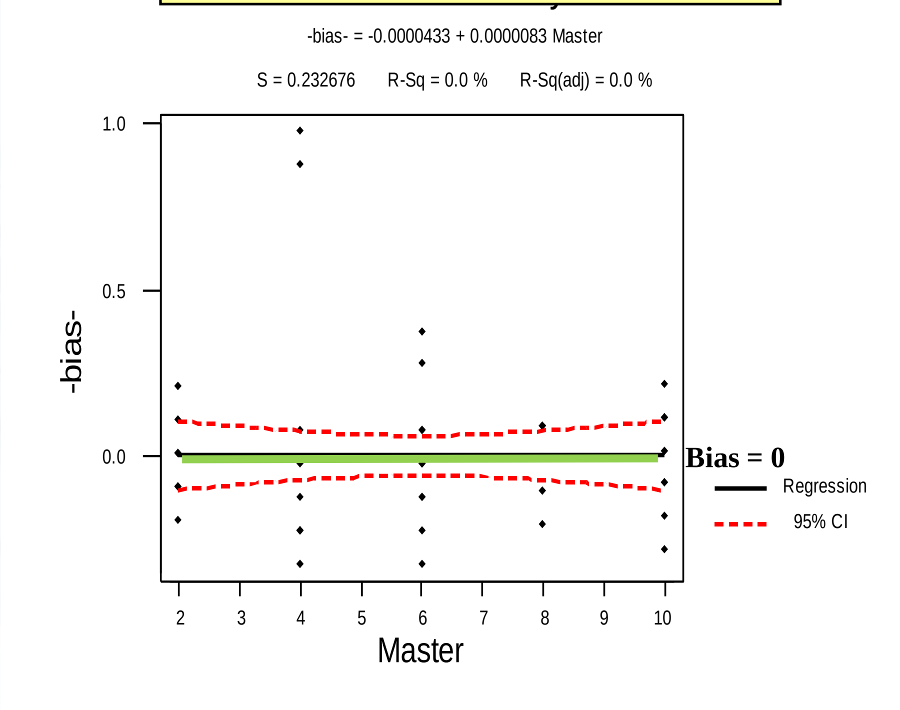


Linearity Study - Graphical Analysis

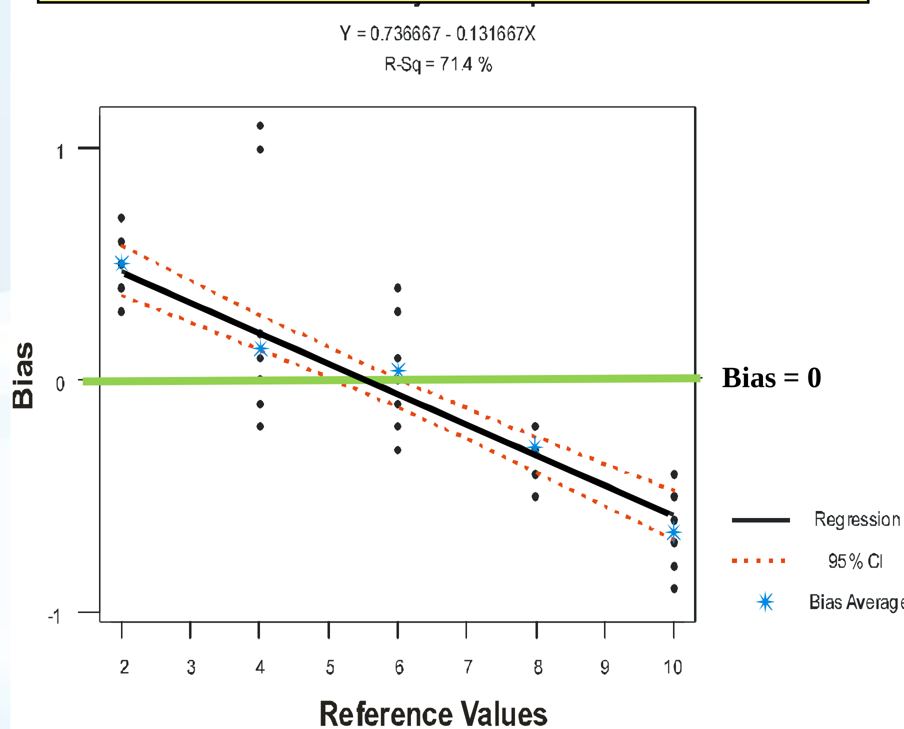
Linearity

- Difference in the bias values of a measurement system through its expected operating range.

Acceptable Linearity



Unacceptable Linearity



Linearity is acceptable if the bias=0 line falls inside the confidence bands

Linearity Study

Linearity Study Work Instruction

1. Select three to eight parts that can be measured at different points in the operating range of the measurement system.
2. Determine reference value for each part using layout inspection or use a set of standards.
3. Use one appraiser and the same instrument to measure parts.
4. Take 5 or more repeated measurements on each part.
5. Calculate each part's bias.

bias = observed value - reference value

Linearity Study

6. Create a scatter plot by putting the reference values from smallest to largest on the X-axis, and the corresponding bias values and averages on the Y-axis.

7. Determine the best fit line through the averages.

8. Calculate the 95% confidence intervals for the average (line) and apply.

9. Analyze the results.

Linearity Study

10. To analyze the graph:
    a. The bias = 0 line must fall entirely within the CI for acceptable linearity.
    b. Watch for individual readings that do not follow the pattern of the groups (e.g. outliers); also watch for other patterns indicating unusual variation or abnormal behavior.

Remember that a measurement system with large (i.e., unacceptable) repeatability can indicate a statistically acceptable bias even if it is practically unacceptable.

If the measurement system has a linearity problem, use problem-solving methods to determine modifications necessary to achieve zero linearity.

Charting Linearity

LINEARITY STUDY DATA

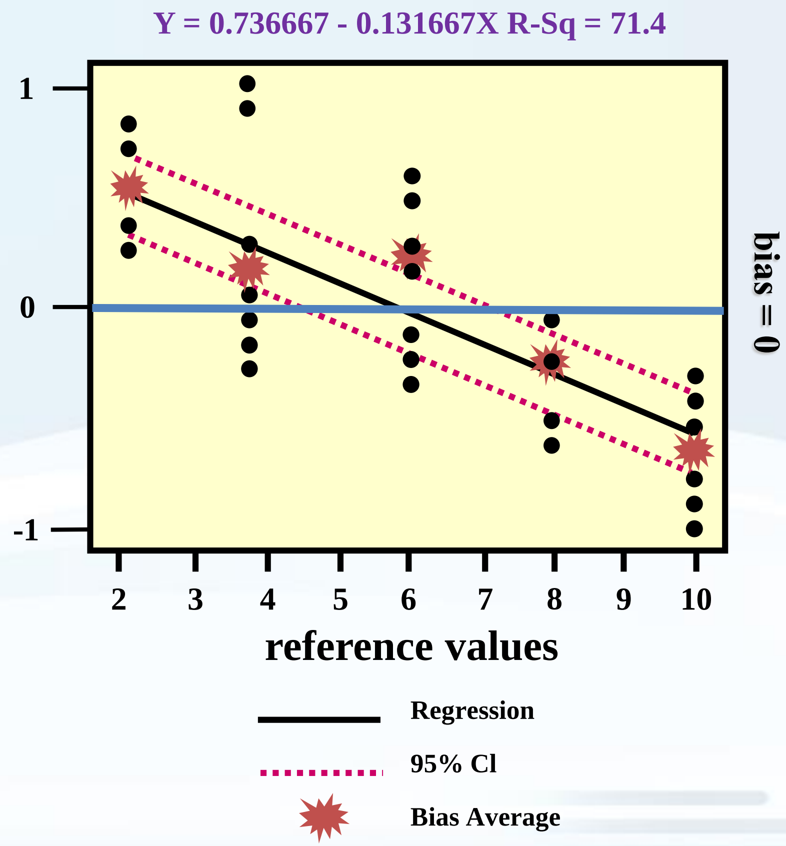
TRIALS

PART REFERENCE VALUE	1 2.00	2 4.00	3 6.00	4 8.00	5 10.00
1	2.70	5.10	5.80	7.60	9.10
2	2.50	3.90	5.70	7.70	9.30
3	2.40	4.20	5.90	7.80	9.50
4	2.50	5.00	5.90	7.70	9.30
5	2.70	3.80	6.00	7.80	9.40
6	2.30	3.90	6.10	7.80	9.50
7	2.50	3.90	6.00	7.80	9.50
8	2.50	3.90	6.10	7.70	9.50
9	2.40	3.90	6.40	7.80	9.60
10	2.40	4.00	6.30	7.50	9.20
11	2.60	4.10	6.00	7.60	9.30
12	2.40	3.80	6.10	7.70	9.40

BIAS

PART REFERENCE VALUE	1 2.00	2 4.00	3 6.00	4 8.00	5 10.00
1	0.7	1.1	-0.2	-0.4	-0.9
2	0.5	-0.1	-0.3	-0.3	-0.7
3	0.4	0.2	-0.1	-0.2	-0.5
4	0.5	1	-0.1	-0.3	-0.7
5	0.7	-0.2	0.0	-0.2	-0.6
6	0.3	-0.1	0.1	-0.2	-0.5
7	0.5	-0.1	0.0	-0.2	-0.5
8	0.5	-0.1	0.1	-0.3	-0.5
9	0.4	-0.1	0.4	-0.2	-0.4
10	0.4	0.0	0.3	-0.5	-0.8
11	0.6	0.1	0.0	-0.4	-0.7
12	0.4	-0.2	0.1	-0.3	-0.6
BIAS AVG	0.491667	0.125	0.025	-0.29167	-0.61667

LINEARITY EXAMPLE

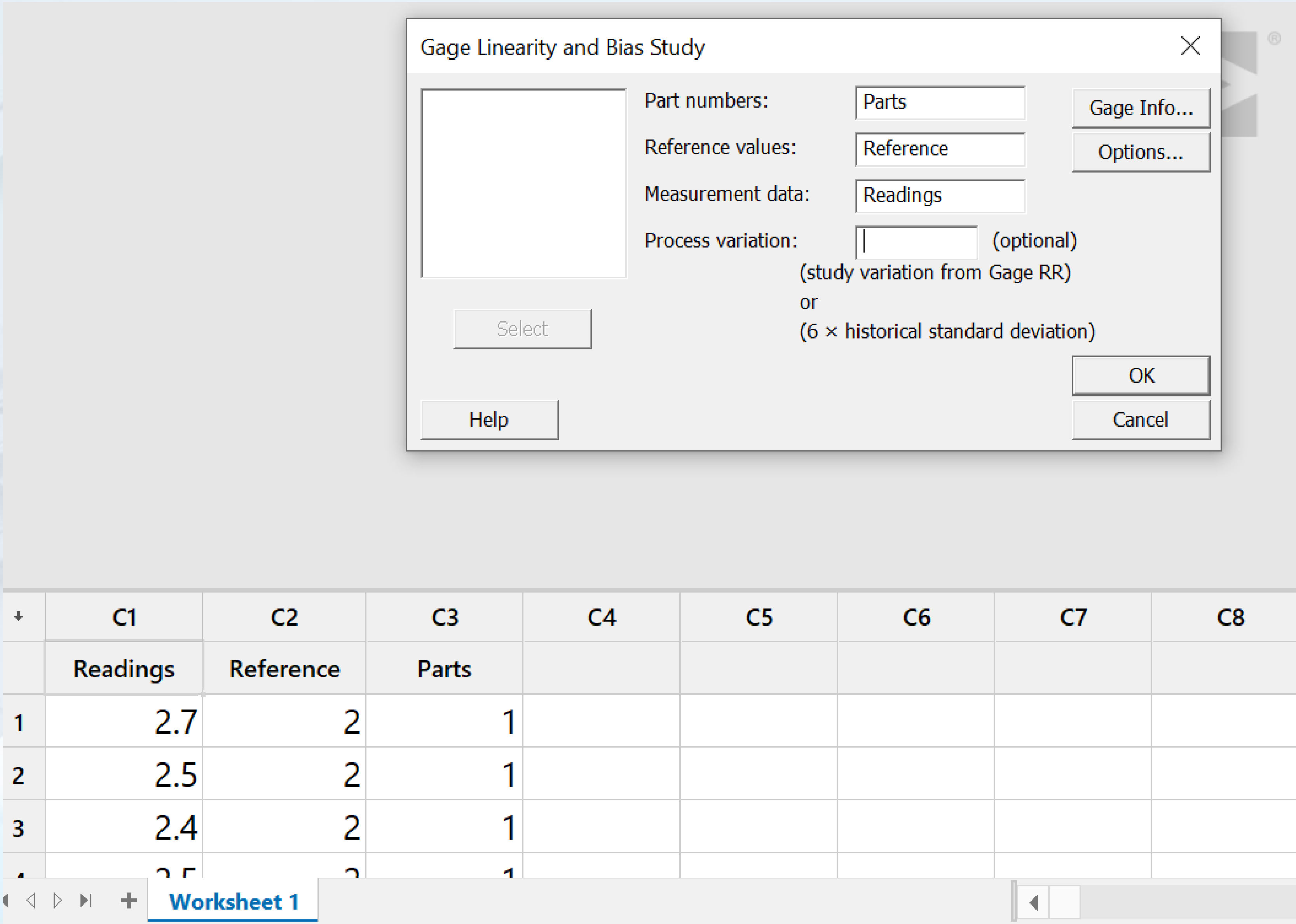


Linearity Study - Graphical Analysis

LINEARITY EXAMPLE using Minitab

1. Copy data into Minitab from ***@msa e class data*** Excel file
   - Highlight columns A, B, C in the ***linearity*** tab
   - Copy these data
   - In Minitab click in the to cell (grey) of column 1 and paste the data
2. Stat > Quality Tools > Gage Study > Gage Linearity and Bias Study
3. Select: appropriate columns for Part Numbers; Reference Values, and Measurement Data
4. Click OK

LINEARITY EXAMPLE using Minitab

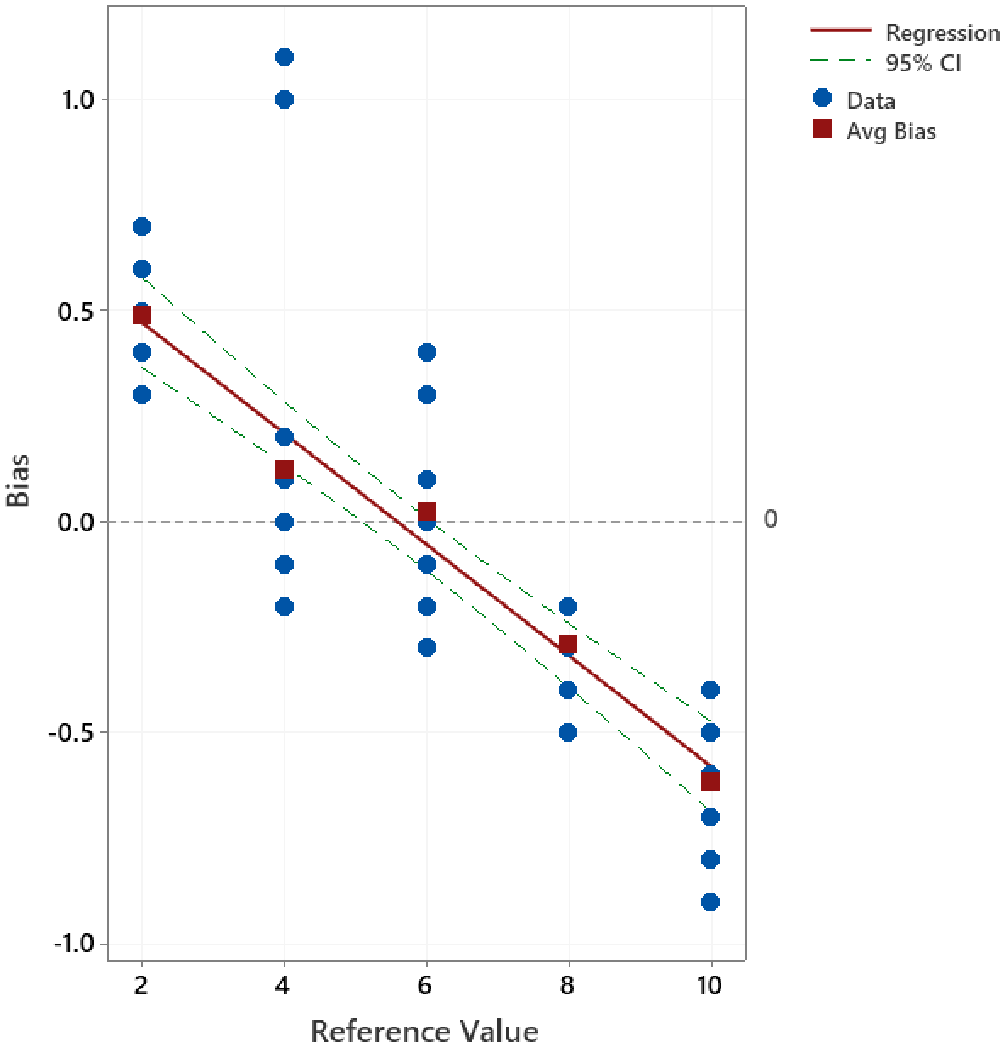


Gage Linearity and Bias Report for Readings

Minitab

Gage name:
Date of study:

Reported by:
Tolerance:
Misc:



Gage Linearity

Predictor	Coef	SE Coef	P
Constant	0.73667	0.07252	0.000
Slope	-0.13167	0.01093	0.000

S 0.239540 R-Sq 71.4%

Gage Bias

Reference	Bias	P
Average	-0.053333	0.040
2	0.491667	0.000
4	0.125000	0.293
6	0.025000	0.688
8	-0.291667	0.000
10	-0.616667	0.000

Breakout Exercise 2

Bias and Linearity

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Breakout Exercise 2: Bias and Linearity

Use the data in Breakout Workbook, Breakout Exercise 2 or *@msa e class data* Excel file; tab: *linearity – brk #2*

- Determine the bias for each reading
- Determine the average bias for each reference value
- Graph the results with the Bias on the Y-axis and the reference values on the X-axis
- Evaluate the acceptability of the repeatability
- Draw the best fit line for the averages on the graph
- Evaluate the acceptability of the linearity
- Share analysis

Breakout Exercise 2: Bias and Linearity using Minitab

1. Copy columns B, C, D from ***@msa e class data*** **Excel file; tab:** ***linearity – brk #2*** and paste into Minitab

2. Create Values column: Data > Stack > Columns
   – Select columns 2, 5, 7

3. Store data in column Data
   – Store subscripts in Ref

4. Click OK

5. Select (click on) column Ref

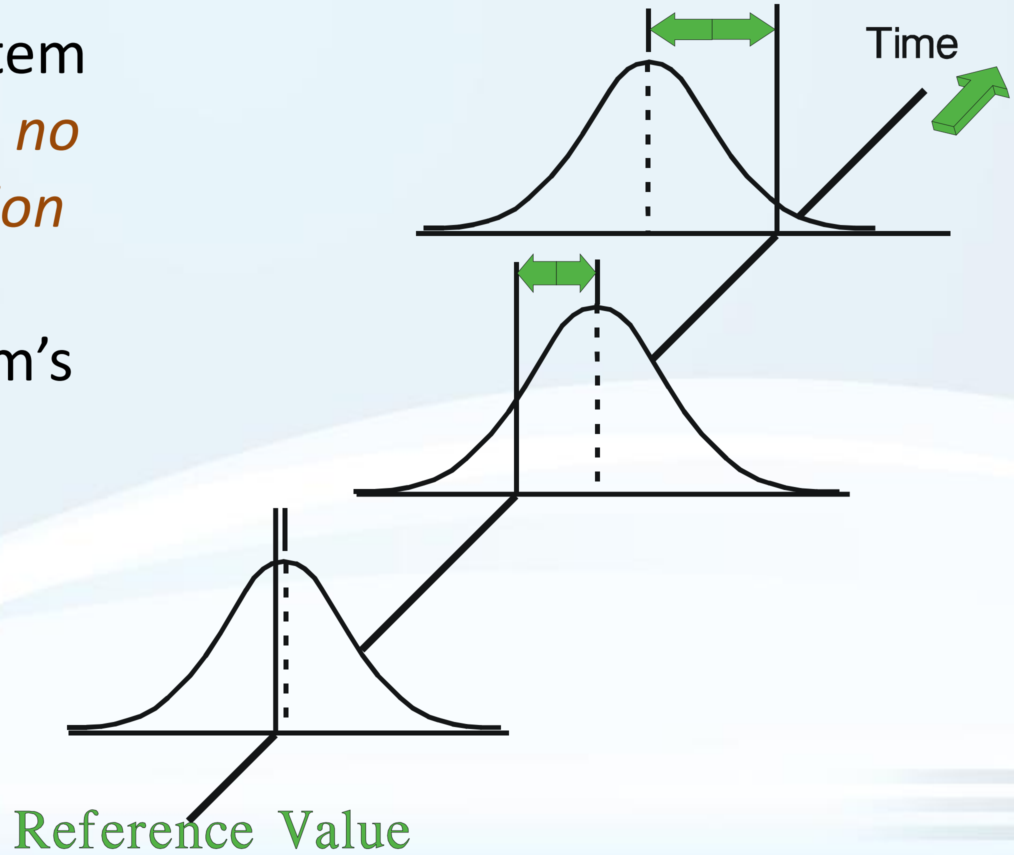
6. Data > Change Data Type
   – Select Ref
   – Click OK

Breakout Exercise 2: Bias and Linearity using Minitab

7. Calc > Make Patterned Data > Simple Set of Numbers
   - Store in Parts
   - First Value: 1
   - Last Value: 3
   - Number of Times each value: 20
   - Click OK
8. Stat > Quality Tools > Gage Study > Gage Linearity and Bias Study
   - Select Parts, Ref, Data
   - Click OK

Stability

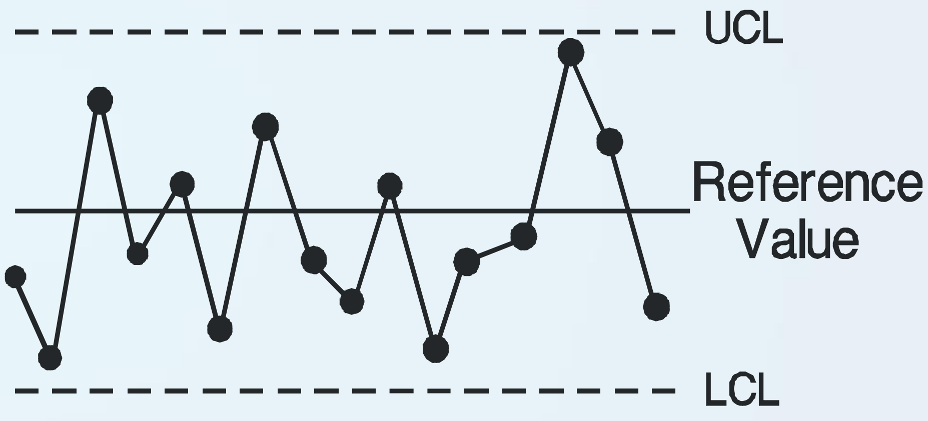
A measurement system is **Stable** if there are *no special cause variation* affecting the measurement system's bias over time.



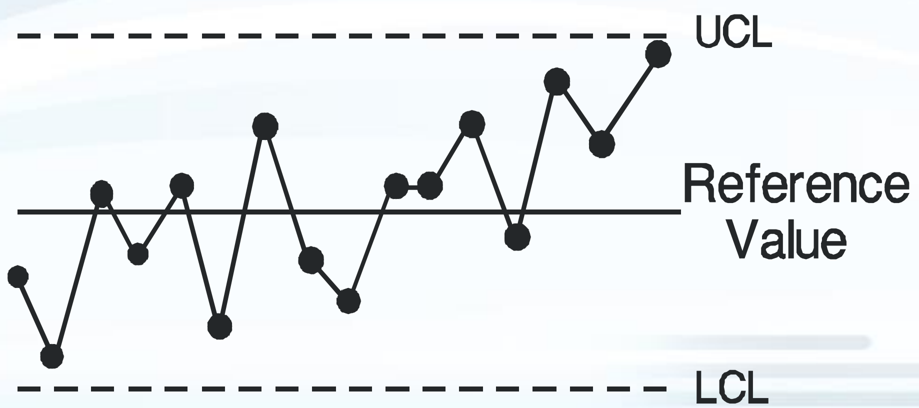
Stability

Stability (or drift) in a measurement system is evaluated by measuring the same master(s) or part(s) on a single characteristic over an extended time period (a time period is days, not hours).

Acceptable



Not Acceptable



Measurement System Stability

- Typically not as large a problem as GRR
- Useful in helping to determine calibration intervals
- Should track from test to test and chart (or at least record actual readings and other pertinent data in the gage record)

Measurement Stability Study

Stability Analysis Instructions

1. Use a standard set of parts or reference/master materials as sample.
   - Retain these as appropriate (life of product) in a protected environment.
   - Label them with name and number for tracking and further studies include samples at the low, mid and high range.

2. **(Recommended)** Perform a bias or linearity study on the sample – use this information to establish the control chart parameters.
   - Measure part(s) three to five times (based on knowledge of measurement system) at different times of the day.
     Plot data on $\overline{X}$ & R or $\overline{X}$ & S chart.

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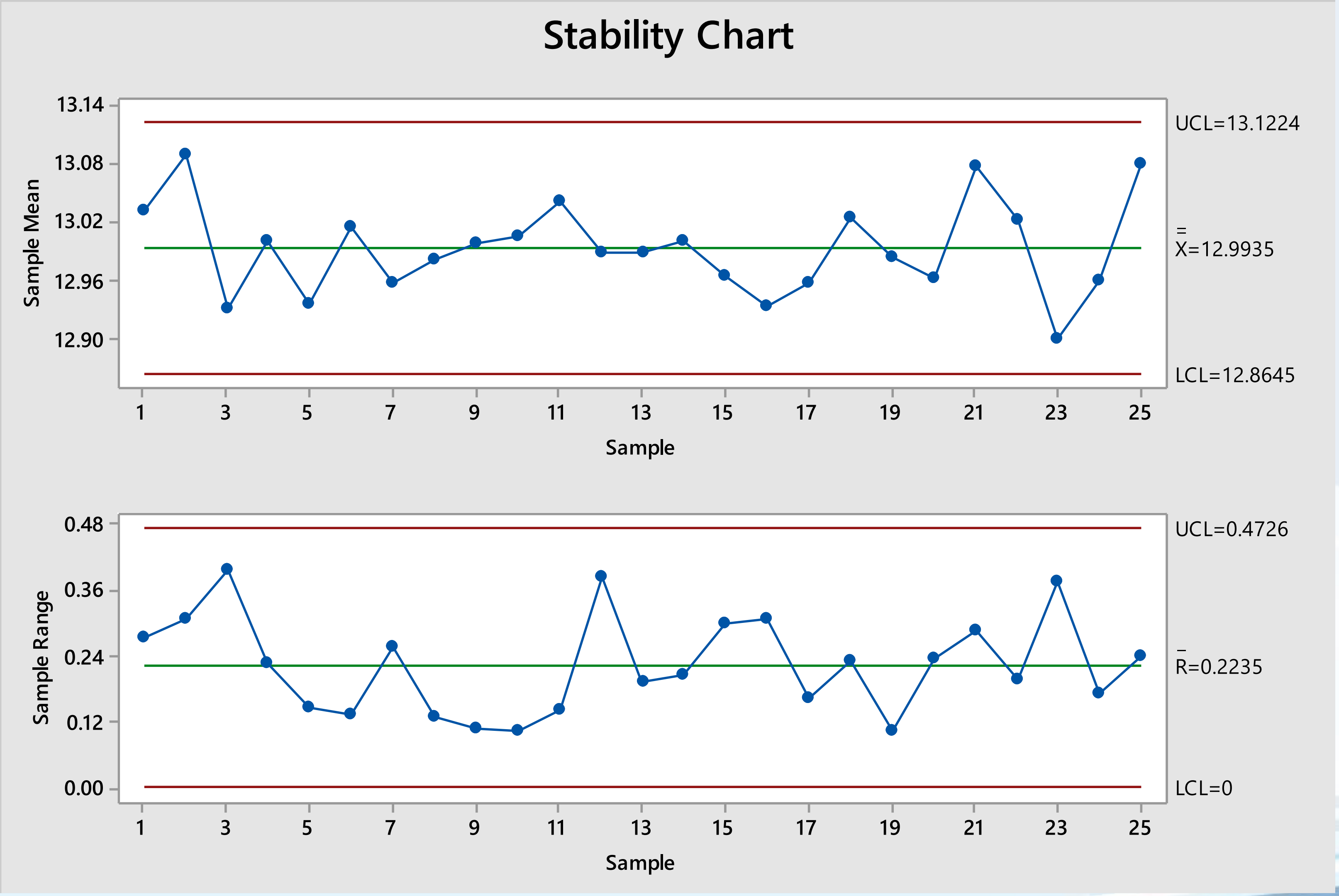
Gage Stability Study

3. Evaluate per normal SPC requirements.

   ***NOTE**: Maintain a chart for each part/master*

4. Evaluate the within-sample standard deviation (repeatability) of measurements to determine suitability for the application.

Analyzing Stability Charts



Analyzing Stability Charts

- If stability is not acceptable, the $\overline{X}$ and possibly S or R charts will show a shift or out-of-control condition.
  - Out-of-control chart conditions indicate measurement system not measuring consistently.
  - Check for:
    - Bias changed – determine cause of change and correct
    - If cause is wear – may be fixed by re-calibration

Breakout Exercise 3

Stability

Breakout Exercise 3: Stability

Use the data in Breakout Workbook, Breakout Exercise 3 or *@msa e class data* Excel file; tab: *stability – brk #3*

- Plot the average and range charts
- Analyze the stability

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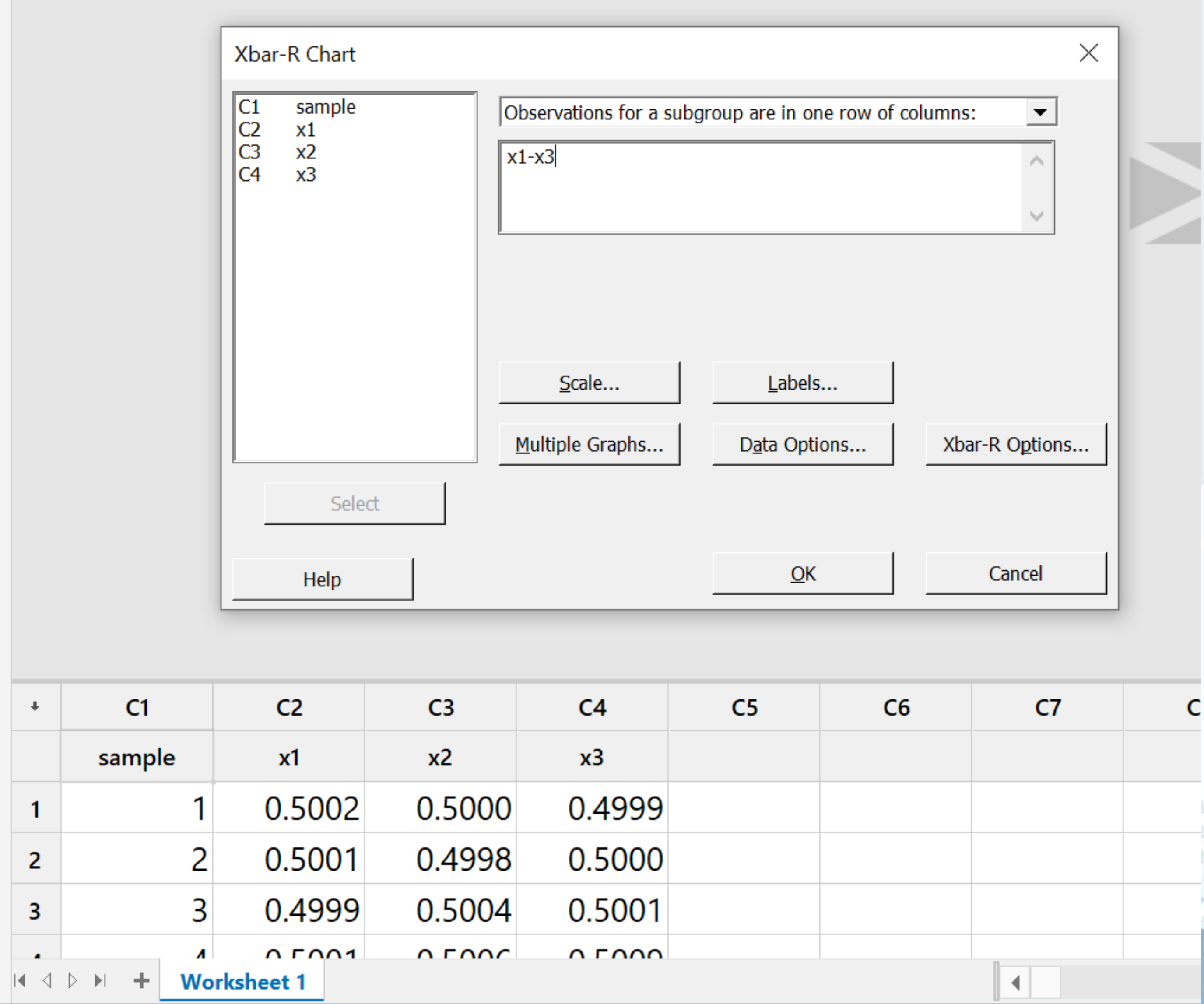
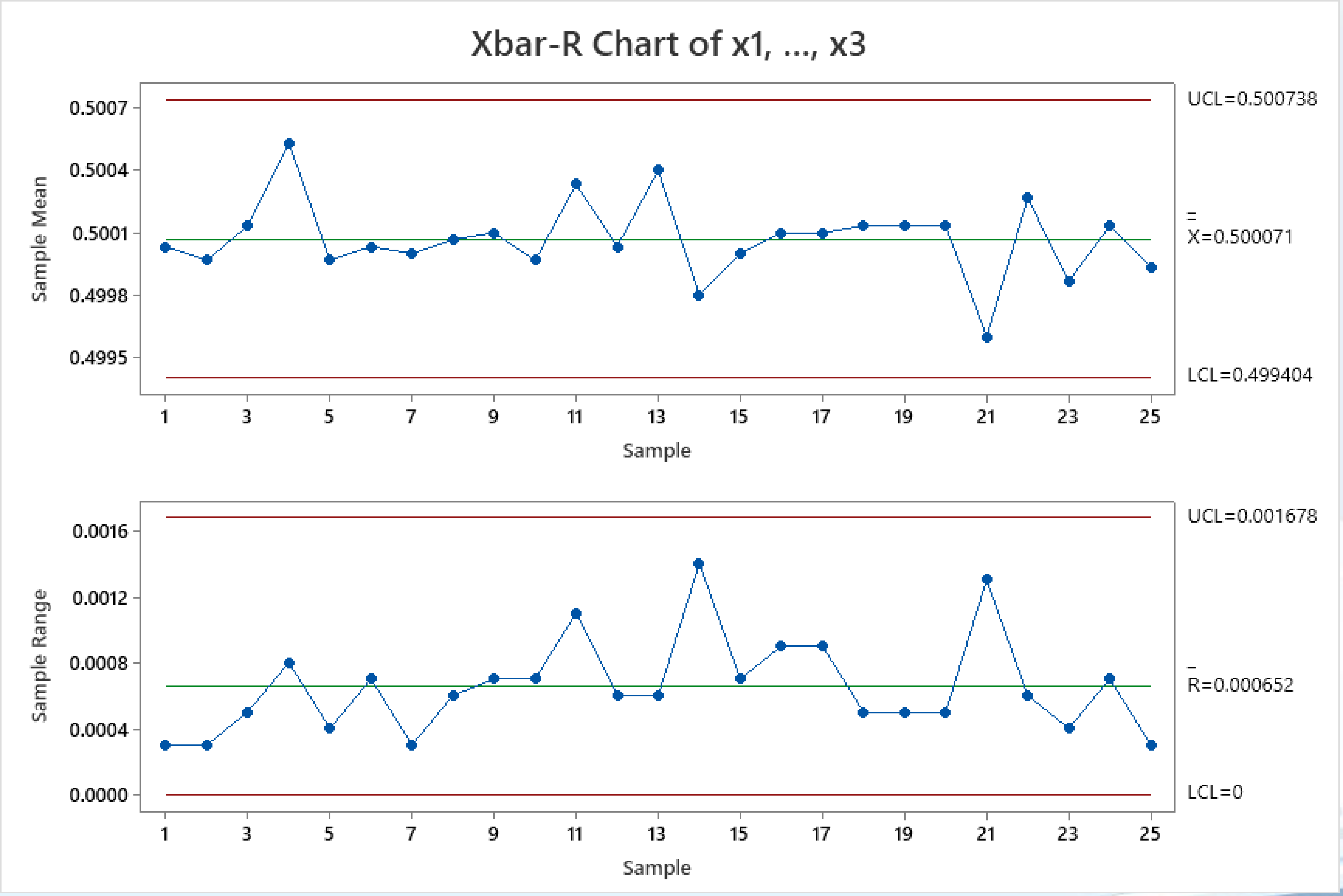
Breakout Exercise 3: Stability using Minitab

1. Copy columns A-D from ***@msa e class data*** **Excel file; tab:** ***stability – brk #3*** and paste into Minitab
2. Stat > Control Charts > Variable Charts for Subgroups > Xbar and R
3. Select Observations for a subgroup are in one row of columns
4. Select columns x1, x2, x3
5. Click OK

Breakout Exercise 3: Stability using Minitab





Xbar-R Chart of x1, ..., x3
Sample Mean
0.5007
0.5004
0.5001
0.4998
0.4995
UCL=0.500738
X=0.500071
LCL=0.499404
Sample
1
3
5
7
9
11
13
15
17
19
21
23
25
Sample Range
0.0016
0.0012
0.0008
0.0004
0.0000
UCL=0.001678
R=0.000652
LCL=0
Sample

Chapter 4: Bias, Linearity and Stability – What We Covered

Learning Objectives

You should now be able to:

- Describe and explain the statistical properties of Bias, Linearity and Stability in a measurement system
- Illustrate these properties. O*M*N*E*X*
- Determine the Bias, Linearity and Stability of a Measurement System

Chapter Agenda

- Define Reference Value
- Describe and Analyze a Measurement System's Bias
  - **Breakout Exercise #1**
- Describe and Analyze a Measurement System's Linearity
  - **Breakout Exercise #2**
- Describe and Analyze a Measurement System's Stability
  - **Breakout Exercise #3**

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Chapter 5

GRR Studies

Chapter 5: GRR Studies – What We Will Cover

Learning Objectives

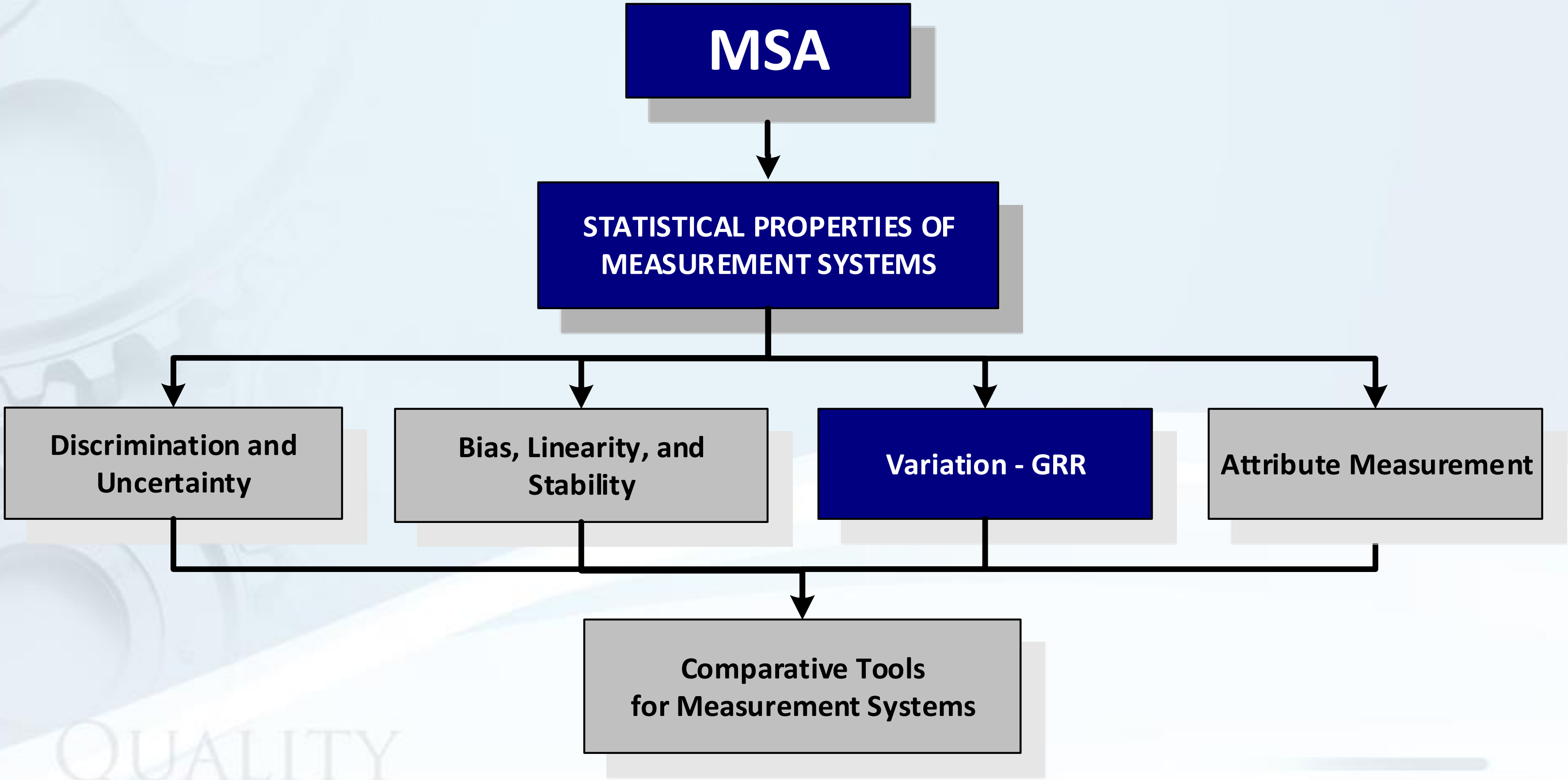
At the end of this chapter, you will be able to:

- Describe and explain the statistical properties of Repeatability and Reproducibility in a measurement system
- Illustrate these properties
- Determine the GRR of a Measurement System

Chapter Agenda

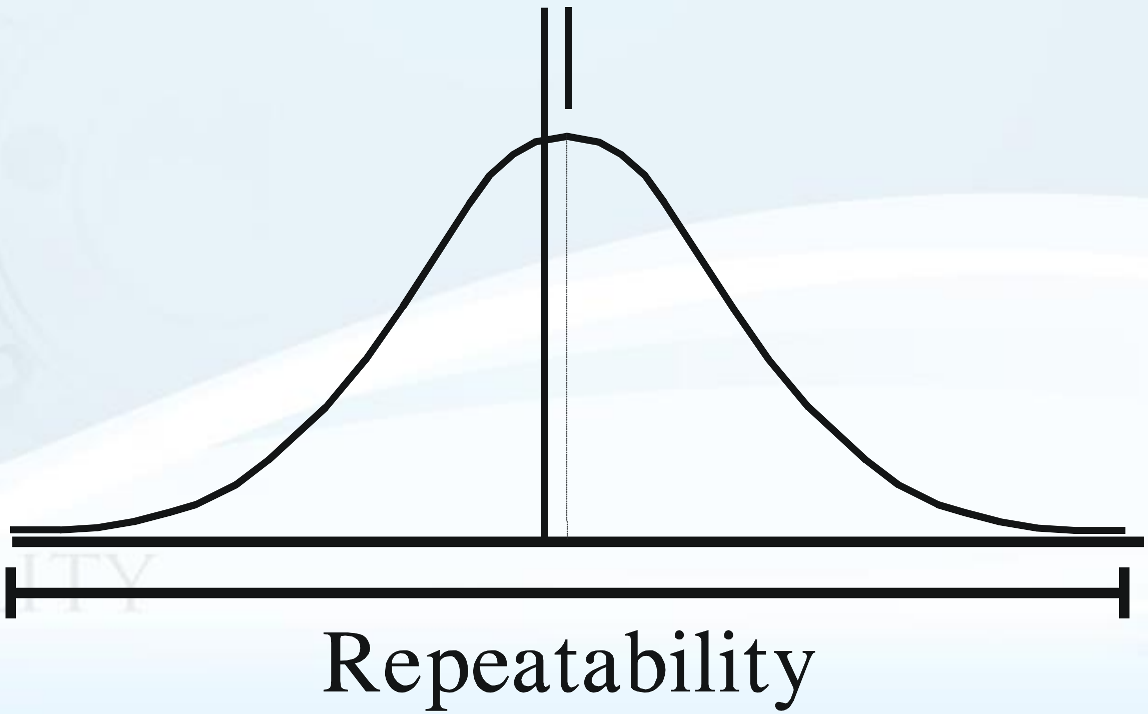
- Define GRR
- Describe and Analyze a Measurement System's GRR (Repeatability and Reproducibility)
  - **Breakout Exercise #4**
- Describe Acceptance Guidelines for GRR and ndc
  - **Breakout Exercise #5**

Application of MSA



Repeatability

- Variation in measurements obtained with **one measurement instrument** when used several times by **one appraiser** while measuring the same characteristic on the **same part.**



Repeatability

- The inherent variability of the measurement system
- Estimated by the pooled standard deviation of the distribution of repeated measurements

$$\sigma_r = \frac{\bar{R}}{d_2^*} \qquad \sigma_r = \sqrt{\frac{\sum_{i=1}^{n}(X_i - \bar{X})^2}{n-1}}$$

- Repeatability is less than the total variation of the measurement system

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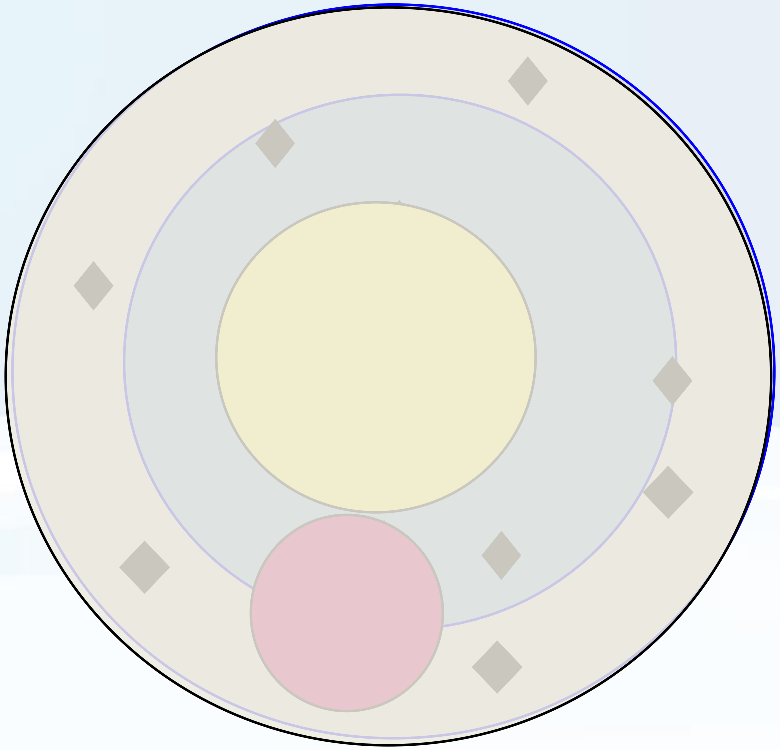
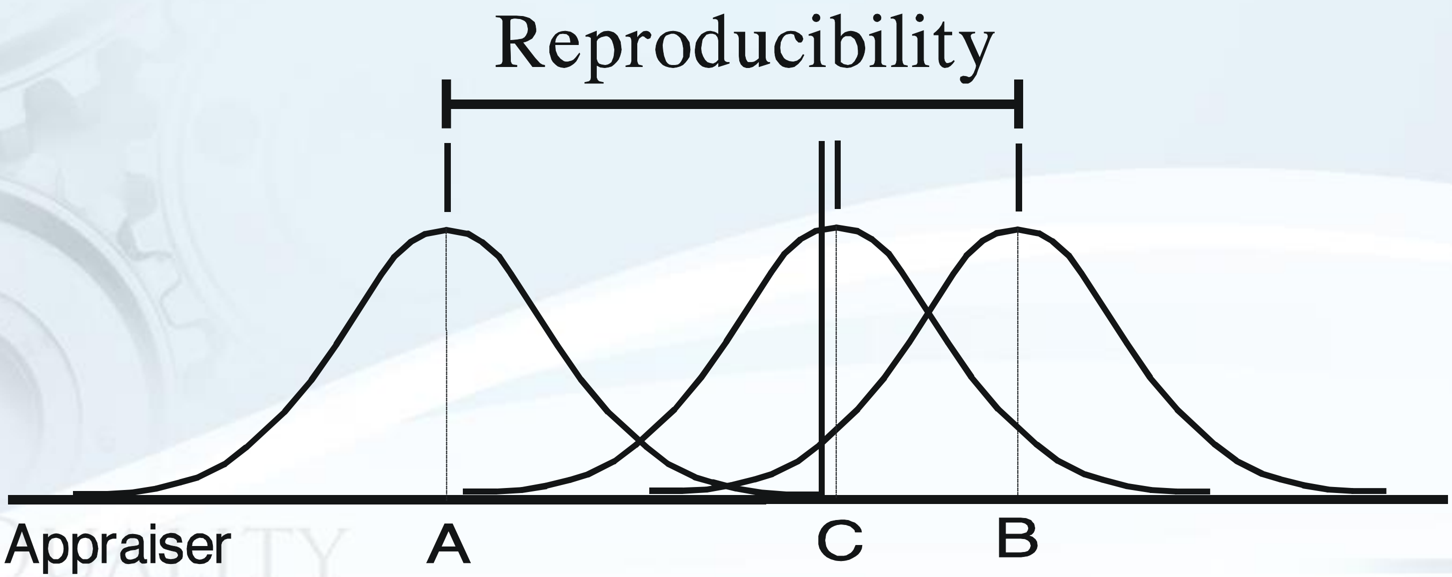
Repeatability Example

- ★ Contestant A
- ✸ Contestant B
- ◆ Contestant C
- ☆ Average for Contestant A
- ✺ Average for Contestant B
- ◇ Average for Contestant C



Reproducibility

- Variation in average of measurements made by different appraisers using same measuring instrument when measuring the same characteristic on the same parts.

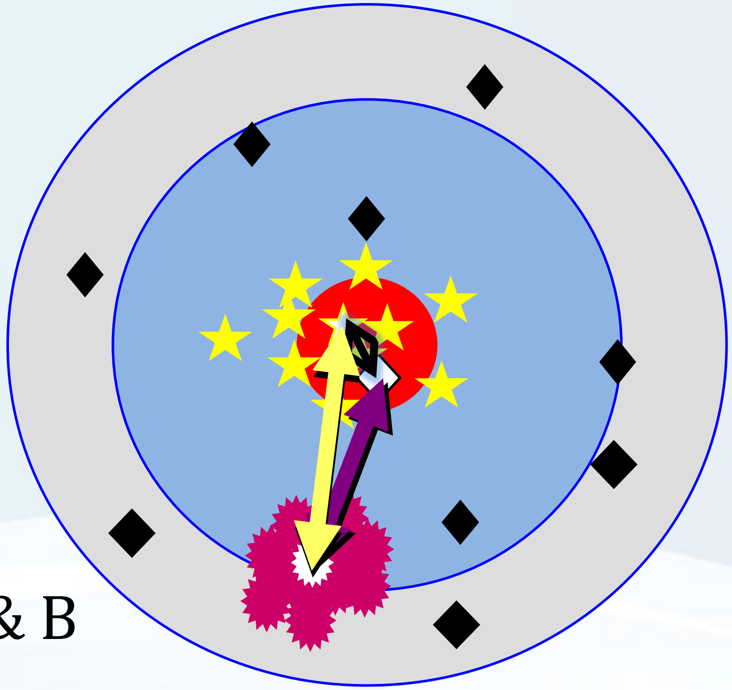


Reproducibility

- Appraiser variability of the measurement system
- Must be adjusted for repeatability
- Reproducibility is less than the total variation of the measurement system

Reproducibility Example

- ☆ Contestant A
- ✸ Contestant B
- ◆ Contestant C
- ☆ Average for Contestant A
- ✸ Average for Contestant B
- ◇ Average for Contestant C
- ☆ to ✸ Reproducibility between A & B
- ☆ to ◇ Reproducibility between A & C
- ✸ to ◇ Reproducibility between B & C



Preparation for a Measurement (GRR) Study

- Determine if reproducibility is an issue. If it is, select the number of appraisers to participate.
- Appraisers selected should normally use the measurement system.
- Select samples that represent the entire operating range.
- Gage must have graduations that allow at least one-tenth of the expected process variation.
- Ensure defined gaging procedures are followed.
- Measurements should be made in random order.
- Study must be observed by someone who recognizes the importance of conducting a reliable study.

GRR Study

GRR Study Instructions

1. Select two or three appraisers who are users of the measurement system.

2. Obtain a sample of *n* (10 or more) parts that represent actual or expected range of process variation.

3. Number parts 1 through *n* so that numbers are not visible to appraisers.

4. Follow the normal setup and gaging procedures.

GRR Study

5. Measure the *n* parts in random order by appraiser A, with an observer recording results.

6. Repeat step 5 with other appraisers – do not share the other appraisers' readings.

7. Repeat step 5 and 6 using a different random order of measurement for readings 2 and 3 for all appraisers.

8. Using the Average and Range approach, enter the data onto the form and follow the form instructions.
   – Calculate the average and ranges for all readings for each appraiser.

9. Plot the average and range charts and analyze for stability.

Breakout Exercise 4a

GR&R Study

Breakout Exercise 4a: GR&R Study

- Assign following roles within your team
  - Scribe (runs the program; enters the data)
  - Appraisers: 3 (collect the data)
  - Study administrator (runs the study)
- Collect the data for the GRR study using one of the forms or directly into the computer

– OR –

- Share the data collected as pre-work
- Enter the data into Minitab

Breakout Exercise 4a: GR&R Study using Minitab

Using Minitab to create data collection forms:

1. Stat > Quality Tools > Gage Study > Create Gage R&R Study Worksheet
2. Select responses to fit the study to be conducted; e.g., 3 operators, 10 parts, 3 replicates (i.e., a 3x10x3 study)
3. Click OK
4. Use the form to collect the data (randomized)

Breakout Exercise 4a: GR&R Study using Minitab

Minitab

1. Copy columns R-T from ***@msa e class data*** **Excel file; tab:** ***GRR – brk #4*** and paste into Minitab
2. Stat > Quality Tools > Gage Study > Gage R&R study (crossed)
3. Enter appropriate response columns
4. Select option Xbar and R
5. Click OK

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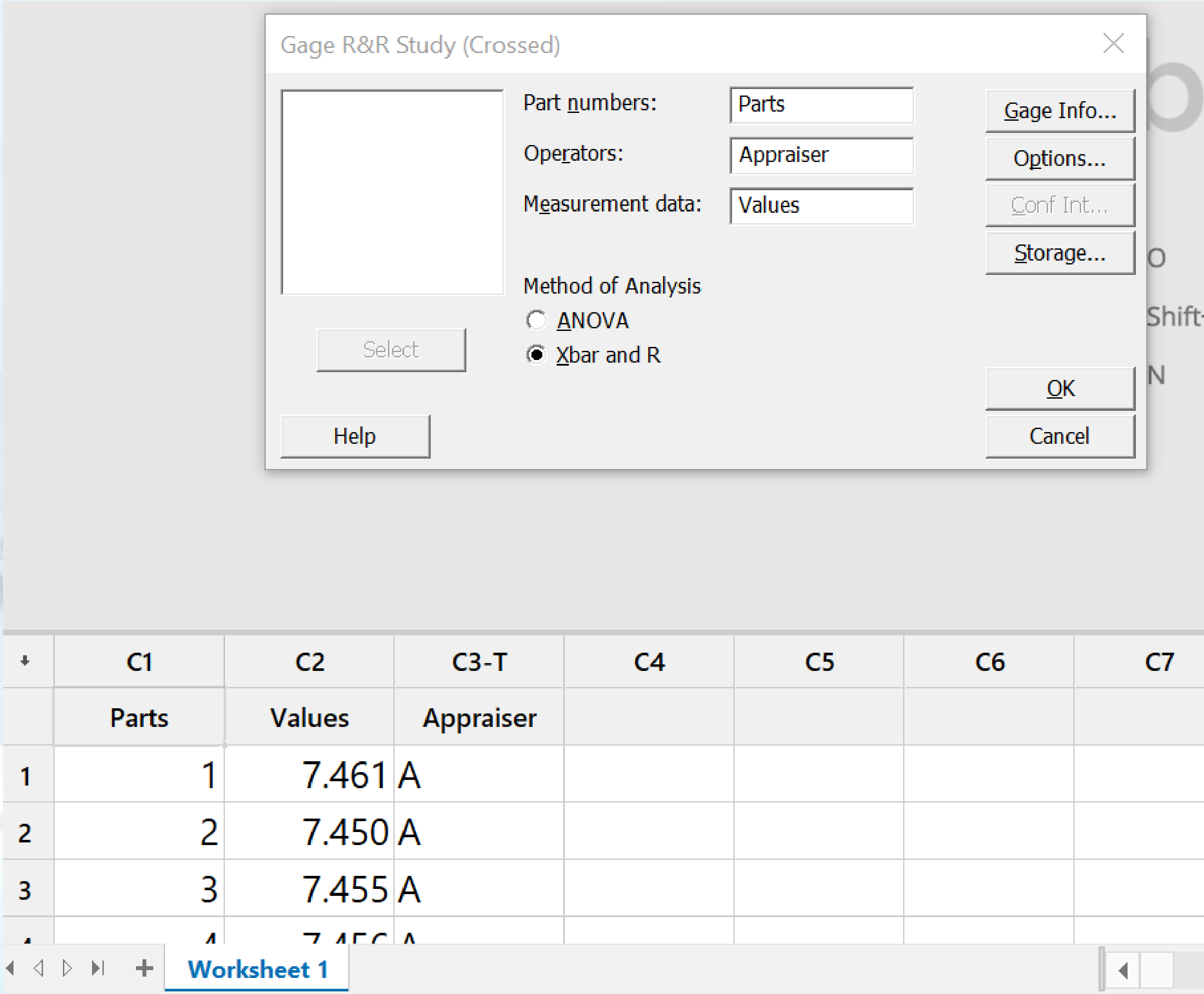
Example: Using Minitab to Analyze GR&R Data



Variance Components

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0.0000095	2.48
Repeatability	0.0000037	0.98
Reproducibility	0.0000058	1.51
Part-To-Part	0.0003722	97.52
Total Variation	0.0003817	100.00

Gage Evaluation

Source	StdDev (SD)	Study Var (6 × SD)	%Study Var (%SV)
Total Gage R&R	0.0030783	0.018470	15.76
Repeatability	0.0019300	0.011580	9.88
Reproducibility	0.0023981	0.014389	12.27
Part-To-Part	0.0192930	0.115758	98.75
Total Variation	0.0195370	0.117222	100.00

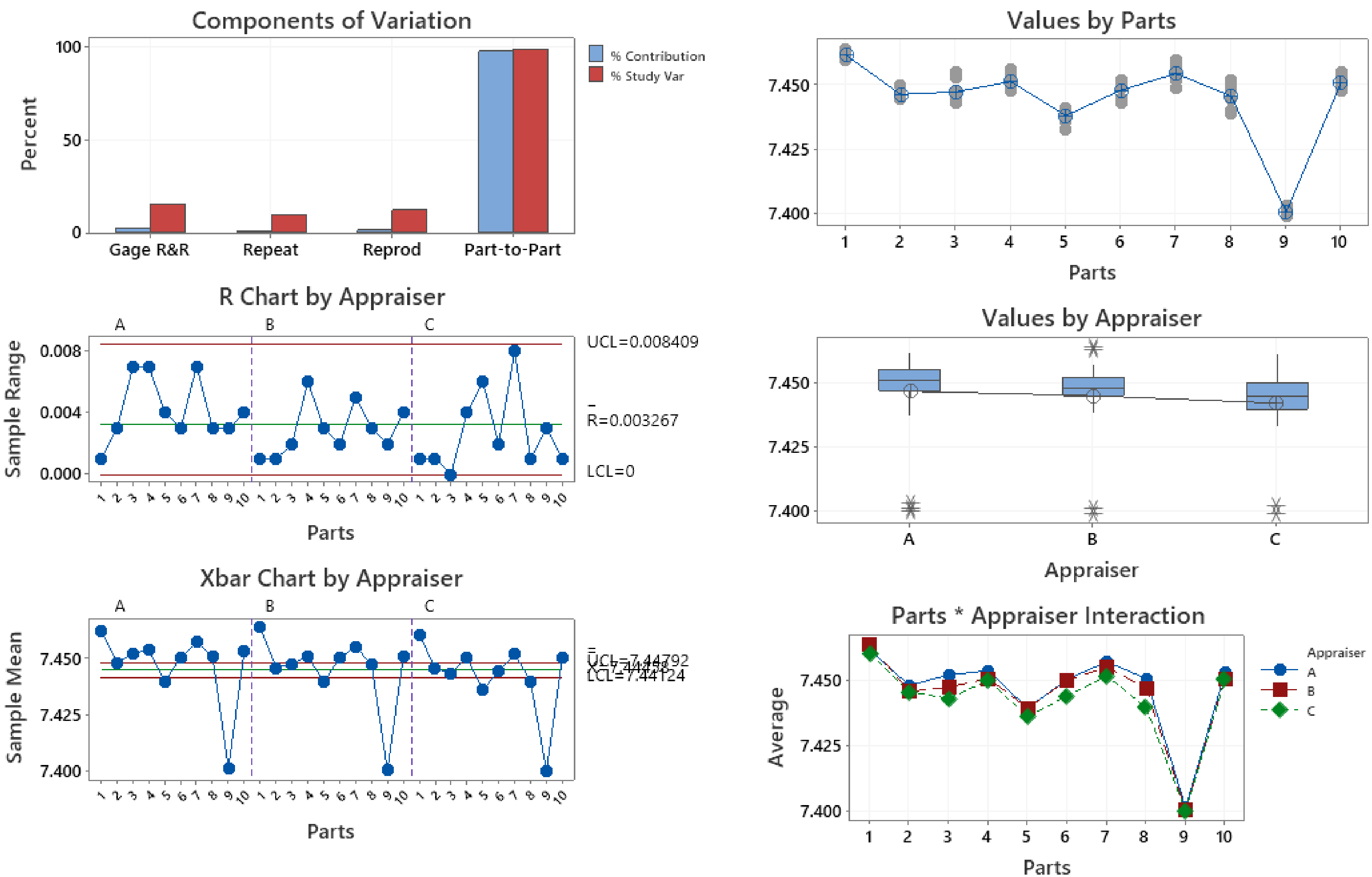
Number of Distinct Categories = 8

Gage R&R (Xbar/R) Report for Values

Minitab

Reported by:
Tolerance:
Misc:

Gage name:
Date of study:



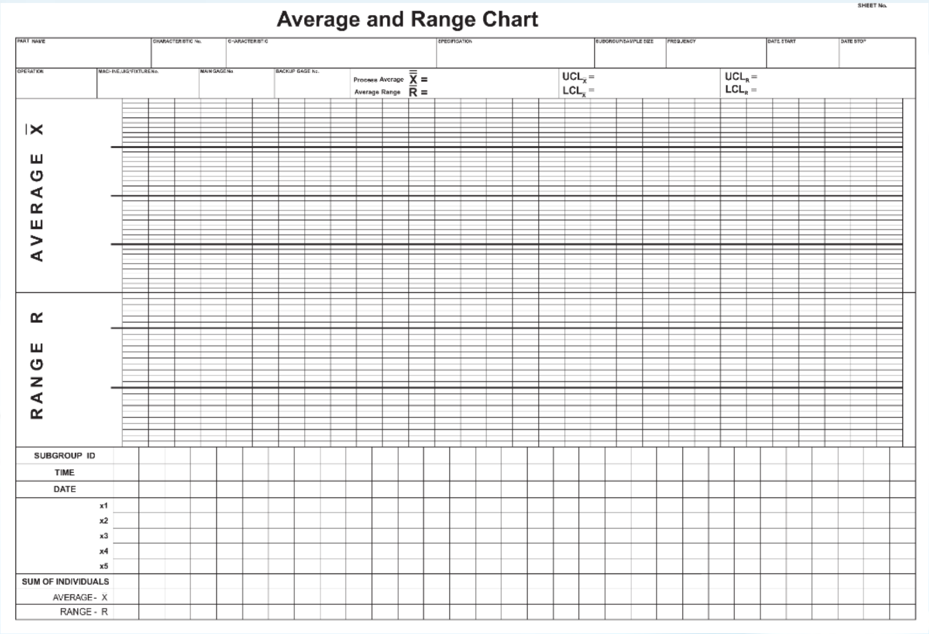
GR&R

Repeatability

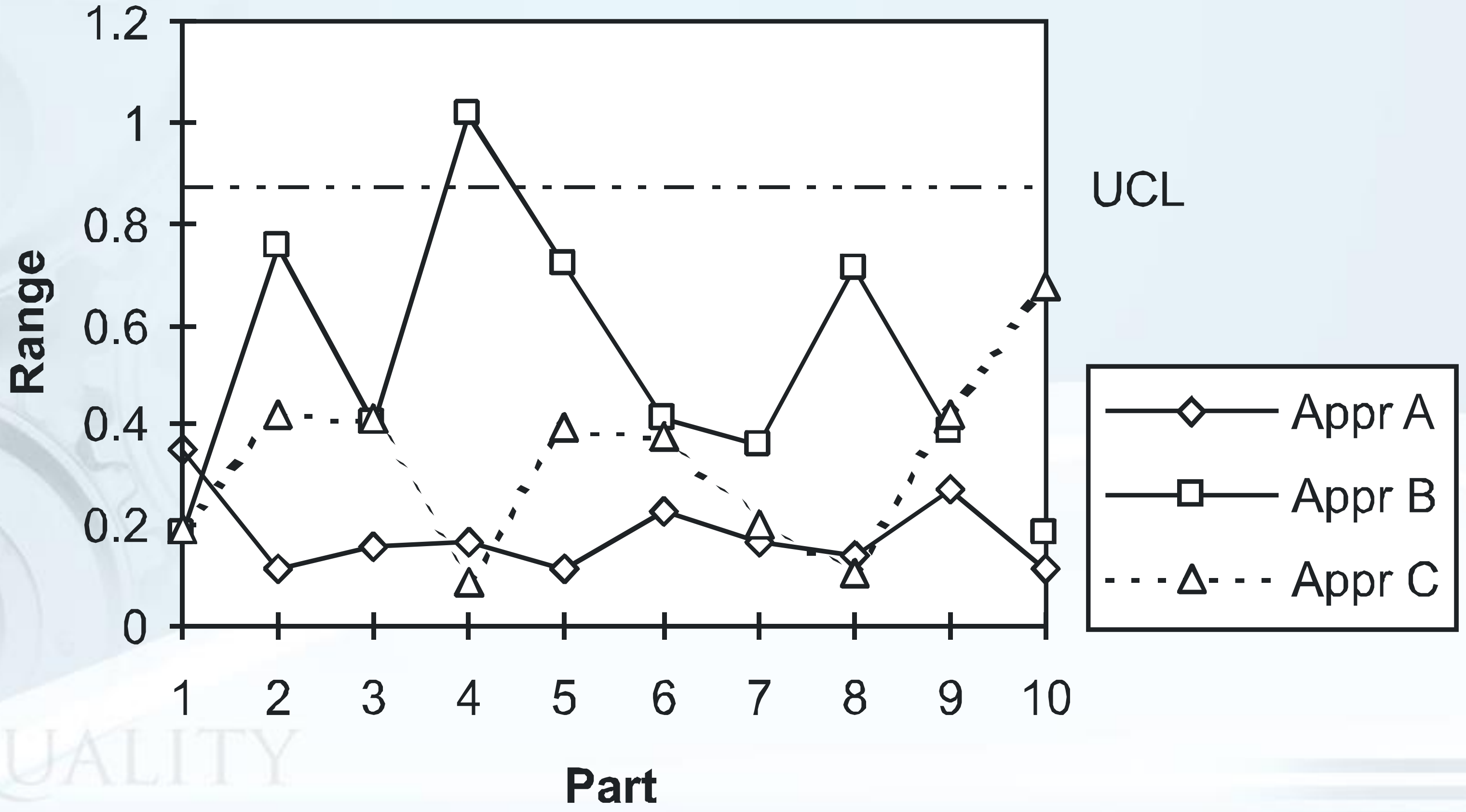
- Analyze by graphing on the *R* chart

Reproducibility

- Analyze by graphing on the average chart



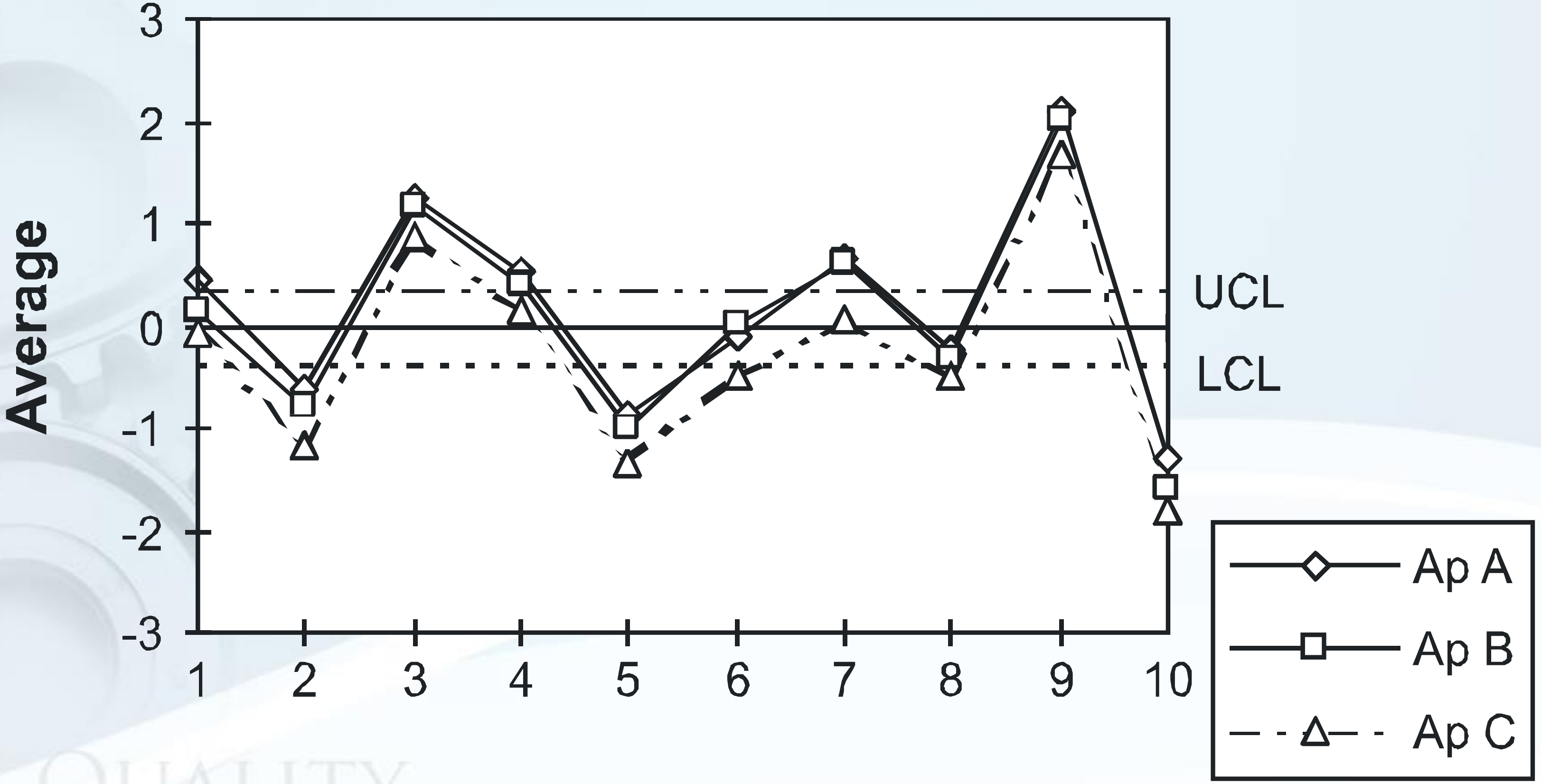
Range Chart Example



Range Chart Conclusion

- There appears to be differences among assessors:
  - A reading of one appraiser is outside the control limits; the conclusion is that the appraiser’s method differs from other appraisers.
  - In general, if all appraisers have some points outside control limit, then conclusion is that the measurement system is sensitive to appraiser technique and needs improvement to obtain useful data.

Average Chart Example



Average Chart Conclusion

- Used to determine:
  - Consistency between appraisers
  - Adequacy to detect part variation
  - Adequacy of resolution
  - Adequacy of sample
- In this study, 22 out of 30 points are outside the control limit.
  - Since this is more than half of the points, the conclusion is that the measurement system is adequate to detect part-to-part variations.

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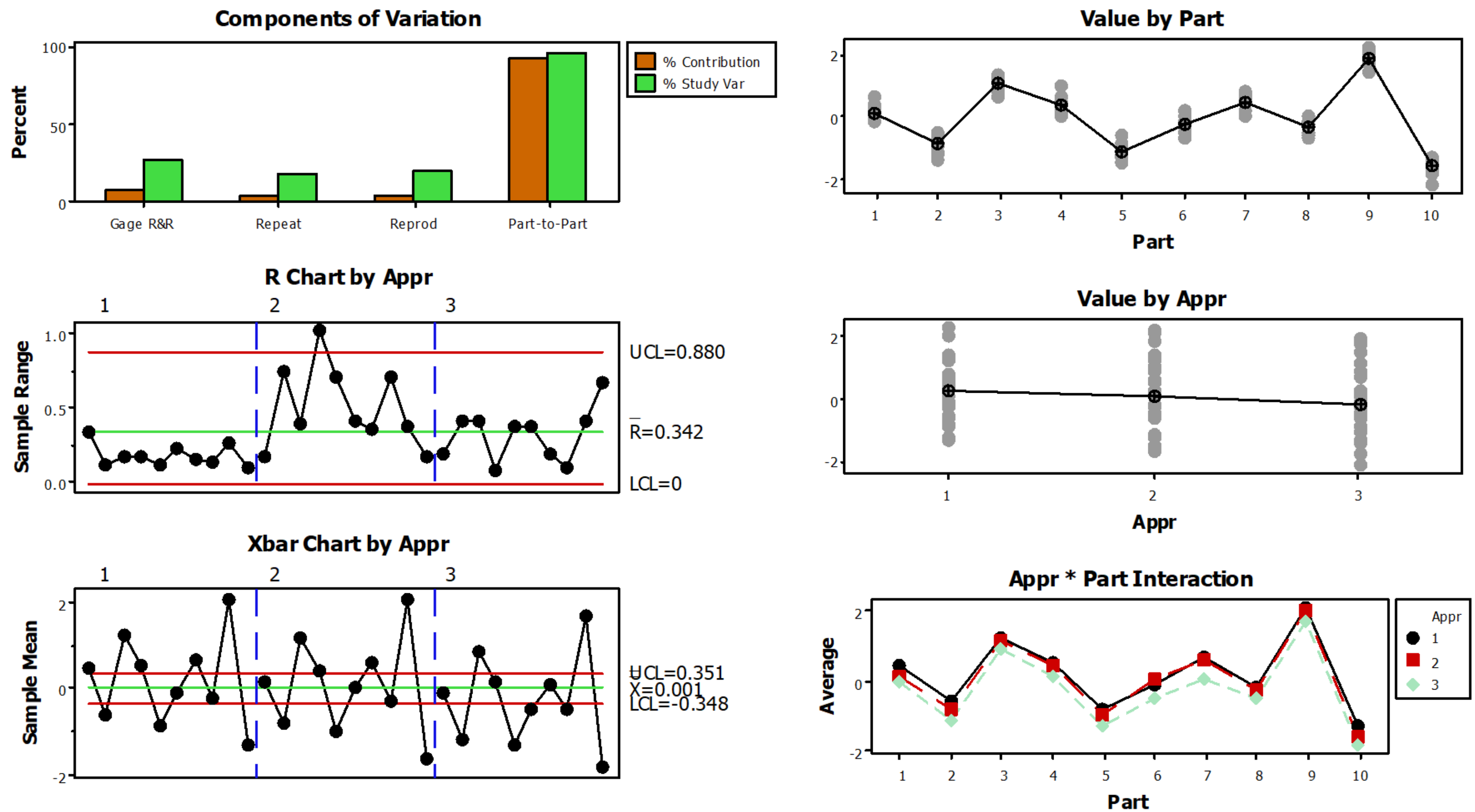
Gage R&R (Xbar/R) for Value

Gage name:
Date of study:

Reported by:
Tolerance:
Misc:



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Breakout Exercise 4b

Graphing GR&R

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Breakout Exercise 4b: GR&R Study

- Analyze the results based on the data you collected

  Using Minitab:

  1. Stat > Quality Tools > Gage Study >Gage R&R study (crossed)
  2. Enter appropriate response columns
  3. Select option Xbar and R
  4. Click OK

- Compare the graphic results with other teams
- What conclusions can you make at this point?
- Analyze and discuss the data and percentages

Breakout Exercise 4b: Graphing GR&R

- Calculate the average and range for each subgroup
- Calculate the overall part average and average range
- Plot on $\overline{X}$ & R chart
- Analyze

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Breakout Exercise 5a

Calculating GR&R

Breakout Exercise 5a: GRR Study

- Calculate the overall average and range, part range, and maximum difference between appraiser averages
- Calculate repeatability for equipment variation
- Calculate reproducibility for appraiser variation
- Calculate GRR
- Calculate part variation
- Calculate total variation
- Calculate the percent indices for above
- Calculate the NDC
- **Analyze the numerical results**

Breakout Exercise 5a: GRR Study

- Analyze the results based on the data you collected
    1. Stat > Quality Tools > Gage Study >Gage R&R study (crossed)
    2. Enter appropriate response columns
    3. Select option Xbar and R
    4. Click OK
- Compare numerical answers with other teams.
- What conclusions can you make at this point?
- Analyze and discuss the data and percentages.

Note: you have already executed this command: just go to the top of the session window to see the numerical results

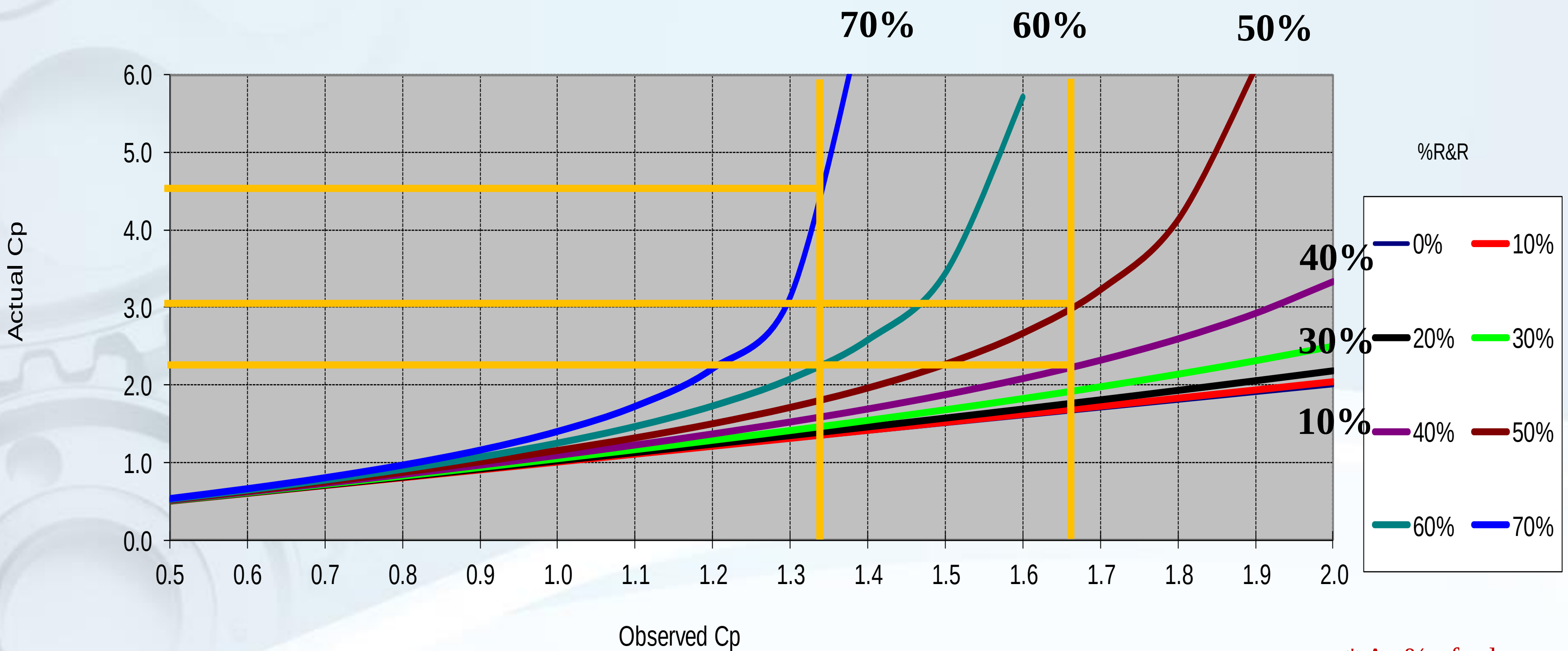
GRR Acceptance Guidelines

For Analysis and Control

%Tolerance % StudyVar	% Contribution	System
< 10%	< 1%	Ideal
10% - 20%	1% - 4%	Acceptable
20% - 30%	4% - 9%	Marginal
> 30%	> 10%	Unacceptable

Note: The sum of the percent Study Var or Tolerance by each factor will ***not*** equal 100%.

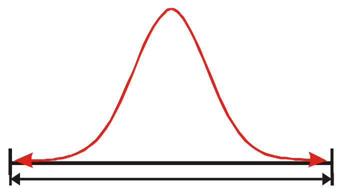
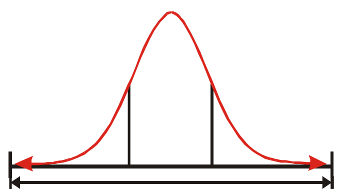
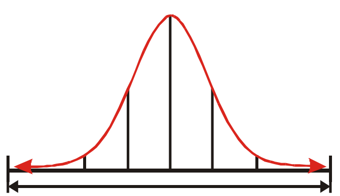
R&R Effect on Capability



* As % of tolerance

NDC

Impact of Number of Distinct Categories (*ndc*) of the Process Distribution on Control and Analysis Activities

Number of Categories	Control	Analysis
 1 Data Category	Can be used for control only if: • The process variation is small when compared to the specifications • The loss function is flat over the expected process variation • The main source of variation causes a mean shift	• Unacceptable for estimating process parameters and indices • Only indicates whether the process is producing conforming or nonconforming parts
 2 - 4 Data Categories	• Can be used with semi-variable control techniques based on the process distribution • Can produce insensitive variables control charts	• Generally unacceptable for estimating process parameters and indices since it only provides coarse estimates
 5 or more Data Categories	• Can be used with variables control charts	• Recommended

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Gage Error Compensation

If you want to decrease your measurement error take advantage of the standard error square root of the sample:

$$\sigma_{\bar{x}} = \frac{\sigma_x}{\sqrt{n}}$$

n = sample size

Example: A measurement error of 50% can be cut in *half* if you measure each part four 4 times and use the average as the part value.

THIS CAN BE USED AS A SHORT TERM APPROACH TO PERFORM A STUDY, BUT YOU MUST IMPROVE THE MEASUREMENT SYSTEM.

Application of GRR

- When repeatability is large compared to reproducibility:
  - Instrument needs maintenance
  - Equipment needs to be redesigned for more rigidity
  - Equipment needs to have improved clamping or location points
  - There may be excessive within-part variation

- When reproducibility is large compared to repeatability:
  - Appraisers need better gage use training
  - Appraisers need better operational definition
  - The incremental divisions on instrument are not readable
  - There is a need for a fixture to provide consistency in measurement system use

Chapter 5: GRR Studies – What We Covered

Learning Objectives

You should now be able to:

- Describe and explain the statistical properties of Repeatability and Reproducibility in a measurement system
- Illustrate these properties
- Determine the GRR of a Measurement System

Chapter Agenda

- Define GRR
- Describe and Analyze a Measurement System's GRR (Repeatability and Reproducibility)
  – **Breakout Exercise #4**
- Describe Acceptance Guidelines for GRR and ndc
  – **Breakout Exercise #5**

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Chapter 6

Advanced Analysis – Analysis of Variance (ANOVA)

Chapter 6: Advanced Analysis – Analysis of Variance (ANOVA) What We Will Cover

Learning Objectives

At the end of this chapter, you will be able to:

- Apply ANOVA to the analysis of the GRR of a Measurement System

Chapter Agenda

- What is ANOVA?
- Application of ANOVA to GRR Analysis
- Interpretation of Results

Analysis of Variance

- Analysis of variance (ANOVA) is a collection of statistical models and their associated estimation procedures used to analyze the differences among group means in a sample.
- The ANOVA is based on the law of total variance, where the observed variance in a particular variable is partitioned into components attributable to different sources of variation.
- In its simplest form, ANOVA provides a statistical test of whether two or more population means are equal, and therefore generalizes the t-test beyond two means.

$$X_{total} = \begin{cases} \bar{x} + \varepsilon \\ \bar{x} + \sum\limits_{Components} a_i + \varepsilon \end{cases}$$

$$\sigma^2_{total} = \sum_{Components} \sigma^2_{a_i} + \sigma^2_{error}$$

Advanced Analysis

Intent

- Provide an understanding of how to evaluate measurement systems variation using Analysis of Variance (ANOVA).

Scope

- ANOVA is a standard statistical technique and can be used to analyze the measurement error and other sources of variability of data in a measurement systems study.
  - The variance can be decomposed into four categories:
    - parts
    - appraisers
    - interaction between parts and appraisers
    - replication error due to the gage

Note: This approach does not evaluate location errors (bias, linearity, stability)

When To Use ANOVA

- Product cannot be used again, such as destructive tests
  - pull test
  - tensile strength test
  - chemical composition test
- Product changed by evaluation equipment
- There is interactions between the part and appraisers or other sources of variation

- ANOVA can quantify variation contributed by:
  - equipment
  - appraisers
  - parts measured
  - their interaction
  - other sources of variation

ANOVA Table

Two-Way ANOVA Table With Interaction

Source	DF	SS	MS	F	P
part No.	9	0.0019950	0.0002217	162.053	0.000
operator	2	0.0000006	0.0000003	0.212	0.811
part No. * operator	18	0.0000246	0.0000014	4.376	0.000
Repeatability	60	0.0000188	0.0000003		
Total	89	0.0020389			

α to remove interaction term = 0.05

* Significant at = 0.05 level

ANOVA Table

- The ANOVA table on the previous slide is composed of six columns:
  - **Source** column is the cause of variation.
  - **DF** column is the *degree of freedom* associated with the source.
    - *DF* = n – 1 = sample size -1
  - **SS** or **sum of squares** column is the deviation around the mean of the source.
  - **MS** or **mean square** column is the sum of squares divided by degrees of freedom.
  - **F-ratio** column, calculated to determine the statistical significance of the source value.
  - **P** column, the calculated probability of the **F-Ratio**. If this value is less than 0.05 then the source is considered to have a significant effect on the Total.

ANOVA Table with and w/o Interaction

Two-Way ANOVA Table With Interaction

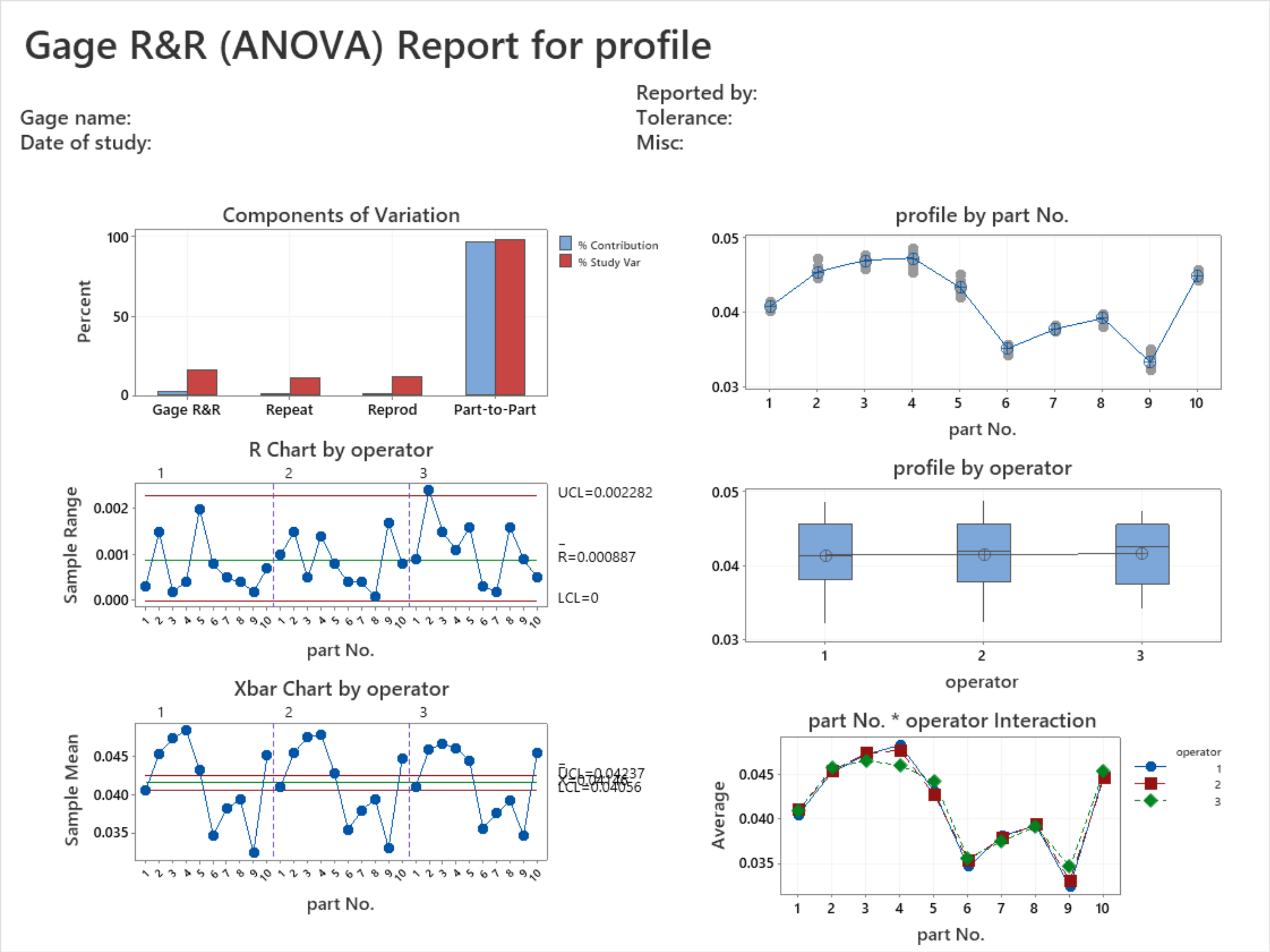
Source	DF	SS	MS	F	P
Parts	9	0.0000102	0.0000011	0.63825	0.751
Appraiser	2	0.0000015	0.0000007	0.41788	0.665
Parts * Appraiser	18	0.0000321	0.0000018	1.04793	0.424
Repeatability	60	0.0001020	0.0000017		
Total	89	0.0001458			

α to remove interaction term = 0.05

Two-Way ANOVA Table Without Interaction

Source	DF	SS	MS	F	P
Parts	9	0.0000102	0.0000011	0.661528	0.741
Appraiser	2	0.0000015	0.0000007	0.433118	0.650
Repeatability	78	0.0001341	0.0000017		
Total	89	0.0001458			

GR&R Study Analysis



6

1

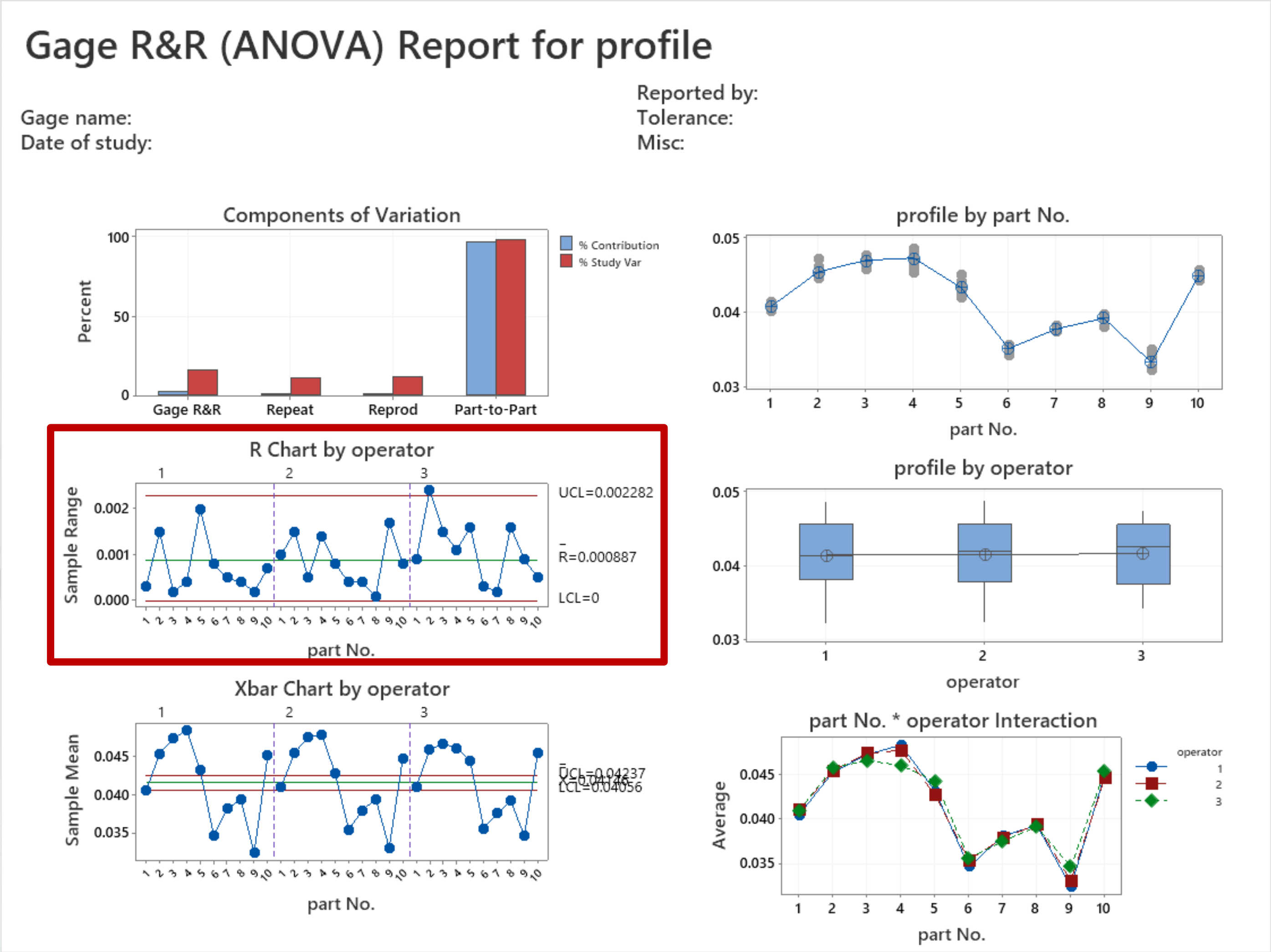
2

3

4

5

GR&R Study Analysis



1

2

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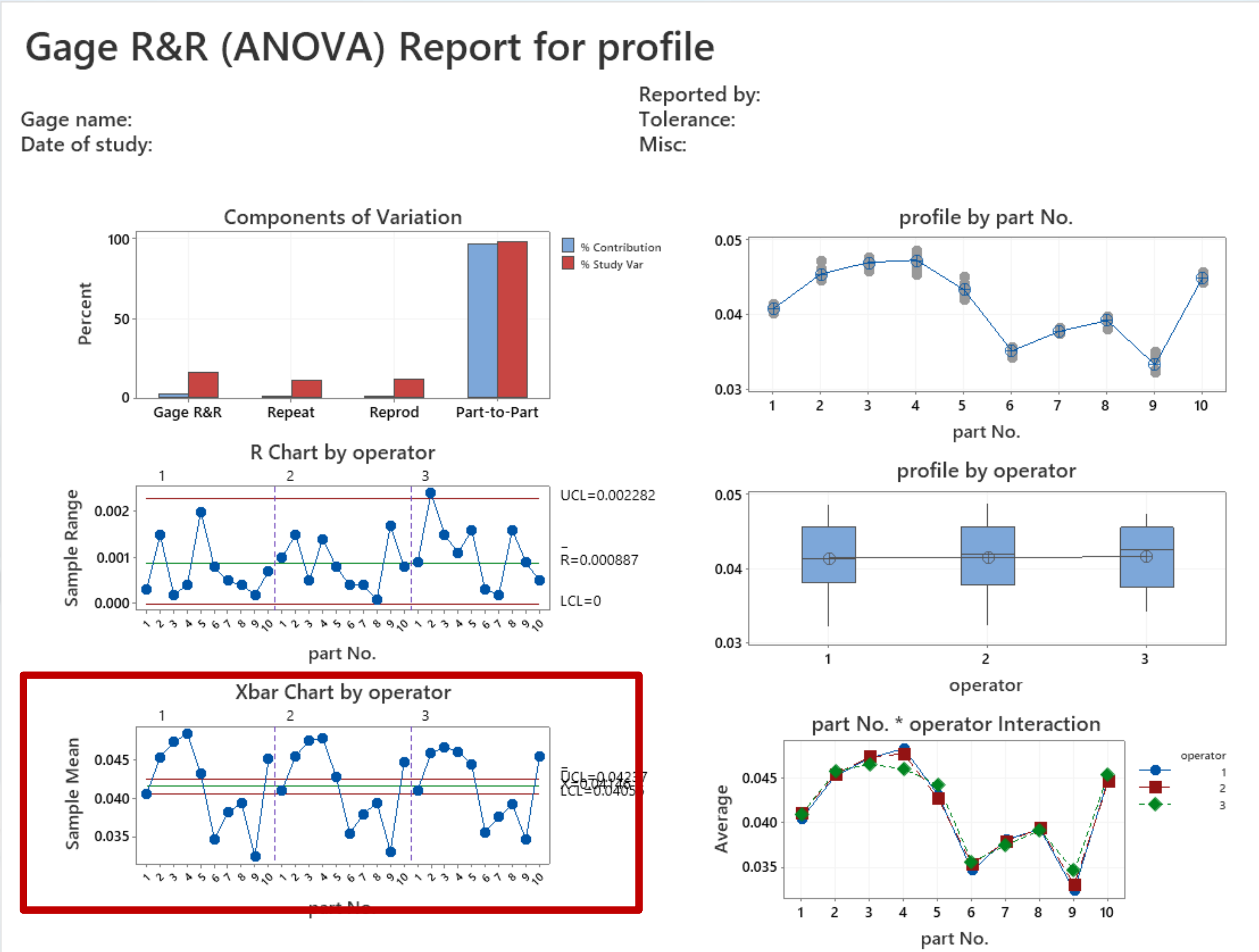
Interpretation of Chart

Range Chart:

- First look at the Range Chart for Stability – if any reading falls outside the UCL, they need to be eliminated and the procedure repeated. 1
  - In our example, the second reading is outside for the third appraiser.
- Also, it is important to assess discrimination from the range chart – at least five levels of possible values should come in the range chart including zero to show sufficient discrimination.
  - In our example, multiple values are shown; appears to be sufficient discrimination 2
- Also for discrimination, check:
  - Number of Distinct Categories ≥ 5 (in the session window)

GR&R Study Analysis



3

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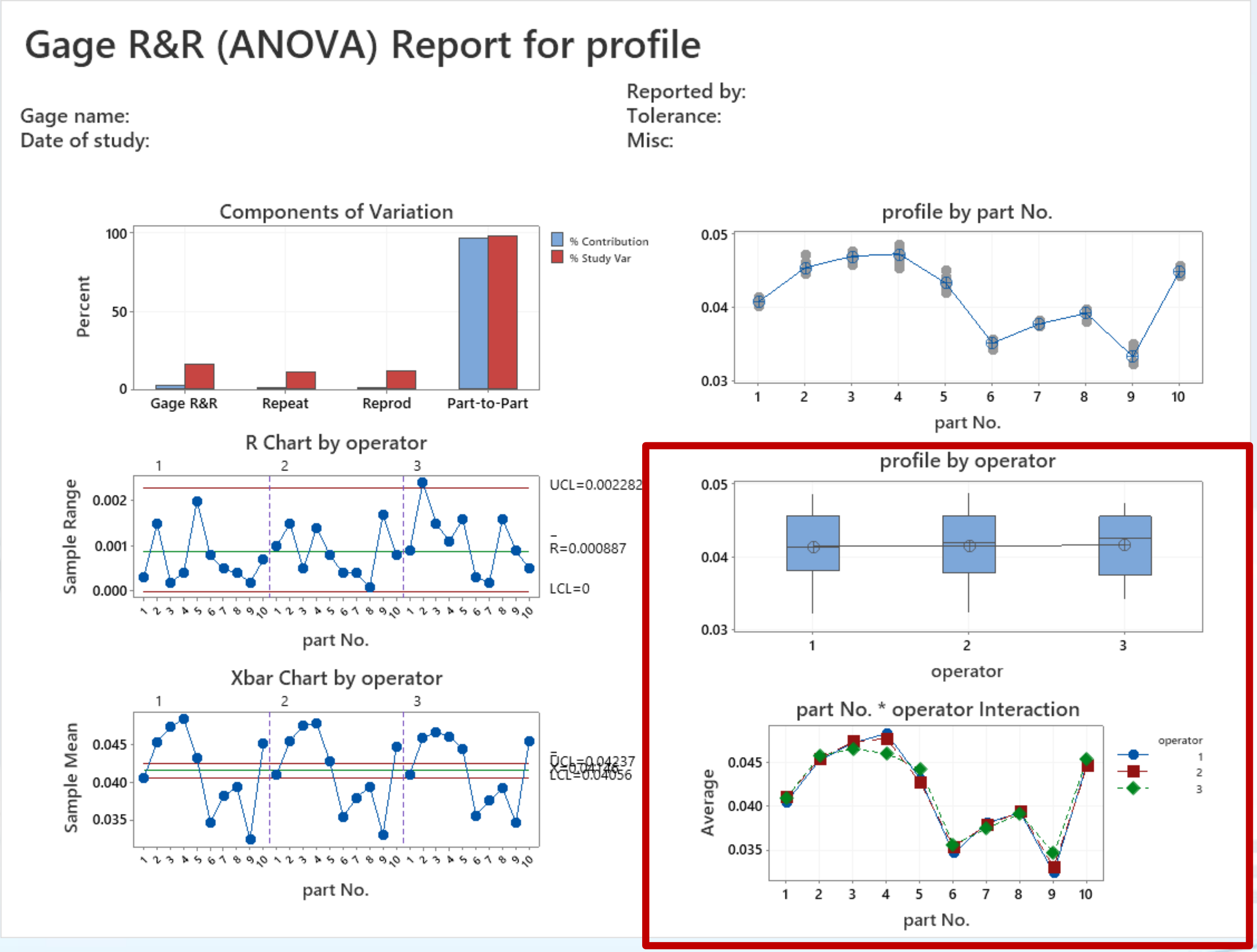
Interpretation of Chart

Xbar Chart:

- The distance between the UCL and the LCL indicate the extent of measurement error.
- Since we want the majority of the variation in measurement to be between part-to-part, it is ideal to have as many points as possible outside the control limits.
  - This indicates that the measurement variation is much smaller when compared to the part-to-part variation.

3

GR&R Study Analysis



4

5

Interpretation of Chart

By Operator Chart:

4

- Reproducibility is shown by the by operator chart.
- Since all operators measured the same parts, if there is no reproducibility error between operators, the results would be the same or the pattern would be the same with a constant bias.
  - If not, there are reproducibility issues.

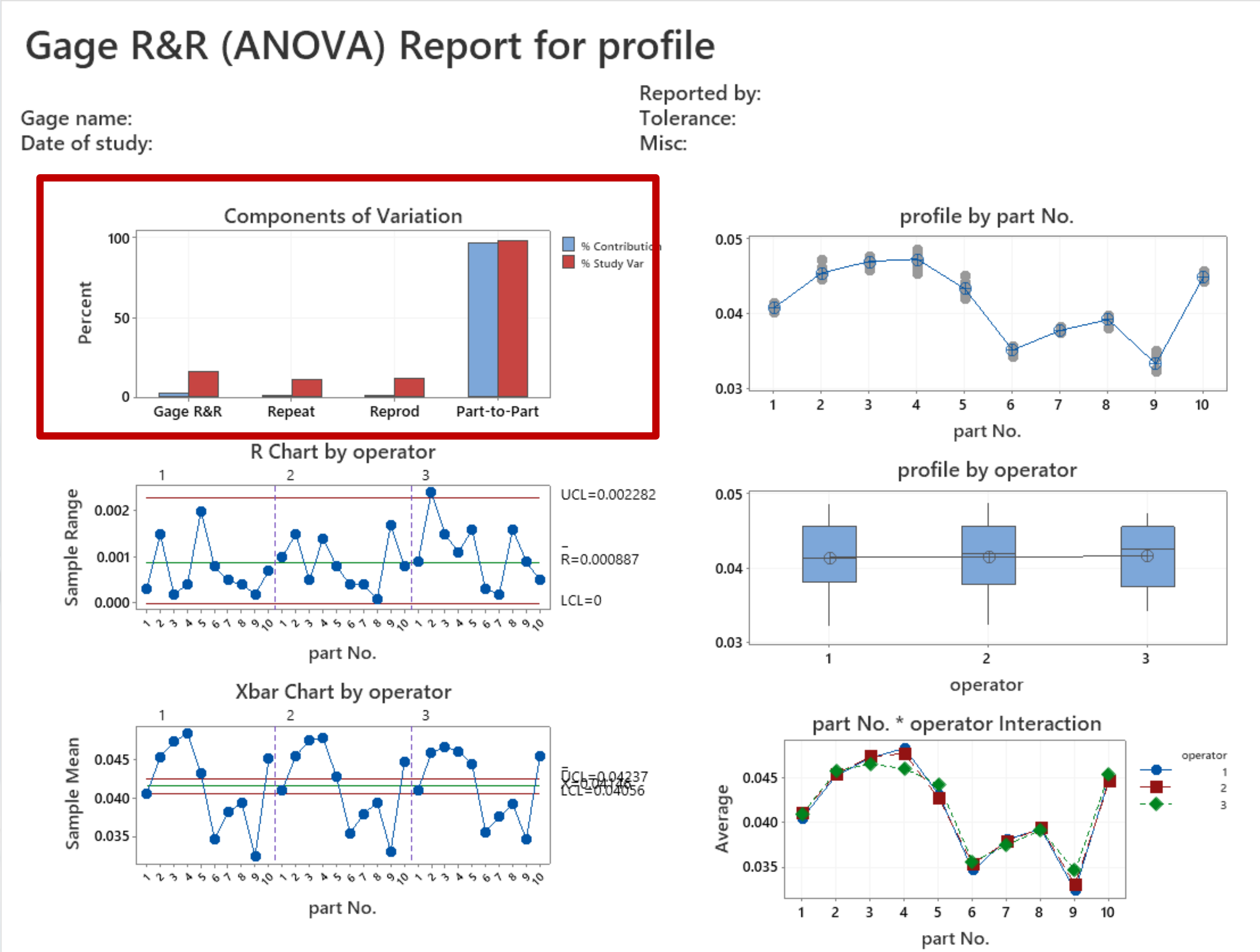
Operator Part Interaction Chart:

5

- Since the sampling plan is crossed, there is a potential for an interaction between operator and part.
- Ideally, all the lines in the operator part interaction chart should be parallel to each other.
  - If not, there is excessive interaction, meaning the measurement depends upon the nature of the part.

GR&R Study Analysis

6



Interpretation of Chart

6

Components of Variation Chart:

- This chart shows the proportion of repeatability and reproducibility as compared to the part-to-part variation.
- Majority of the variation should be in part-to-part with minor percentages in repeatability and reproducibility.
  - The Gage R&R histogram is the total of the repeatability and reproducibility.

Interpretation of Session Results

Variance Components

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0.0000007	2.64
Repeatability	0.0000003	1.24
Reproducibility	0.0000004	1.40
operator	0.0000000	0.00
operator*part No.	0.0000004	1.40
Part-To-Part	0.0000245	97.36
Total Variation	0.0000251	100.00

Interpretation of Session Results

Gage Evaluation

Source	StdDev (SD)	Study Var (6 × SD)	%Study Var (%SV)
Total Gage R&R	0.0008151	0.0048904	16.26
Repeatability	0.0005591	0.0033544	11.15
Reproducibility	0.0005931	0.0035586	11.83
operator	0.0000000	0.0000000	0.00
operator*part No.	0.0005931	0.0035586	11.83
Part-To-Part	0.0049475	0.0296848	98.67
Total Variation	0.0050141	0.0300849	100.00

% Contribution GRR

% Contribution Repeatability

% Contribution Reproducibility

% Contribution Part-to-part

Number of Distinct Categories = 8

Interpretation of Session Results

- Study Var is the variation under study – under the Study Var column, the actual variation in the units of measure is shown
  - Based on the sample used in the study
- The % Study Var is the same variation in terms of percentage
- % Tolerance:
  - This will be presented if the tolerance is provided
  - This column shows how much of the tolerance has been taken up due to the process and measurement variation
  - Typically, we are looking for over 90% of the tolerance to be "used up" in the part-to-part variation, with the Total GR&R % of tolerance not exceeding 10% for acceptable measuring systems

Interpretation of Session Results

- Looking at the numbers for *repeatability*, *reproducibility*, operator, and *operator * part no.* can tell us from where the majority of the variation is coming:
  - If the repeatability is high, the operators are not measuring consistently.
  - If the reproducibility is high, there are differences in the way each operator is measuring the parts.
  - The reproducibility error could be a combination of differences in the methods of each operator and the way they are measuring each part.

Breakout Exercise 5b

GR&R Study – ANOVA

Breakout Exercise 5b: GR&R Study – ANOVA

Use the data analyzed in Breakout 5

- Analyze your team's GR&R using the ANOVA approach
- Compare answers with the Xbar and R approach
- What conclusions can you make at this point?
- Analyze and discuss the data and percentages

Breakout Exercise 5b: GR&R Study – ANOVA Using Minitab

- Analyze the results based on the data you collected
  1. Stat > Quality Tools > Gage Study > Gage R&R study (crossed)
  2. Enter appropriate response columns
  3. Select option ANOVA
  4. Click OK
- Compare numerical answers with other teams
- What conclusions can you make at this point?
- Analyze and discuss the data and percentages

Chapter 6: Advanced Analysis – Analysis of Variance (ANOVA) What We Covered

Learning Objectives

You should now be able to:

- Apply ANOVA to the analysis of the GRR of a Measurement System

Chapter Agenda

- What is ANOVA?
- Application of ANOVA to GRR Analysis
- Interpretation of Results

Chapter 7

Automated and Non-Replicable Systems

Chapter 7: Automated and Non-Replicable Systems – What We Will Cover

Learning Objectives

At the end of this chapter, you will be able to:

- Analyze automated Measurement Systems
- Analyze non-replicable Measurement Systems

Chapter Agenda

- Analyzing Automated Measurement Systems
- Analyzing Non-Replicable Measurement Systems
  - **Non-Replicable Case Study**

Automatic Test Systems

- Address during APQP – highest importance:
  - Program measurement system identification
  - Determination of limits, ranges, targets, thresholds
  - Compensate for settling times, rise and fall times of equipment, mechanical and environmental phenomena
- Determine discrimination level needed and plan for Process Control
- Choose an appropriate set of nominal values for the process

Automatic Test Systems

- Identify expected variability for the Process Controls
- Use capability of the equipment to read out variable data or at least to store it for retrieval when needed
- Analyze for improvement in each variable and/or identified range

Automatic Test Systems

- Conduct Bias, Linearity and GR&R (GR) studies on the measurement/test system for that product with these limits.
  - If a single test stand is used then there will be no reproducibility evaluated.
  - If multiple test stands are used:
    - A full GR&R study can be used with the variability of the different stands being evaluated by reproducibility.
    - A correlation analysis among the stands can be used.

Automatic Test Systems

- Test Setup
  - Plan testing sequences carefully.
  - MSA cannot be done on test fixtures or load boards separately. It has to be done as part of the system.
  - Conduct studies considering *All* normal variables, *Where* the tests are done, By the personnel assigned to set up and run them.

Automatic Test Systems GR Study

GRR Study Instructions

1. ***Verify that appraisers have no effect on the results of the measurement system.***
2. Obtain a sample of *n* (10 or more) parts that represent actual or expected range of process variation.
3. Number parts 1 through *n*.
4. Follow the normal setup and gaging procedures.

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Automatic Test Systems GR Study

5. Measure the *n* parts in random order, with an observer recording results.

6. Using the ANOVA approach, enter the data into Minitab.

   Stat > Quality Tools > Gage Study > Gage R&R study (crossed)

Use the data in *@msa e class data* Excel file; tab: *Test Stand* columns A-C

* NOTE * There are no operator values, or they are all the same. The operator factor will be omitted from the analysis.

One-Way ANOVA Table

Source	DF	SS	MS	F	P
Parts	9	0.0077243	0.0008583	273.911	0.000
Repeatability	20	0.0000627	0.0000031		
Total	29	0.0077870			

α to remove interaction term = 0.05

Variance Components

Source	VarComp	%Contribution (of VarComp)
Total Gage R&R	0.0000031	1.09
Repeatability	0.0000031	1.09
Part-To-Part	0.0002850	98.91
Total Variation	0.0002882	100.00

Gage Evaluation

Source	StdDev (SD)	Study Var (6 × SD)	%Study Var (%SV)
Total Gage R&R	0.0017701	0.010621	10.43
Repeatability	0.0017701	0.010621	10.43
Part-To-Part	0.0168831	0.101299	99.45
Total Variation	0.0169757	0.101854	100.00

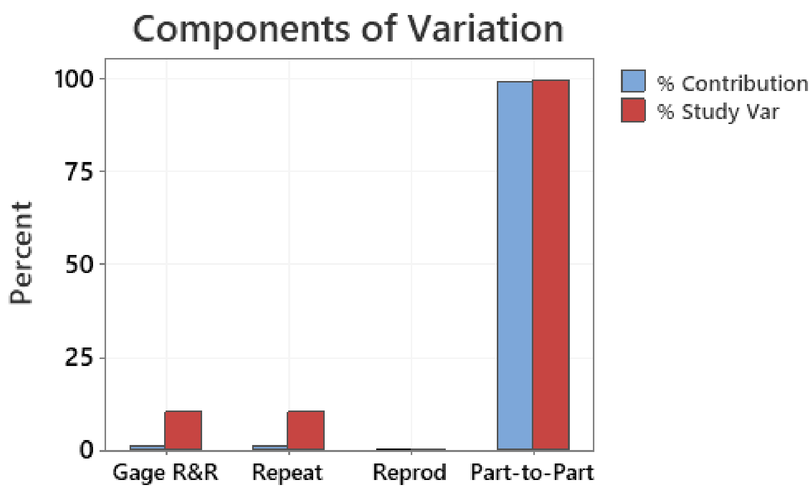
Number of Distinct Categories = 13

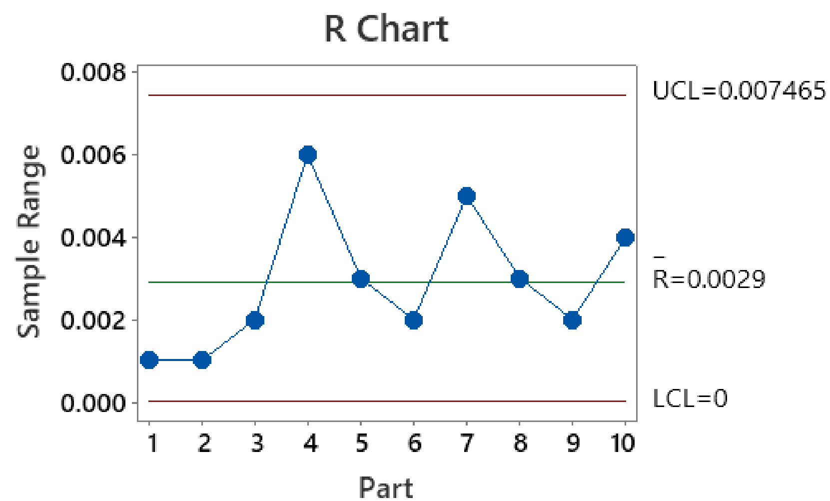
Note: there is no evaluation of reproducibility since there are no appraisers.

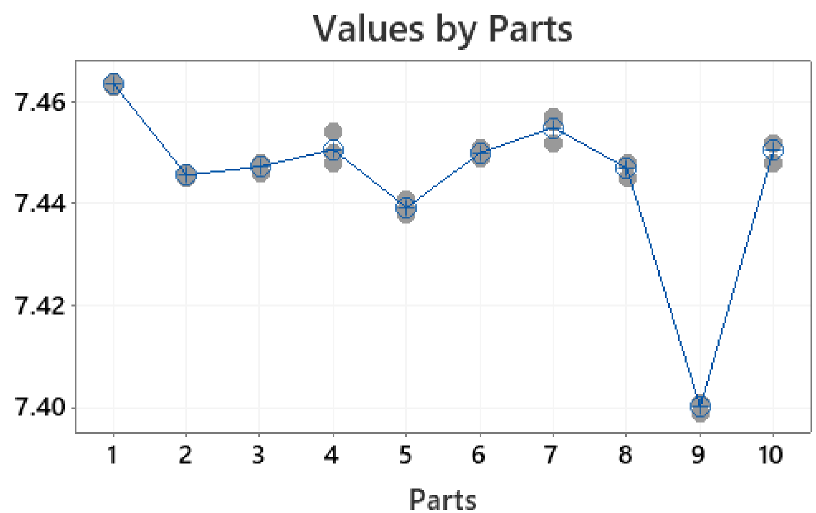
Gage R&R (ANOVA) Report for Values

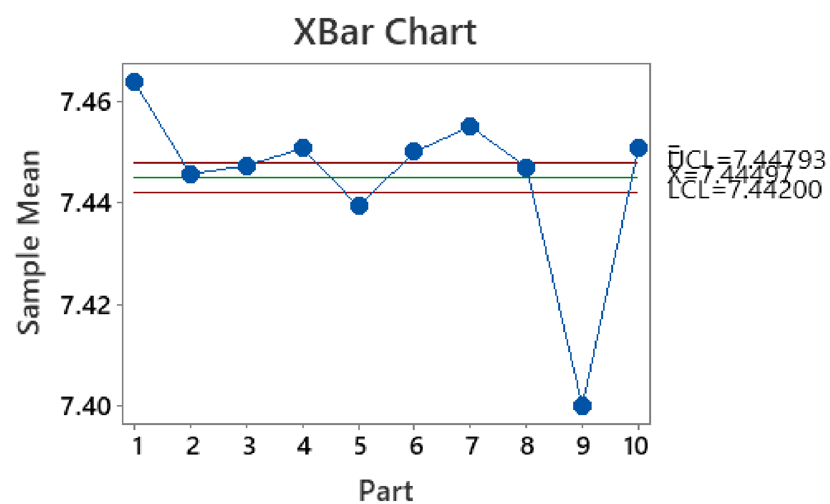
Gage name:
Date of study:

Reported by:
Tolerance:
Misc:









NON-REPLICABLE SYSTEMS

QUALITY

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Non-Replicable Analysis-Guidelines

- Tightly control all variables
- Use a large sample from a stable process
- Take samples from a homogeneous lot
- Use multiple lots to represent the parts
- The part is not expected to “age” during the study
- Each trial is conducted with a new sample
- Use standard GRR techniques
- ANOVA can be used to highlight variation from appraisers, materials, day-to-day, etc.

NON-REPLICABLE GRR CASE STUDY

“Non-Replicable”

- **Replication:** *“the action or process of reproducing; performance of an experiment or procedure more than once”*
- Not always Destructive!
- Another “R” – sorry!

Standardize Conditions

- Qualified appraisers
- Adequate lighting, environment
- Proper work instructions
- Equipment properly maintained
- Failure modes understood
- etc., etc., etc.

Assumptions/Prerequisites

- Only looking at Repeatability
- Need to use the ANOVA (nested) analysis

Samples

- homogeneous within (e.g., consecutive parts)
- heterogeneous between (e.g., from different lots; shifts, operators etc.)

Pre-research on Process

- stable
- nature of variation understood

A Thought

- If process is **Stable**
- And if process is **Capable**
- May be no need to do study
  - process variation includes measurement
  - this requires some process history/research

Standard GRR Layout

	Appraiser 1			Appraiser 2		
Part #	Trial 1	Trial 2	Trial 3	Trial 1	Trial 2	Trial 3
1	1	1	1	1	1	1
2	2	2	2	2	2	2
3	3	3	3	3	3	3
4	4	4	4	4	4	4
5	5	5	5	5	5	5
6	6	6	6	6	6	6
7	7	7	7	7	7	7
8	8	8	8	8	8	8
9	9	9	9	9	9	9
10	10	10	10	10	10	10

Each part measured 6 times

Standard GRR Layout – as applied

	Appraiser 1			Appraiser 2		
Part #	Trial 1	Trial 2	Trial 3	Trial 1	Trial 2	Trial 3
1	1-6	1-6	1-8	1-7	1-5	1-4
2	2-10	2-8	2-3	2-1	2-4	2-9
3	3-8	3-1	3-5	3-5	3-10	3-5
4	4-7	4-5	4-6	4-9	4-3	4-2
5	5-1	5-4	5-4	5-6	5-7	5-8
6	6-5	6-3	6-7	6-8	6-9	6-1
7	7-4	7-7	7-9	7-10	7-6	7-3
8	8-3	8-2	8-10	8-3	8-2	8-10
9	9-9	9-9	9-2	9-2	9-8	9-7
10	10-2	10-10	10-1	10-4	10-1	10-6

Data collection randomized within Trials

Non-Replicable GRR Layout – as applied

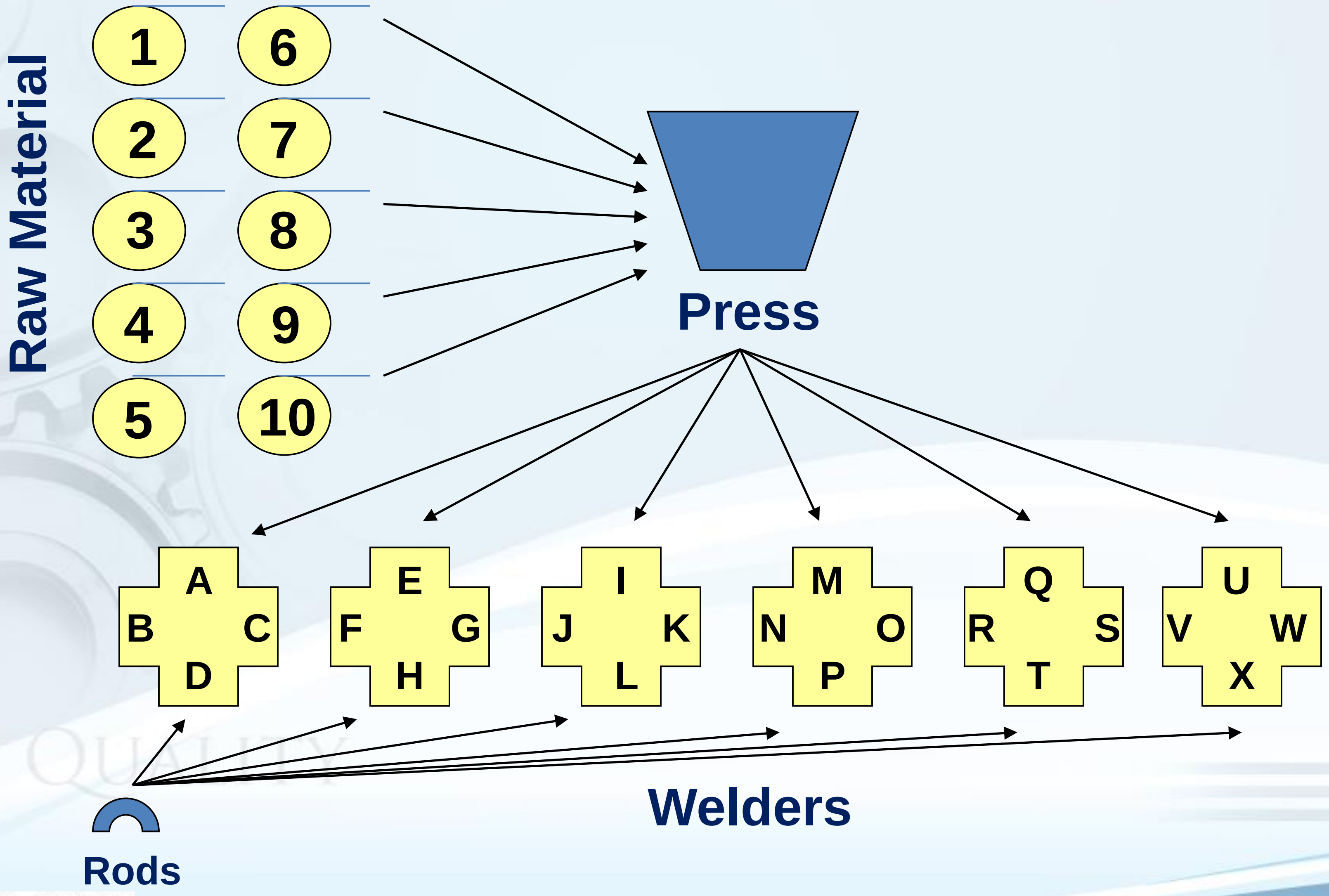
	Appraiser 1			Appraiser 2		
Part #	Trial 1	Trial 2	Trial 3	Trial 1	Trial 2	Trial 3
1-1A…1-6A	1-6A$_{53}$	1-5A$_{25}$	1-3A$_{7}$	1-4A$_{40}$	1-1A$_{34}$	1-2A$_{32}$
2-1B…2-6B	2-2B$_{27}$	2-6B$_{35}$	2-5B$_{57}$	2-4B$_{12}$	2-3B$_{43}$	2-1B$_{17}$
3-1C…3-6C	3-1C$_{21}$	3-2C$_{36}$	3-6C$_{1}$	3-5C$_{56}$	3-4C$_{10}$	3-3C$_{26}$
4-1D…4-6D	4-4D$_{46}$	4-6D$_{42}$	4-3D$_{8}$	4-2D$_{28}$	4-1D$_{55}$	4-5D$_{30}$
5-1E…5-6E	5-4E$_{5}$	5-3E$_{20}$	5-1E$_{13}$	5-6E$_{54}$	5-2E$_{39}$	5-5E$_{50}$
6-1F…6-6F	6-1F$_{52}$	6-3F$_{3}$	6-4F$_{37}$	6-5F$_{29}$	6-2F$_{51}$	6-6F$_{45}$
7-1G…7-6G	7-6G$_{16}$	7-4G$_{11}$	7-1G$_{23}$	7-2G$_{6}$	7-3G$_{15}$	7-5G$_{14}$
8-1H…8-6H	8-6H$_{49}$	8-3H$_{60}$	8-1H$_{33}$	8-5H$_{41}$	8-2H$_{44}$	8-4H$_{19}$
9-1J…9-6J	9-5J$_{31}$	9-6J$_{59}$	9-3J$_{24}$	9-2J$_{4}$	9-4J$_{9}$	9-1J$_{2}$
10-1K…10-6K	10-2K$_{22}$	10-5K$_{18}$	10-3K$_{47}$	10-4K$_{58}$	10-1K$_{48}$	10-6K$_{38}$

Six homogeneous parts represent a “single” part
Randomized within and between Trials

Non-Replicable MSA Study Example

- We want to evaluate a measurement system that measure the pull apart force on a welded part.
- The process has 24 individual welders at 6 stations.
- Components are provided to the welders randomly from a press and from an outside supplier.

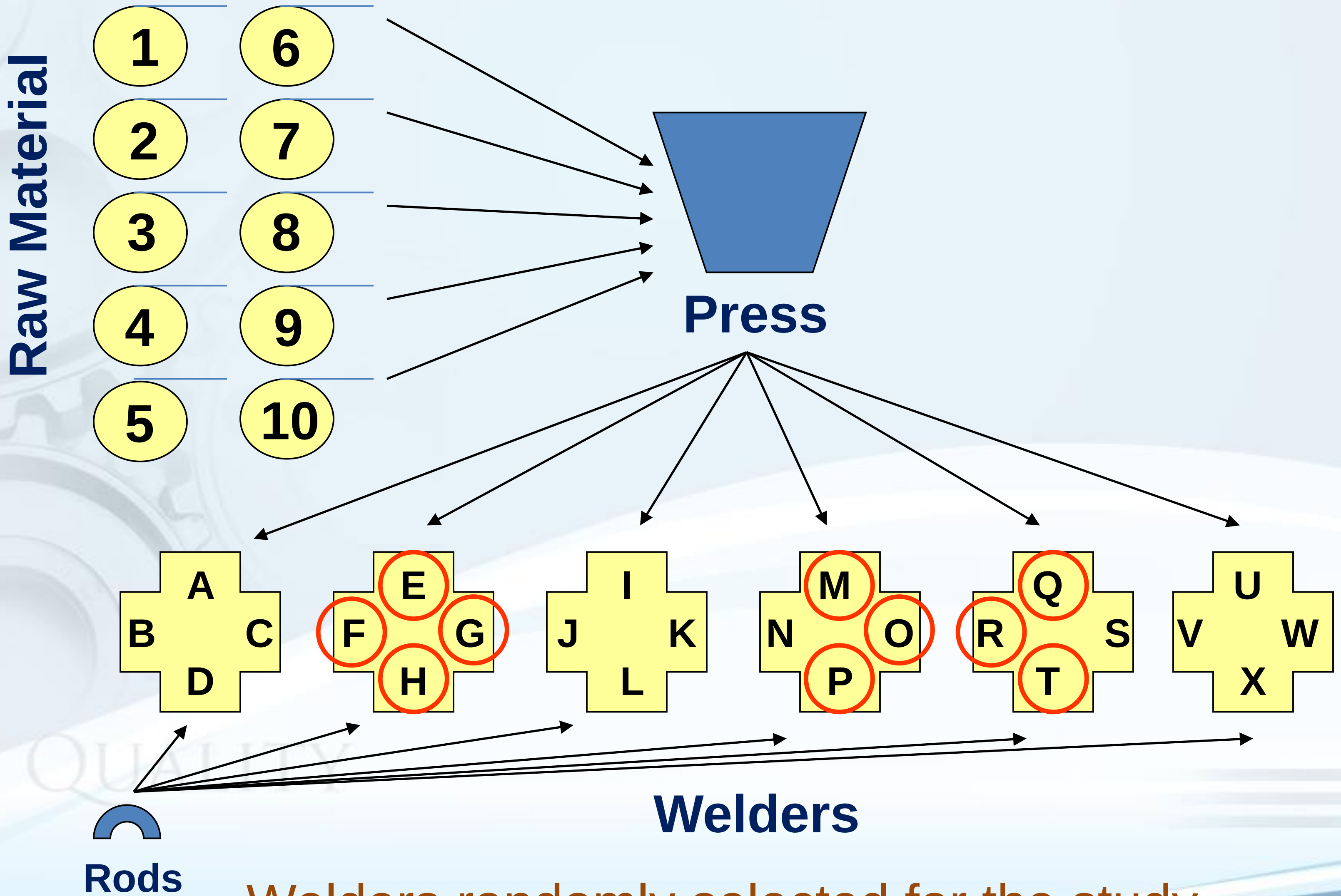
Process Information



Randomize Presentation – Across Study

- Each part has equal chance of being selected
- Not haphazard
- Not convenience

Process Information



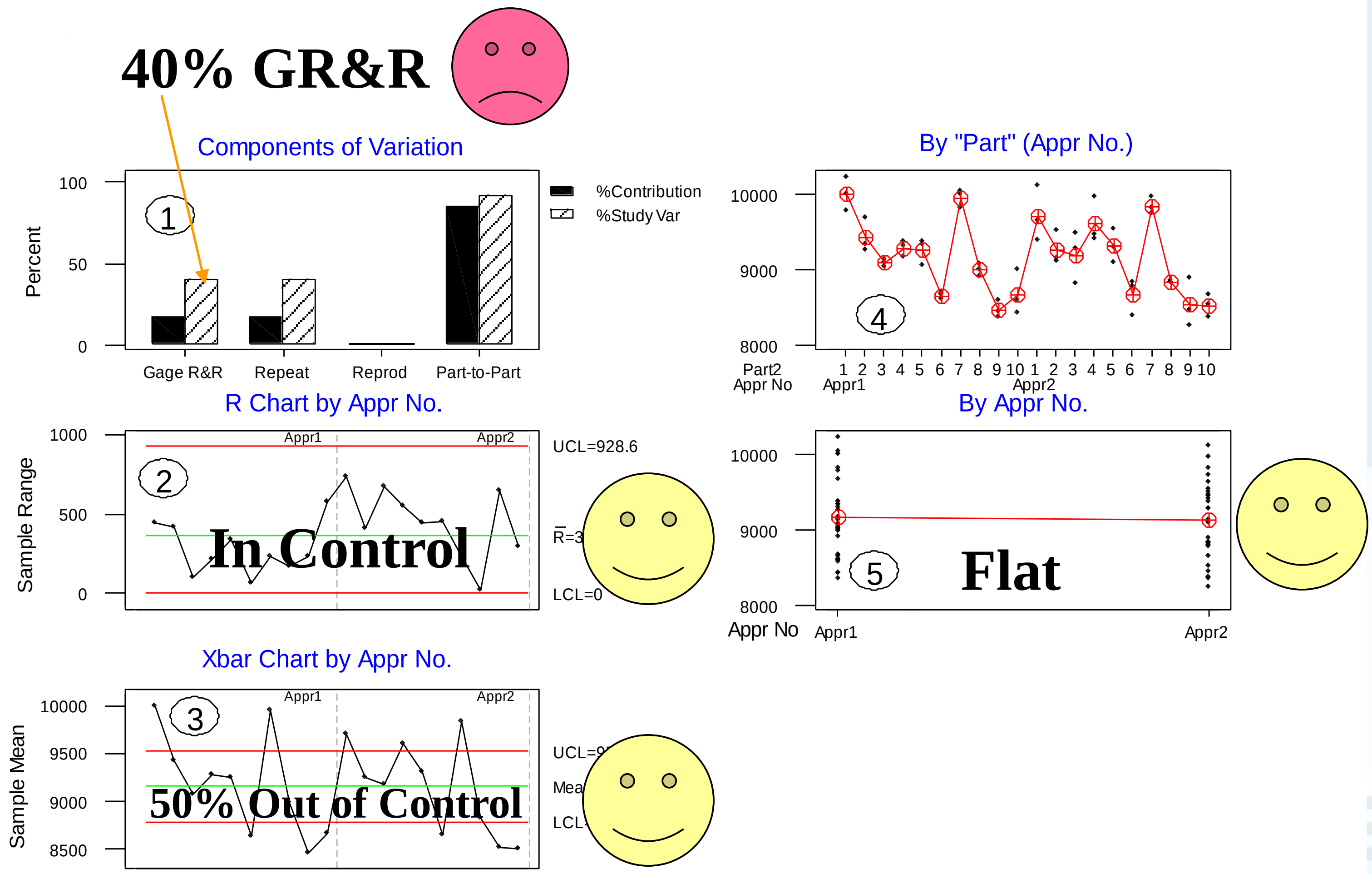
Welders randomly selected for the study

Non-Replicable GRR Layout – as applied

Part #	Appraiser 1 Trial 1	Appraiser 1 Trial 2	Appraiser 1 Trial 3	Appraiser 2 Trial 1	Appraiser 2 Trial 2	Appraiser 2 Trial 3
1-1R…1-6R	$1\text{-}6R_{53}$	$1\text{-}5R_{25}$	$1\text{-}3R_{7}$	$1\text{-}4R_{40}$	$1\text{-}1R_{34}$	$1\text{-}2R_{32}$
2-1P…2-6P	$2\text{-}2P_{27}$	$2\text{-}6P_{35}$	$2\text{-}5P_{57}$	$2\text{-}4P_{12}$	$2\text{-}3P_{43}$	$2\text{-}1P_{17}$
3-1H…3-6H	$3\text{-}1H_{21}$	$3\text{-}2H_{36}$	$3\text{-}6H_{1}$	$3\text{-}5H_{56}$	$3\text{-}4H_{10}$	$3\text{-}3H_{26}$
4-1G…4-6G	$4\text{-}4G_{46}$	$4\text{-}6G_{42}$	$4\text{-}3G_{8}$	$4\text{-}2G_{28}$	$4\text{-}1G_{55}$	$4\text{-}5G_{30}$
5-1E…5-6E	$5\text{-}4E_{5}$	$5\text{-}3E_{20}$	$5\text{-}1E_{13}$	$5\text{-}6E_{54}$	$5\text{-}2E_{39}$	$5\text{-}5E_{50}$
6-1F…6-6F	$6\text{-}1F_{52}$	$6\text{-}3F_{3}$	$6\text{-}4F_{37}$	$6\text{-}5F_{29}$	$6\text{-}2F_{51}$	$6\text{-}6F_{45}$
7-1M…7-6M	$7\text{-}6M_{16}$	$7\text{-}4M_{11}$	$7\text{-}1M_{23}$	$7\text{-}2M_{6}$	$7\text{-}3M_{15}$	$7\text{-}5M_{14}$
8-1O…8-6O	$8\text{-}6O_{49}$	$8\text{-}3O_{60}$	$8\text{-}1O_{33}$	$8\text{-}5O_{41}$	$8\text{-}2O_{44}$	$8\text{-}4O_{19}$
9-1Q…9-6Q	$9\text{-}5Q_{31}$	$9\text{-}6Q_{59}$	$9\text{-}3Q_{24}$	$9\text{-}2Q_{4}$	$9\text{-}4Q_{9}$	$9\text{-}1Q_{2}$
10-1T…10-6T	$10\text{-}2T_{22}$	$10\text{-}5T_{18}$	$10\text{-}3T_{47}$	$10\text{-}4T_{58}$	$10\text{-}1T_{48}$	$10\text{-}6T_{38}$

Randomized within and between Trials

Results



40% GR&R
Components of Variation
Percent
100
50
0
1
%Contribution
%Study Var
Gage R&R
Repeat
Reprod
Part-to-Part
By "Part" (Appr No.)
10000
9000
8000
4
Part2
Appr No
1 2 3 4 5 6 7 8 9 10 1 2 3 4 5 6 7 8 9 10
Appr1
Appr2
R Chart by Appr No.
Sample Range
1000
500
0
Appr1
Appr2
2
In Control
UCL=928.6
LCL=0
By Appr No.
10000
9000
8000
5
Flat
Appr No
Appr1
Appr2
Xbar Chart by Appr No.
Sample Mean
10000
9500
9000
8500
Appr1
Appr2
3
50% Out of Control

Case Study Summary

- Doing SOMETHING is better than doing NOTHING (with customer approval)
- Develop approach for each situation
- Focus on learning
- Be careful conducting study and interpreting results
- Consult statistical resources

Chapter 7: Automated and Non-Replicable Systems – What We Covered

Learning Objectives

You should now be able to:

- Analyze automated Measurement Systems
- Analyze non-replicable Measurement Systems

Chapter Agenda

- Analyzing Automated Measurement Systems
- Analyzing Non-Replicable Measurement Systems
  - **Non-Replicable Case Study**

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Chapter 8

Attribute MSA

Chapter 8: Attribute MSA – What We Will Cover

Learning Objectives

At the end of this chapter, you will be able to:

- Analyze Attribute Measurement Systems

Chapter Agenda

- Analyzing Attribute Measurement Systems
  - **Inspection Exercise**
  - **Breakout Exercise #6**
  - **Breakout Exercise #7**

Measuring System Analysis for Attributes

Attributes

- Attributes data can be binary, nominal, or ordinal
  - **Binary** – one of two values (acceptable or unacceptable)
    - Successful or unsuccessful operation
    - Good or bad part
    - Incomplete or complete assembly
    - Insufficient or satisfactory weld
  - **Nominal** – multiple qualitative data (soft, mushy, crispy, crunchy)
  - **Ordinal** – multiple ordered data (XS, S, M, L, XL, XXL)

Analyzing Attribute Data

Always Try To Convert Attribute To Variables

Examples:

- End Disk Height (low/okay/high)
- Likert Scale (1 – 5)
- Leak Rate (go/no go)
- Mass Spec (low/okay/high)

Then use Variable Data Analysis Techniques

The Inspection Exercise

Task: Count the number of times the 6th letter of the alphabet appears in the following text. ***One minute time limit***

The Necessity of Training Farm Hands for First Class Farms in the Fatherly Handling of Farm Live Stock is Foremost in the Eyes of Farm Owners. Since the Forefathers of the Farm Owners Trained the Farm Hands for First Class Farms in the Fatherly Handling of Farm Live Stock, the Farm Owners Feel they should carry on with the Family Tradition of Training Farm Hands of First Class Farmers in the Fatherly Handling of Farm Live Stock Because they Believe it is the Basis of Good Fundamental Farm Management.

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The Inspection Exercise

Operational Definitions

"An operational definition is one that people can do business with. An operational definition of safe, round, reliable, or any other quality [characteristic] must be communicable, with the same meaning to vendor as to the purchaser, same meaning yesterday and today to the production worker. Example:

1. "A specific test of a piece of material or an assembly
2. "A criterion (or criteria) for judgment
3. "Decision: yes or no, the object or the material did or did not meet the criterion (or criteria)"

W. E. Deming, *Out of the Crisis* (1982, 1986), p. 277.

Attribute MSA Study

Approaches:

- Risk Analysis Method
  - Hypothesis Test Analyses
    - Contingency table analysis
  - Signal detection theory
- Analytic Method

Risk Analysis Methods

- In some attribute situations, it is not feasible to get sufficient parts with variable reference values; in such cases, the risks of making wrong or inconsistent decisions can be evaluated by using:
  - Hypothesis Test Analyses
  - Signal Detection Theory

- These methods do not quantify the measurement system variability, they should be used only with the consent of the customer.

Risk Analysis Methods

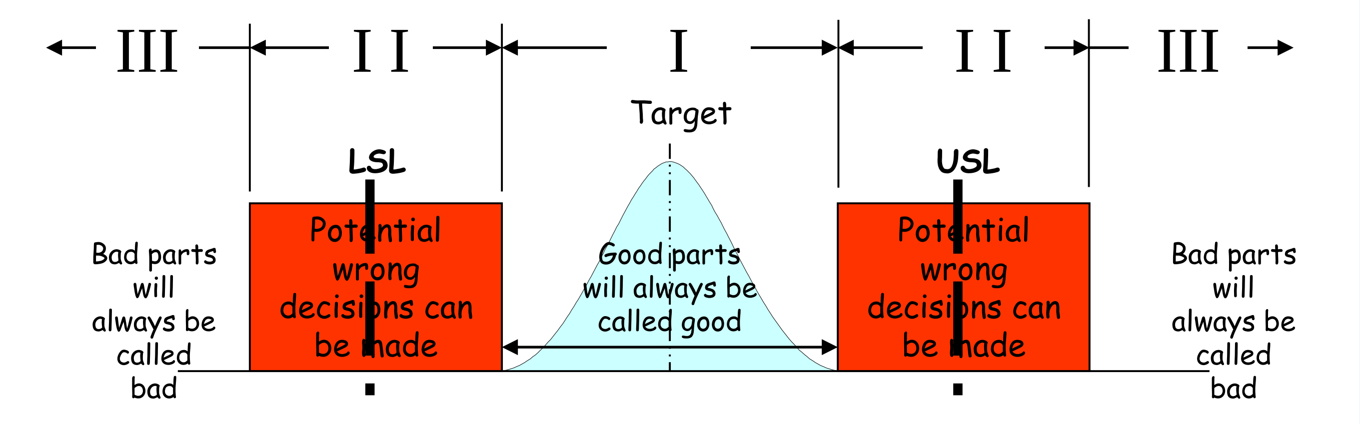
- Selection and use of such techniques should be based on good statistical practices, an understanding of the potential sources of variation that can affect the product and measurement processes, and the effect of an incorrect decision on the remaining processes and the final customer.

Note: The sources of variation of attribute systems should be minimized by using the results of human factors and ergonomic research.

Attribute MSA Study

- Used when measurements are subjective classifications or ratings by people.
- Attribute data can be ORDINAL or NOMINAL.
  - Ordinal Data are categorical variables that have three or more possible levels *with a natural ordering*, such as strongly disagree, disagree, neutral, agree, and strongly agree (or you can use a numeric scale such as 1-5).
    - Kendall's Coefficients are used to measure nonparametric correlations.
  - Nominal Data are categorical variables that have two or more possible levels with *no natural ordering*.
    - E.g., pass, fail; crunchy, mushy, and crispy (food tasting study).
    - Kappa Coefficients are used to measure inter-rater agreement.

Effects on Product Decisions



Two options exist to maximize making the 'correct' decision, they are:

1. **Improve the production process:** reduce variability of the process so that no parts will be produced in the type "II" areas above.
2. **Improve the measurement system:** reduce the measurement system error by reducing the size of the type "II" areas above so all parts will fall in the type "I" area above to minimize risk of a wrong decision.

Nominal Data

Kappa Coefficients

- An indicator of inter-rater agreement
- The ratio of the proportion of agreement (corrected for chance) divided by the maximum number of times they could agree (corrected for chance)

$$K = \frac{\Pr(agreement) - \Pr(expected)}{1 - \Pr(expected)}$$

Where

Pr (agreement) = Proportion of time appraisers agreed

Pr (expected) = Proportion of expected agreement

- A Kappa coefficient of 90% may be interpreted as 90% agreement

Kappa Coefficients

- Based on an article by Altman, 1991 the following kappa interpretation scale is recommended:
  - The definition of the interpretations, such as "Poor", must be agreed upon by the customer and the supplier.

Kappa Value	Interpretation
< 0.20	Poor
0.21-0.40	Fair
0.41-0.60	Moderate
0.61-0.80	Good
0.81-1.00	Very Good

- In addition, Gardner (1995) recommends that kappa exceed .70 before you proceed with additional data analyses.

Hypothesis Test Analyses

A * B Crosstabulation					
			B		Total
			Bad	Good	
A	Bad	Count	44	6	50
	Good	Count	3	97	100
Total		Count	47	103	150

Bad = 0 **Good = 1**

Part	A - 1	A - 2	A - 3	B - 1	B - 2	B - 3	C - 1	C - 2	C - 3	Reference
1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	1	1	1
3	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0
6	1	1	0	1	1	0	1	0	0	1
7	1	1	1	1	1	1	1	0	1	1
8	1	1	1	1	1	1	1	1	1	1
9	0	0	0	0	0	0	0	0	0	0
10	1	1	1	1	1	1	1	1	1	1
11	1	1	1	1	1	1	1	1	1	1
12	0	0	0	0	0	0	0	1	0	0
13	1	1	1	1	1	1	1	1	1	1
14	1	1	0	1	1	1	1	0	0	1
15	1	1	1	1	1	1	1	1	1	1
16	1	1	1	1	1	1	1	1	1	1
17	1	1	1	1	1	1	1	1	1	1
18	1	1	1	1	1	1	1	1	1	1
19	1	1	1	1	1	1	1	1	1	1
20	1	1	1	1	1	1	1	1	1	1
21	1	1	0	1	0	1	0	1	0	1
22	0	0	1	0	1	0	1	1	0	0
23	1	1	1	1	1	1	1	1	1	1
24	1	1	1	1	1	1	1	1	1	1
25	0	0	0	0	0	0	0	0	0	0
26	0	1	0	0	0	0	0	0	1	0
27	1	1	1	1	1	1	1	1	1	1
28	1	1	1	1	1	1	1	1	1	1
29	1	1	1	1	1	1	1	1	1	1
30	0	0	0	0	0	1	0	0	0	0
31	1	1	1	1	1	1	1	1	1	1
32	1	1	1	1	1	1	1	1	1	1
33	1	1	1	1	1	1	1	1	1	1
34	0	0	1	0	0	1	0	1	1	0
35	1	1	1	1	1	1	1	1	1	1
36	1	1	0	1	1	1	1	0	1	1
37	0	0	0	0	0	0	0	0	0	0
38	1	1	1	1	1	1	1	1	1	1
39	0	0	0	0	0	0	0	0	0	0
40	1	1	1	1	1	1	1	1	1	1
41	1	1	1	1	1	1	1	1	1	1
42	0	0	0	0	0	0	0	0	0	0
43	1	0	1	1	1	1	1	1	0	1
44	1	1	1	1	1	1	1	1	1	1
45	0	0	0	0	0	0	0	0	0	0
46	1	1	1	1	1	1	1	1	1	1
47	1	1	1	1	1	1	1	1	1	1
48	0	0	0	0	0	0	0	0	0	0
49	1	1	1	1	1	1	1	1	1	1
50	0	0	0	0	0	0	0	0	0	0

ATTRIBUTE GAGE CALCULATIONS FOR "COUNTS"

There are 34 times where A-1 = 1 and B-1 = 1

(that is, of the 50 parts checked there were 34 matches by A and B on their FIRST check)

Table 12: Attribute Study Data Set

Part	A - 1	A - 2	A - 3	B - 1	B - 2	B - 3	C - 1	C - 2	C - 3	Reference
1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	1	1	1
3	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0
6	1	1	0	1	1	0	1	0	0	1
7	1	1	1	1	1	1	1	0	1	1
8	1	1	1	1	1	1	1	1	1	1
9	0	0	0	0	0	0	0	0	0	0
10	1	1	1	1	1	1	1	1	1	1
11	1	1	1	1	1	1	1	1	1	1
12	0	0	0	0	0	0	0	1	0	0
13	1	1	1	1	1	1	1	1	1	1
14	1	1	0	1	1	1	1	0	0	1
15	1	1	1	1	1	1	1	1	1	1
16	1	1	1	1	1	1	1	1	1	1
17	1	1	1	1	1	1	1	1	1	1
18	1	1	1	1	1	1	1	1	1	1
19	1	1	1	1	1	1	1	1	1	1
20	1	1	1	1	1	1	1	1	1	1
21	1	1	0	1	0	1	0	1	0	1
22	0	0	1	0	1	0	1	1	0	0
23	1	1	1	1	1	1	1	1	1	1
24	1	1	1	1	1	1	1	1	1	1
25	0	0	0	0	0	0	0	0	0	0
26	0	1	0	0	0	0	0	0	1	0
27	1	1	1	1	1	1	1	1	1	1
28	1	1	1	1	1	1	1	1	1	1
29	1	1	1	1	1	1	1	1	1	1
30	0	0	0	0	0	1	0	0	0	0
31	1	1	1	1	1	1	1	1	1	1
32	1	1	1	1	1	1	1	1	1	1
33	1	1	1	1	1	1	1	1	1	1
34	0	0	1	0	0	1	0	1	1	0
35	1	1	1	1	1	1	1	1	1	1
36	1	1	0	1	1	1	1	0	1	1
37	0	0	0	0	0	0	0	0	0	0
38	1	1	1	1	1	1	1	1	1	1
39	0	0	0	0	0	0	0	0	0	0
40	1	1	1	1	1	1	1	1	1	1
41	1	1	1	1	1	1	1	1	1	1
42	0	0	0	0	0	0	0	0	0	0
43	1	0	1	1	1	1	1	1	0	1
44	1	1	1	1	1	1	1	1	1	1
45	0	0	0	0	0	0	0	0	0	0
46	1	1	1	1	1	1	1	1	1	1
47	1	1	1	1	1	1	1	1	1	1
48	0	0	0	0	0	0	0	0	0	0
49	1	1	1	1	1	1	1	1	1	1
50	0	0	0	0	0	0	0	0	0	0

ATTRIBUTE GAGE CALCULATIONS FOR "COUNTS"

There are 32 times where
A-2 = 1 and B-2 = 1
(that is, of the 50 parts checked there were 32 matches by A and B on their SECOND check)

Part	A - 1	A - 2	A - 3	B - 1	B - 2	B - 3	C - 1	C - 2	C - 3	Reference
1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	1	1	1	1	1	1
3	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0
6	1	1	0	1	1	0	1	0	0	1
7	1	1	1	1	1	1	1	0	1	1
8	1	1	1	1	1	1	1	1	1	1
9	0	0	0	0	0	0	0	0	0	0
10	1	1	1	1	1	1	1	1	1	1
11	1	1	1	1	1	1	1	1	1	1
12	0	0	0	0	0	0	0	1	0	0
13	1	1	1	1	1	1	1	1	1	1
14	1	1	0	1	1	1	1	0	0	1
15	1	1	1	1	1	1	1	1	1	1
16	1	1	1	1	1	1	1	1	1	1
17	1	1	1	1	1	1	1	1	1	1
18	1	1	1	1	1	1	1	1	1	1
19	1	1	1	1	1	1	1	1	1	1
20	1	1	1	1	1	1	1	1	1	1
21	1	1	0	1	0	1	0	1	0	1
22	0	0	1	0	1	0	1	1	0	0
23	1	1	1	1	1	1	1	1	1	1
24	1	1	1	1	1	1	1	1	1	1
25	0	0	0	0	0	0	0	0	0	0
26	0	1	0	0	0	0	0	0	1	0
27	1	1	1	1	1	1	1	1	1	1
28	1	1	1	1	1	1	1	1	1	1
29	1	1	1	1	1	1	1	1	1	1
30	0	0	0	0	0	1	0	0	0	0
31	1	1	1	1	1	1	1	1	1	1
32	1	1	1	1	1	1	1	1	1	1
33	1	1	1	1	1	1	1	1	1	1
34	0	0	1	0	0	1	0	1	1	0
35	1	1	1	1	1	1	1	1	1	1
36	1	1	0	1	1	1	1	0	1	1
37	0	0	0	0	0	0	0	0	0	0
38	1	1	1	1	1	1	1	1	1	1
39	0	0	0	0	0	0	0	0	0	0
40	1	1	1	1	1	1	1	1	1	1
41	1	1	1	1	1	1	1	1	1	1
42	0	0	0	0	0	0	0	0	0	0
43	1	0	1	1	1	1	1	1	0	1
44	1	1	1	1	1	1	1	1	1	1
45	0	0	0	0	0	0	0	0	0	0
46	1	1	1	1	1	1	1	1	1	1
47	1	1	1	1	1	1	1	1	1	1
48	0	0	0	0	0	0	0	0	0	0
49	1	1	1	1	1	1	1	1	1	1
50	0	0	0	0	0	0	0	0	0	0

ATTRIBUTE GAGE CALCULATIONS FOR "COUNTS"

There are 31 times where
A-3 = 1 and B-3 = 1
(that is, of the 50 parts checked there were 31 matches by A and B on their THIRD check)

Total : where A-x =1 and B-x
= 1
= 34+32+31= 97

Count & Expected Count Calculations

A * B Crosstabulation					
			B		**Total**
			.00	1.00	
A	.00	Count	44	6	50
	1.00	Count Expected Count	3	97 68.7	100
Total		Count Expected Count	47	103	150 150.0

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Expected Counts

The expected counts is calculated using the following formula (based on Chi-Square)

97 from previous slide

Expected Count = Column Total x [Row Total/Grand Total]

From the A*B Crosstabulation Table

Column Total = 103
Row Total = 100
Grand Total = 150

A * B Crosstabulation					
			B		Total
			.00	1.00	
A	.00	Count	44	6	50
		Expected Count	15.7	34.3	50.0
	1.00	Count	3	97	100
		Expected Count	31.3	68.7	100.0
Total		Count	47	103	150
		Expected Count	47.0	103.0	150.0

Hence
For A=1 and B=1
the Expected Count = 103 x [100/150] = 68.7

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Hypothesis Test Analyses

A * B Crosstabulation					
			B		**Total**
			.00	1.00	
A	.00	Count	44	6	50
		Expected Count	15.7	34.3	50.0
	1.00	Count	3	97	100
		Expected Count	31.3	68.7	100.0
Total		Count	47	103	150
		Expected Count	47.0	103.0	150.0

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Kappa

A * B Crosstabulation					
			B		Total
			.00	1.00	
A	.00	Count	44	6	50
		Expected Count	*15.7*	34.3	50.0
	1.00	Count	3	97	100
		Expected Count	31.3	*68.7*	100.0
Total		Count	47	103	150
		Expected Count	47.0	103.0	*150.0*

Only uses the diagonal

Kappa

$$kappa = \frac{p_o - p_e}{1 - p_e}$$

where p_o = Sum of the observed proportions in the diagonal cells (left to right direction)
p_e = Sum of the expected proportions in the diagonal cells (left to right direction)

$$p_o = \frac{44+97}{150} = 0.94 \qquad p_e = \frac{15.7+68.7}{150} = 0.56$$

$$kappa = \frac{p_o - p_e}{1 - p_e} = \frac{0.94 - 0.56}{1 - 0.56} = 0.86$$

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Miss Rate & False Alarm Rate For Appraiser "A"

A * Standard Crosstabulation					
			Standard		Total
			.00	1.00	
A	.00	Count	45	5	50
		Expected Count	16.0	34.0	50.0
	1.00	Count	3	97	100
		Expected Count	32.0	68.0	100.0
Total		Count	48	102	150
		Expected Count	48.0	102.0	150.0

Miss Rate[1]: Calling a "BAD" part GOOD

= 3/48 = 6.3%

False Alarm Rate[2]: Calling a "GOOD" part BAD

= 5/102 = 4.9%

[1] Type II error, Consumer's risk

[2] Type I error, Producer's risk

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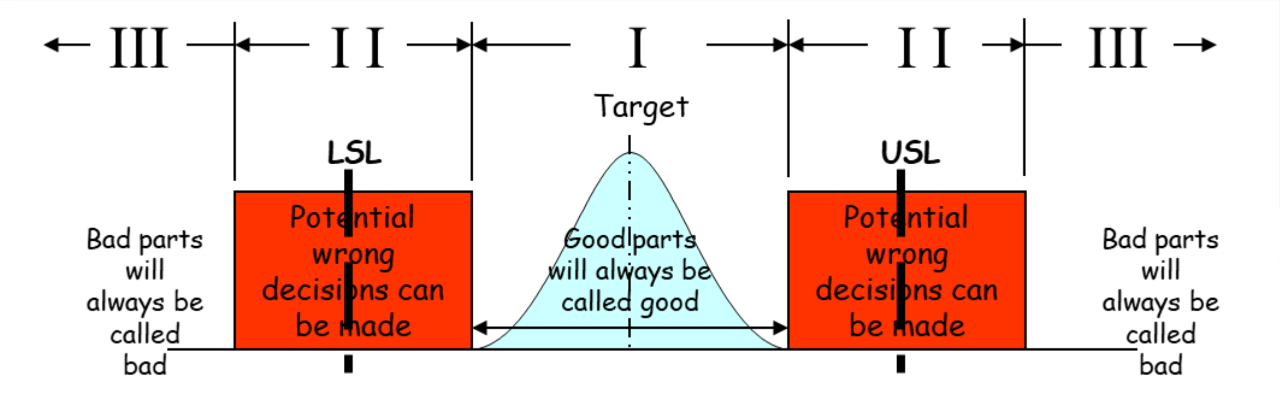
Sample Size

- Need to take "enough"
  - Need to include part in category I



Sample Size

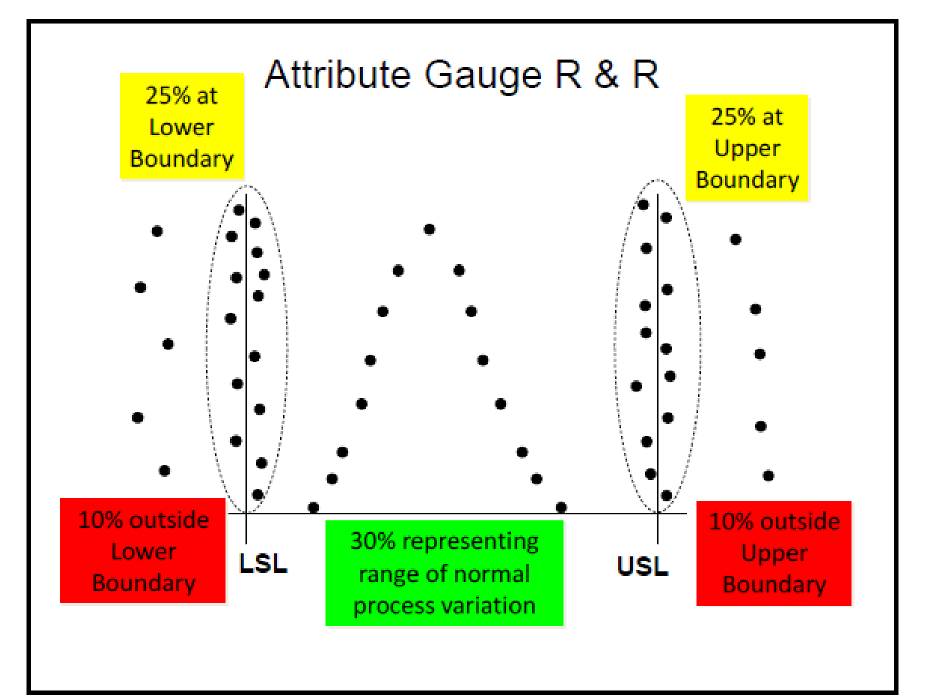
From Ford's CSR: **Parts for Attribute Gage R&R Study**

- 25% of the parts should be near the lower specification limit (on both sides of the specification).
- 25% of the parts should be near the upper specification limit (on both sides of the specification).
- 30% of the parts should represent the expected process variation.
- 10% of the parts should be outside the upper gauge specification limit and beyond the 25% of the parts near the specification as described above.
- 10% of the parts should be outside the lower gauge specification limit and beyond the 25% of the parts near the specification as described above.

Sample Size

From Ford's CSR: **Parts for Attribute Gage R&R Study**

- Graphic representing the data distribution for Attribute Gage R&R:



Depending on the characteristic, the above parts should be independently measured with a variable gauge (such as a CMM or other known standard) so that the physical measurement of each part is known.

Breakout Exercise 6

Attribute Analysis

Breakout Exercise 6: Attribute Analysis

Use the data in *@msa e class data* Excel file; tab: *attr – brk #6*

- In this study, 3 operators inspect 30 parts, twice, for a total of 180 readings. A column is included for the master readings.

Analysis:

- Determine Kappa of
  - A vs Master readings
- Approach
  - Create Crosstabulations
  - Determine expected values
  - Calculate Kappa

Breakout Exercise 6: Attribute Analysis

Use the data in Breakout Workbook, Breakout Exercise 6 or *@msa e class data* Excel file; tab: *attr – brk #6*

- Analyze data in columns N-Q

  Using Minitab:

  1. Stat > Quality Tools > Attribute Agreement Analysis

- Compare answers with other teams
- What conclusions can you make at this point?
- Analyze and discuss the data and percentages

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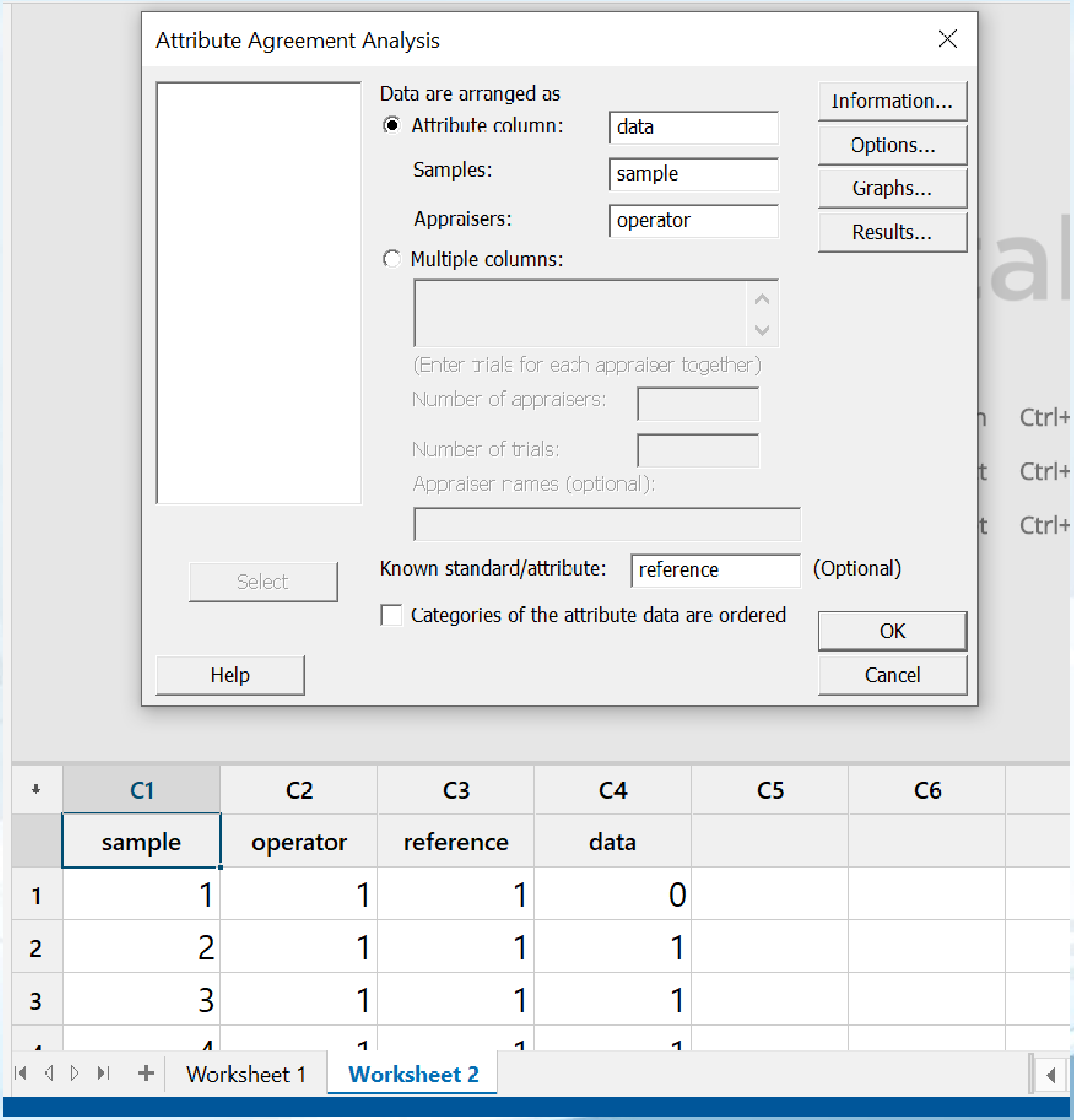

Attribute Agreement Analysis
Data are arranged as
Attribute column: data
Samples: sample
Appraisers: operator
Multiple columns:
(Enter trials for each appraiser together)
Number of appraisers:
Number of trials:
Appraiser names (optional):
Known standard/attribute: reference (Optional)
Categories of the attribute data are ordered
Select
Help
Information...
Options...
Graphs...
Results...
OK
Cancel
C1 C2 C3 C4 C5 C6
sample operator reference data
1 1 1 1 0
2 2 1 1 1
3 3 1 1 1
Worksheet 1
Worksheet 2

Using Kappa Statistics

- The stronger the agreement, the higher the value of Kappa:
  - Kappa = 1 means perfect agreement.
  - Kappa = 0 means the agreement is the same as would be expected by chance.
  - Kappa < 0 – agreement is weaker than chance (this rarely happens).
  - If Kappa is > 0.9, the agreement is considered excellent, Kappa > 0.7 is considered good.

Measuring System Analysis for Attributes

A*REFERENCE TABLE:			REF		
			0	1	TOTAL
	0	COUNT	12	7	19
		EXP COUNT	4.433333	14.567	0
A	1	COUNT	2	39	41
		EXP COUNT	9.566667	31.433	0
	TOTAL	COUNT	14	46	60
		EXP COUNT	14	46	60
A*REFERENCE: KAPPA =		0.627			

MR = 14.29%

FAR = 15.22%

Measuring System Analysis for Attributes

Within Appraiser

Assessment Agreement

Appraiser	# Inspected	# Matched	Percent (%)	95.0% CI
1	30	21	70.0	(50.6, 85.3)
2	30	28	93.3	(77.9, 99.2)
3	30	21	70.0	(50.6, 85.3)

Matched: Appraiser agrees with him/herself across trials.

- Consistency of responses of the inspectors.
- Inspectors 1 and 3 were consistent 70% of the time, and inspector 2 was consistent 93.3%.

Measuring System Analysis for Attributes

Kappa Statistics

Appraiser	Response	Kappa	SE Kappa	Z	P(vs > 0)
1	f	0.3068	0.1826	1.6804	0.046
	p	0.3068	0.1826	1.6804	0.046
2	f	0.8295	0.1826	4.5436	0.000
	p	0.8295	0.1826	4.5436	0.000
3	f	0.3068	0.1826	1.6804	0.046
	p	0.3068	0.1826	1.6804	0.046

- The Kappa value should be > 0.7 for a good measurement system – Kappa < 0.7 needs improvement.
- This applies to all tables with a Kappa value.
- In the above, Appraiser 1 & 3 have low Kappa values.

Measuring System Analysis for Attributes

Each Appraiser vs. Standard

Assessment Agreement

Appraiser	# Inspected	# Matched	Percent (%)	95.0% CI
1	30	21	70.0	(50.6, 85.3)
2	30	26	86.7	(69.3, 96.2)
3	30	21	70.0	(50.6, 85.3)

Matched: Appraiser's assessment across trials agrees with standard

- How the appraisers did with the standard is given in this table.
- Appraiser 2 matched 86.7% against 70 for the other two.

Measuring System Analysis for Attributes

Each Appraiser vs. Standard

Assessment Disagreement

Appraiser	# p/f	Percent (%)	# f/p	Percent (%)	# Mixed	Percent (%)
1	0	0.0	0	0.0	9	30.0
2	1	14.3	1	4.3	2	6.7
3	0	0.0	0	0.0	9	30.0

- The #p/f column contains the number of parts that the appraiser passed but should have failed from all trials.
- The #f/p column contains the parts that were failed that should have passed.
- The #Mixed are the number of parts for which the responses across trials did not match.

Measuring System Analysis for Attributes

Between Appraisers

Assessment Agreement

# Inspected	# Matched	Percent (%)	95.0% CI
30	11	36.7	(19.9, 56.1)

All Appraisers vs. Standard

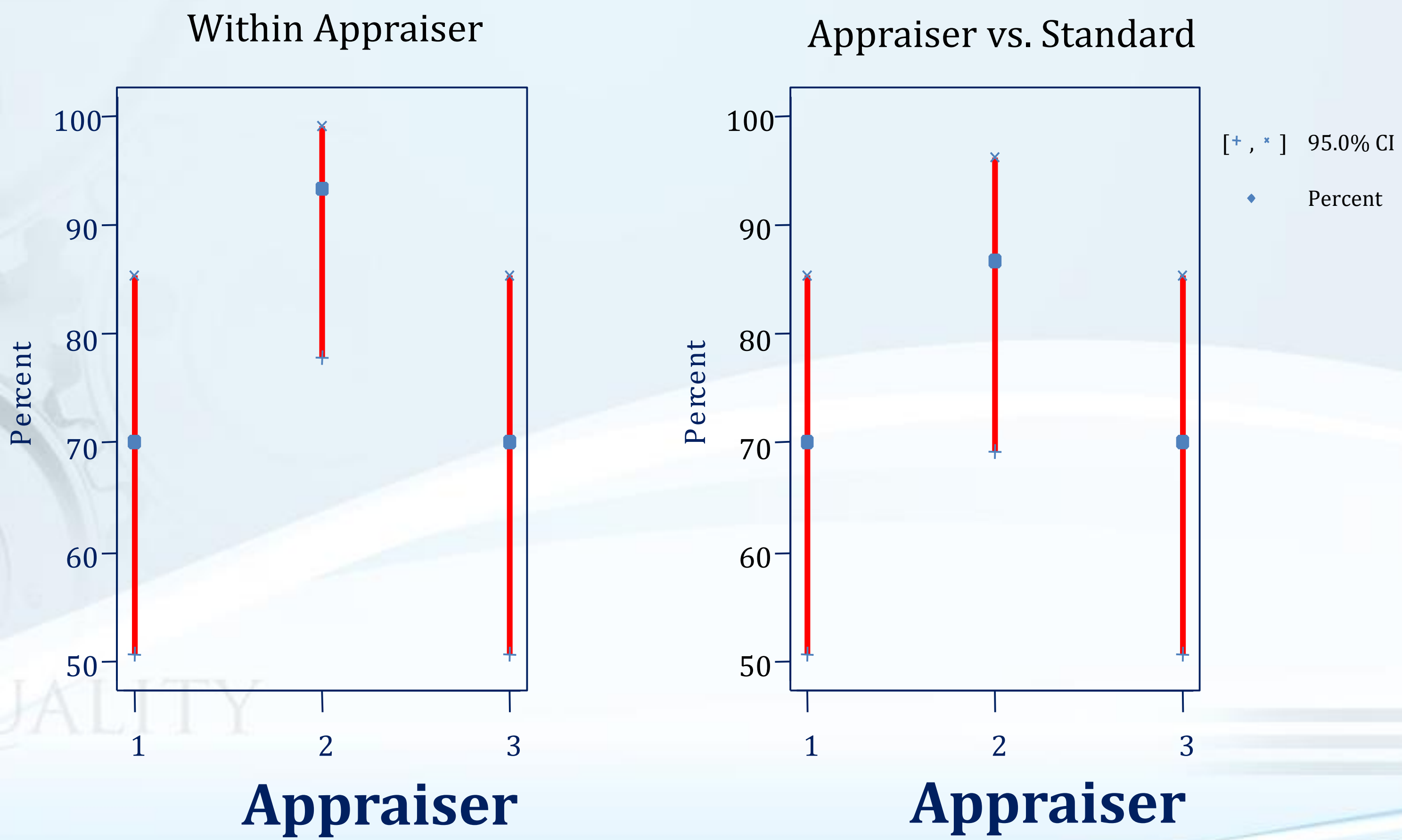
Assessment Agreement

# Inspected	# Matched	Percent (%)	95.0% CI
30	11	36.7	(19.9, 56.1)

- Between Appraisers shows how the appraiser’s responses agree with each other, not with the standard.
- All Appraisers vs. Standard shows how the appraiser’s responses agree with the standard.

Measuring System Analysis Graph

Assessment Agreement



Measuring System Analysis Graph

Within Appraiser:

- This graph shows the consistency of each appraiser's response with respect to each other.
- From the graph, appraisers 1 & 3 seem consistent, but they are consistently wrong against the standard getting only 70% correct against around 93% for appraiser 2.

Appraiser vs. Standard:

- This graph shows the correctness of each appraiser's response with respect to the standard.
- From the graph, appraisers 1 & 3 seem consistently wrong against the standard.

Tables in Minitab

1. Stat > Tables > Cross Tabulation and Chi Square
2. Provide responses:
   - Use raw data
   - Rows → data
   - Columns → reference
   - Layers → operator
   - Chi Square: Expected counts
   - Other tests: Kappa

Minitab

Rows: data   Columns: reference

	0	1	All
0	12	7	19
	4.433	14.567	
1	2	39	41
	9.567	31.433	
All	14	46	60

Cell Contents
Count
Expected count

Measure of Observer Agreement

Kappa 0.627072

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Minitab

Results for operator = 2

Rows: data   Columns: reference

	0	1	All
0	12	4	16
	3.73	12.27	
1	2	42	44
	10.27	33.73	
All	14	46	60

Cell Contents
Count
Expected count

Measure of Observer Agreement

Kappa 0.733728

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Minitab

Results for operator = 3

Rows: data   Columns: reference

	0	1	All
0	12	7	19
	4.433	14.567	
1	2	39	41
	9.567	31.433	
All	14	46	60

Cell Contents
Count
Expected count

Measure of Observer Agreement

Kappa 0.627072

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Final Conclusions

- There seems to be consistency issues amongst the appraisers
- Training and standard work will have to be implemented to get similar results
- Better gauging/visual means will have to be provided to the operators

Breakout Exercise 7

Calculating Attribute Analysis

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Breakout Exercise 7: Calculating Attribute Analysis

- Determine the operational definition for visual defects for solder joints
  - e.g., sufficient solder, contact with wire and PCB etc., etc.
- Perform attribute risk analysis study using the provided Visual Defects Case Study
  - Use 3 appraisers
  - Use a random sample of 20 solder joints
- Complete attribute risk analysis and report results
- Compare answers with other teams
- What conclusions can you make at this point?
- Analyze and discuss the data and percentages

Note: To generate the data collection form in Minitab
Stat > Quality Tools > Create Attribute Agreement Worksheet Analysis

Chapter 8: Attribute MSA – What We Covered

Learning Objectives

You should now be able to :

- Analyze Attribute Measurement Systems

Chapter Agenda

- Analyzing Attribute Measurement Systems
  - **Inspection Exercise**
  - **Breakout Exercise #6**
  - **Breakout Exercise #7**

Chapter 9

Measurement Planning

Chapter 9: Measurement Planning – What We Will Cover

Learning Objectives

At the end of this chapter, you will be able to:

- Describe the approach to Measurement Systems Planning

Chapter Agenda

- Measurement Systems Planning

Where To Start?

- Evaluate the components of the measuring system and control variation as much as possible to ensure that an item of measuring equipment is in a state of compliance with requirements for its intended use.
- Expand your consideration of Measurement Process Variation to Measurement System Statistical Properties and Measurement Uncertainty.
- Follow the basics of SPC.

Measurement Planning

- MSA Plan is the output of APQP Phase III – the Process Development.
- This plan should originate in process development and be completed by the production verification team.
- It starts with the customer requirements and ends with confidence of determination that these requirements are met and result in customer satisfaction.
- It is repeated as often as appropriate to control new equipment, new processes, new methods, new personnel, changes or any variables that may affect your ability to make accurate decisions.

Measurement System Data

- Define data needed, how to use the measurement system at APQP.
- Determine if measurement system statistical properties meet needed limits and requirements and are worth time and cost of using the system.
- The quality of a measurement system is determined by the statistical properties of data produced:
  - Bias and Linearity, acceptable (statistically zero)
  - R&R < 10%; 10-30% marginal and
  - total measurement uncertainty < 30%

Common Properties

Measurement System

- Must be in a state of statistical control
- Variation must be small compared to the manufacturing process variation and specification limits
- Increments no greater than 1/10th or smaller of either process variability or specification limits
- Worst variation must be small relative to smaller of either process variation or specification limits

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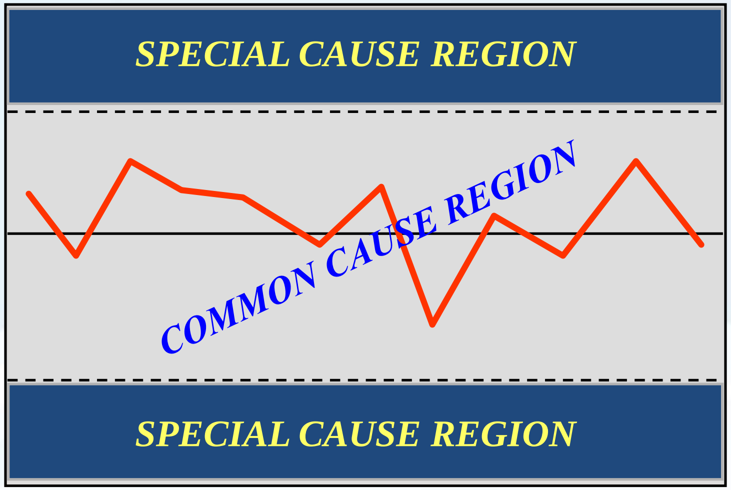
Statistical Control

Measurement Systems must be in a state of statistical control i.e., free of *special causes*, as is true of all processes



1. In general, the absence of points in the special cause region indicates the process is in a state of statistical control.

2. If there is no trend or shift in the data as explained in SPC, then along with (1) we could say that the process is in a state of statistical control.

Measurement Planning

- The Data
  - What is to be measured: physical, contact, electrical, condition, dynamic
  - How important is this data?
  - What will be done with the results?
  - Who cares about the results?
  - Process capability
  - Data range
  - What is the acceptance criteria?

Measurement Planning

- The Appraisers
  - Operators, engineers, inspectors
  - Training or certification?
  - Instructions: Selection, set up, execution
  - Automated vs. manual
  - Can they influence results?
  - Will attitude, stress affect results?
  - Will the environment allow them to “read” the same results?
  - Special handling, storage

Measurement Planning

- Defining the physical system
  - Dedicated or flexible
  - Contact vs. non-contact
  - Destructive
  - Measurement points
  - Fixturing
  - Part orientation
  - Part preparation
  - Transducer location
  - Resolution, sensitivity
  - Environment

Measurement Planning

- Supporting Activities
  - What is the objective of the study?
  - Has an equipment and measurement system FMEA been done?
  - Does the equipment/fixtures have to be built?
  - How have we defined the specifications?
  - Is the source selected and proven?
  - How will acceptance be conducted?
  - Is the cost in the budget?
  - Is there a preventative maintenance plan?
  - Is there a user/troubleshooting guide?
  - What are the utility requirements?
  - What is the calibration plan?
  - Can results be correlated with others: same gage, same method, same measurements?
  - What inputs are required?

Chapter 9: Measurement Planning – What We Covered

Learning Objectives

You should now be able to:

- Describe and approach to Measurement Systems Planning

Chapter Agenda

- Measurement Systems Planning

Summary

MSA Definitions

- **MSA – Measurement System Analysis:** deals with analyzing the effect of the measurement system on the measured value in quantifiable terms.
- **Variation:** caused by man, material, method, equipment and/or environment.
- **Discrimination:** ability of the measurement system to detect small changes in measured values.
- **Accuracy:** absolute correctness of measurements compared with a known standard.
- **Precision:** ability of the measurement system to reproduce or duplicate readings.
- **Bias:** difference between observed average of measurements and the reference value.

MSA Definitions

(continued)

- **Stability:** statistically in control with no special cause variation (also called drift) is the total variation in measurements obtained with a measurement system on the same master or parts when measuring a single characteristic over extended time.
- **Linearity:** difference in the bias values through the operating range of the gage.
- **GRR – Gage Repeatability and Reproducibility = (Equipment +Appraiser)Variation**
  - **Repeatability:** Variation in measurements using one instrument several times by the same operator on the same characteristic on the same part.
  - **Reproducibility:** Variation in the average of measurements made by different operators using the same instrument measuring the same characteristic on the same product.

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MSA Definitions

(continued)

- **Total Variation = Manufacturing Process Variation + Measurement Systems Variation**
- **Control Charts:** graphical displays of system or process data used in real time to help analyze variation and react to the cause if the process is not in control.
- **ANOVA – Analysis of Variance:** Studying of the variability found in data by use of mathematical methods such as complicated calculations, statistical tables, sum of squares, control charts and graphical comparison.

Measurement System Study

- Typical preparation includes:
  - Work Instruction for the study
  - Number of appraisers and sample parts
  - Number of repeated readings or trials
  - Criticality of dimension
  - Part configuration
  - Operators who use measurement
  - Equipment as part of their work
  - Sample parts that represent entire operating range
  - Measurement equipment must have discrimination that allows at least 1/10th of process variation of characteristic to be read

Thank You!

Questions?

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Appendix

Fleiss' Kappa

Kappa Statistic

Use kappa when classifications are nominal.

In the description of the method, without loss of generality, we assume that single rating on each subject is made by each rater, and there are m raters involved per subject. To calculate kappa when the standard is unknown, the m raters represent the m trials for each rater.

When true standard is unknown, Minitab estimates the kappa coefficient by:

$$\frac{P_o - P_e}{1 - P_e}$$

P_o = the proportion of times k appraisers agree

$$P_o = \frac{1}{Nn(n-1)}\left(\sum_{i=1}^{N}\sum_{j=1}^{k} x_{ij}^2 - Nn\right)$$

P_e = the expected proportion of times k appraisers agree

Minitab calculates P_e by $\Sigma\, p_j^2$

where:

p_j^2 = the expected proportion agreement for each category.

N = the number of subjects

n = the number of raters

k = the number of categories of the scale

x_{ij} = the number of raters who assigned the i^{th} subject to the j^{th} category

Cohen's Kappa

Kappa Statistic

Use Cohen's kappa statistic when classifications are nominal. When the standard is not known, and you choose to obtain Cohen's kappa, Minitab will calculate the statistic when the data satisfy the following conditions:

- **Within Appraiser** – there are exactly two trials with an appraiser
- **Between Appraisers** – there are exactly two appraisers each having one trial only