Lean Six Sigma Green Belt Certification Course

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Measurement System Analysis

Learning Objectives

By the end of this lesson, you will be able to:

- Interpret measurement system analysis
- List the measurement system characteristics and system concepts
- Outline the measurement system properties
- Describe G R&R study

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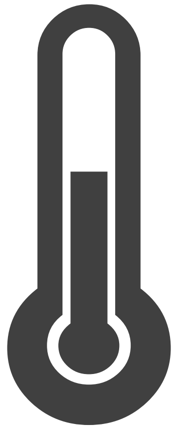
Problems at Java House Coffee

Java House Coffee customers had been complaining about the coffee temperature. However, investigation showed that the temperature was within the customers' desired range.



The investigation team discovered that the device used to take and read coffee temperature was malfunctioning. A new device showed coffee temperature was colder than what they had previously thought.

Calculate and Interpret Measurement System Capability using GR&R

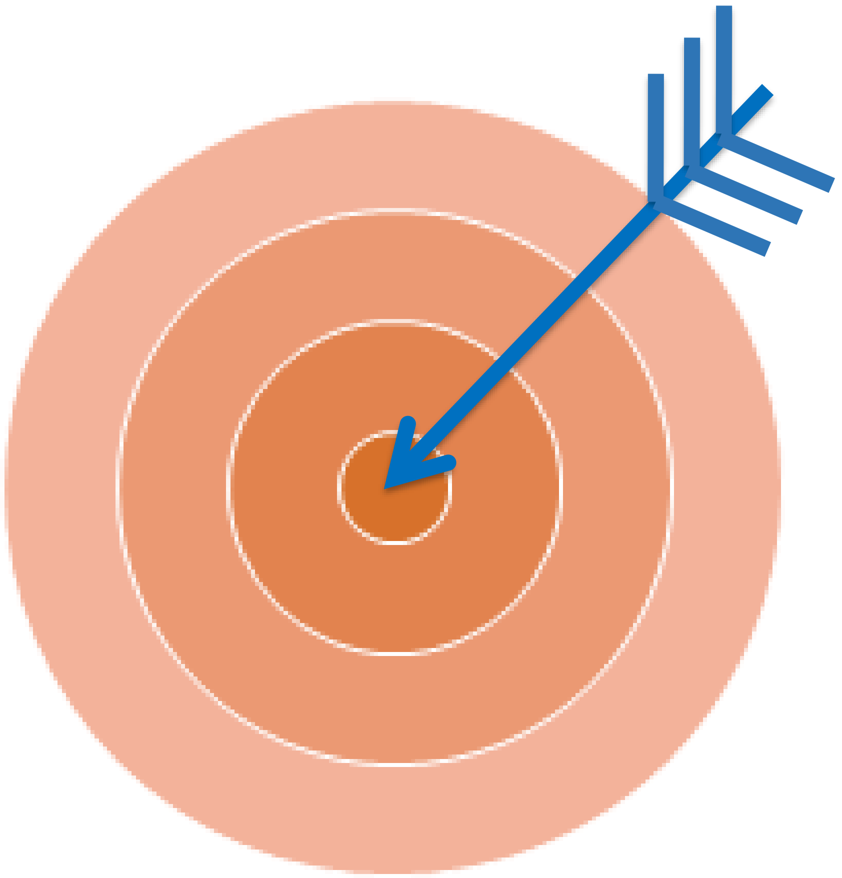
Measurement System Analysis

Analysis

Intended Results

Measurement System Analysis is a technique that identifies measurement error or variation and its sources to reduce variation.

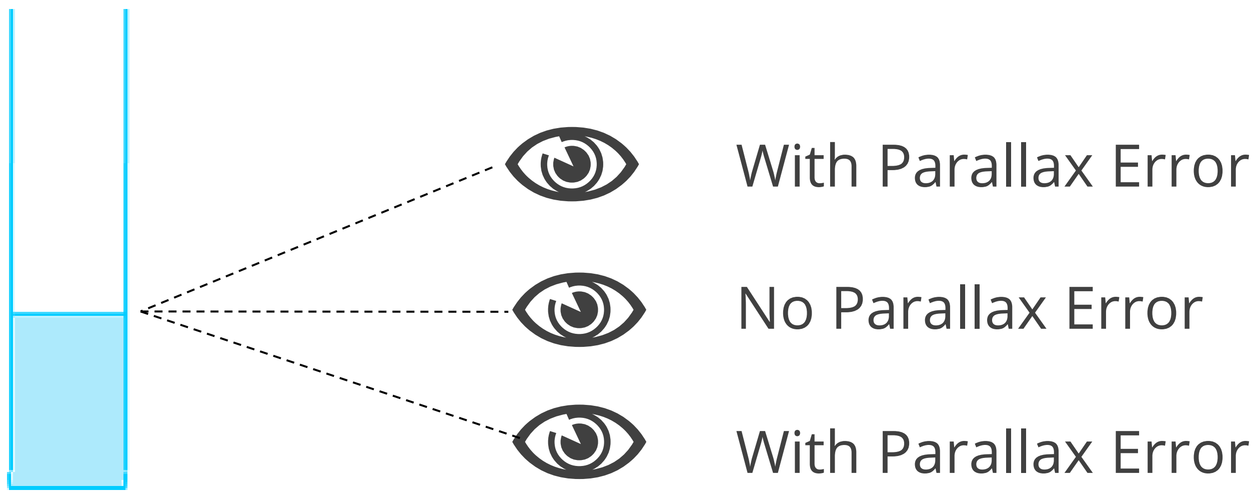
Measurement System Analysis



- Obtain information
- Establish criteria
- Compare measurement methods
- Form basis for evaluating a measurement method

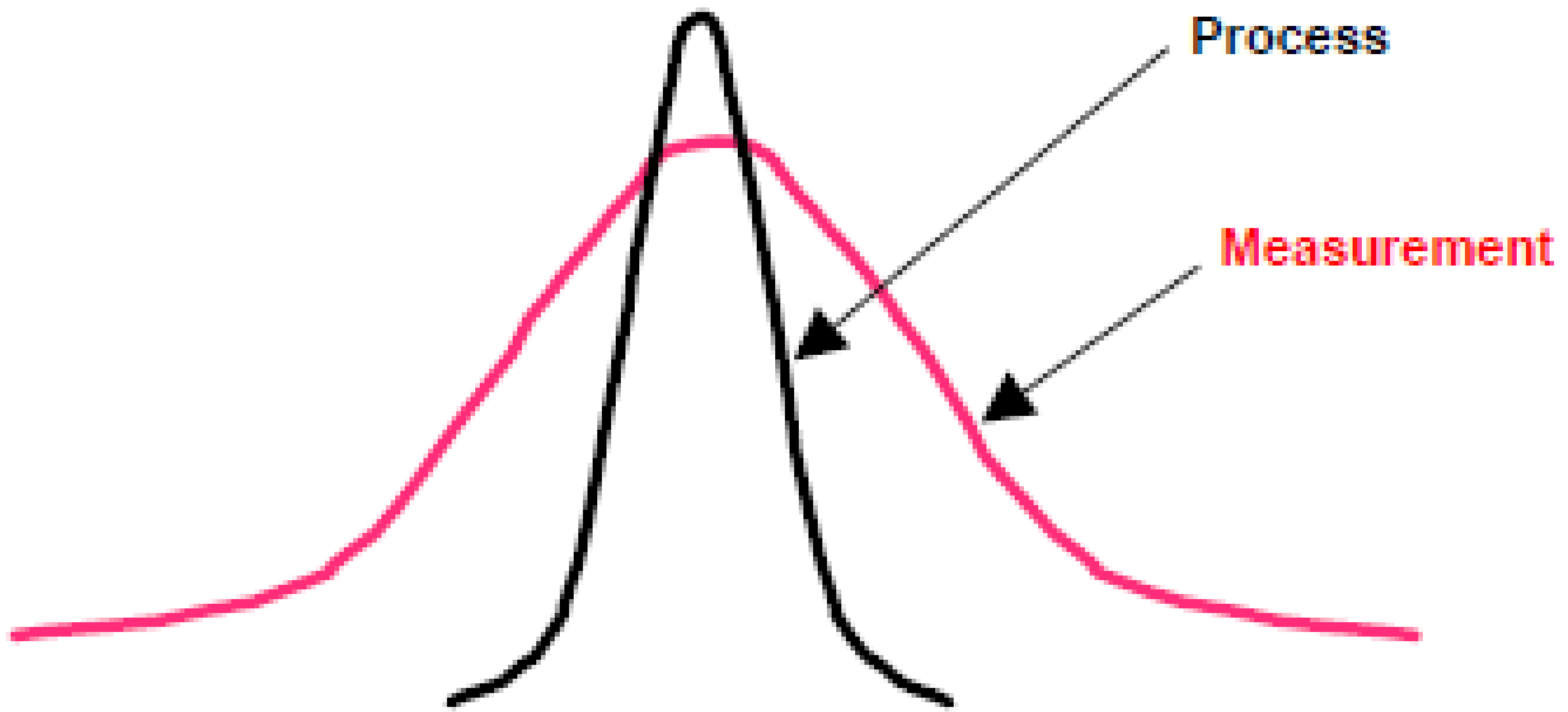
Measurement System Analysis

Observed value = True value ± Measurement error



Measurement System Analysis

True variability = Process variability + Measurement variability



Measurement System Properties

System Characteristics

Accuracy

$\mu_{total} = \mu_{process} \pm \mu_{measurement}$

Precision

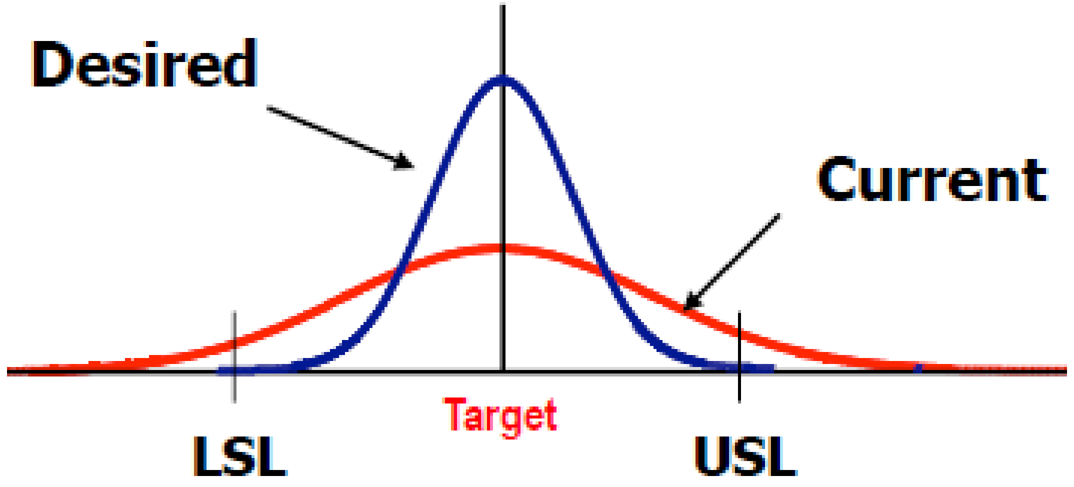
$\sigma^2_{total} = \sigma^2_{process} + \sigma^2_{measurement}$

To have stable measurement system, it is important to focus on the accuracy, first by addressing measurement issues and then getting accurate results.

Measurement System Properties

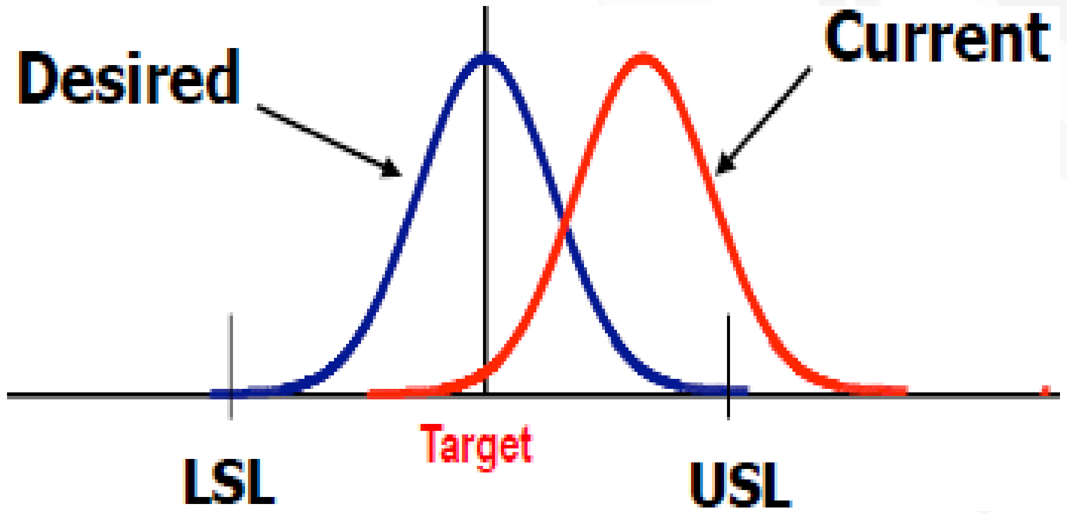
Accuracy

Degree of conformity of measured or calculated value to its actual or true value



Precision

Degree to which repeated measurements, under unchanged conditions, show the same results



Measurement System Properties

Accurate Precise

Not Accurate Precise

Accurate Not Precise

Not Accurate Not Precise

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Understand Measurement System Characteristics

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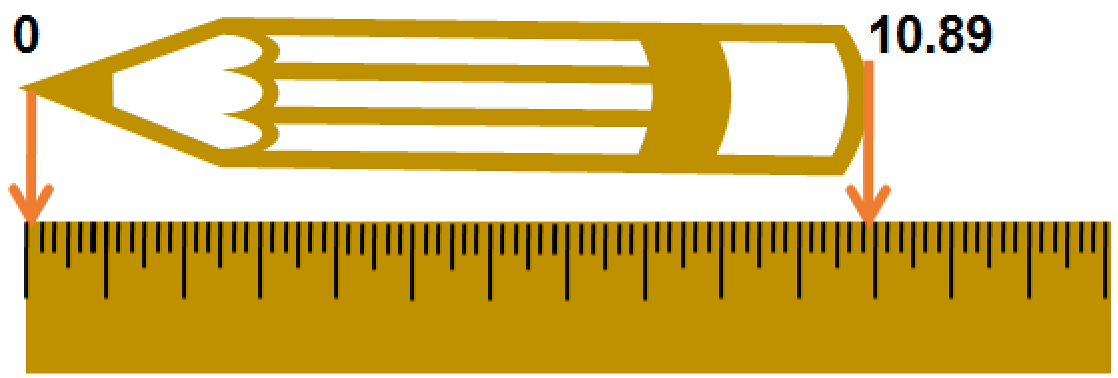
Measurement System Characteristics

- Measurement System Characteristics
  - Resolution
  - Accuracy
    - Bias
    - Linearity
    - Stability
  - Precision
    - Repeatability
    - Reproducibility

Measurement Characteristics: Resolution

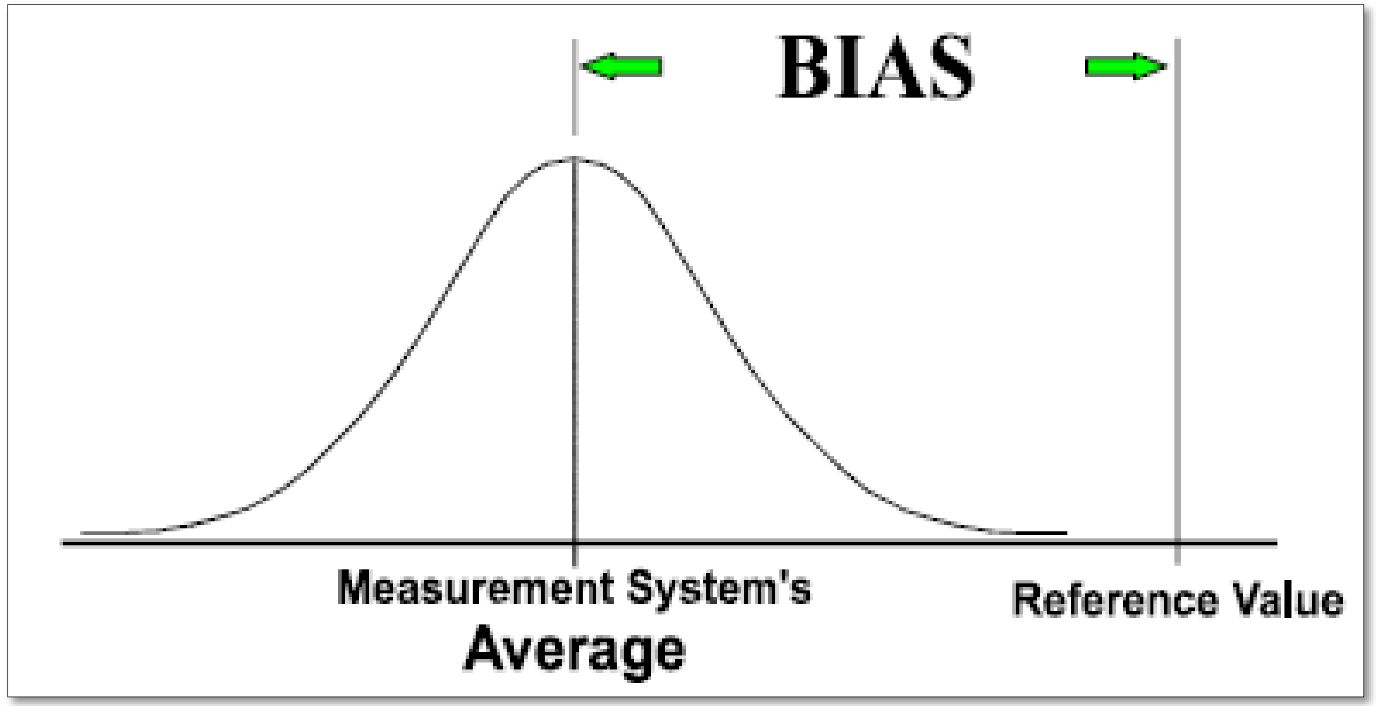
Resolution is the smallest reading the measurement scale can detect.



Resolution is the first characteristic that needs to be tested in an MSA.

Measurement Characteristics: Bias

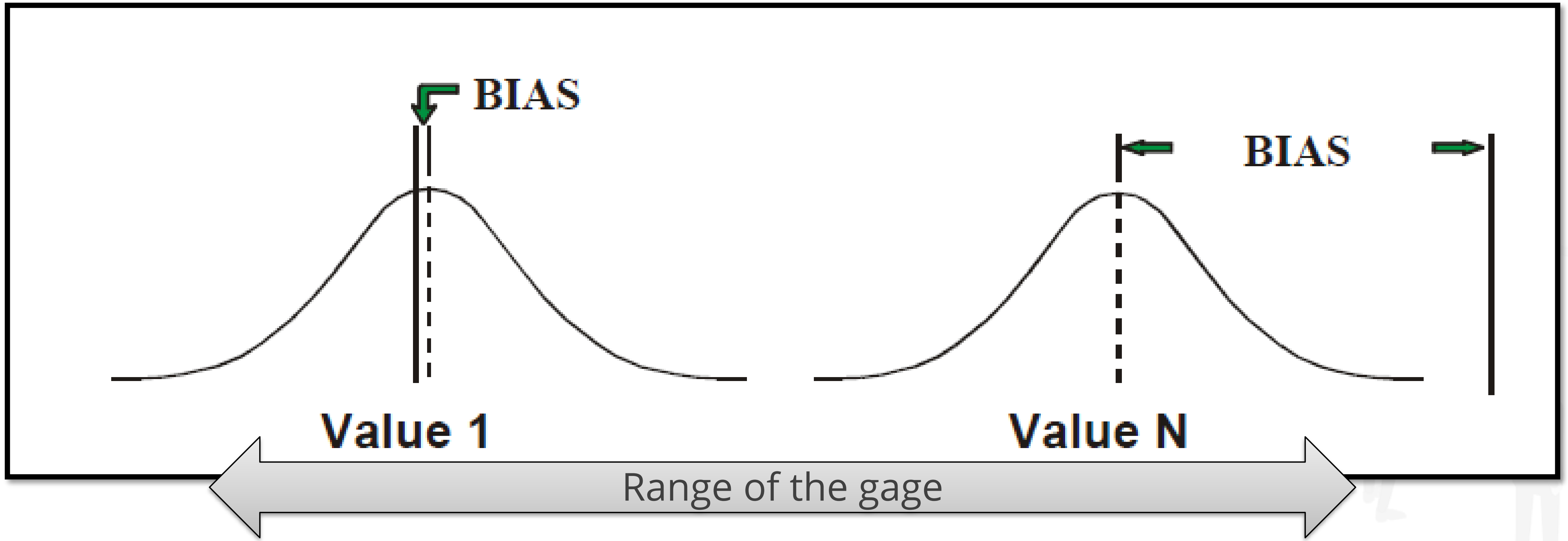
Bias is the measure of the distance between the measured value and the true or actual value.



Possible causes for bias are need for equipment calibration, improper calibration, or the wrong gage used for the job.

Measurement Characteristics: Linearity

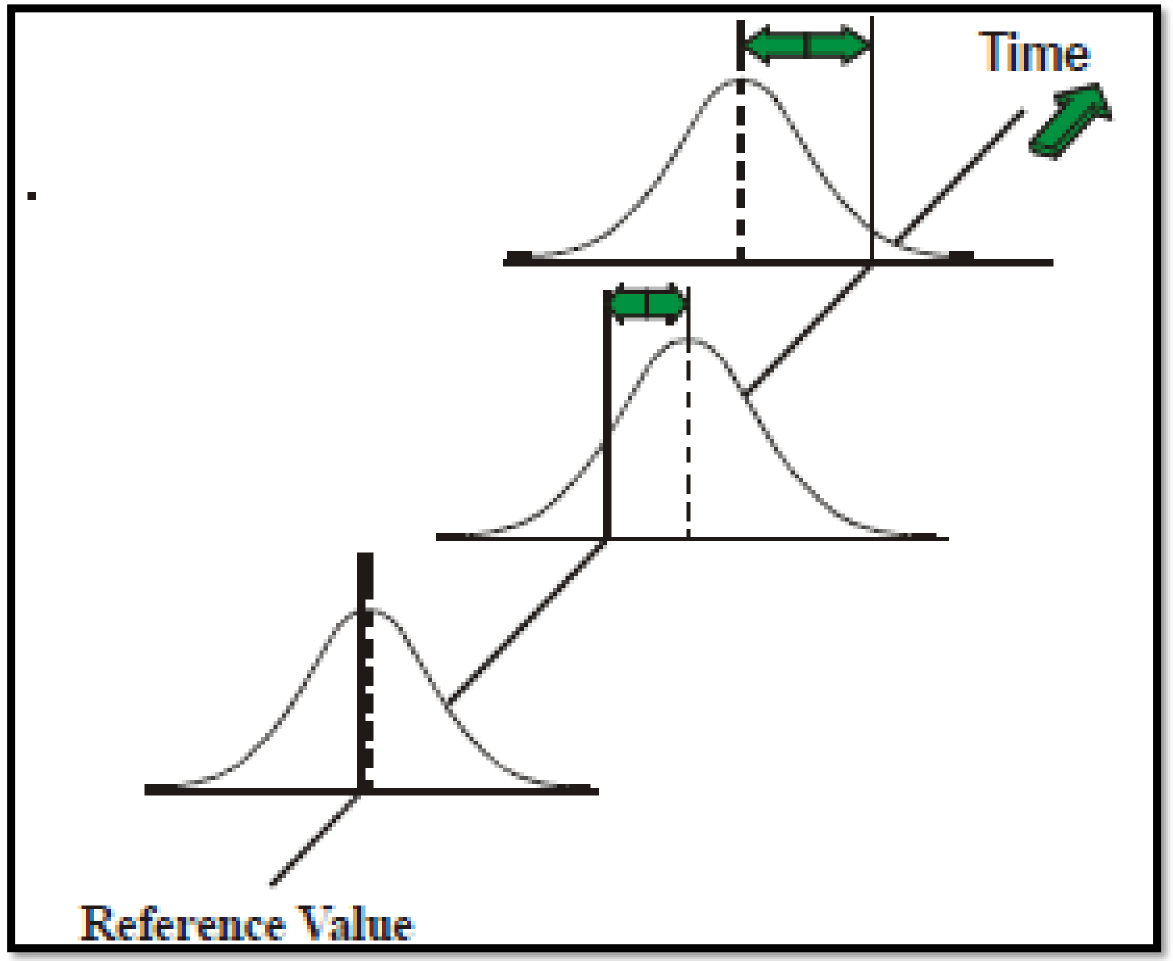
Linearity is a measure of consistency of bias over a range of measurement from the smallest number to a higher number and vice-versa.



Possible causes for linearity issues could be poor maintenance, worn instrument or equipment, or application measurement method.

Measurement Characteristics: Stability

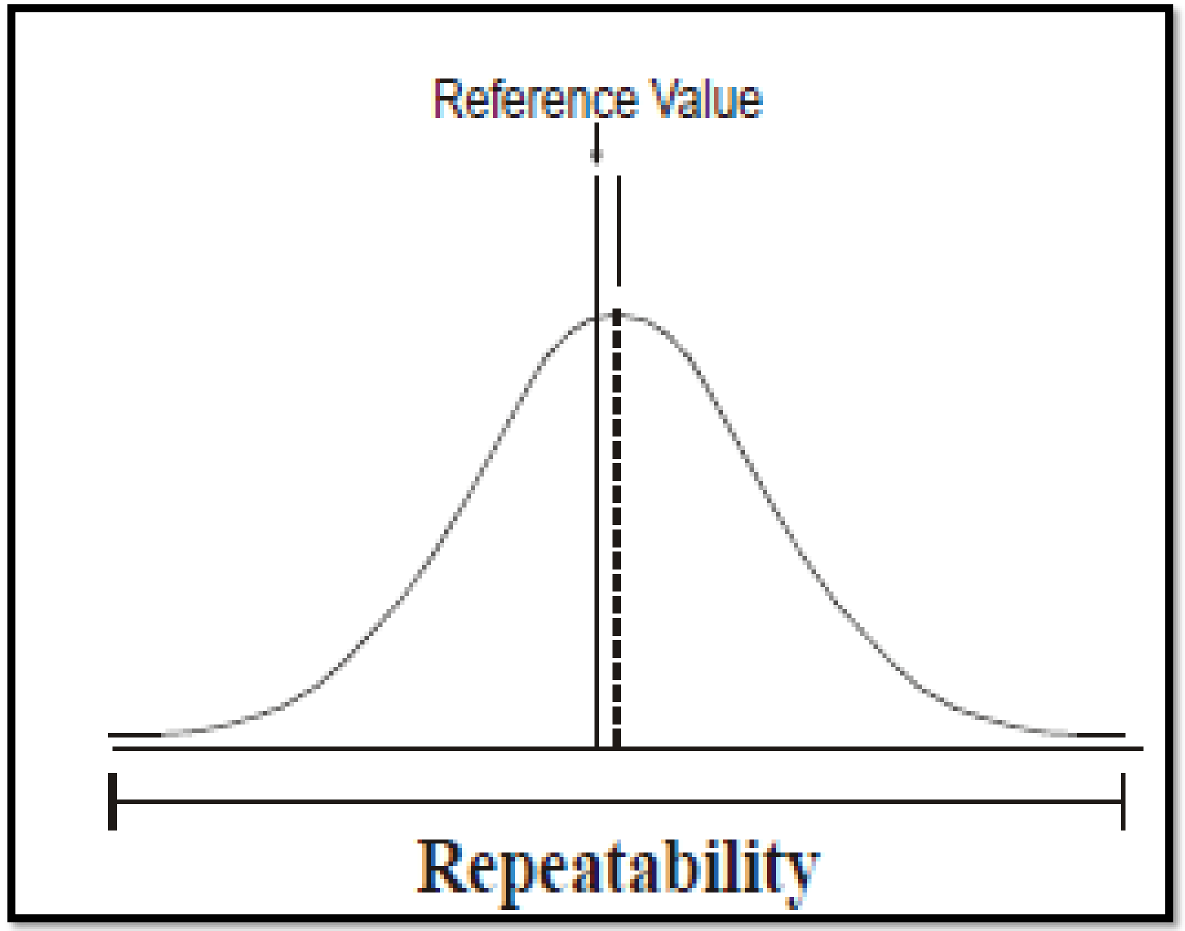
Stability refers to the ability of a measurement system to show the same values, every time the same item is measured.



Possible causes for instability issues are normal aging and worn instrument.

Measurement Characteristics: Repeatability

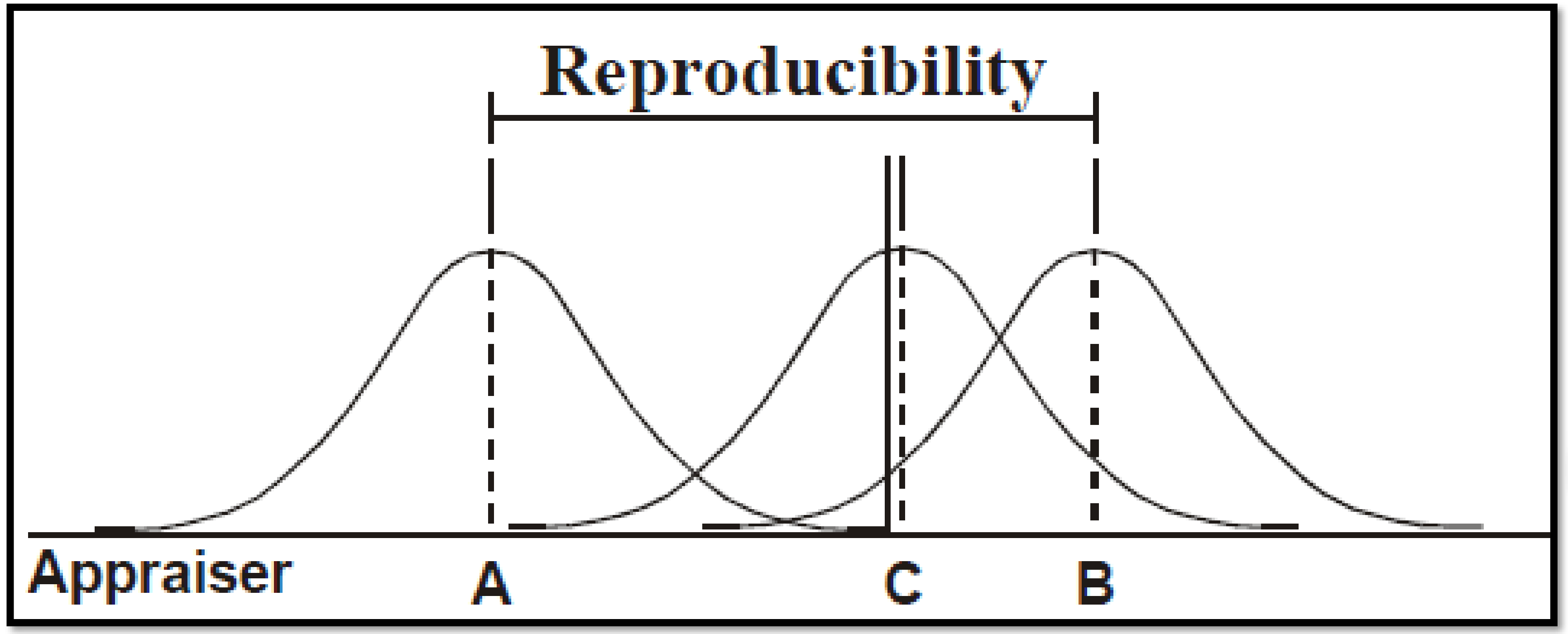
Repeatability is the variation in measurements obtained with one measurement instrument, when it is used several times by one appraiser while measuring the same characteristic on the same part, repeatedly.



Possible causes for repeatability variation could be appraiser technique, position on part where measurement is taken, and lack of training.

Measurement Characteristics: Reproducibility

Reproducibility is variation in the average of measurements made by different operators using the same gage when measuring identical characteristics of the same part.



Possible causes for reproducibility variation could be difference in operator training, technique, or experience.

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Measurement System Concepts

Measurement Correlation

Measurement Correlation is the strength of relationship of multiple measurement systems for use by quantifying accuracy relative to a Gold Standard or Gold Tester.

A Gold Standard is the measurement system used to determine and assign specifications values.

Precision / Tolerance (P/T)

Precision/Tolerance (P/T) addresses what percent of the tolerance is taken up by measurement error.

5.15 standard deviation is chosen as an industry standard and accounts for 99% of MS variation.

P/T is a ratio that is usually expressed as a percentage.

$$P/T = \frac{5.15 \ * \sigma_{MS}}{Tolerance}$$

Target: P/T < 30%

Tolerance is the difference between the upper and lower customer specification limit.

A measurement system is acceptable if P/T is less than 30%.

GAGE R&R and %GRR

Gage RR or Gage Repeatability and Reproducibility is a measure of measurement system variation.

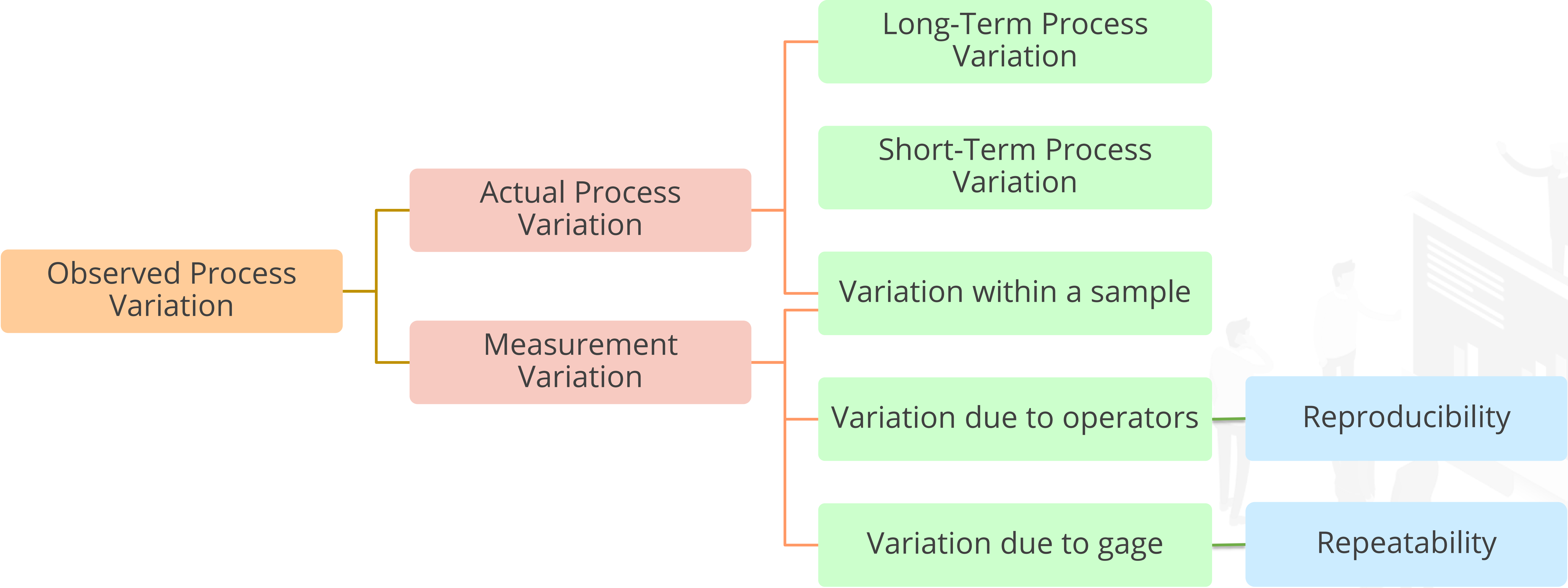
$$\sigma_{MS} = \sqrt{\sigma_{EV}{}^2 + \sigma_{AV}{}^2}$$

Percent Gage R and R is a measurement system capability index.

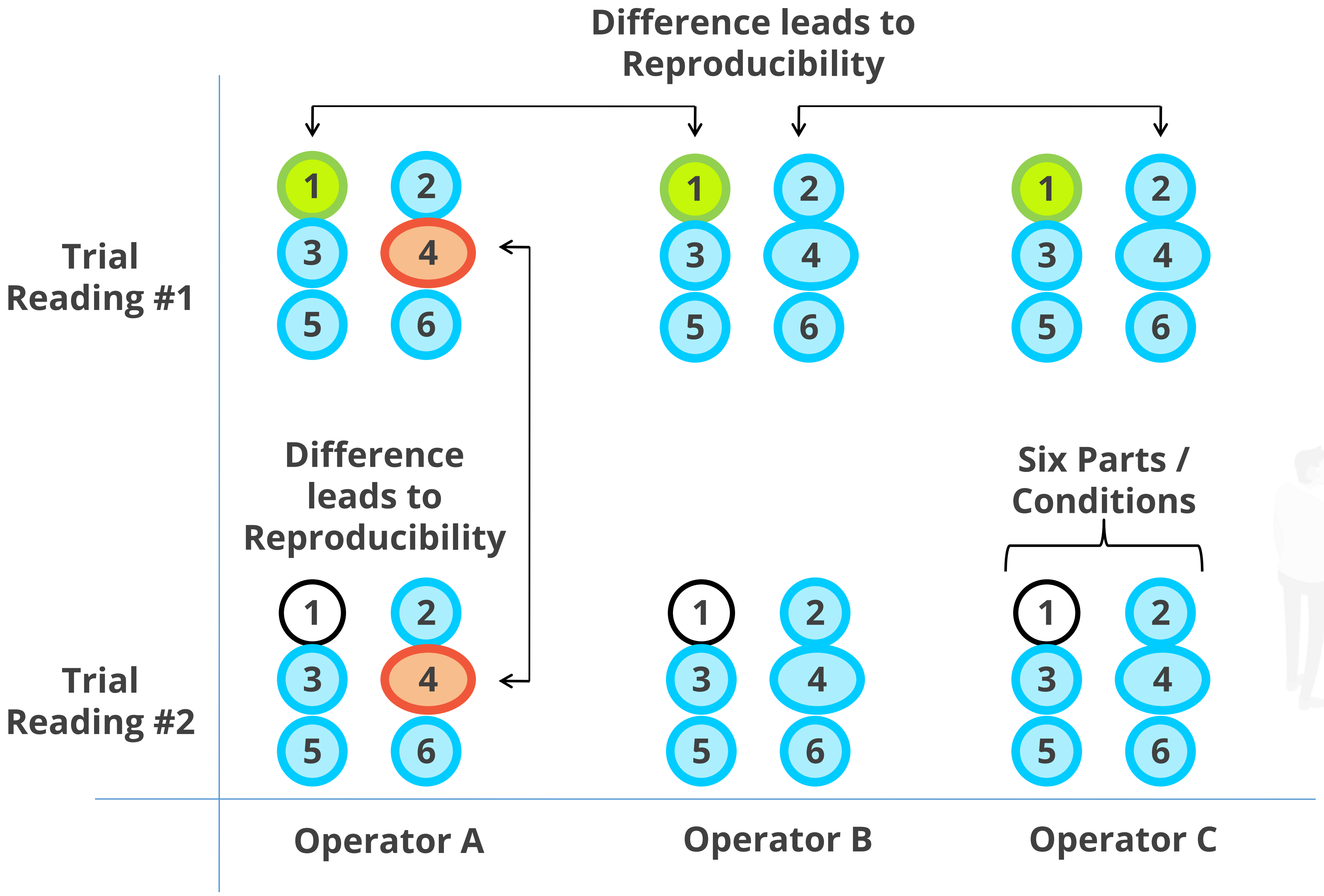
$$\%GRR = \frac{\sigma_{MS}}{\sigma_{Process}} * 100$$

Target: %GRR< 30%

Sources of Variation



GRR Study: Components



GRR Study: Guidelines

GRR studies should be performed over the range of expected observations

Actual equipment should be used

Written procedures or approved practices should be followed

Measurement variability should be presented as is

Measurement variability should be separated into causal components, prioritized, and targeted for action

GRR Study: Variable and Attribute Gage R&R

Variable Gage R&R

Analyzes measurement systems with the help of variable or continuous data

Measurement system typically involves a physical gage.

The result of this is quantification of the percentage of variation contributed by the measurement system.

Attribute Gage R&R

Analyzes measurement systems using attribute or discrete data

Measurement system typically utilizes manual or automated counting/monitoring.

The result of this is quantification of the proportion of defective measurements in DPMO, % Agreement, or Sigma Level.

Variable Gage R&R: Data Collection

The number of operators are usually 3.

The number of units to measure is usually 10.

General sampling techniques are used to represent the population.

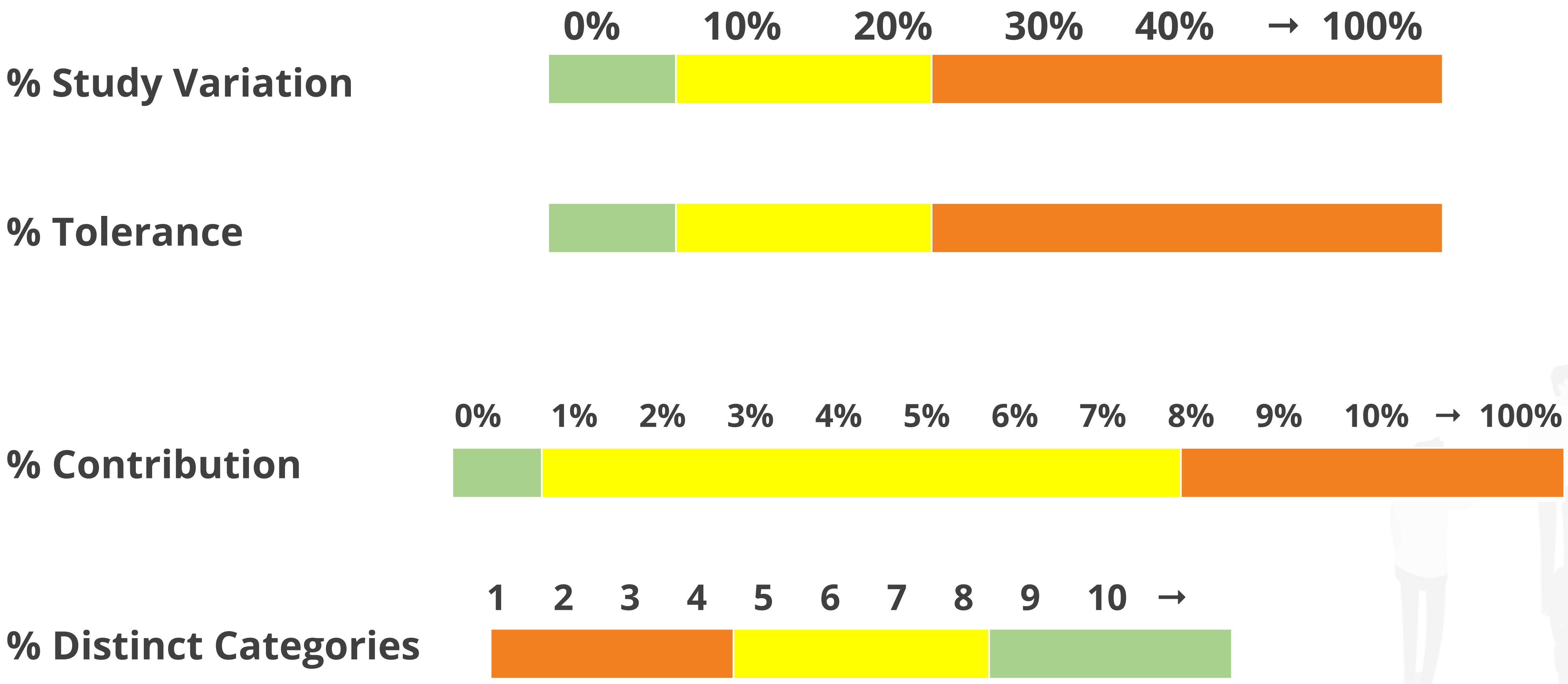
The number of trials for each operator is 2 to 3.

The gage is checked for calibration and resolution.

The units are measured by the first operator in random order, and the same order is followed by the other operators.

Each trial is repeated.

Variable Gage R&R: Four Criteria



It is important to assess these values to determine whether each value meets the requirement to ensure that the measurement system can reliably measure the process.

Variable Gage R&R

Average and Range Method

- For years, the most used method for Gage R&R was the Average and Range Method
- Many people refer to the AIAG's Measurement Systems Analysis Manual when doing Gage R&R studies
    - AIAG stands for Automotive Industry Action Group
- Calculates the % of the total variation, using standard deviation, that is due to the Gage R&R

ANOVA Method

- ANOVA is considered the best method for analyzing GRR studies due to the following reasons:
    - It separates equipment and operator variation and provides insight on the combined effect of the two.
    - It uses variance instead of standard deviation as a measure of variation and therefore gives a better estimate of the measurement system variation.
- Allows you to estimate the variance of the components

Variable Gage R&R: Continuous Gage R&R Example

Characteristics:	Outside Diameter	Gage Number:	1234	Performed by:	AJH
Specifications:	25 plus or minus 5	Gage Type:	Indicator		

Upper Spec	30	# of Trials =	3	K_1 =	0.5908	Xbar diff =	1.05	D_4 =	2.58
Lower Spec	20	# of appraisers =	3	K_2 =	0.5231	Rbarbar =	1.40951	R_p =	6.94476
Total Tol	10	# of parts =	10	K_3 =	0.3146				

Appraiser/Trial #		Part 1	2	3	4	5	6	7	8	9	10	Average
A	1	25.2853	27.2206	24.9934	29.1691	22.6385	25.6739	28.1287	22.6879	27.5386	27.6878	26.10238349
	2	24.3149	26.3773	26.3198	29.7438	22.398	24.5878	29.2963	22.988	25.1735	27.4172	25.86167087
	3	23.9702	27.5079	25.2571	29.5507	23.0531	26.3858	28.8585	22.9091	25.0981	26.3628	25.8953406
	Average	24.5235	27.0353	25.5235	29.4879	22.6965	25.5492	28.7612	22.8617	25.9367	27.1559	$Xbar_a$ = 25.9531
	Range	1.31504	1.13068	1.32638	0.57474	0.6551	1.79798	1.16761	0.30011	2.44047	1.32507	$Rbar_a$ = 1.20332
B	1	24.2795	26.4859	24.3112	29.4141	22.4786	24.9739	28.5552	22.9627	26.1618	26.9581	25.6580863
	2	24.6539	26.1579	25.1468	29.7305	23.5527	25.1368	27.5264	21.1795	25.6621	26.6376	25.53839788
	3	24.6816	25.7614	24.2967	29.7714	23.4755	25.5896	28.9718	21.3315	26.5696	26.7966	25.72457364
	Average	24.5383	26.1351	24.5849	29.6386	23.1689	25.2334	28.3511	21.8246	26.1312	26.7974	$Xbar_b$ = 25.6404
	Range	0.40219	0.72453	0.85009	0.35728	1.07411	0.61569	1.4454	1.78315	0.90758	0.3205	$Rbar_b$ = 0.84805
C	1	25.5592	26.49	25.2298	31.759	25.0551	28.2445	30.1261	23.5133	27.1405	28.0329	27.11504426
	2	24.5037	27.094	25.1838	29.3502	22.7241	27.1026	27.5052	22.8021	25.379	26.9182	25.85627872
	3	27.7377	25.6571	24.1554	28.4375	25.8523	28.7592	29.9997	24.0493	27.2547	29.0944	27.09974051
	Average	25.9335	26.4137	24.8563	29.8489	24.5438	28.0354	29.2103	23.4549	26.5914	28.0151	$Xbar_c$ = 26.6904
	Range	3.23396	1.43681	1.07436	3.32146	3.12815	1.6566	2.62097	1.24724	1.87571	2.17621	$Rbar_c$ = 2.17715
Part Average		24.9985	26.528	24.9882	29.6585	23.4698	26.2727	28.7742	22.7137	26.2198	27.3228	Xbarbar = 26.0946 R_p = 6.94476

[(Rbar a = 1.20331882984201 + Rbar b = 0.848052350183393 + Rbar c = 2.17714672507304) / # of appraisers = 3] = Rbarbar	Rbarbar = 1.40951
(Max Xbar = 26.6903544987033) - Min Xbar = 25.640352606906) = Xbar diff	Xbar diff = 1.05
(Rbarbar = 1.40950596836615) x (D4 = 2.58) = UCL R	UCL R = 3.63653

Variable Gage R&R: Continuous Gage R&R Example

Part No. & Name:	123456, Shaft	Gage Name:	Shaft Gage	Date:	March 30th
Characteristics:	Outside Diameter	Gage Number:	1234	Performed by:	AJH
Specifications:	25 plus or minus 5	Gage Type:	Indicator		

Upper Spec	30	# of Trials =	3	K_1 =	0.5908	Xbar diff =	1.05	D_4 =	2.58
Lower Spec	20	# of appraisers =	3	K_2 =	0.5231	Rbarbar =	1.40951	R_p =	6.94476
Total Tol	10	# of parts =	10	K_3 =	0.3146				

Measurement Unit Analysis

Repeatability – Equipment Variation (EV)

EV = (Rbarbar) x (K_1)
= (1.40950596836615) x (0.5908)
= 0.8327

Trials	K_1
2	0.8862
3	0.5908

Reproducibility – Appraiser Variation (AV)

AV = SQRT{(Xbar diff x K 2)^2 – (EV/[(# parts) x (# trials)])}
= SQRT(0.3017 – 0.0231)
= 0.5278

Appraisers	2	3
K2	0.7071	0.5231

Repeatability & Reproducibility (GRR)

GRR = SQRT[(EV^2) + (AV^2)]
= SQRT [0.6934 + 0.2786]
= 0.9859

Part Variation (PV)

PV = R_p x K_3
= 2.1848

Total Variation (TV)

TV = SQRT[(GRR^2) + (PV^2)]
= SQRT [0.972 + 4.7734]
= 2.3969

Parts	K_3
2	0.7071
3	0.5231
4	0.4467
5	0.403
6	0.3742
7	0.3534
8	0.3375
9	0.3249
10	0.3146

% Total Variation

Percent Equipment Variation

%EV = 100 [EV / TV]
= 100 [0.8327 / 2.3969]
= 34.741 %

Percent Appraiser Variation

%AV = 100 [AV / TV]
= 100 [0.5278 / 2.3969]
= 22.020 %

Percent Gage Repeatability & Reproducibility Variation

%GRR = 100 [GRR / TV]
= 100 [0.9859 / 2.3969]
= 41.132 %

Percent Part Variation

%PV = 100 [PV / TV]
= 100 [2.1848 / 2.3969]
= 91.151 %

Number of Distinct Categories that can be Distinguished

ndc = 1.41(PV / GRR)
= 1.41 (2.1848 / 0.9859)
= 3.125 or approximately: 3

Variable Gage R&R: Continuous Gage R&R Example

Part No. & Name:	123456, Shaft	Gage Name:	Shaft Gage	Date:	March 30th
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Total Tol	10	# of parts =	10	K_3 =	0.3146				

Measurement Unit Analysis

Repeatability – Equipment Variation (EV)

EV = (Rbarbar) x (K_1) x (5.1 Sigma)
= (1.40950596836615) x (0.5908) x (5.1)
= 4.247

Trials	K_1
2	0.8862
3	0.5908

Reproducibility – Appraiser Variation (AV)

AV = (5.1 Sigma) x SQRT{(Xbar diff x K 2)^2 – (EV/[(# parts) x (# trials)])}
= (5.1) x SQRT(0.3017 – 0.0231)
= 2.6918

Appraisers	2	3
K2	0.7071	0.5231

Repeatability & Reproducibility (GRR)

GRR = SQRT[(EV^2) + (AV^2)]
= SQRT [18.037 + 7.2458]
= 5.0282

Part Variation (PV)

PV = (R_p) x (K_3) x (5.1 Sigma)
= (6.94476344409127) x (0.3146) x (5.1)
= 11.1425

Parts	K_3
2	0.7071
3	0.5231
4	0.4467
5	0.403
6	0.3742
7	0.3534
8	0.3375
9	0.3249
10	0.3146

Total Tolerance (Total Tol)

TV = Upper Spec – Lower Spec
= 30 – 20
= 10

% Total Tolerance

Percent Equipment Variation

%EV = 100 [EV / Total Tol]
= 100 [4.247 / 10]
= 42.470 %

Percent Appraiser Variation

%AV = 100 [AV / Total Tol]
= 100 [2.6918 / 10]
= 26.918 %

Percent Gage Repeatability & Reproducibility Variation

%GRR = 100 [GRR / Total Tol]
= 100 [5.0282 / 10]
= 50.282 %

Percent Part Variation

%PV = 100 [PV / Total Tol]
= 100 [11.14248 / 10]
= 111.425 %

Number of Distinct Categories that can be Distinguished

ndc = 1.41(PV / GRR)
= 1.41 (11.14248 / 5.0282)
= 3.125 or approximately: 3

Variable Gage R&R: Continuous Gage R&R Example

Gage R&R Study - ANOVA Method

Variance and Standard Deviation Components

Source	St. Dev.	Variance	% of Variance
Total Gage R&R	1.039055	1.079634	19.00%
Repeatability	0.867345	0.752287	13.24%
Reproducibility	0.572143	0.327347	5.76%
Operator	0.508623	0.258697	4.55%
Operator*Part	0.262011	0.06865	1.21%
Part to Part	2.145093	4.601422	81.00%
Total Variation	2.383497	5.681056	100.00%

Process Tolerance = 10

Gage R&R Using 5.15 Standard Deviations (99%)

Source	Study Variation	% Study Variation	% of Tolerance
Total Gage R&R	5.351131	43.59%	53.51%
Repeatability	4.466826	36.39%	44.67%
Reproducibility	2.946535	24.00%	29.47%
Operator	2.619409	21.34%	26.19%
Operator*Part	1.349357	10.99%	13.49%
Part to Part	11.04723	90.00%	110.47%
Total Variation	12.27501	100.00%	122.75%

ndc = 2

Gage R&R Study - Xbar/Range Method

Variance and Standard Deviation Components

Source	St. Dev.	Variance	% of Variance
Total Gage R&R	0.9859	0.971999	16.92%
Repeatability	0.8327	0.693389	12.07%
Reproducibility	0.5278	0.278573	4.85%
Part to Part	2.1848	4.773351	83.09%
Total Variation	2.3969	5.74513	100.00%

Process Tolerance = 10

Gage R&R Using 5.15 Standard Deviations (99%)

Source	Study Variation	% Study Variation	% of Tolerance
Total Gage R&R	5.077385	41.13%	50.77%
Repeatability	4.288405	34.74%	42.88%
Reproducibility	2.71817	22.02%	27.18%
Part to Part	11.25172	91.15%	112.52%
Total Variation	12.34404	100.00%	123.44%

ndc = 3

Variable Gage R&R: Interpretation

Check the value of %GRR.

If %GRR < 30, Gage Variation is acceptable, and thus the gage is acceptable. If %GRR > 30, the gage is not acceptable.

Check EV first.

If EV = 0, the MS is reliable and the variation in the gage is contributed by different operators. If AV = 0, the MS is precise.

If EV = 0, resolve AV by providing operators with training.

Attribute Data: Data Collection in GR&R

- Select between 20 to 30 samples that represent full range of variation
- 50:50 mix of good/bad parts is recommended
- Have master appraiser categorize each of the test sample as good or bad
- Take two or three inspectors and have them assess each test sample
- Randomize samples and repeat assessment

Attribute Data: Example

Test Samples	Master/Expert	Operator1_1	Operator1_2	Operator2_1	Operator2_2	Operator3_1	Operator3_2
1	okay	okay	okay	okay	okay	okay	okay
2	defective	defective	defective	defective	defective	defective	defective
3	okay	okay	defective		okay	okay	okay
4	okay	okay	okay	okay	okay	okay	okay
5	okay	okay	defective	okay	okay	okay	okay
6	okay	okay	okay	okay	okay	okay	okay
7	okay	okay	okay	okay	okay	okay	okay
22	defective	defective	defective	defective	defective	defective	defective
23	defective	defective	defective	defective	defective	defective	defective
24	okay	okay	okay	okay	okay	okay	okay
25	okay	defective	defective	defective	defective	defective	defective
26	defective	defective	defective	defective	defective	defective	defective
27	okay	okay	okay	okay	okay	okay	okay
28	okay	okay	okay	okay	okay	okay	okay
29	okay	defective	defective	okay	okay	okay	defective
30	okay	defective	okay	okay	okay	okay	okay

Attribute Data: Example

Operator1_1	Operator1_2	Within Op1	Op1 with Standard
okay	okay	1	1
defective	defective	1	1
okay	defective	0	0
okay	okay	1	1
okay	defective	0	0
okay	okay	1	1
okay	okay	1	1
defective	defective	1	1
defective	defective	1	1
okay	okay	1	1
defective	defective	1	0
defective	defective	1	1
okay	okay	1	1
okay	okay	1	1
defective	defective	1	0
defective	okay	0	0
	#Matched	27	27
	#Inspected	30	30
	%Agree	**90.00%**	**80.00%**

Test Samples	Master/Expert	Operator1_1	Between Ops Match	All Ops versus Standard
1	okay	okay	1	1
2	defective	defective	1	1
3	okay	okay	0	0
4	okay	okay	1	1
5	okay	okay	0	0
6	okay	okay	1	1
7	okay	okay	1	1
22	defective	defective	1	1
23	defective	defective	1	1
24	okay	okay	1	1
25	okay	defective	1	0
26	defective	defective	1	1
27	okay	okay	1	1
28	okay	okay	1	1
29	okay	defective	0	0
30	okay	defective	0	0
			25	24
			30	30
			83.33%	**80.00%**

Attribute Data: Example

Decision	Effectiveness	Miss Rate	False Alarm Rate
Acceptable for the appraiser	> 90%	< 2%	< 5%
Marginally acceptable for the appraiser	80% to 90%	2% to 5%	5%to 10%
Unacceptable for the appraiser	< 80%	> 5%	> 10%

Interpretation of MSA

- MSA Result
  - Reproducibility Error > Repeatability Error
    - Operators are not adequately trained in using the gage
    - Calibrations on the gage dial are not clear
  - Repeatability Error > Reproducibility Error
    - Gage needs maintenance
    - Gage needs redesign to be more rigid
    - Gaging location needs improvement
    - Ambiguity is present in SOPs

Key Takeaways

- A Measurement System Analysis (MSA) is needed prior to any data collection activities.
- There are two major system characteristics: accuracy and precision.
- An MSA will help determine if the measurement system characteristics exist.
- The measurement system concepts are Measurement correlation, gage RR and % GRR, and Precision/Tolerance (P/T).
- Gage R&R studies can be conducted for variable and attribute data.
- Average and Range Method and ANOVA Method are the two methods for analyzing GRR Studies.

Knowledge Check

Knowledge Check 1

A team studies the results from measurement system analysis of plate thickness and determines that the average values observed is 3.5 cm, with values close together, and the true value is 4.0 cm. How can the measurement system be described?

A. Low Accuracy, High Precision

B. Low Accuracy, Low Precision

C. High Accuracy, High Precision

D. High Accuracy, Low Precision

Knowledge Check 1

A team studies the results from measurement system analysis of plate thickness and determines that the average values observed is 3.5 cm, with values close together, and the true value is 4.0 cm. How can the measurement system be described?

A. Low Accuracy, High Precision

B. Low Accuracy, Low Precision

C. High Accuracy, High Precision

D. High Accuracy, Low Precision

The correct answer is **A**

The scenario described here is of low accuracy (average observed value does not equal target value) and high precision (the values are close together).

Knowledge Check 2	The change or lack of change of a measurement system readings of the same part over time is an example of _______.

A. Linearity

B. Stability

C. Repeatability

D. Reproducibility

Knowledge Check

2

The change or lack of change of a measurement system readings of the same part over time is an example of _______.

A. Linearity

B. Stability

C. Repeatability

D. Reproducibility

The correct answer is **B**

The change or lack of change of a measurement system readings of the same part over time is an example of stability.

Knowledge Check

3

A team has measured the thickness of a part over and over and has compared the average observed value to the actual value. The difference between the average observed value and the actual value is called:

A. Linearity

B. Bias

C. Stability

D. Gage R&R

Knowledge Check

3

A team has measured the thickness of a part over and over and has compared the average observed value to the actual value. The difference between the average observed value and the actual value is called:

A. Linearity

B. Bias

C. Stability

D. Gage R&R

The correct answer is **B**

Bias is the measurement characteristic described as the difference between the average observed value and a reference value.

Knowledge Check

4

What is the major difference between the ANOVA and Average and Range method for Gage R&R study?

A. The results are significantly different

B. ANOVA is based on standard deviation and the Average and Range method is based on variance

C. There is no difference

D. ANOVA is based on variance and the Average and Range method is based on standard deviation

Knowledge Check 4

What is the major difference between the ANOVA and Average and Range method for Gage R&R study?

A. The results are significantly different

B. ANOVA is based on standard deviation and the Average and Range method is based on variance

C. There is no difference

D. ANOVA is based on variance and the Average and Range method is based on standard deviation

The correct answer is **D**

ANOVA is based on variance and the Average and Range method is based on standard deviation which causes a slight difference in calculations.

Knowledge Check 5

To conduct a continuous Gage R&R study, how many sample parts are needed?

A. 10

B. 20

C. 25

D. 3

Knowledge Check
5

To conduct a continuous Gage R&R study, how many sample parts are needed?

A. 10

B. 20

C. 25

D. 3

The correct answer is **A**

For a continuous Gage R&R study, ideally 10 parts are recommended that represent the range of output possibilities from the process.