Quality & robustness of manufacturing processes

MPR034

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Avdelning Konstruktionsmaterial | Divison of Engineering Material

Content

1. General fundament of continuous improvement in operations
2. Process development in context: VOP vs. VOC
3. Statistical Process Control, SPC
   - Natural behavior of process: self-study exercise
4. Process capability, C_p & C_{pk}
5. Data quality – Precision vs. Accuracy
6. Constructive alignment with courses ahead

Necessary cornerstones when building a Continuous Improvement (CI) culture

Are we solving the right problem?

PULL-thinking
Base for new solutions

y <-> Y

Effective scoping: how to scope an improvement projects to avoid ‘running for a solution’
(PPU215 – research methodology – compulsory in SP3)

Data Quality

Do we have the <u>right</u> resolution to see it properly?

Data quality practices trained in **TRA105 – Stat Eng Practices for industrial development** (elective SP4)

Do we see the problem the same way?

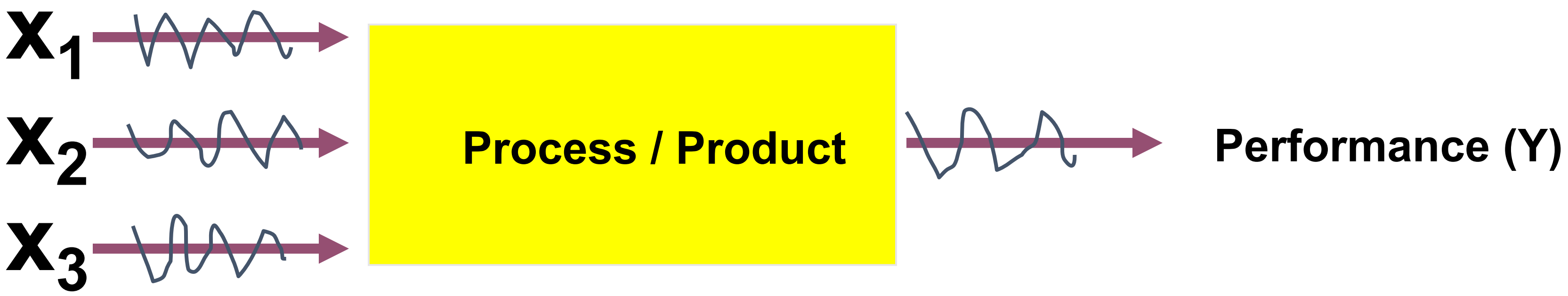
Visualization of variation (Qn/Qv)

Discovers are done on data not in meetings!
EDA ialso ntroduced in PPU215

"Variation (instability, unwanted changes, …)
- is the main enemy to all mass production!

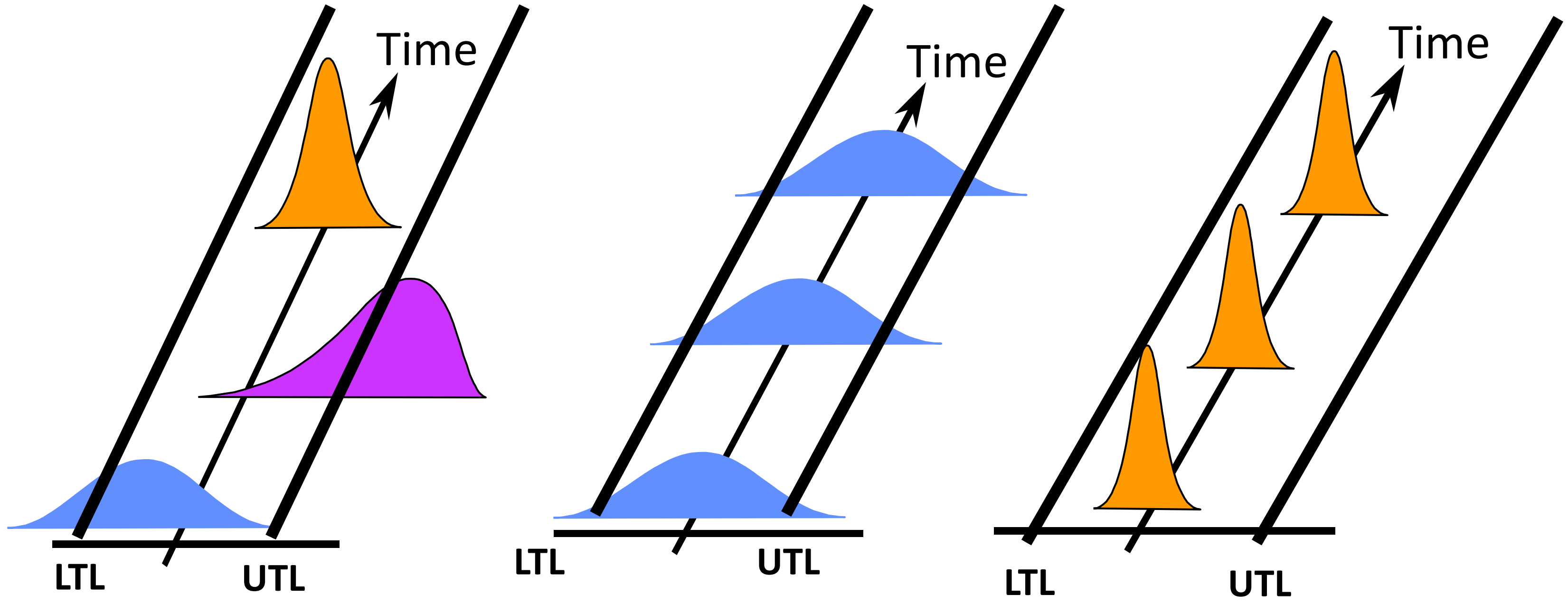
A successful reduction of it will invariably simplify processes, reduce losses and lower cost"

Box, Bisgaard 1988



From prototypes to mass production

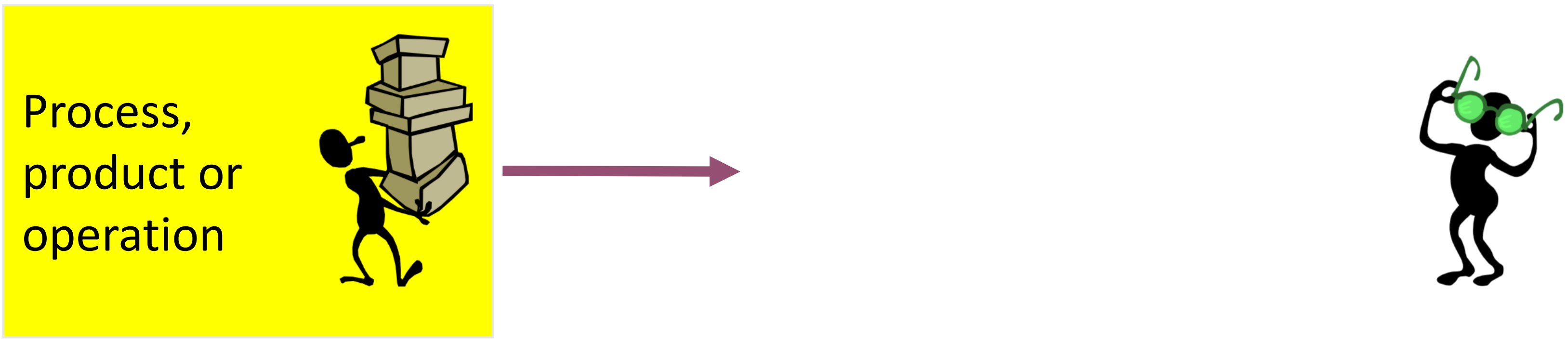
80% of the work left...



	Past	Now	Future
Inventory?	High	Lower	Low
Inspection?	Everywhere	Limited	Unnecessary
Ramp-up time?	Never ending	Shorter	Really short

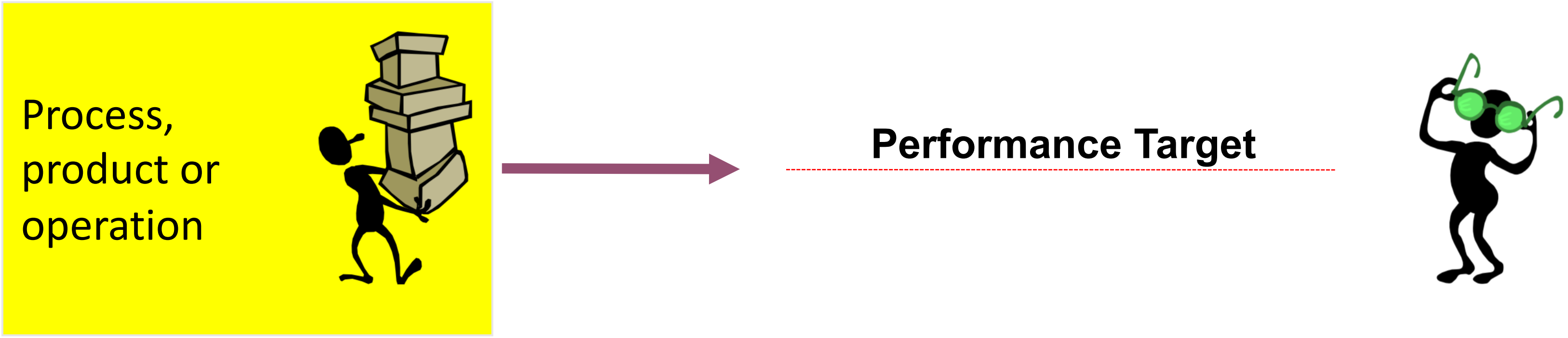
A process, product or operation is doing something for someone

(a customer or context)



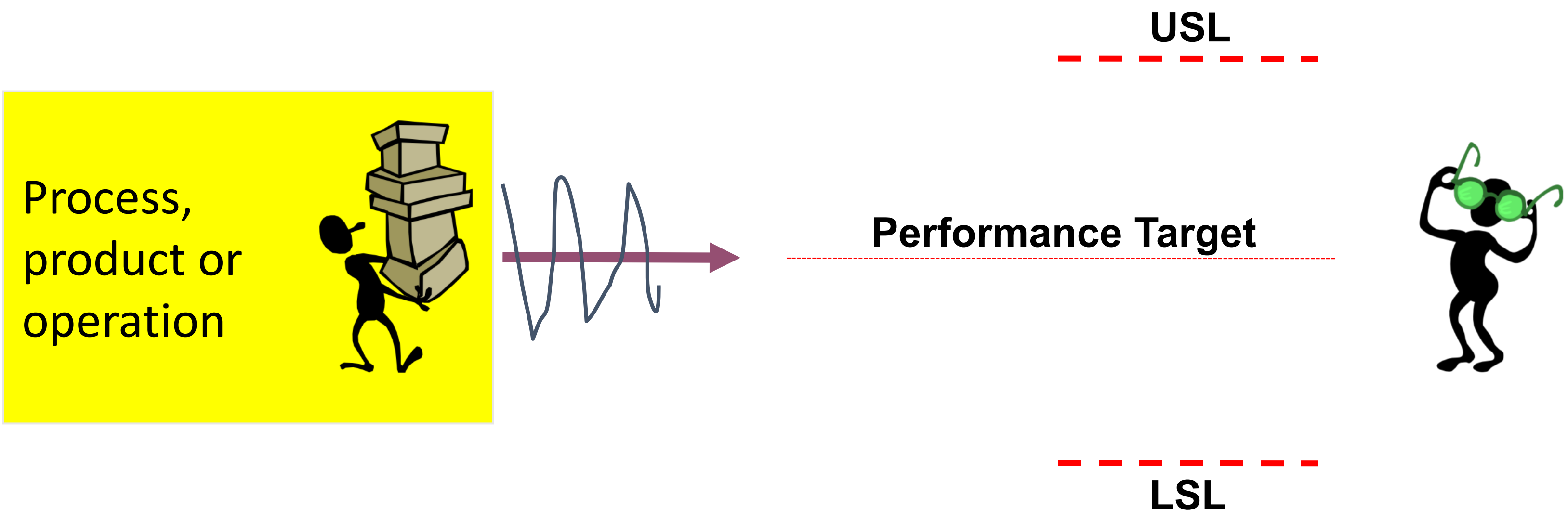
That particular someone typically has a requirement of what is delivered

(monitored with a KPI – Key Performance Indicator)



Since everything vary the customer usually accept deliveries within some specification limits

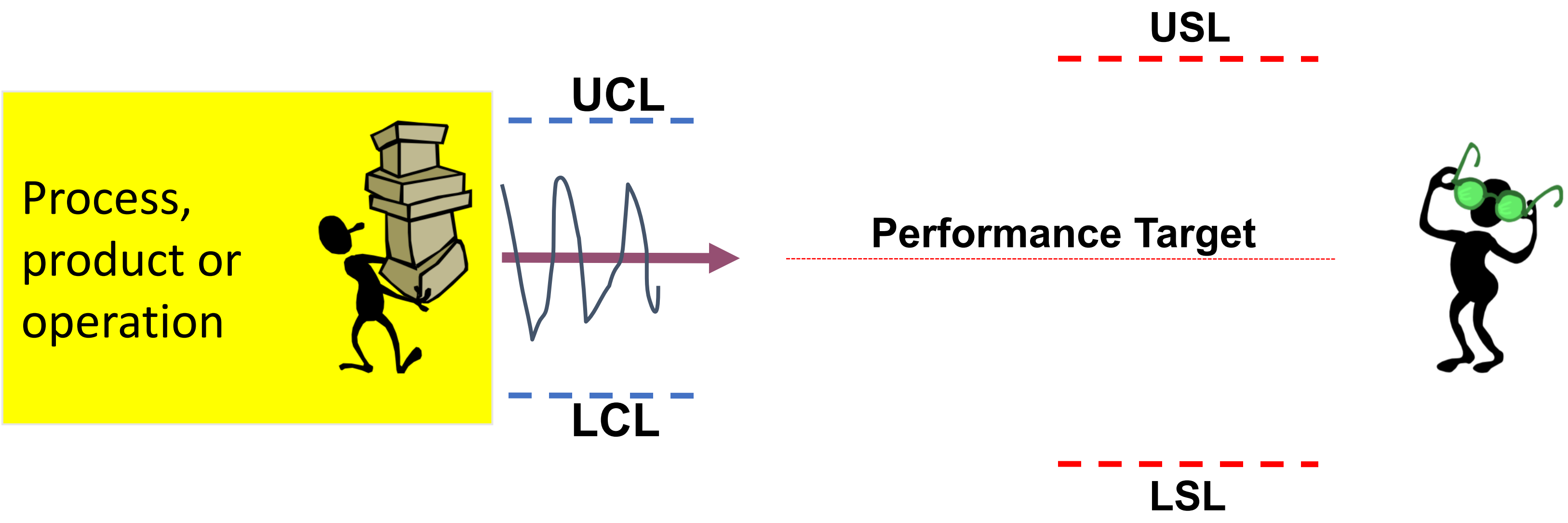
Upper Spec. Limit (USL) and Lower Spec. Limit (LSL)

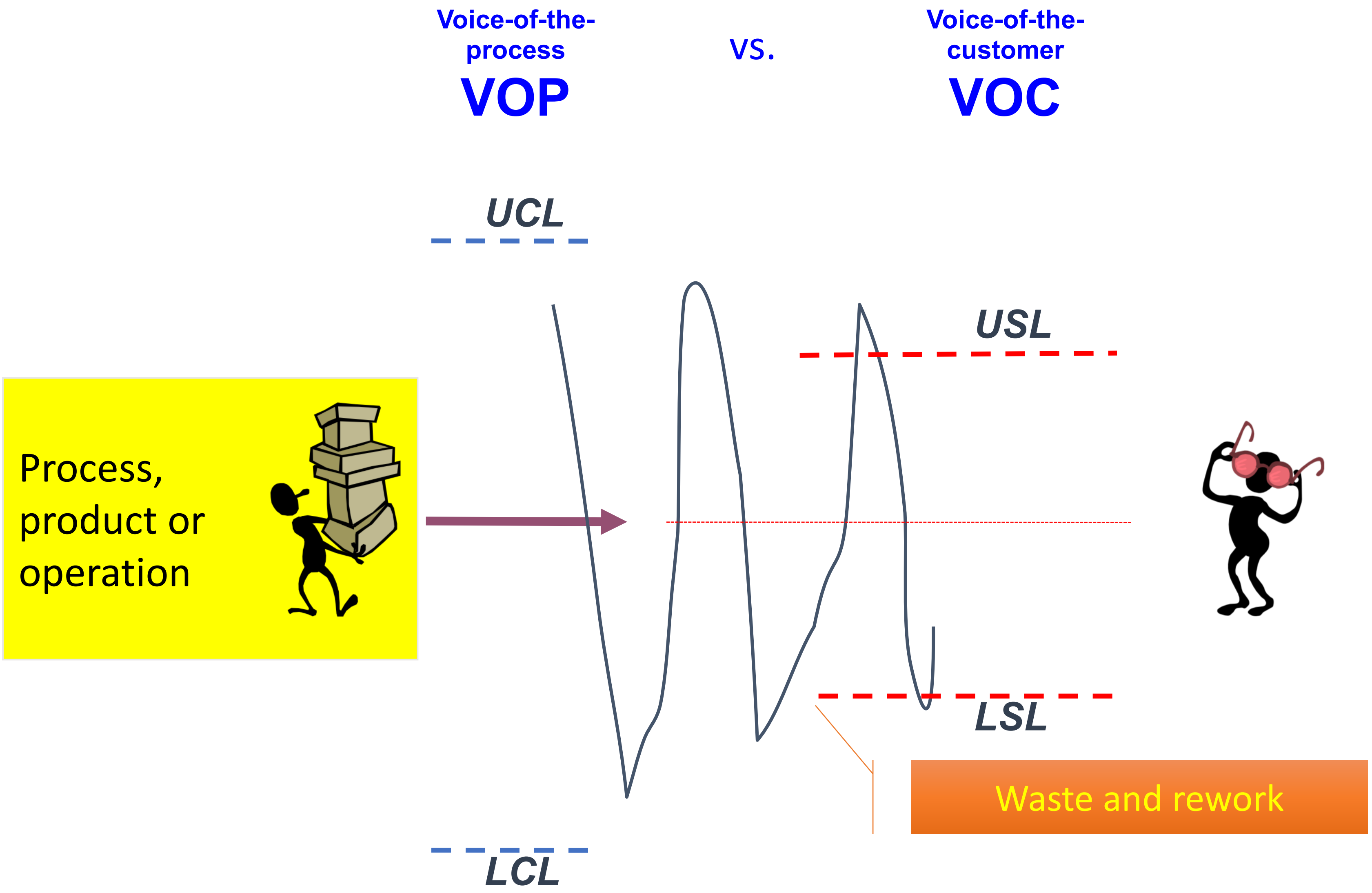


And a stable predictable process (product or operation) varies between control limits

Upper control limit (UCL) and Lower Control Limit (LCL)

the natural process behavior

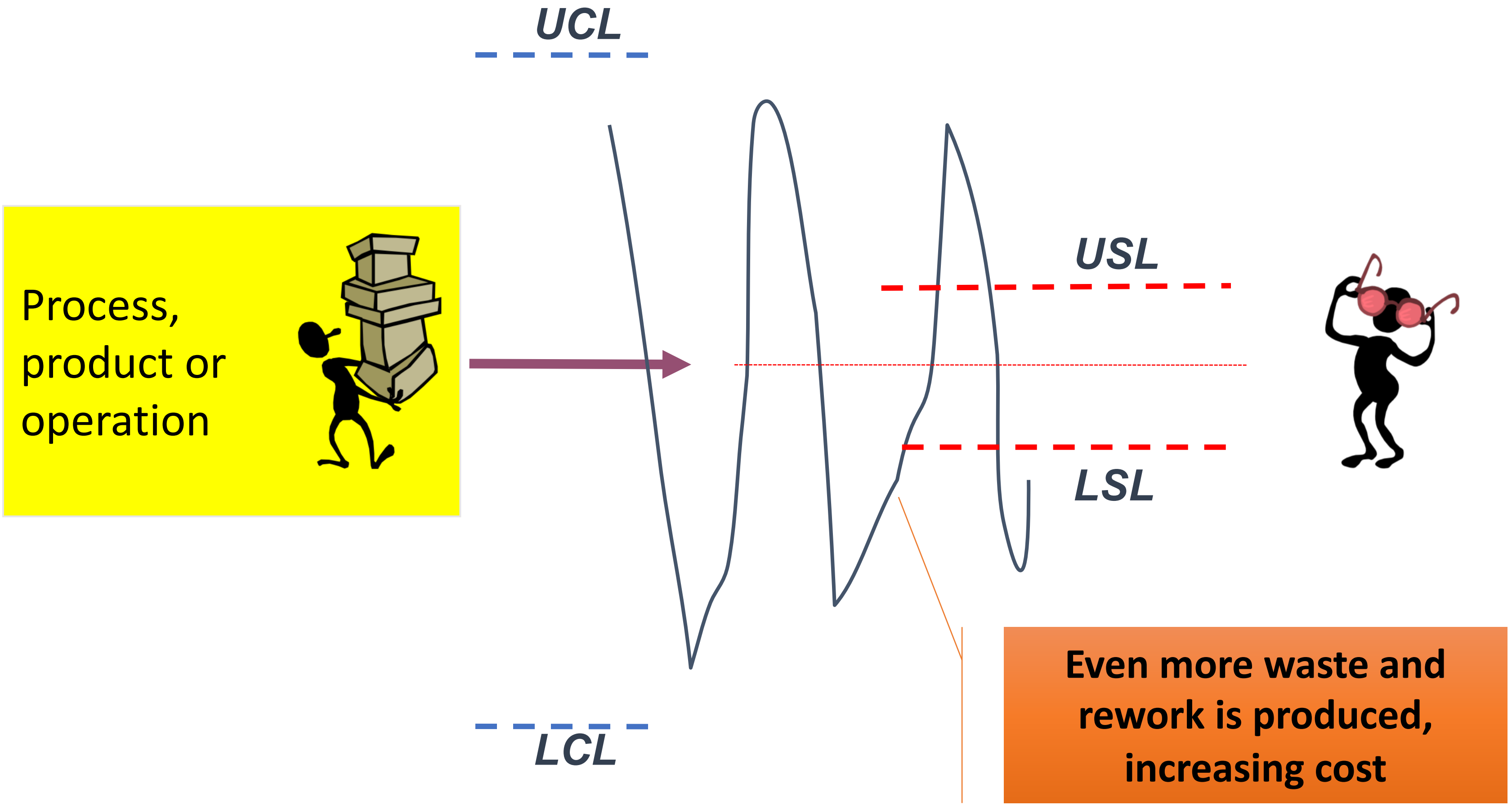


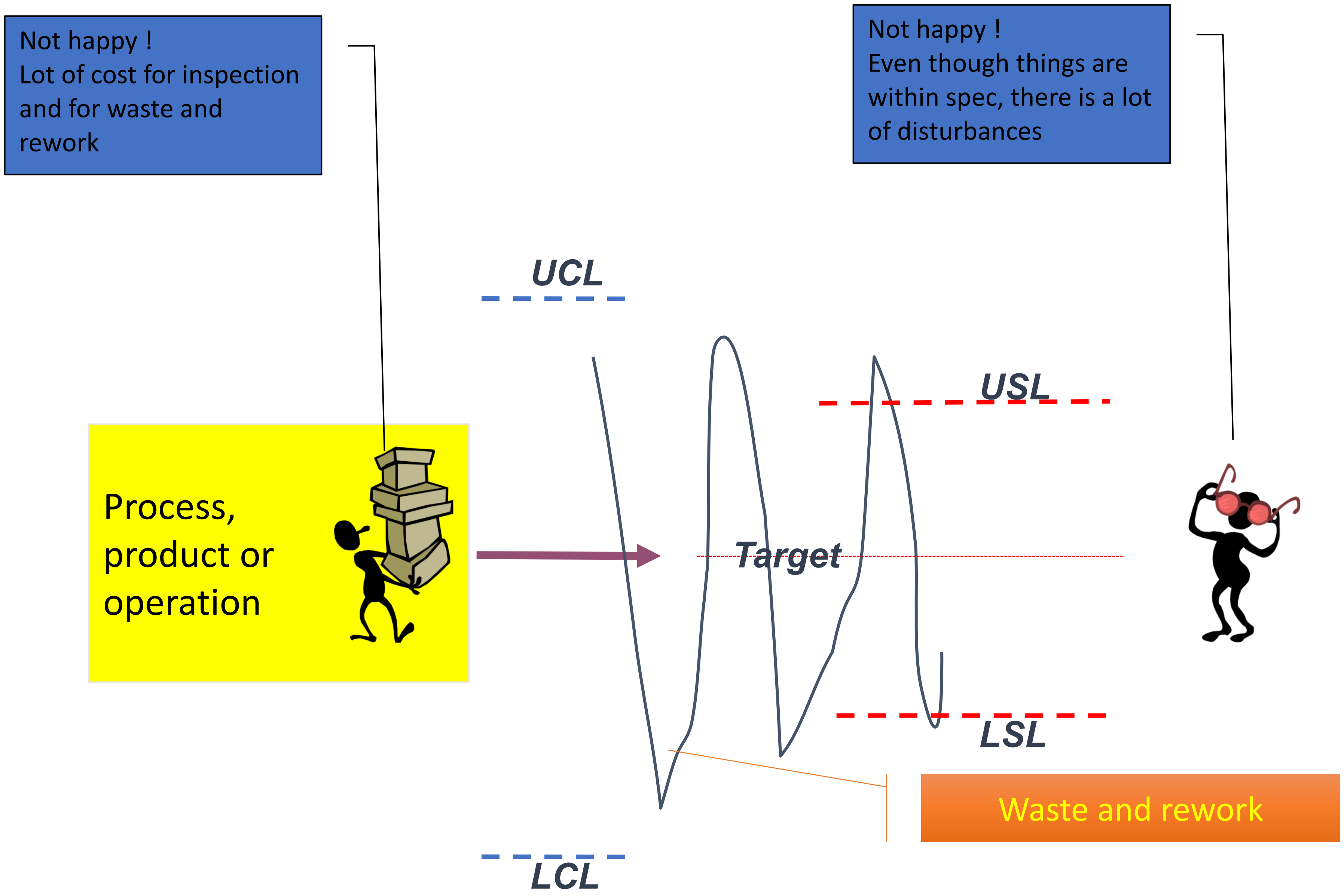

Voice-of-the-process
VOP
VS.
Voice-of-the-customer
VOC
UCL
USL
Process, product or operation
LSL
Waste and rework
LCL

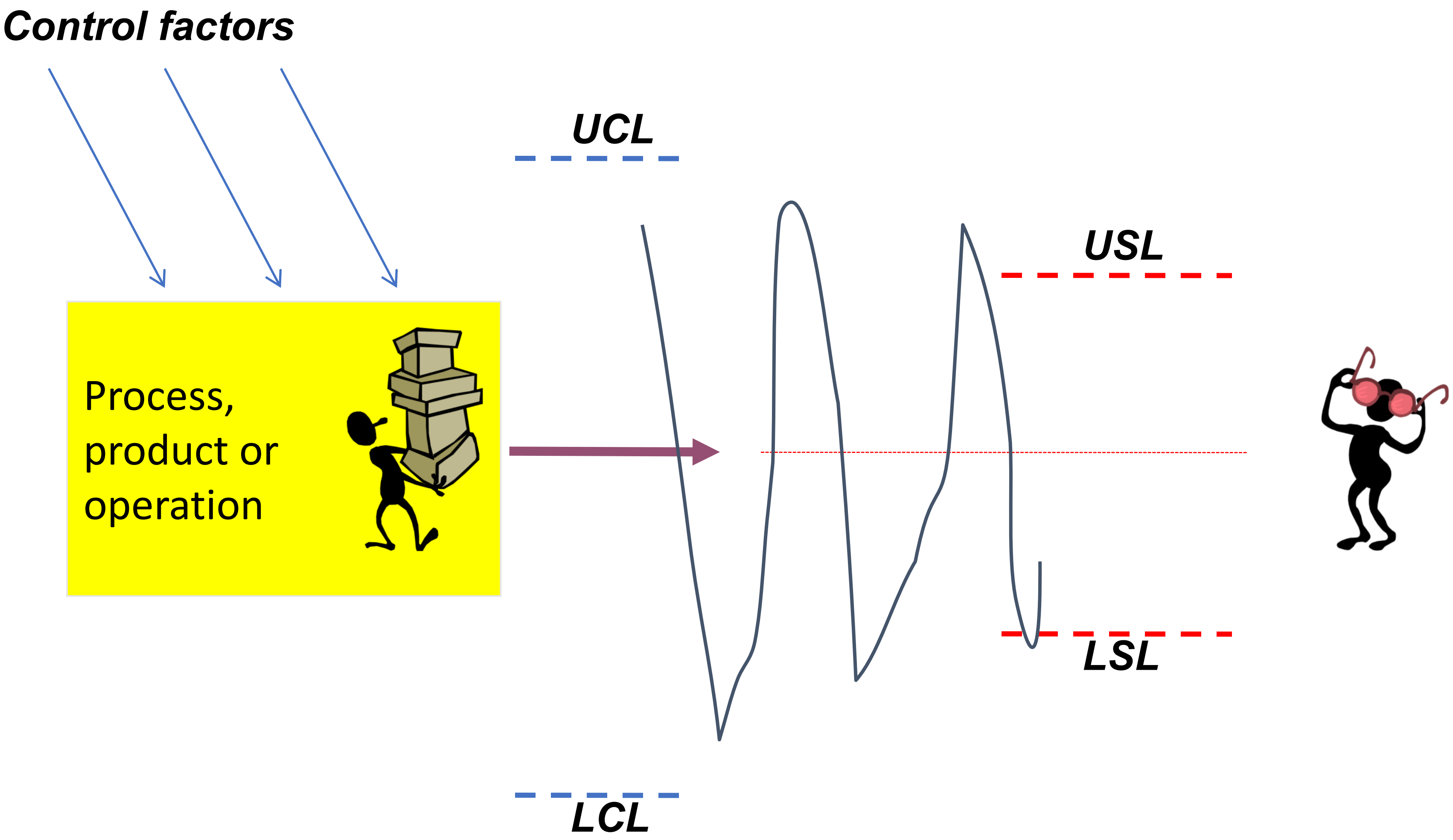
A common behavior when quality is bad is:

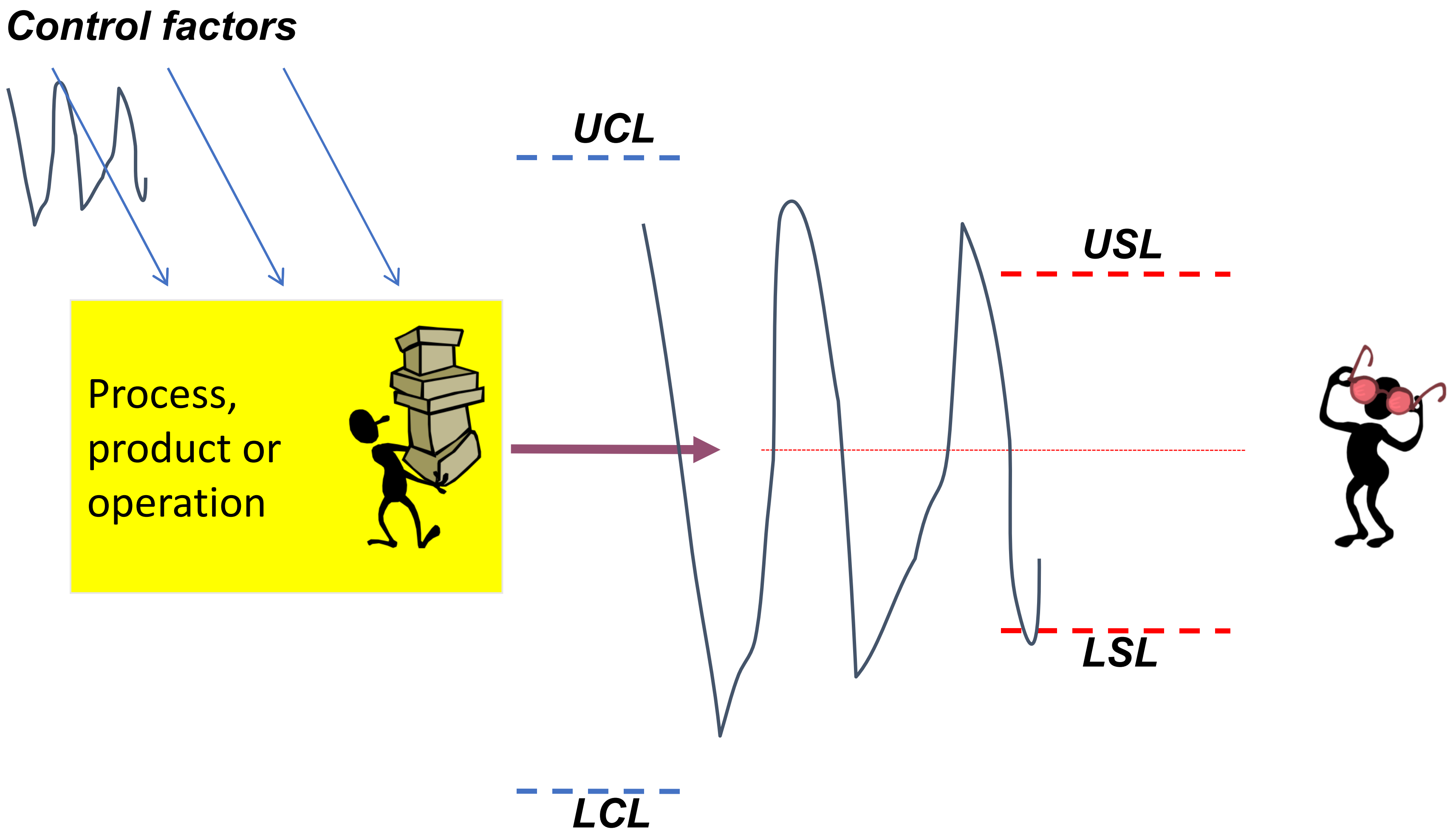
”- Quality is bad – the supplier need to improve - lets sharpen the tolerances”

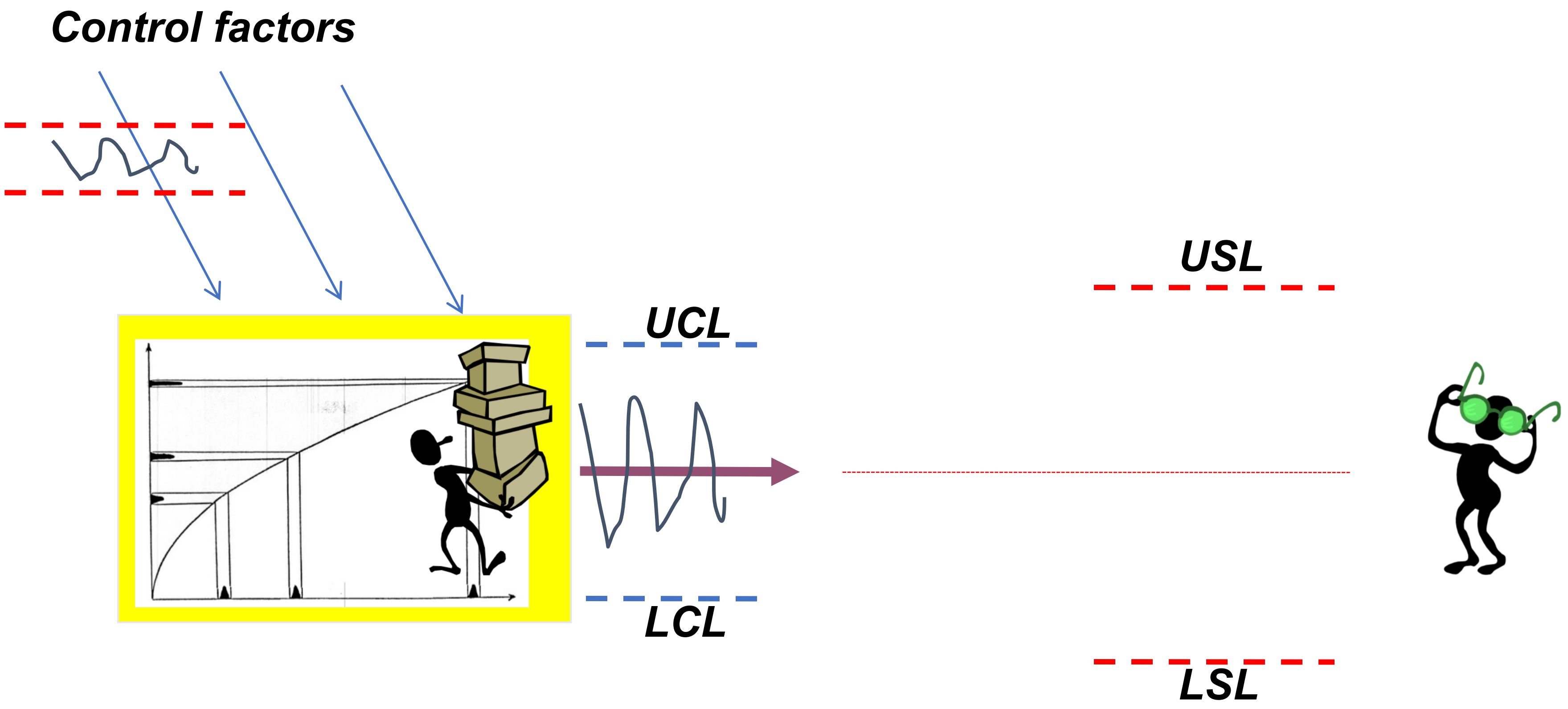
What will happen?

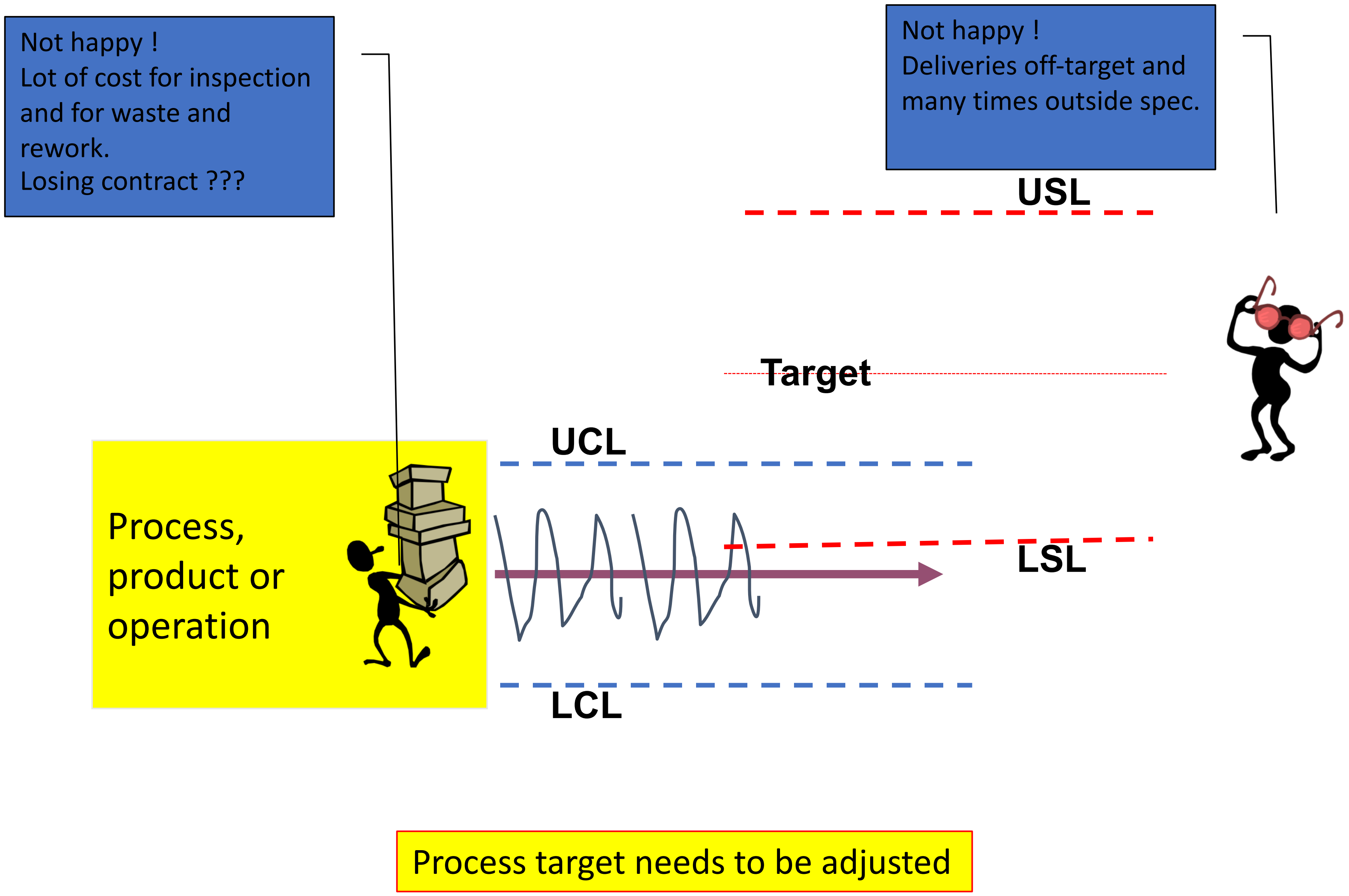


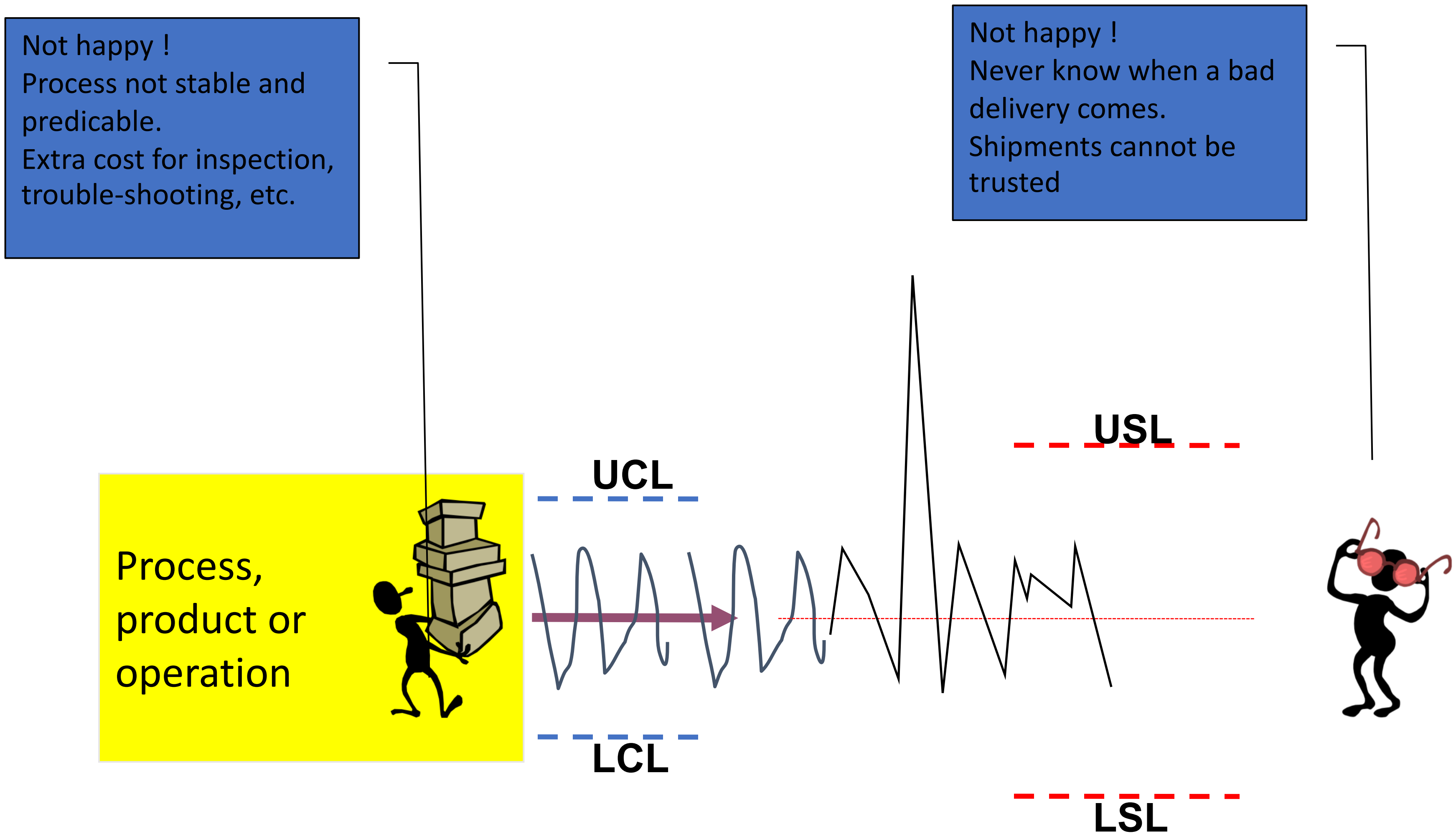

Not happy !
Lot of cost for inspection and for waste and rework
Not happy !
Even though things are within spec, there is a lot of disturbances
UCL
USL
Process, product or operation
Target
LSL
Waste and rework
LCL


Control factors
Process, product or operation
UCL
LCL
USL
LSL


Control factors
UCL
Process,
product or
operation
USL
LSL
LCL


Control factors
UCL
LCL
USL
LSL


Not happy !
Lot of cost for inspection and for waste and rework.
Losing contract ???
Not happy !
Deliveries off-target and many times outside spec.
USL
Target
UCL
Process, product or operation
LSL
LCL
Process target needs to be adjusted



Process is not stable and predictable – very common.
How should the right price be set?

Two mistakes of data analysis

- Mistake One: All ups and downs are <u>seen as signals</u>
  - Interpreting the routine variation of noise as if it amounted to a signal of change in the underlying process, thereby sounding a **false alarm**.
    - People stop listening and does nothing
- Mistake Two: Everything is <u>interpret as noise</u>
  - Thinking that a signal of a change in the underlying process is merely the noise of routine variation, thereby missing a signal
    - People avoid this problem by making mistake one and run on everything
- Trick is to <u>strike a balance</u> between the two by filtering out the noise of routine variation in the data – only react when deviations are large

Statistical Process Control

Checking if the process is stable and predictable with control charts

Statistical Control

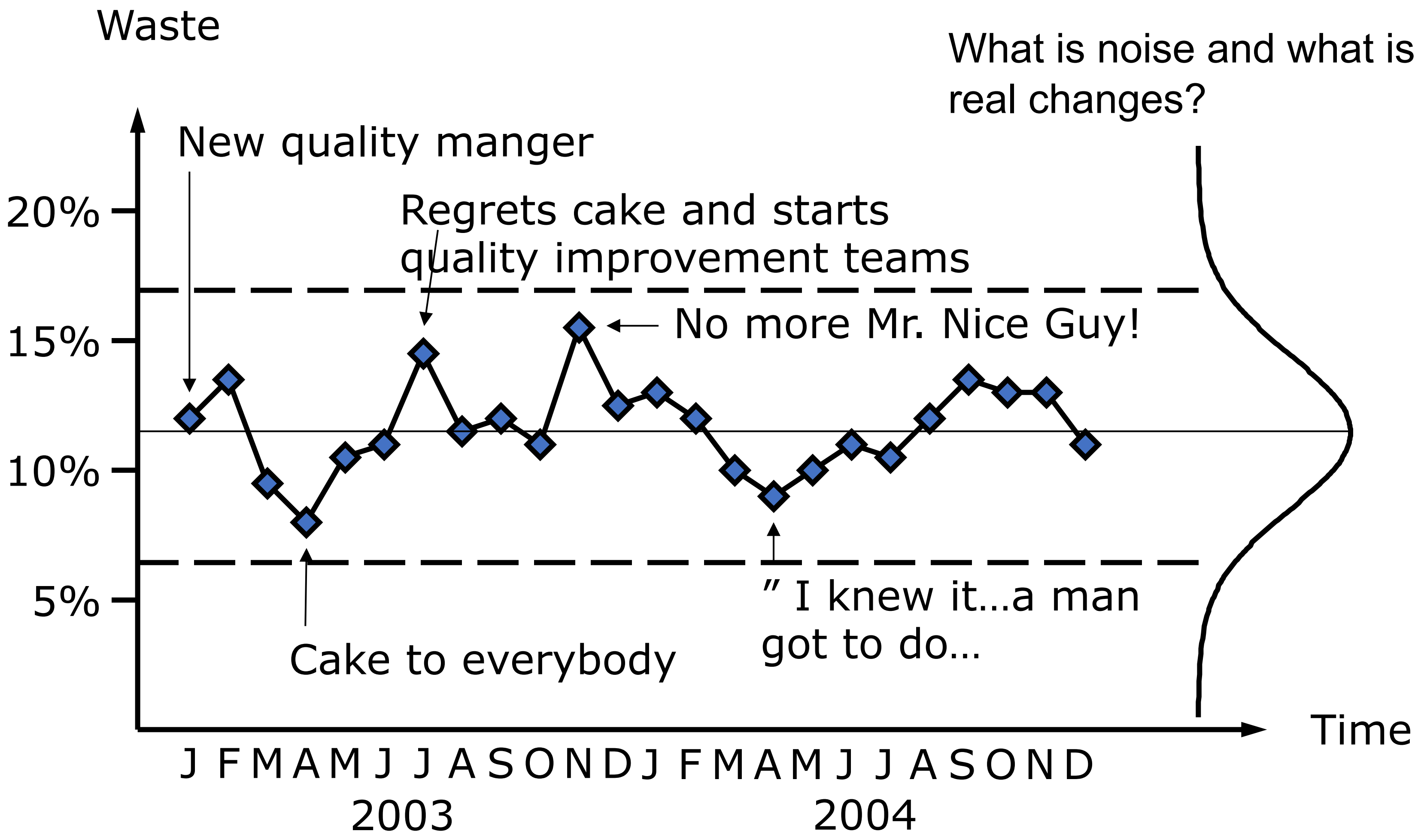
- A process that only contains common causes of variation is said to be in statistical control
- A process in statistical control is stable and predictable

As Deming puts it: when processes are in statistical control, quality and quantity are predictable. Costs are predictable; Just in time" begins to take on meaning…

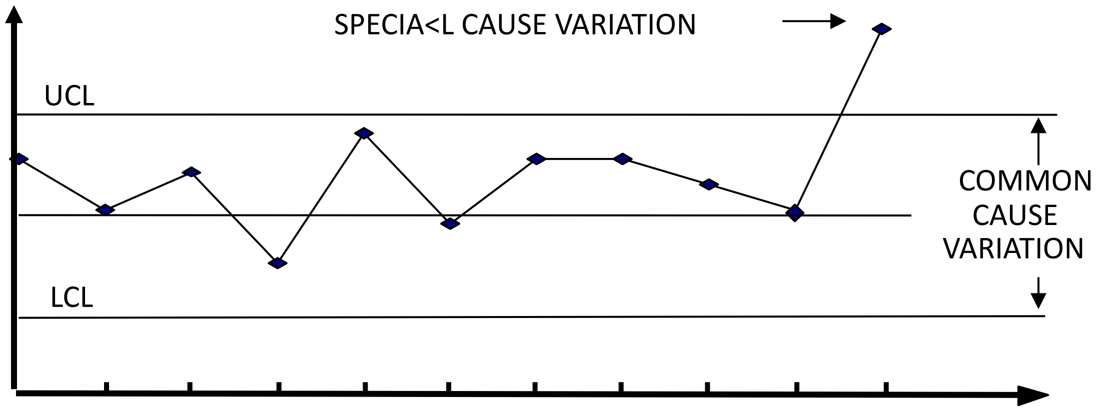
Normal or not?

All processes have noise!

What is noise and what is real changes?



Special cause variation
is our business enemy # 1



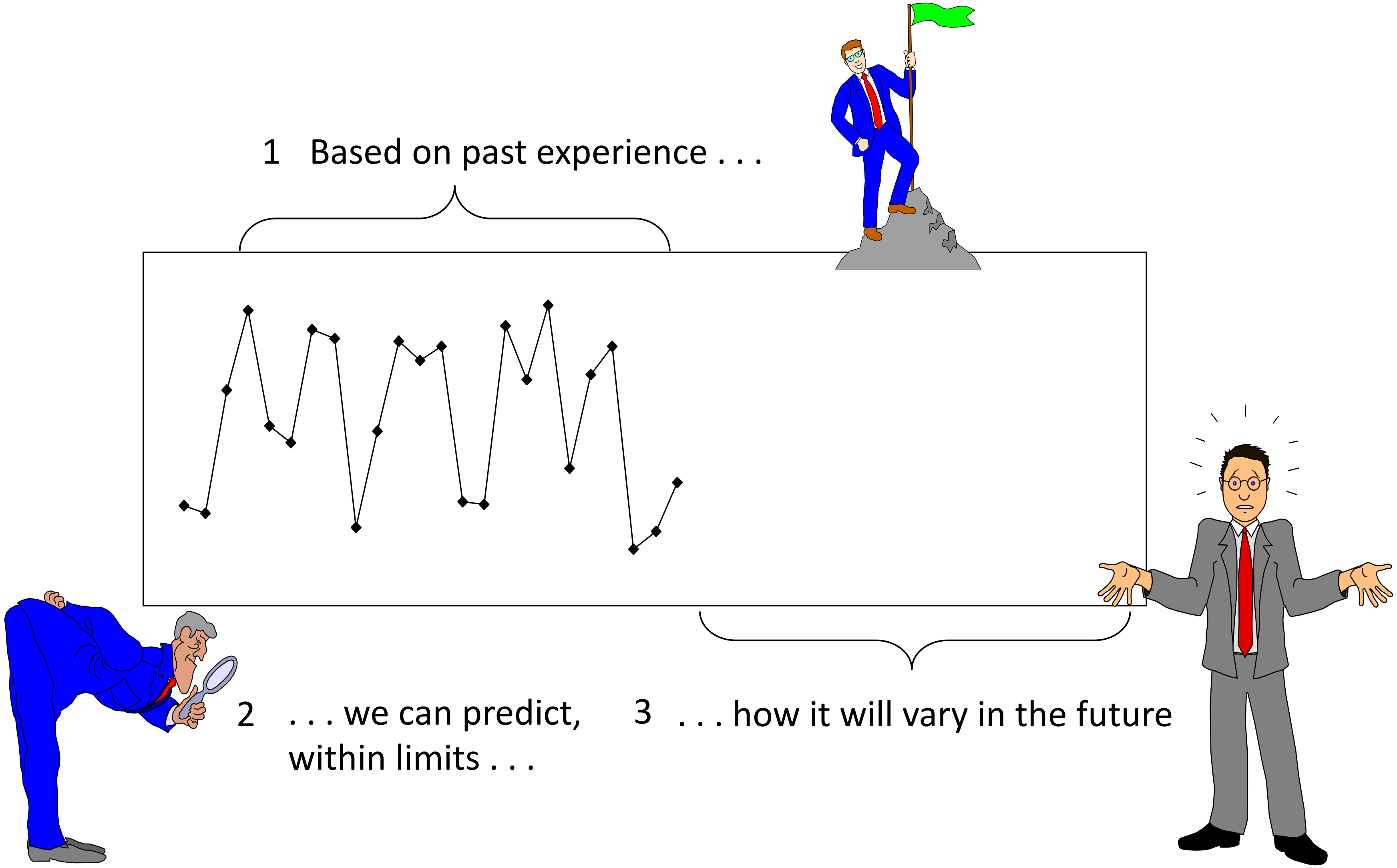
Control charts

Dr. Walter Shewhart, who developed control charts in the late 1920's, explained 'control' this way:

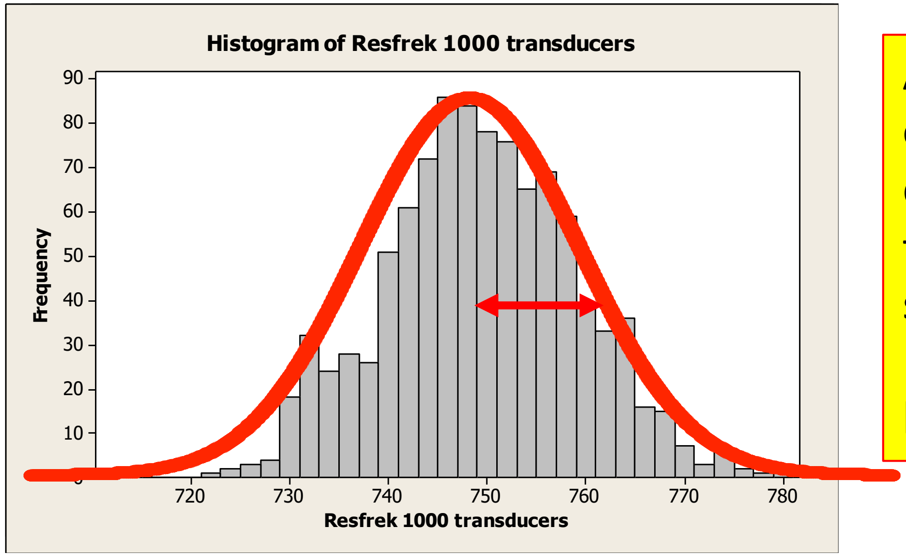
"A phenomenon will be said to be controlled when, through the use of past experience, we can predict, at least within limits, how the phenomenon may be expected to vary in the future."

Control charts are simple, robust tools for understanding process variability.

A Process is in Control When ...

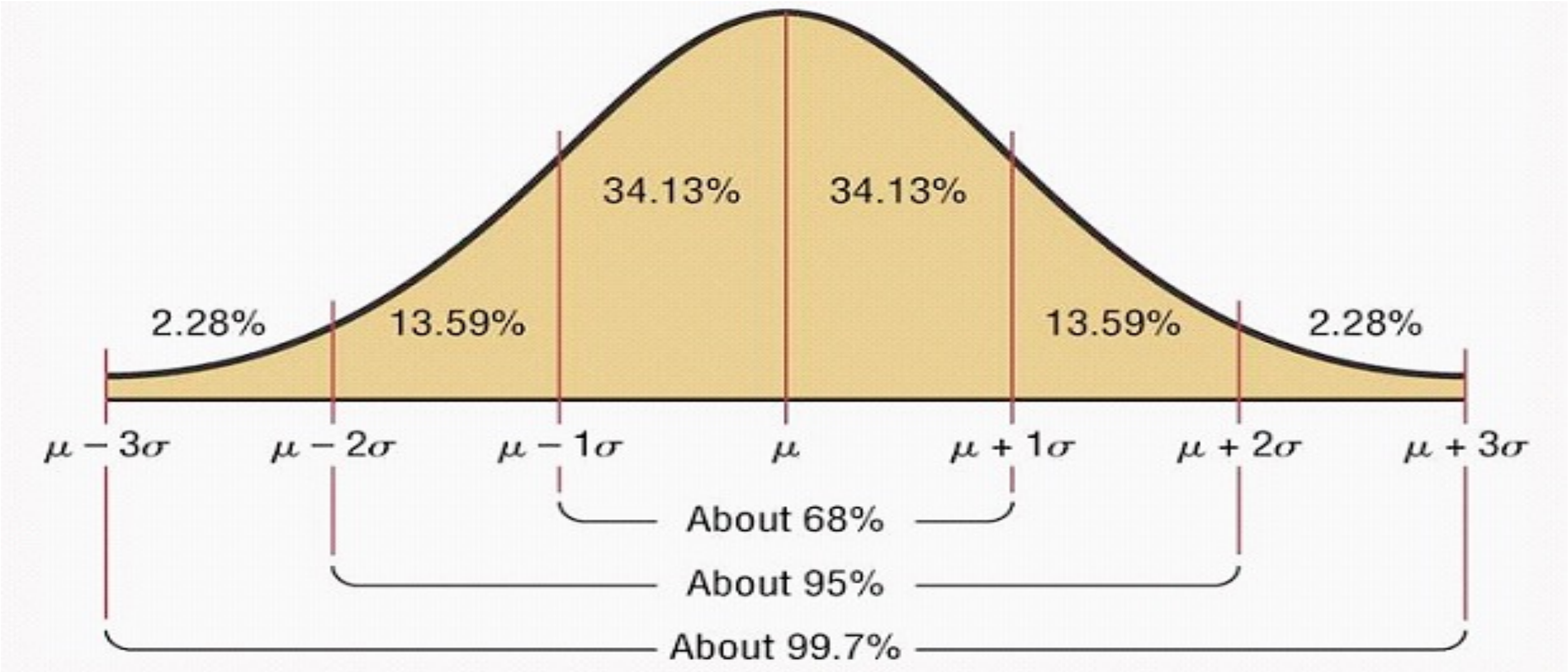


Variation



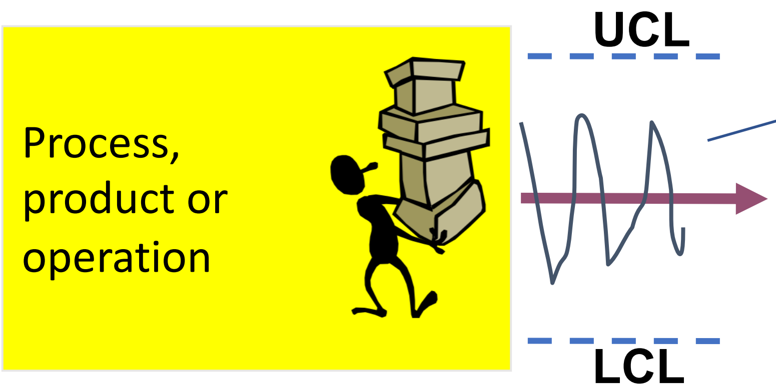
A graphic estimate of the Std.dev is the distance between the mean and the steepest point.
NB: Same unit as the basic parameter.

However: the normal distribution work well when dealing with small deviations from a target and is base for the common definition of: PROCESS CAPABILITY



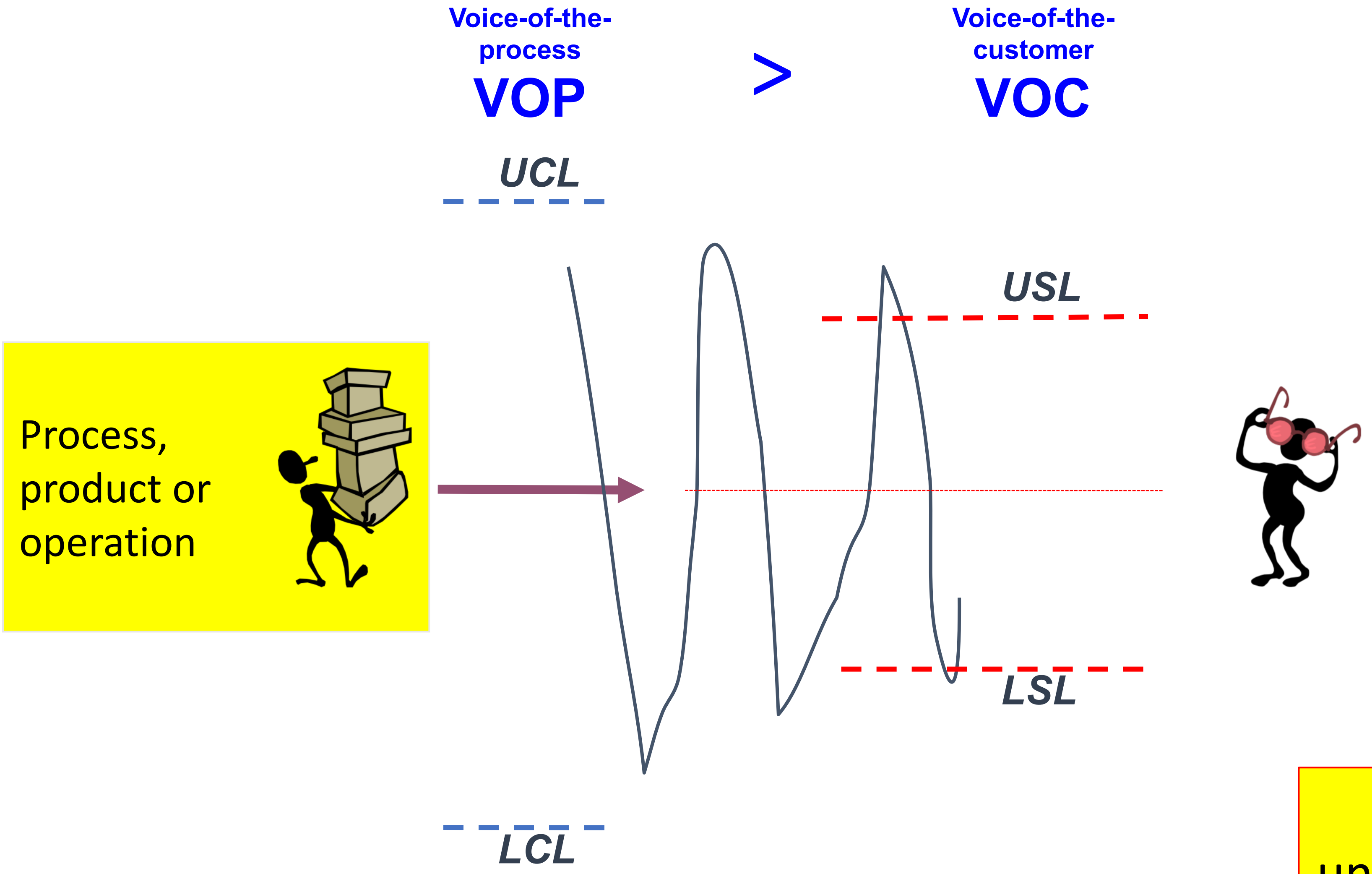
When the contains nothing but Common Causes – the process operates at its economical equilibrium.

It does what it is designed to do at its full potential!



Variation has no explanation it is only noise. It is pointless to try to explain it.

When the level of Common Cause of variation not is acceptable in a stable process, there is no quick fix. It must be rebuilt



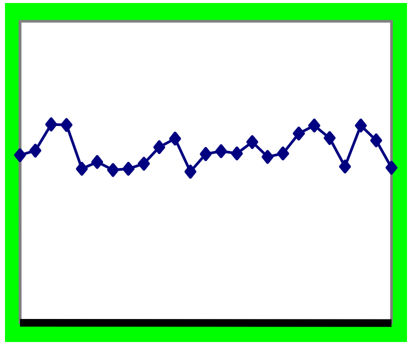
Important understanding!

Goal with Statistical Process Control

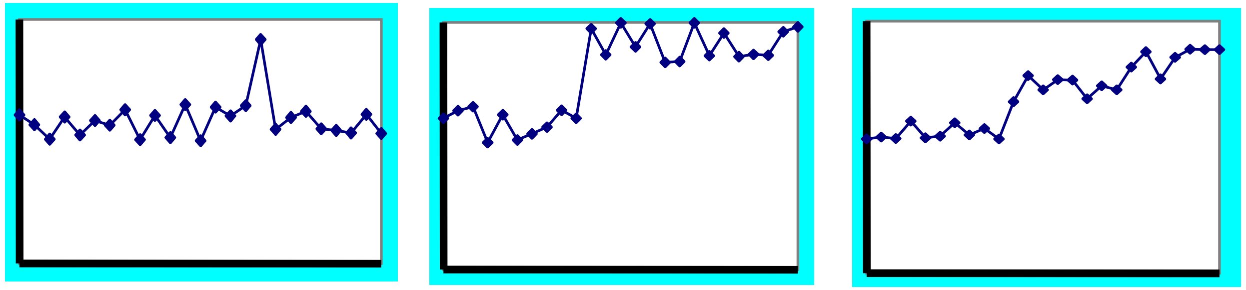
- Control the process so it remains stable (so that no new special causes of variation are introduced)
- To avoid over control of processes
- Find and eliminate special causes of variation

Different causes to variation

Random causes of variation



Special causes of variation



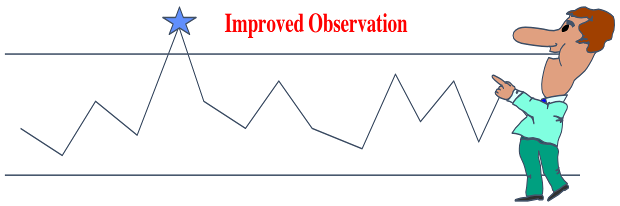
Two types of data - two different techniques

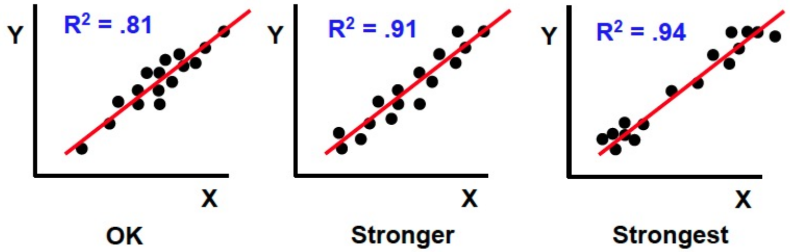
Observational studies

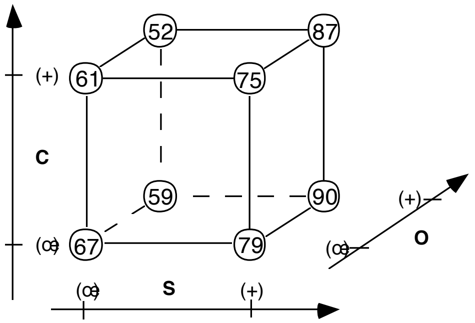
- One condition
- Sequential analysis of streaming data
  - Watching for unplanned changes
- Trivial risk of false alarm
  - +/- 3-sigma ~ 1/400
- D/M/C

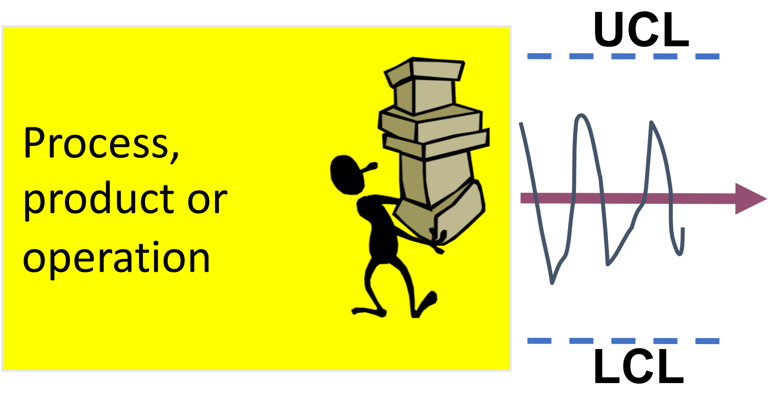
Experimental studies

- Comparing several conditions
- Finite amount of data
- Looking for differences
- Accept non-trivial risk of false alarm
  - alpha risk ~5%
- Conf. int., test of hypothesis, regression tech – designed to get the most info out of limited data
- A/I







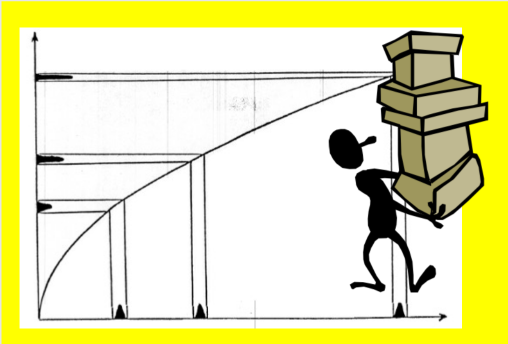


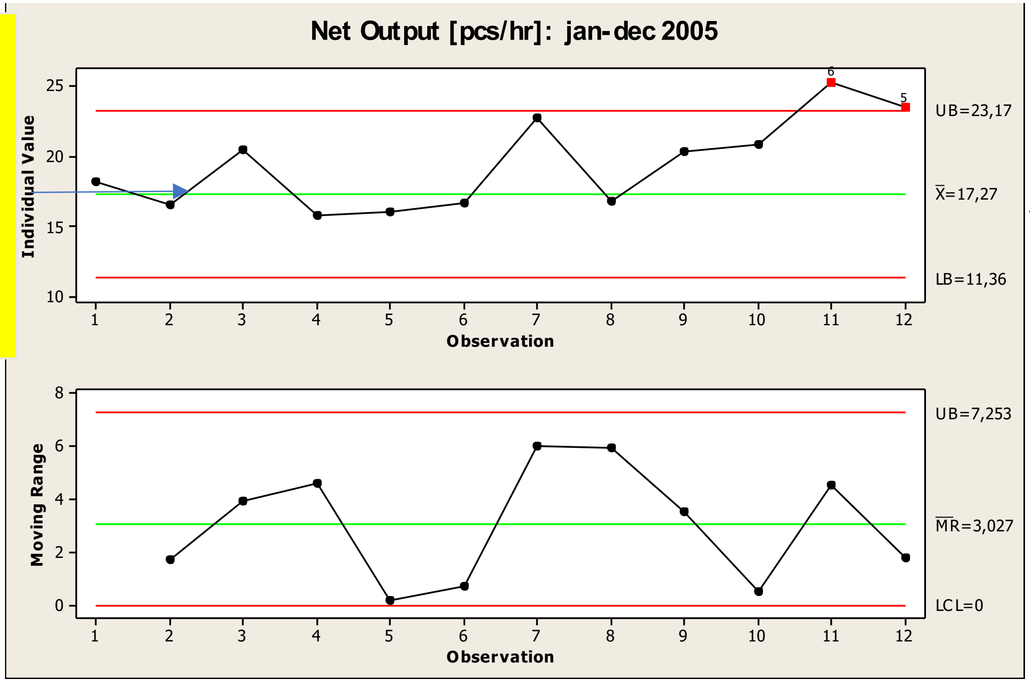
Experimental studies can only test a few factors.

Observational studies are needed to:
- Continuously learn from process data
- Warn for changes
- Identify causes for change
- Operate predictably on target

Individual Observation Moving Range (XmR or IR or ImR): the basic Process Behavior Chart

"The bias correction factors together with the two-point moving average are general and defines the **3-sigma limits** for virtually any type of data.
If it seems like a "one size fits all" approach, it is"
Donald J. Wheeler





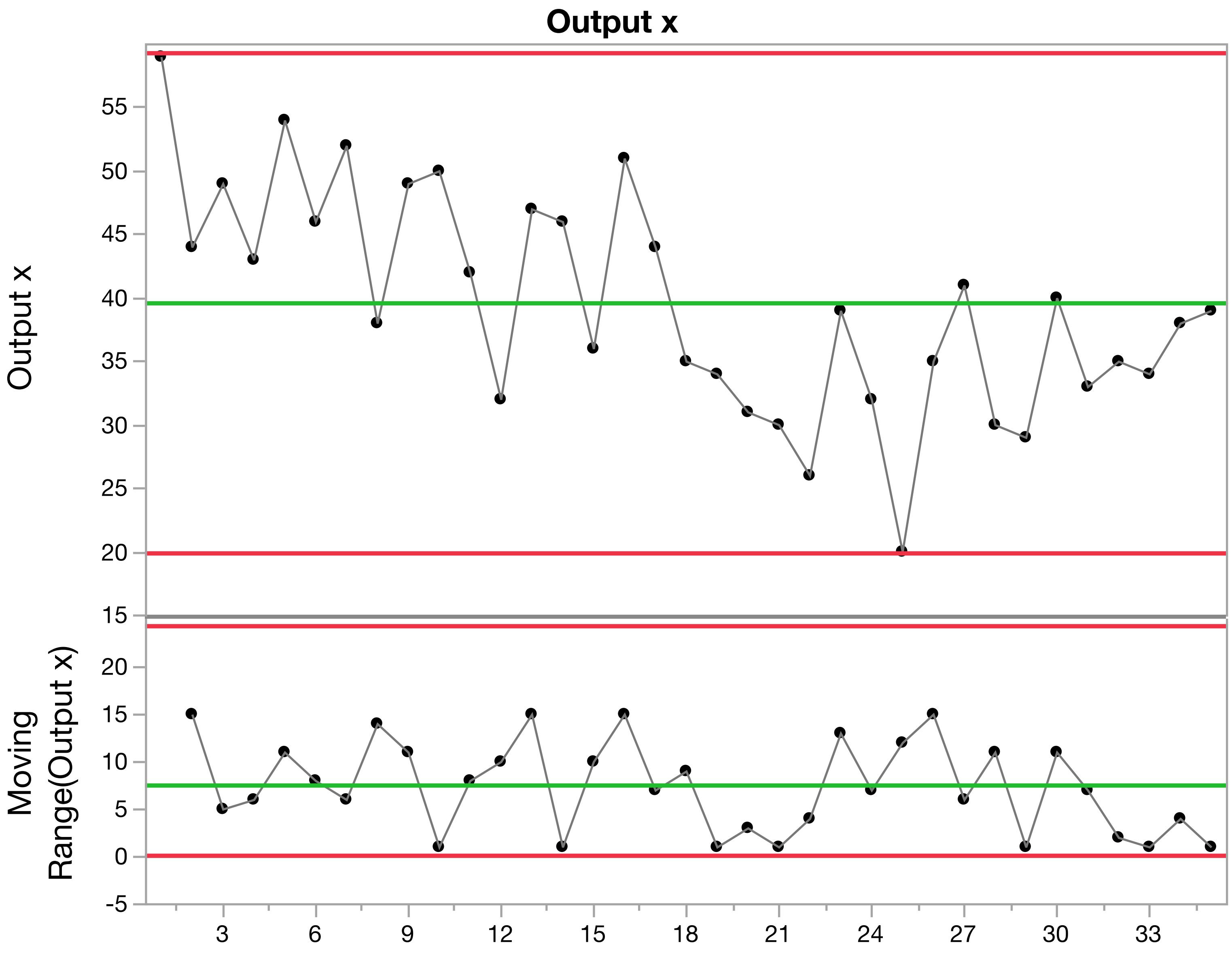
$$UCL = \bar{X} + 2{,}66 \times \overline{mR}$$

$$\bar{X}$$

$$LCL = \bar{X} - 2{,}66 \times \overline{mR}$$

$$URL = 3{,}27 \times \overline{mR}$$

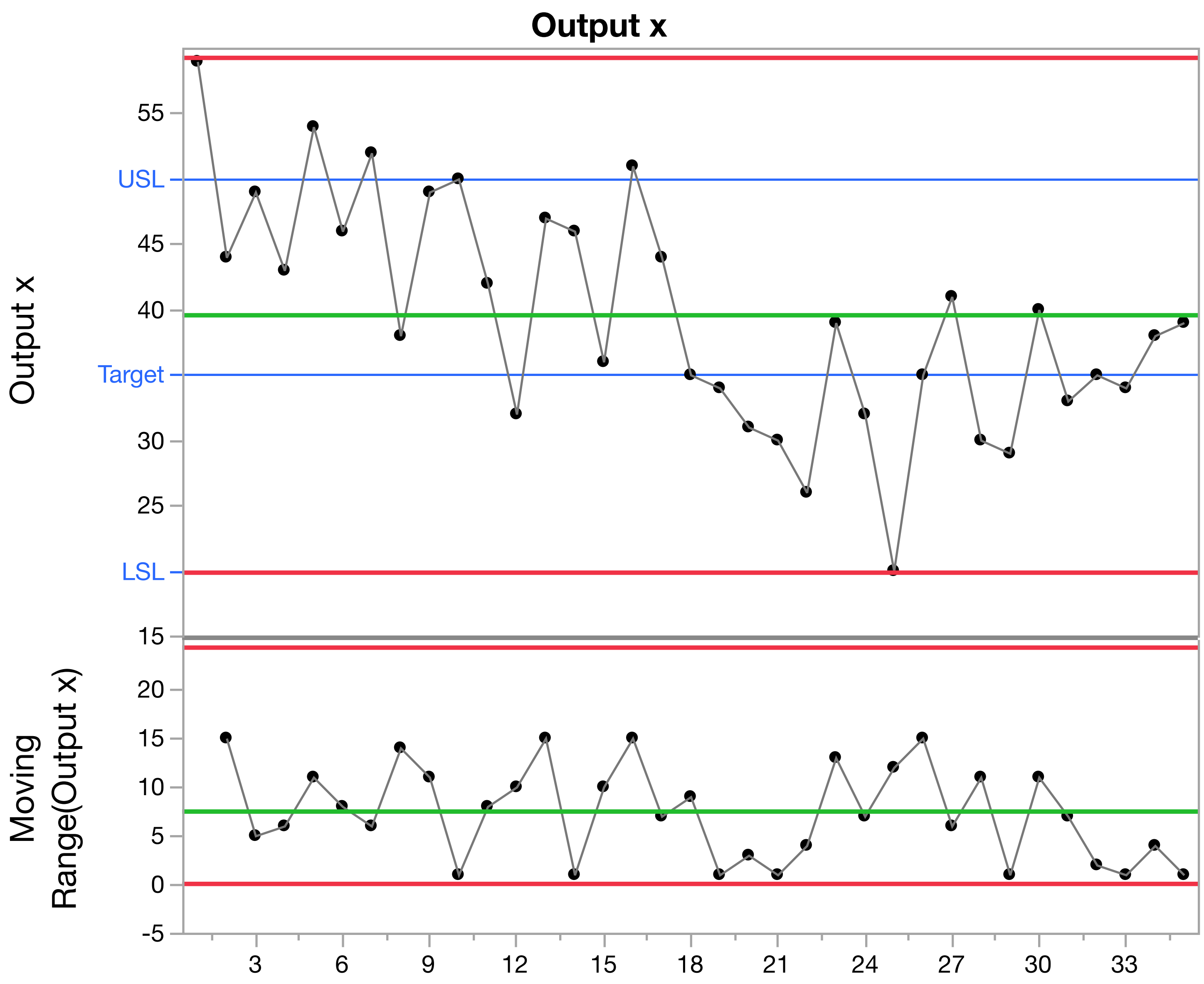
$$\overline{mR}$$



Output x Limit Summaries

Points plotted	LCL	Avg	UCL	Limits Sigma	Sample Size
Individual	19,80877	39,51429	59,2198	Moving Range	1
Moving Range	0	7,411765	24,21077	Moving Range	1

Look at the lower graph first – basic rule



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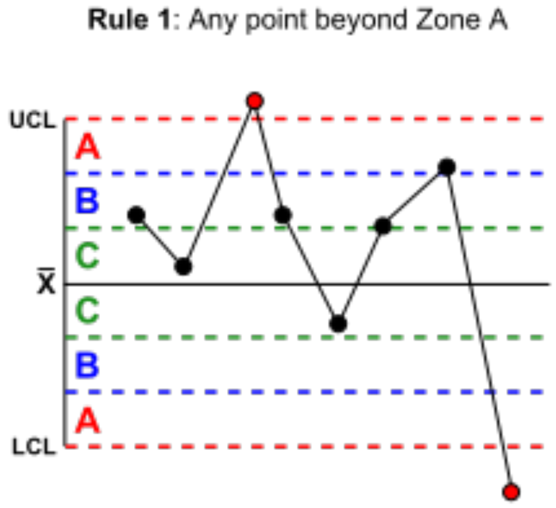
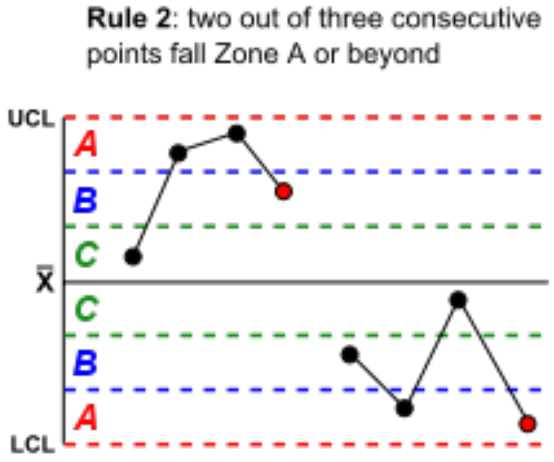
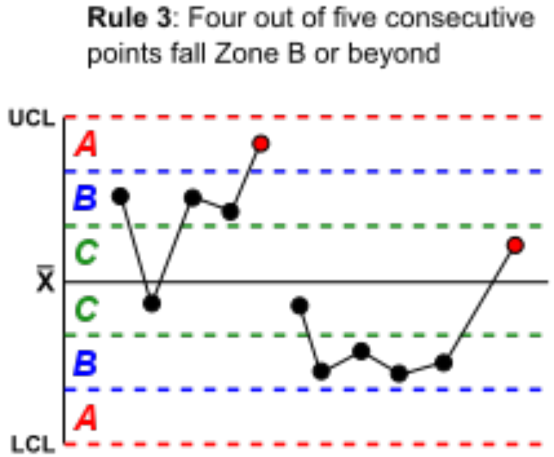
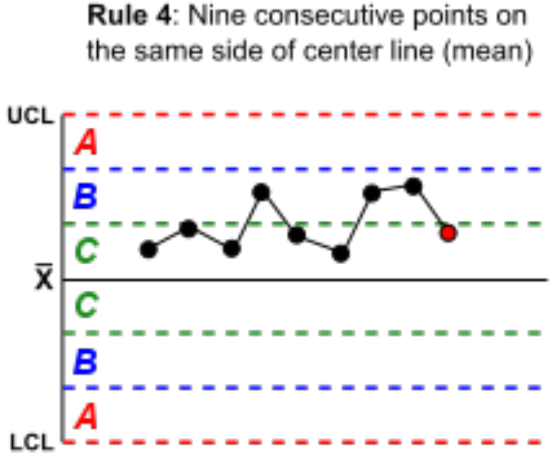
Western Electric Rules



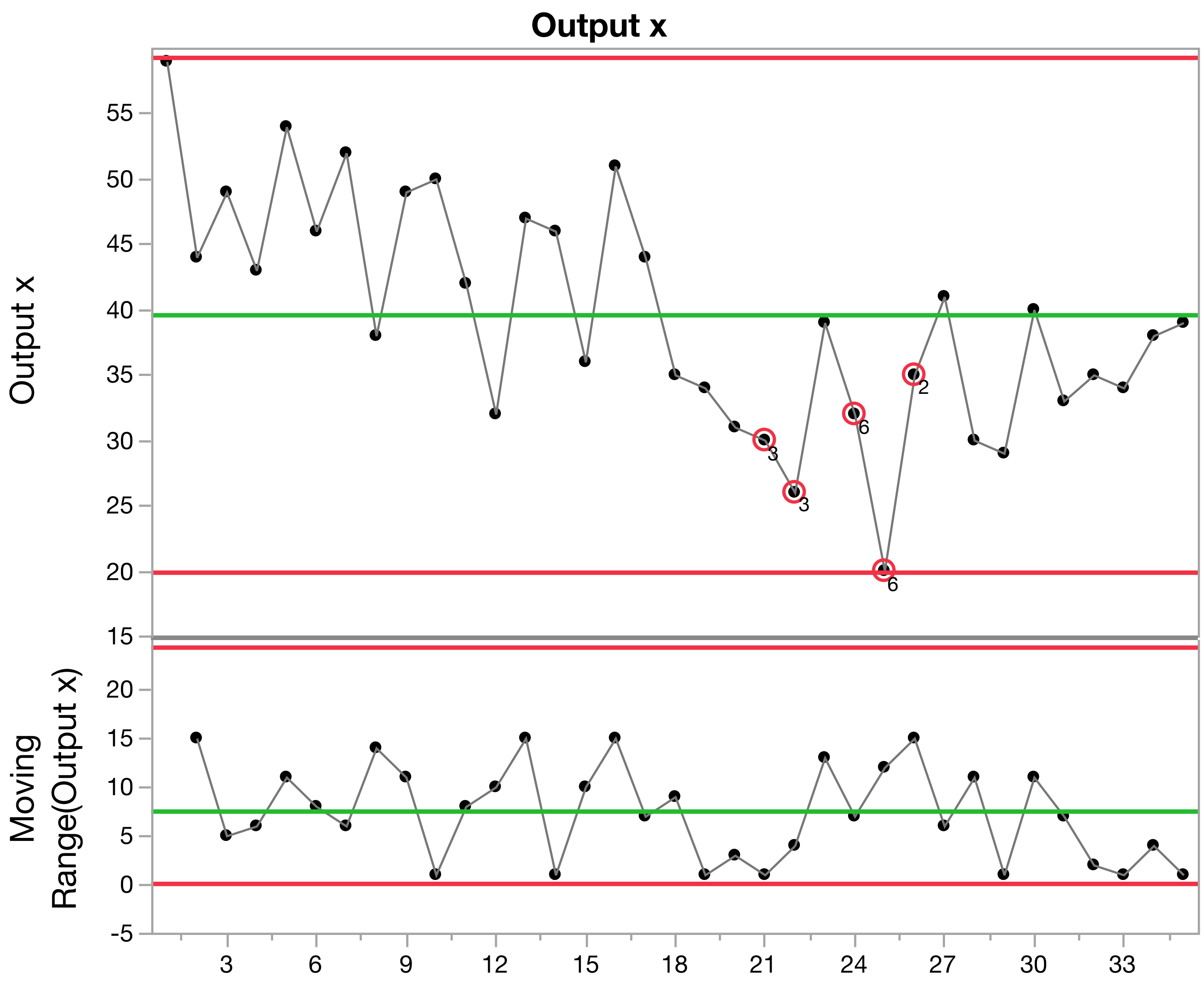


Rule 1	Any single data point falls outside the 3σ limit from the centerline (i.e., any point that falls outside Zone A, beyond either the upper or lower control limit)
Rule 2	Two out of three consecutive points fall beyond the 2σ limit (in zone A or beyond), on the same side of the centerline
Rule 3	Four out of five consecutive points fall beyond the 1σ limit (in zone B or beyond), on the same side of the centerline
Rule 4	Nine consecutive points fall on the same side of the centerline (in zone C or beyond)





Rule 1 and 4 cover most situations:
R1 – test special causes
R4 – test trend shift
'KISS' – keep it simple, stupid



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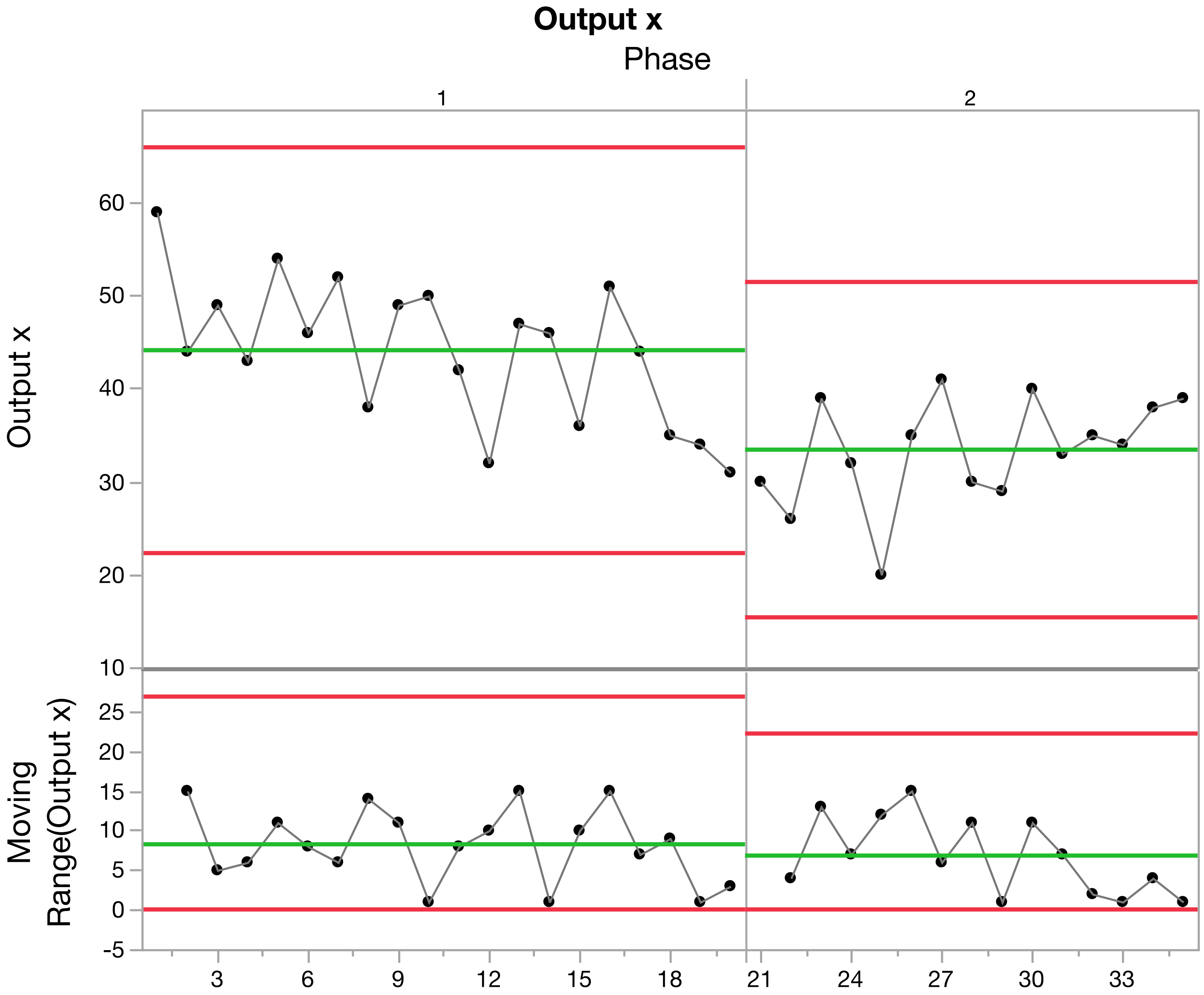
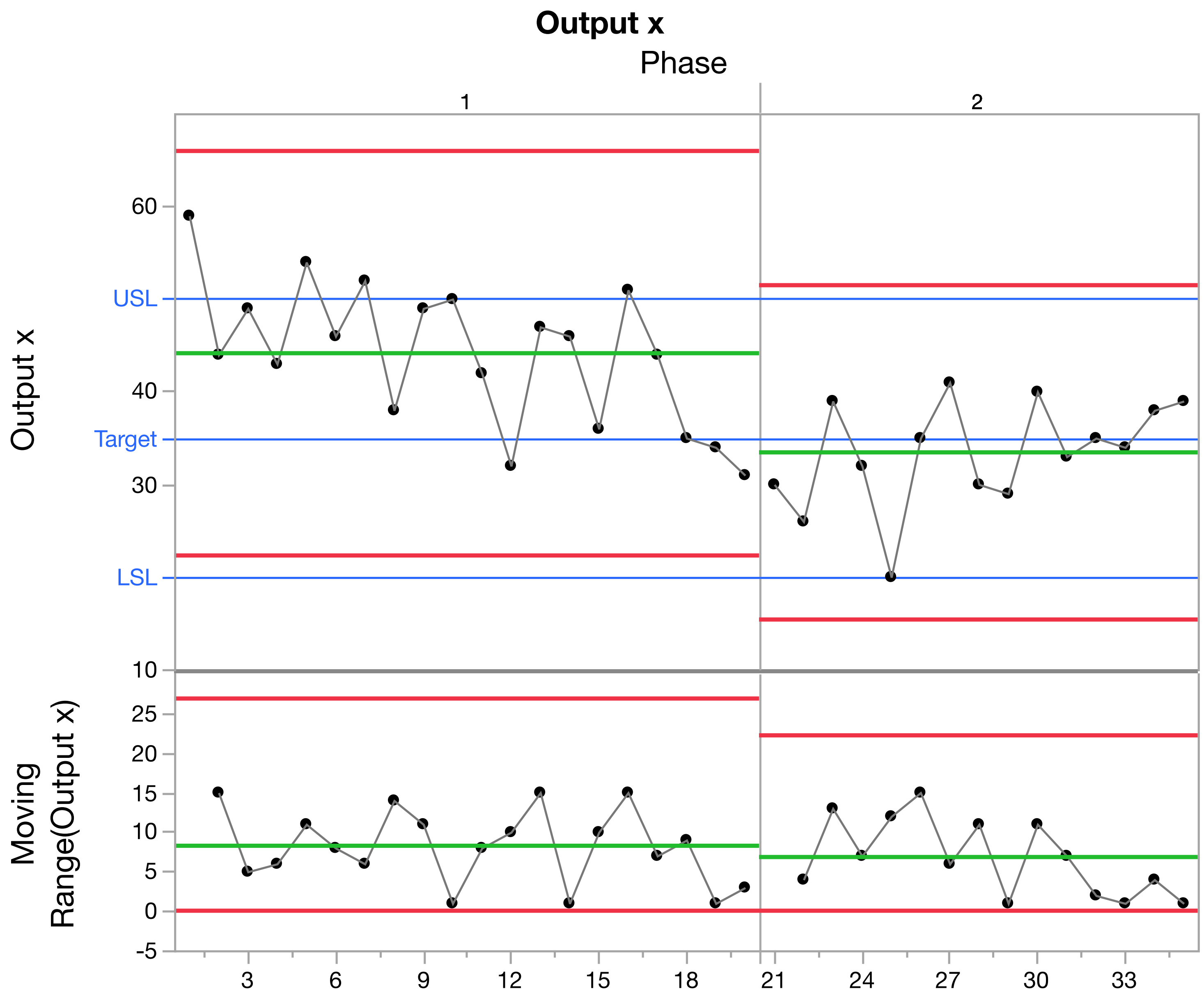


Output x Limit Summaries

Points plotted	Phase	LCL	Avg	UCL	Limits Sigma	Sample Size
Individual	1	22,27083	44,1	65,92917	Moving Range	1
Individual	2	15,35895	33,4	51,44105	Moving Range	1
Moving Range	1	0	8,210526	26,81995	Moving Range	1
Moving Range	2	0	6,785714	22,16575	Moving Range	1



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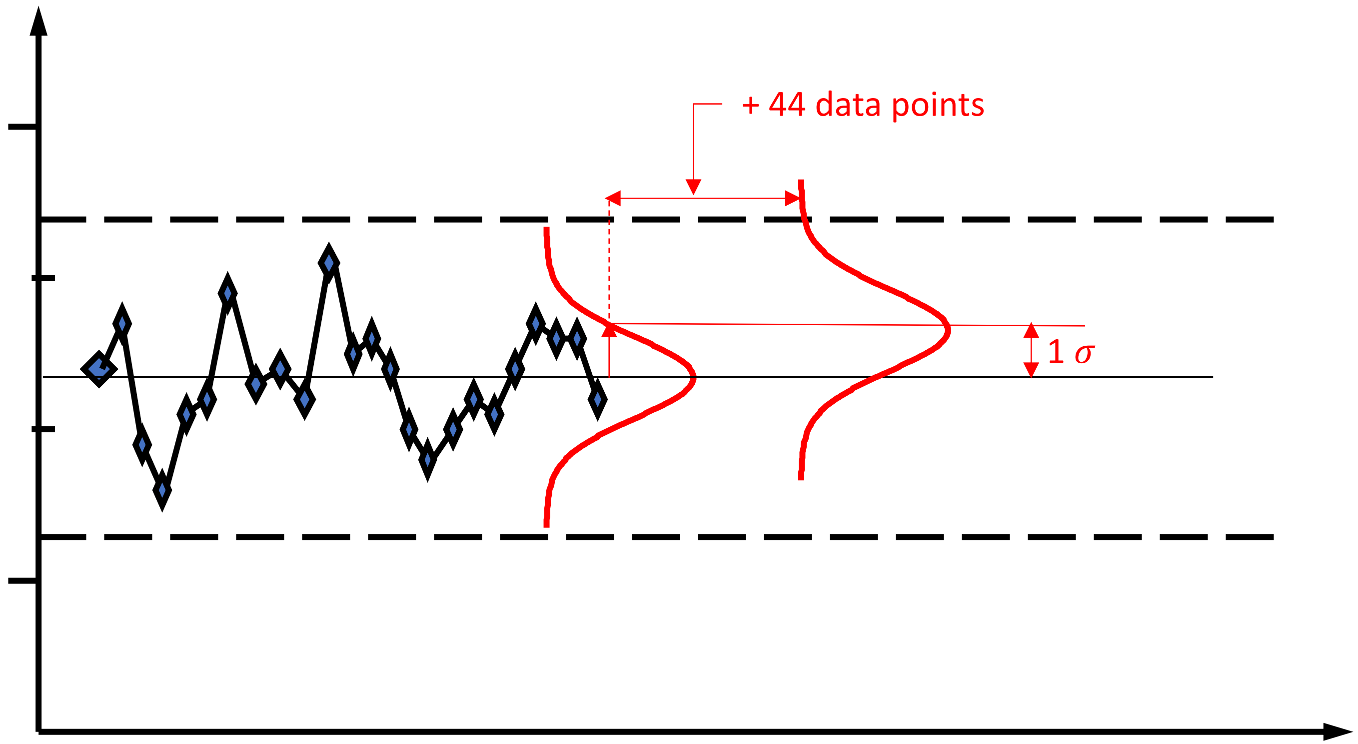
Moving Range	2	0	6,785714	22,16575	Moving Range	1

When does a XmR-control chart detect a process shift

Average run length (ARL)

How many data points extra does it on average take to detect a process shift of:



Shift, in multiples of σ	XmR Average Run Length (ARL)
0	370
0.25	281
0.5	155
0.75	81.83
1	43.96
1.5	15.97
2	6.3
2.5	3.24
3	2
4	1.19
5	1.02

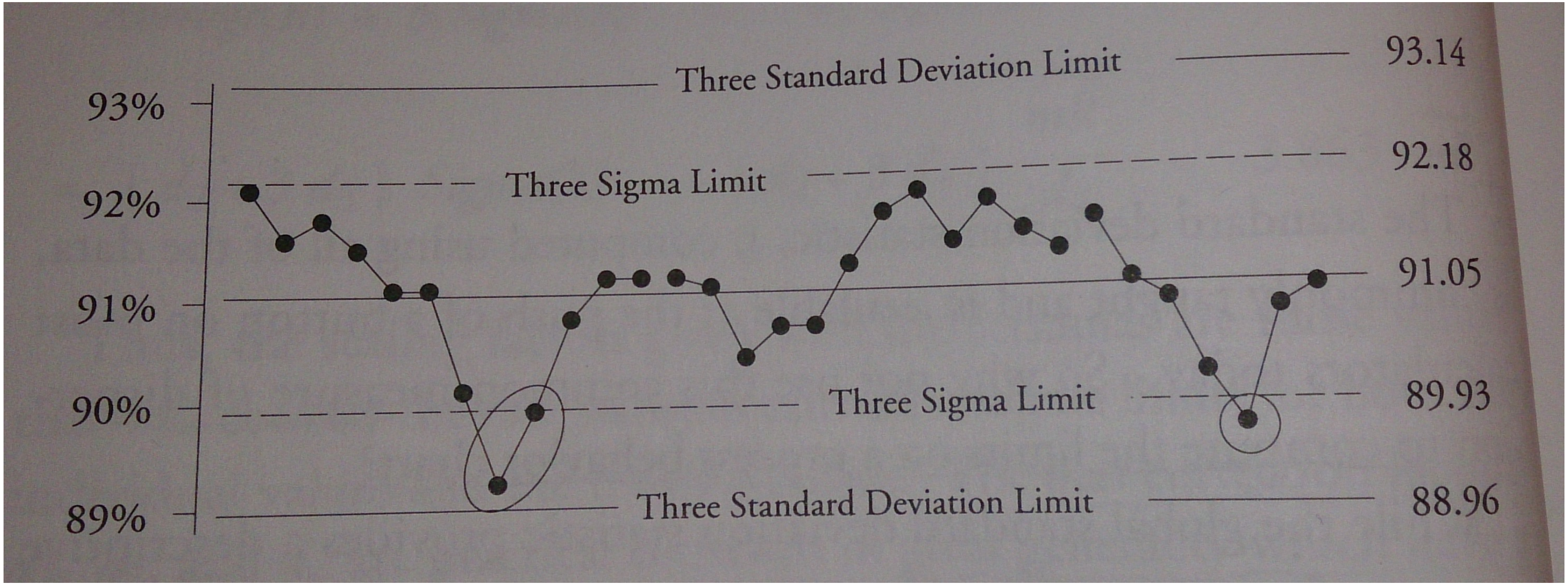
https://community.jmp.com/t5/JMPer-Cable/Using-ARL-Average-Run-Length-to-determine-the-performance-of-a/ba-p/61895

Why not just use the standard deviation statistics?

- While the global standard deviation statistics provides a descriptive summary for a homogeneous data set, it is
- incorrect to use it when analyzing the data for evidence of a possible lack of homogeneity

- The problem is how it is calculated:
  - The global standard deviation use all data – that will blow up the limits
  - The two-point Moving Range use local variation that bypass the problem

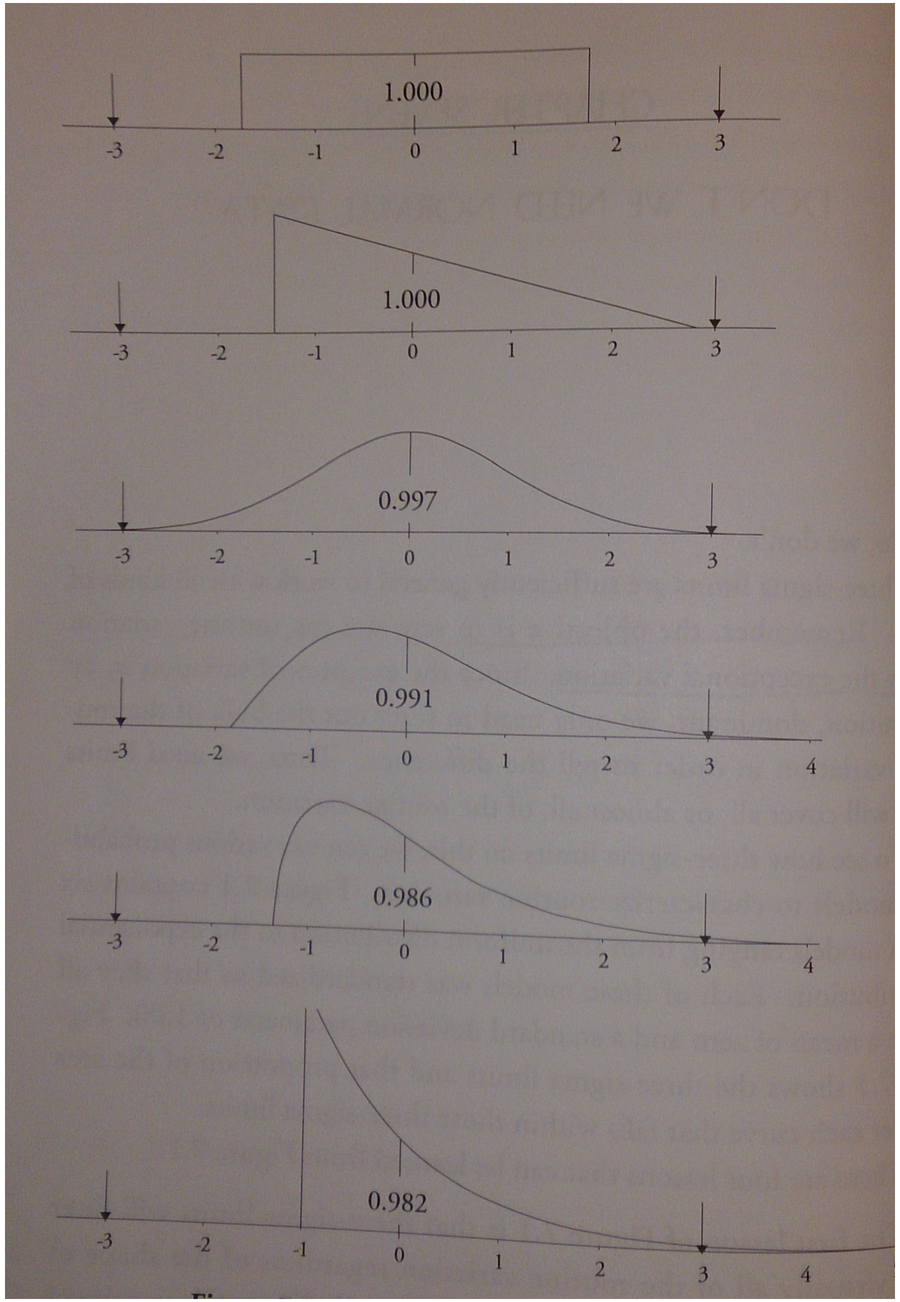
3-sigma limits are more sensitive



When the data is homogeneous the difference will shrink – but totally

3-sigma limits will filter out virtually all of the routine variation regardless of the shape of histogram

1. Points outside the three-sigma limit is a <u>potential</u> signal
2. Symmetric three-sigma limits work with skewed data – transformations not needed
3. Uncertainty in the determination of the limits have marginal effect due to the tails
4. Whenever a boundary value falls within the computed limits, the <u>boundary takes precedence</u> over the computed limit,
   and we end up with a one-sided chart.



Empirical rule:
its true for data not perfectly normal also

Number of Standard Deviations	Theoretical Normal	Empirical – Almost any distribution
+/- 1σ	68%	60-75%
+/- 2σ	95%	90-98%
+/- 3σ	99.7%	99-100%

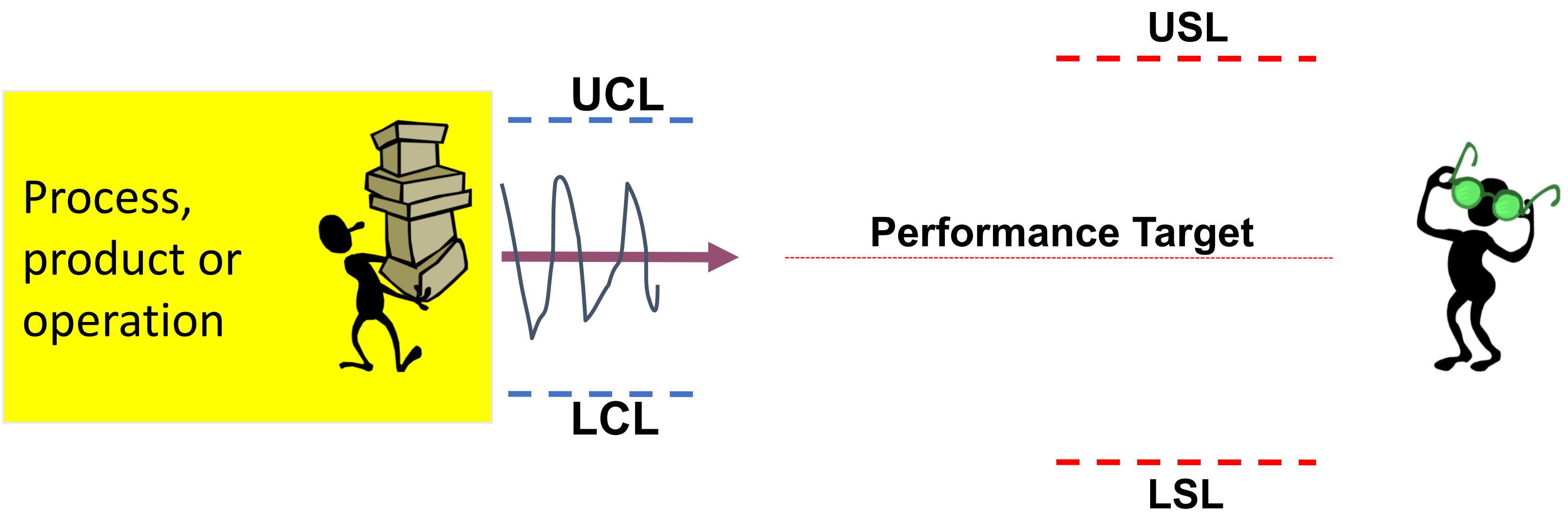
Is the quality of the data good enough to take a decision?
How do we know?

Measurement System Analysis - MSA

(also referred to as **Gage r&R:**
repeatability and reproducability)

The customer requirement (Y)

are characterized with some measures (Qn or Qv).
More or less directly linked to it.



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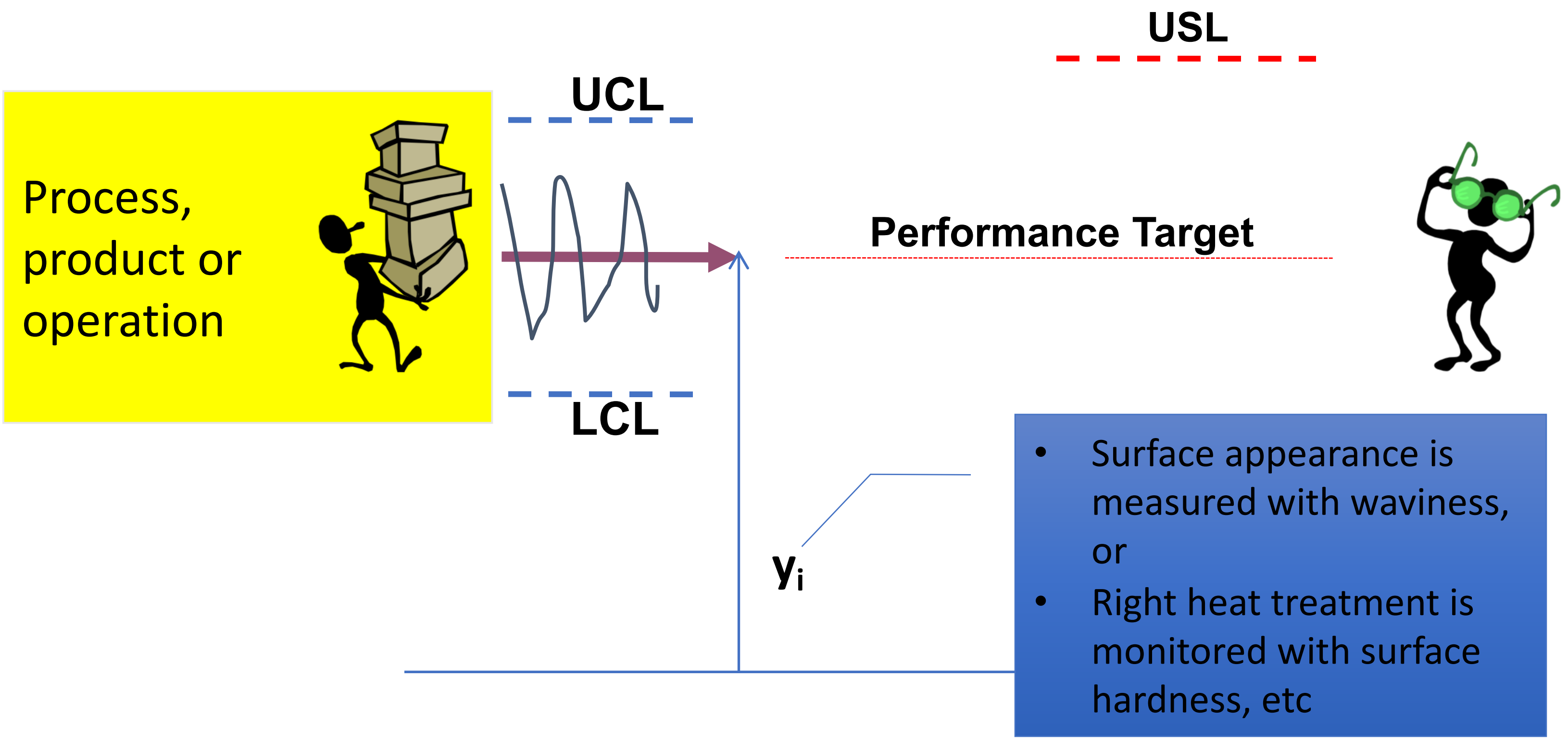


Why

measure?

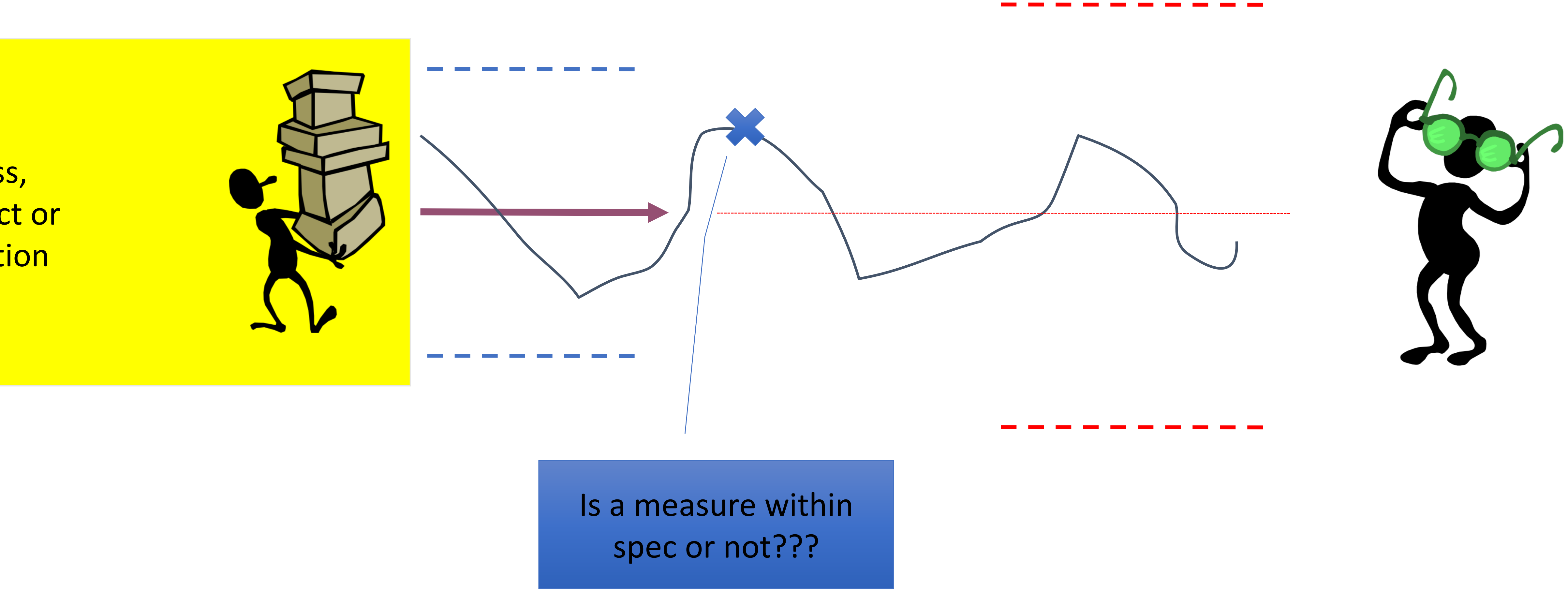
To take decisions:

- On single unit
  - go / no-go (categorical data)
- On process behavior
  - Control charts (trends, variation)
- Two different requirements
  - Which one require the most of the MS?

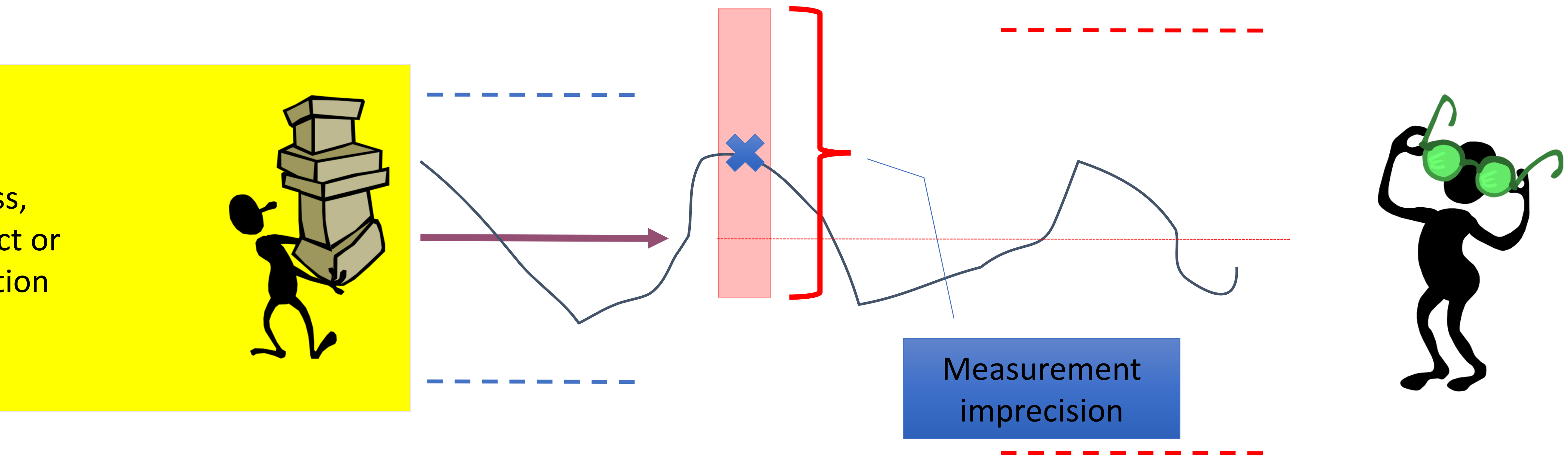
Important question for all measures:

- “Are the measurement noise small enough to let us see the difference we want to see”
  - Measurement Precision
    (which not is the same as calibration…)

Zoom in on the decision to be made…



Imprecision needs to be considered…



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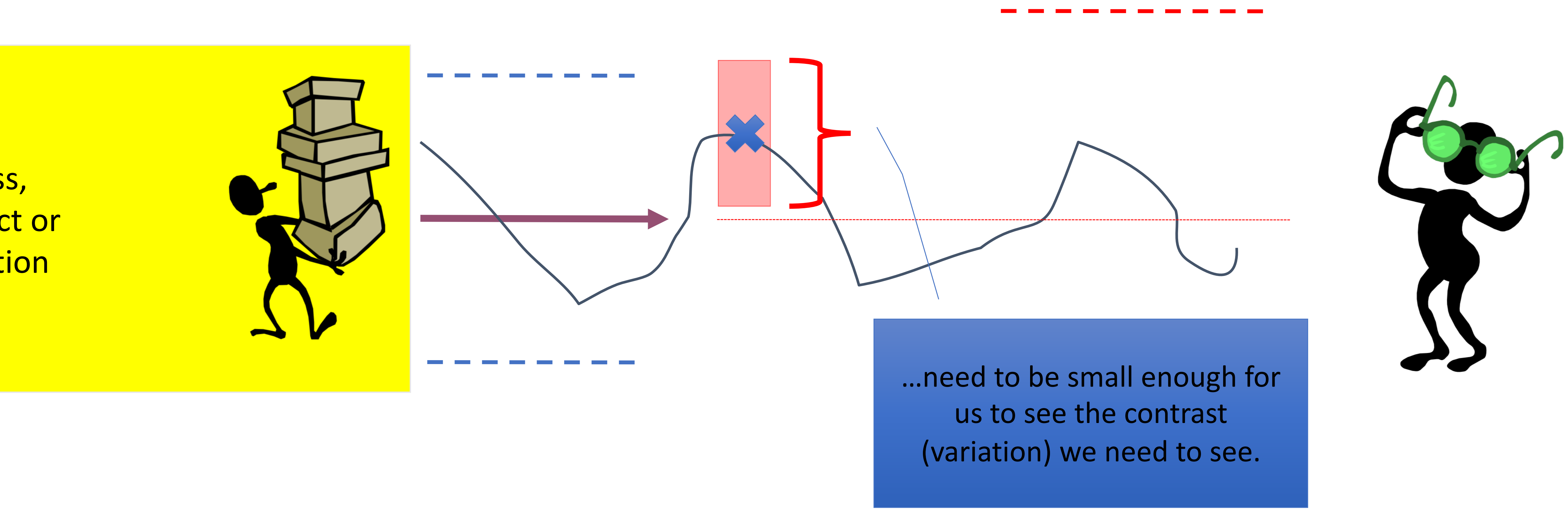


So what…

- How do we know if decisions can be made?
  - Is the precision of the MS high enough to be able to distinguish the contrast of interest?
  - Needs to be figured out for every measure in every process or project!
  - Risk is that decisions are based on noise…

- And calibration is only a small part of the answer…

MSA answers

- Can the intended measurement system be used as a base for the decisions that needs to be taken about:
  - the product or the process or the operation….
- In other words:
  - *Can the measurement system see the variation we are looking for?*
- Measurement system =

  equipment (gauge) + operators (human factor) + procedure

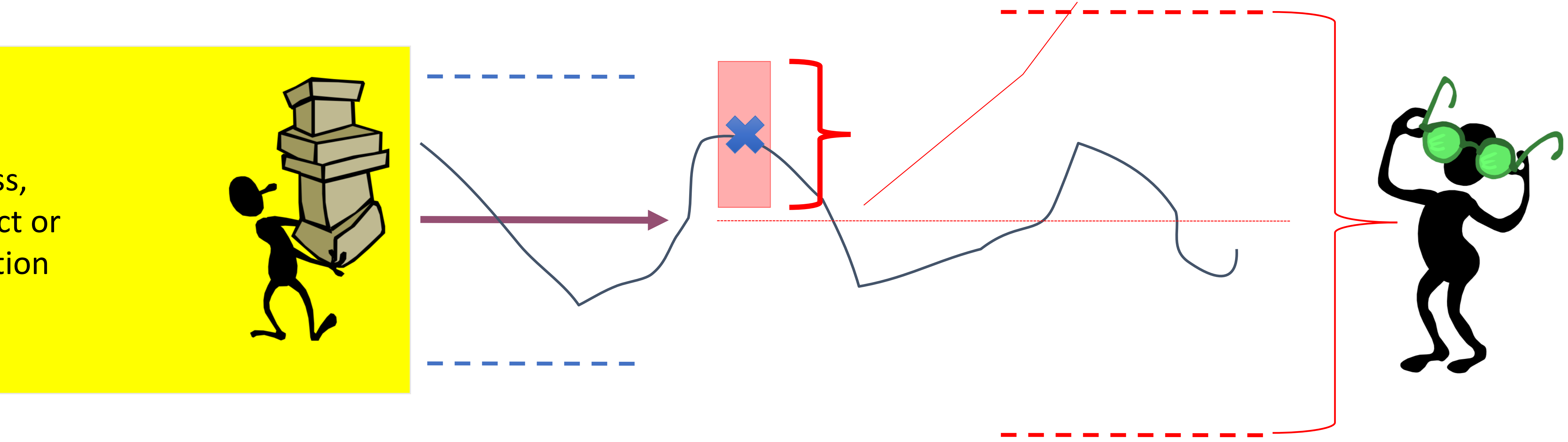
Measurement issues

Three fundamental issues need to be addressed in evaluating a measurement system.

- Does the measurement system have adequate **discrimination**?
- Is the measurement system statistically **stable over time**?
- Are the **statistical properties** consistent over the expected range and acceptable for process control – process decisions?

Standards say…

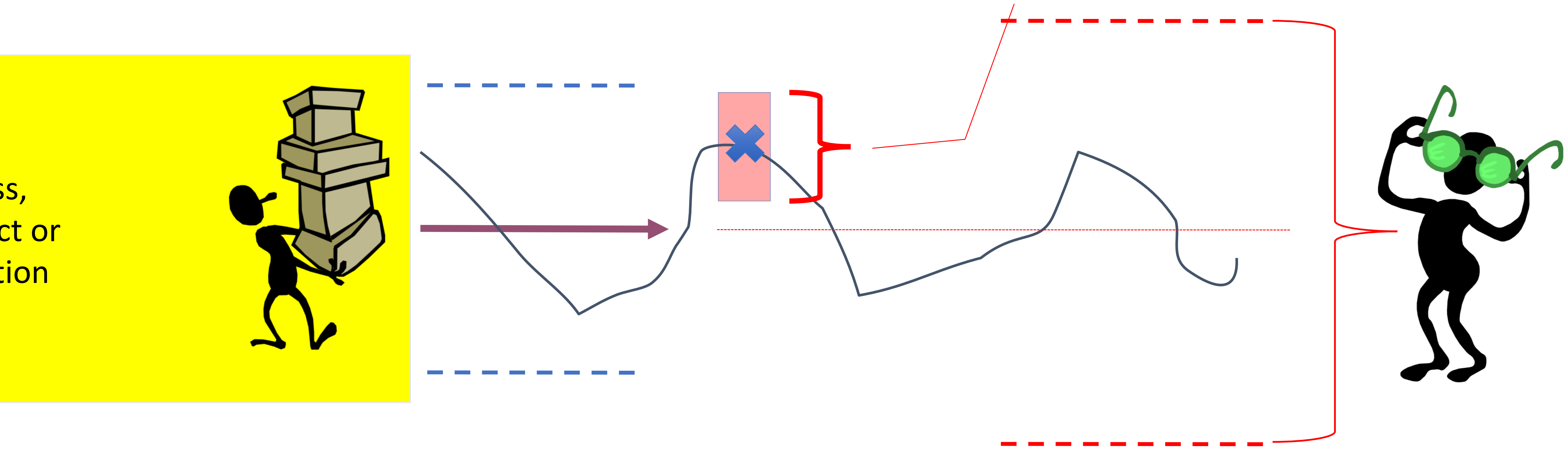
- … to make go/no-go decisions,
    - that is converting numbers to two discrete levels.
- Measurement imprecision can be maximum **30% of spec width**



- The numbers are transformed to **attribute data (y/n)**:
    - 10,2 ----> in
    - 13,4 ----> out
- The value of the numbers are limited

Standards say…

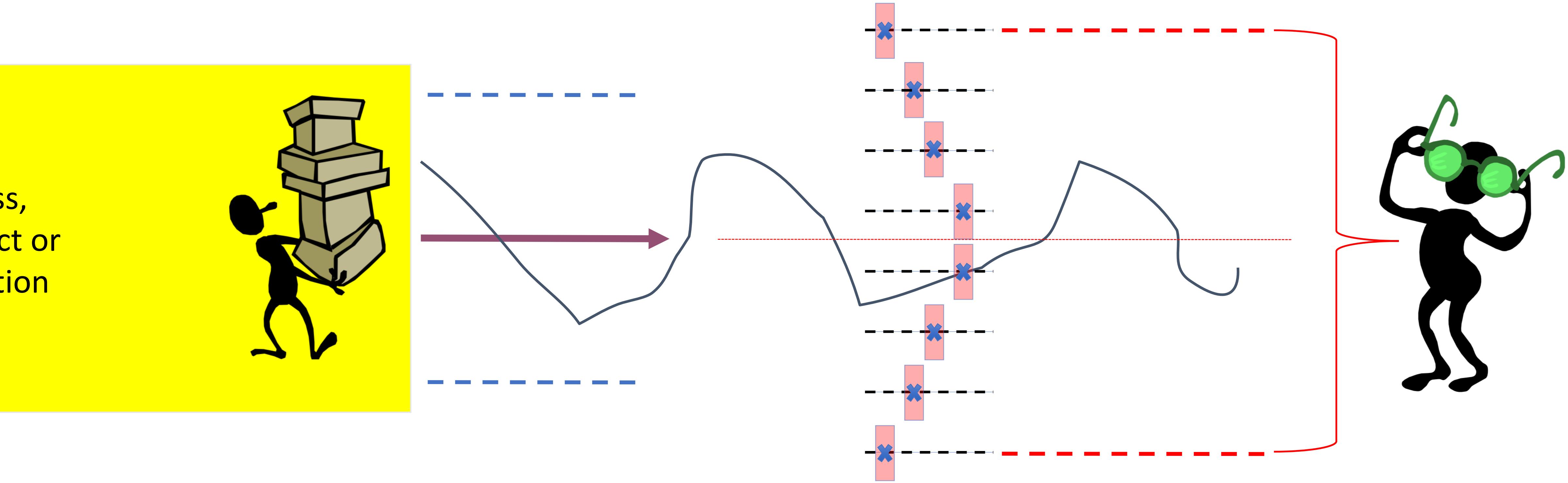
- … if the numbers themselves are going to be used for **process improvements as numbers,**
- higher precision is needed.
- Measurement imprecision can be maximum 20% of spec width



Question is:

Can the measurement system be used for the **decisions** that need to be taken?

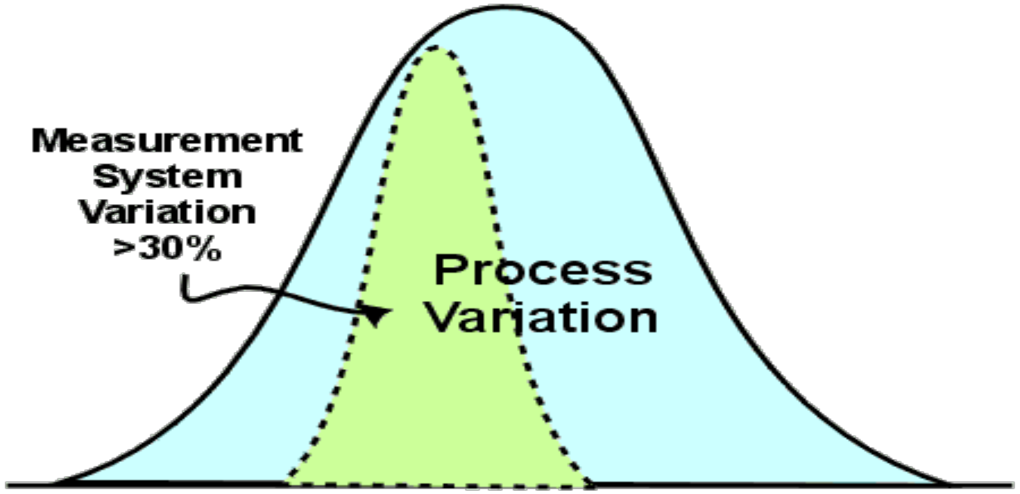
In practice these means…



≥7 unique **discrimination levels** between the specification limits to be able to characterize the performance of the process !

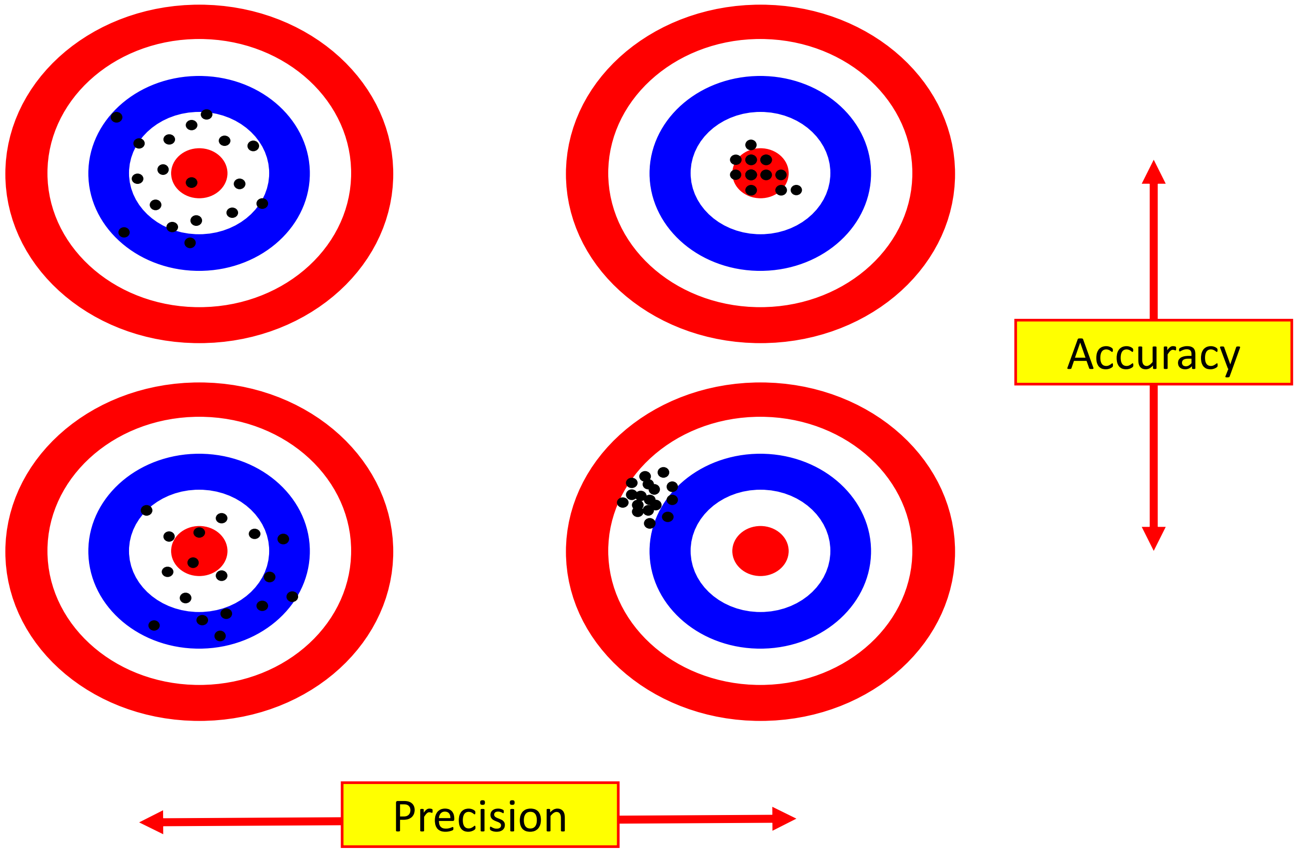
Rule of thumb: Precision of MS needs to be 10x of the precision of the decision, is a little to strict but much easier to interpret.
Example: if you want to be sure to cut the length of something in the right cm you need to have mm on your ruler

Measurement System Analysis



- Variation is inherent in all processes
  - Measurement processes are no different
- If a part characteristic is measured a number of times, different results will be obtained
- Measurement system variation needs to be recognised, accepted and managed
- Calibration only adjust MS mean level - accuracy

Accuracy and precision



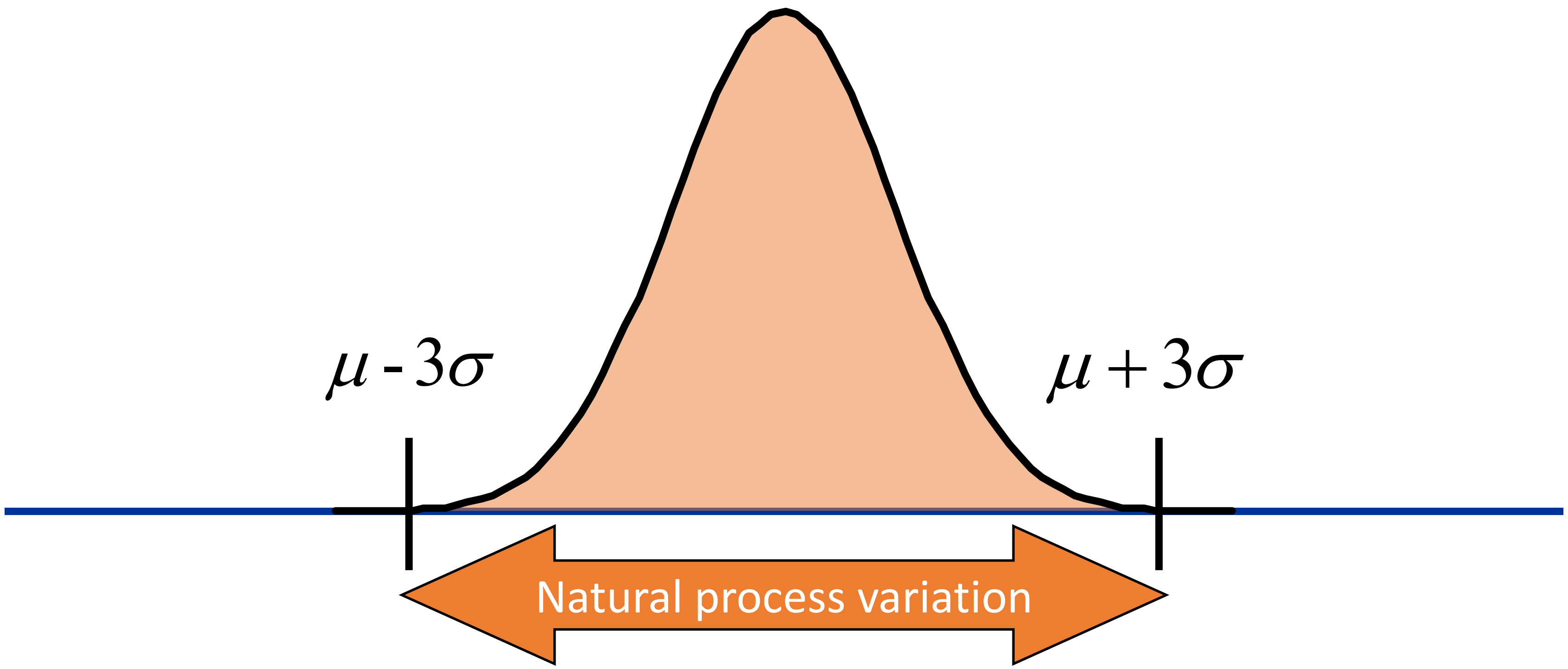
So when we have a stable predictable process:

Is it good enough?
How do we know?

What is Process Capability?

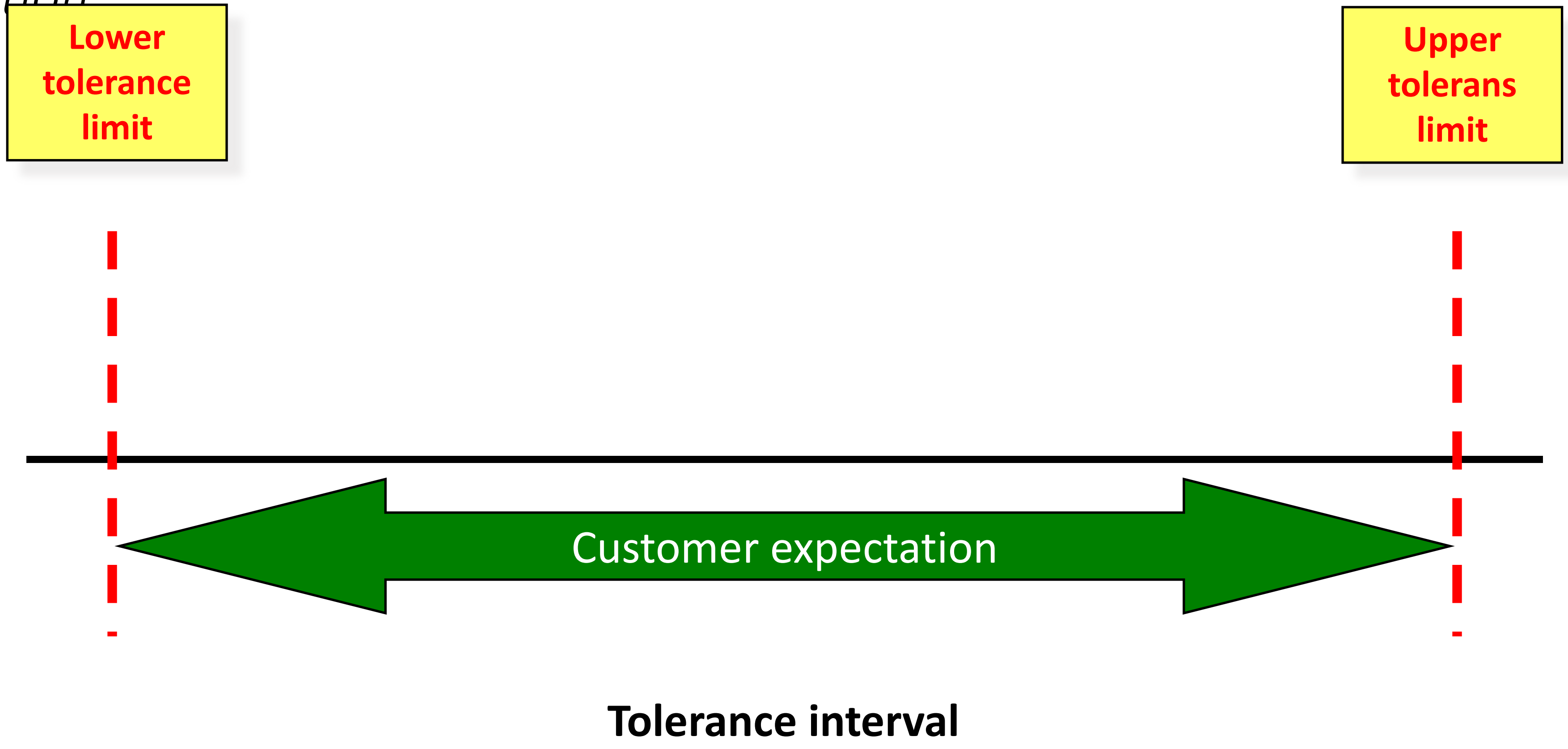
VOP

The natural process limits



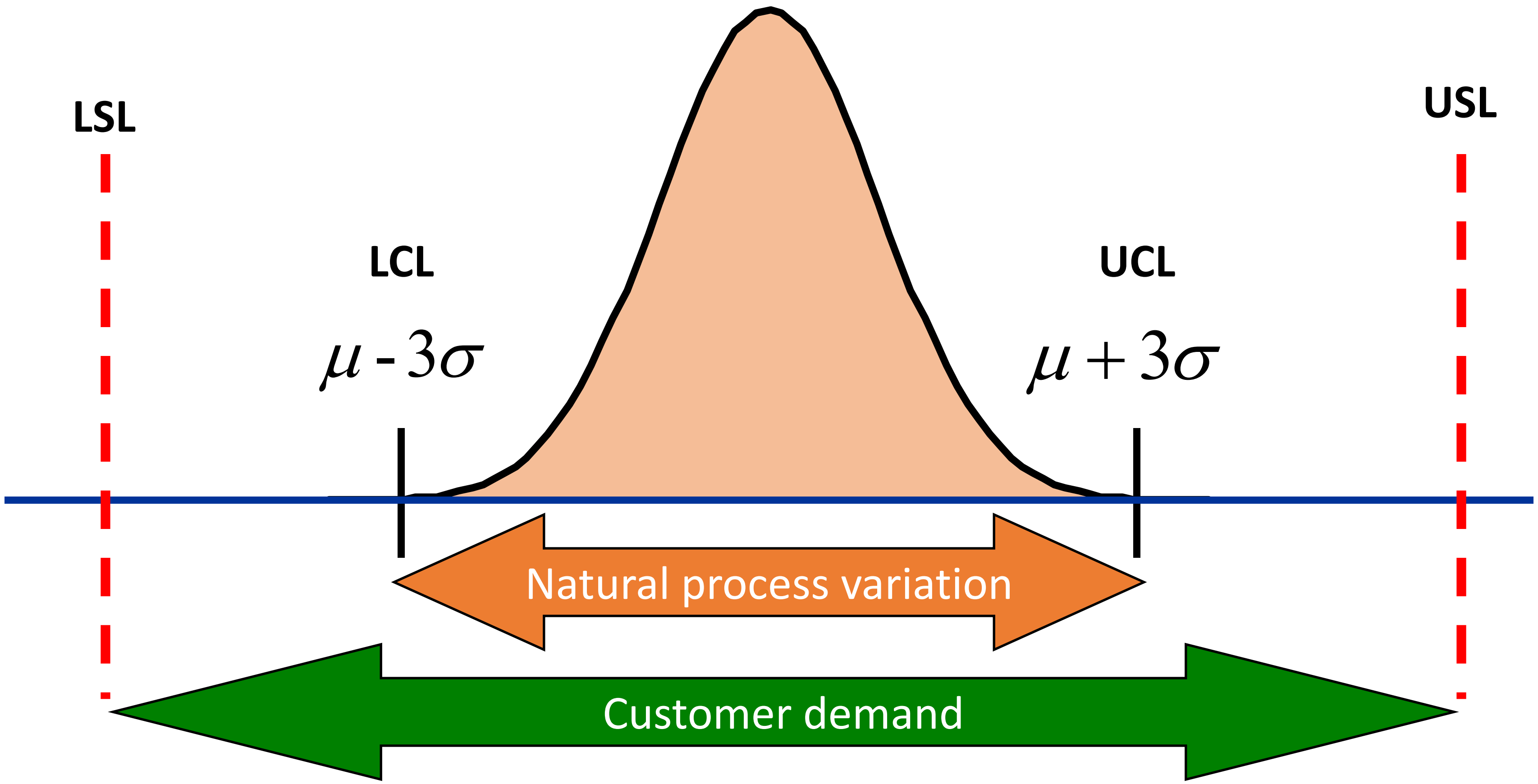
VOC

Specification



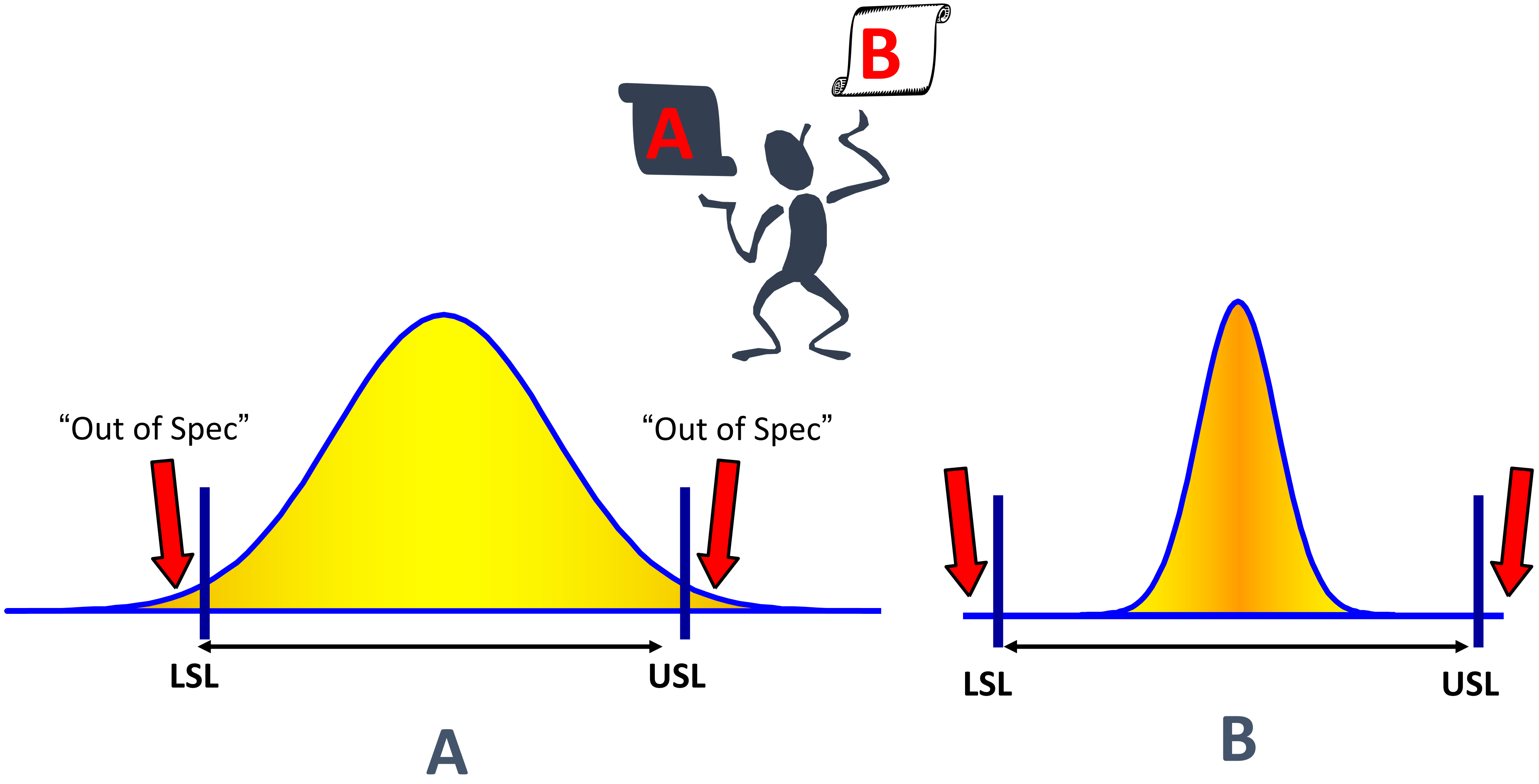
Interaction

Process capability

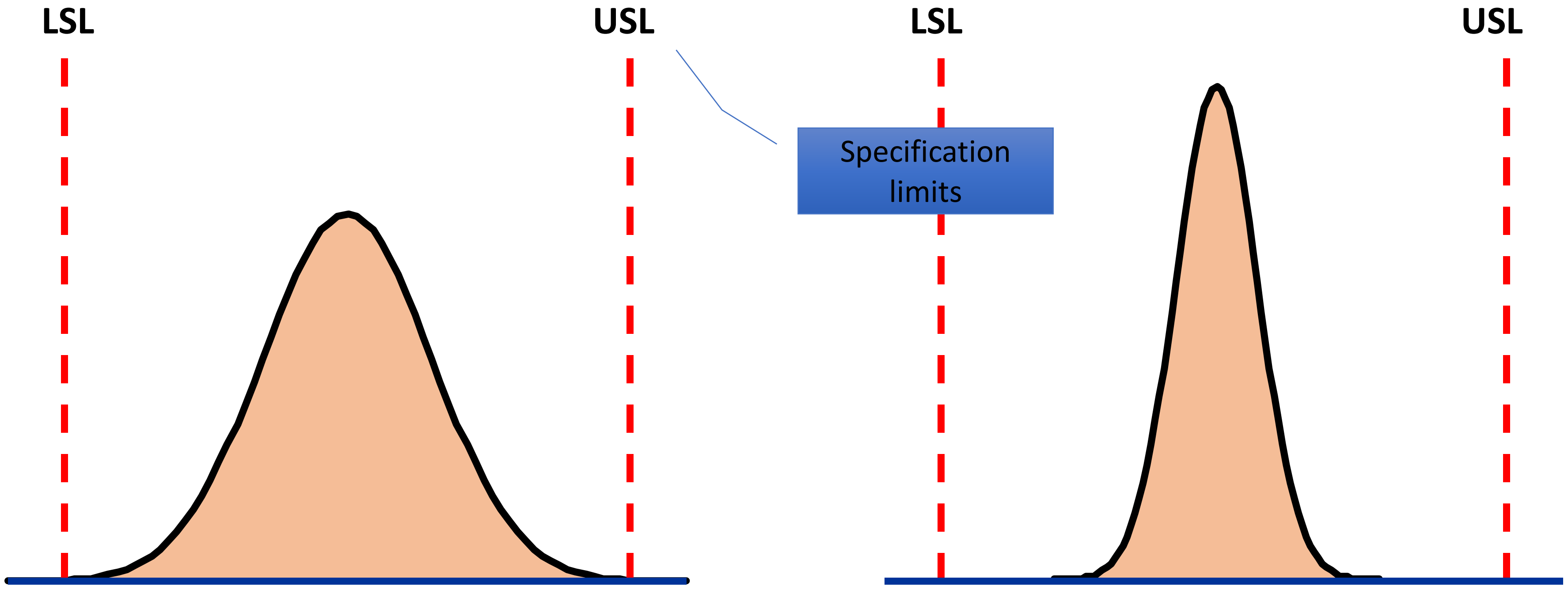


<u>No logical connection between them</u>

What process are most capable?



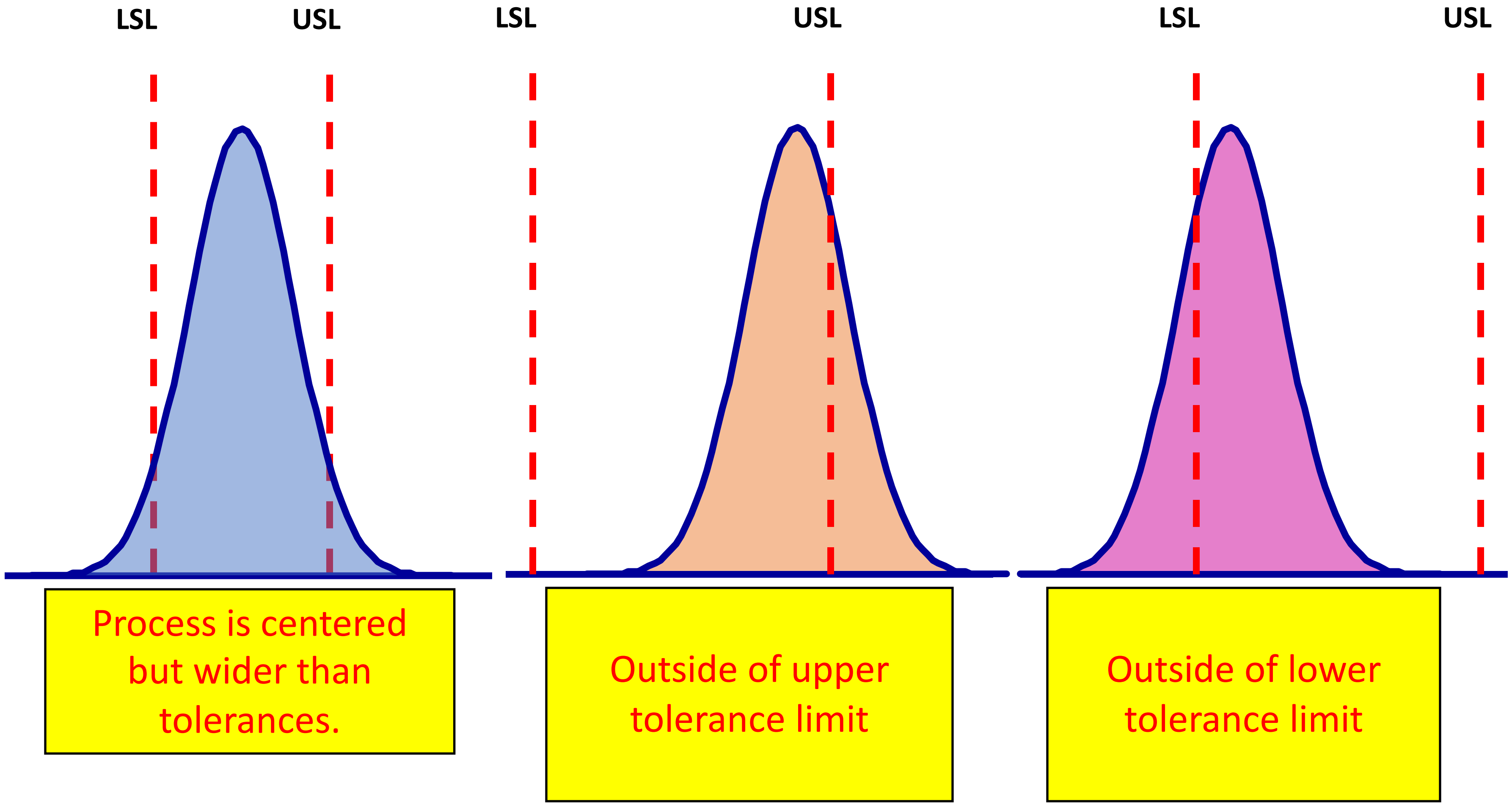
Capable processes



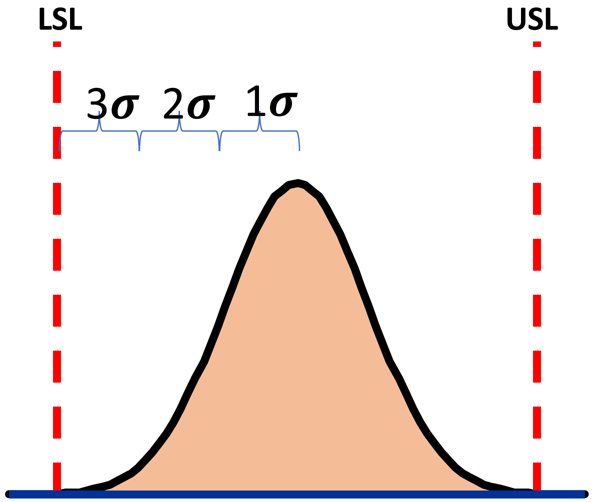
Process is precisely - capable fills out tolerance interval. Centering needs to be maintained.

Process is capable and will remain so even if it will shift sideways over time.

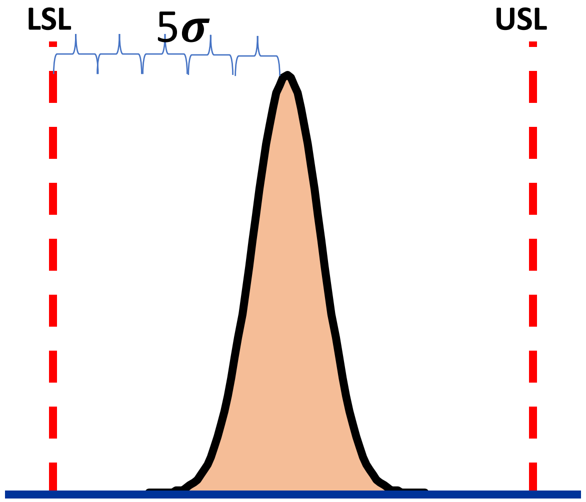
Non-capable processes



C_p/C_{pk} vs. 'sigmas'



Three standard deviations $\boldsymbol{\sigma}$ from the mean to the spec. limit.
C_{pk} = 1 (3 sigma)



Five standard deviations $\boldsymbol{\sigma}$ from the mean to the spec. limit.
C_{pk} = 1,67 (5 sigma)

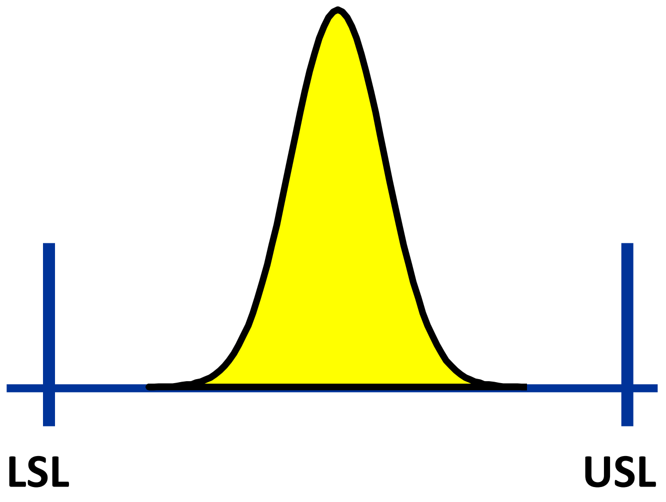
Process capability

Improvement strategies

Decrease variation (standard deviation)

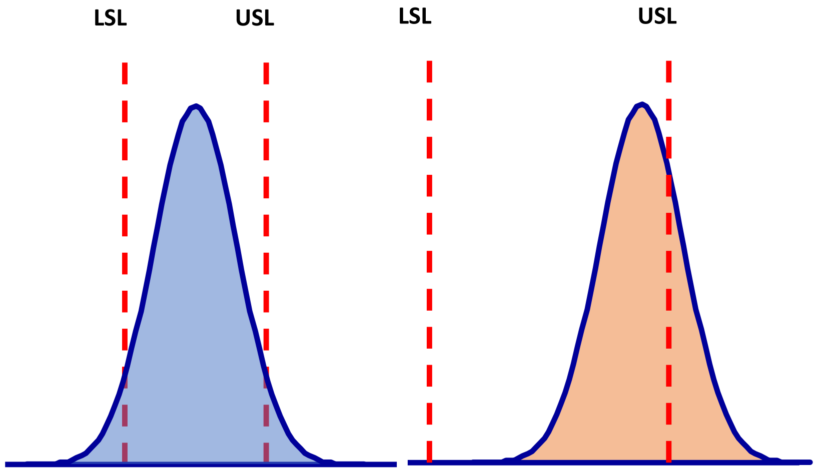
Process towards centre (mean)

What’s easiest?



Capability for process, Cp

$$C_p = \frac{Specification\ width\ VOC}{Process\ variation\ VOP} = \frac{USL - LSL}{6\sigma}$$

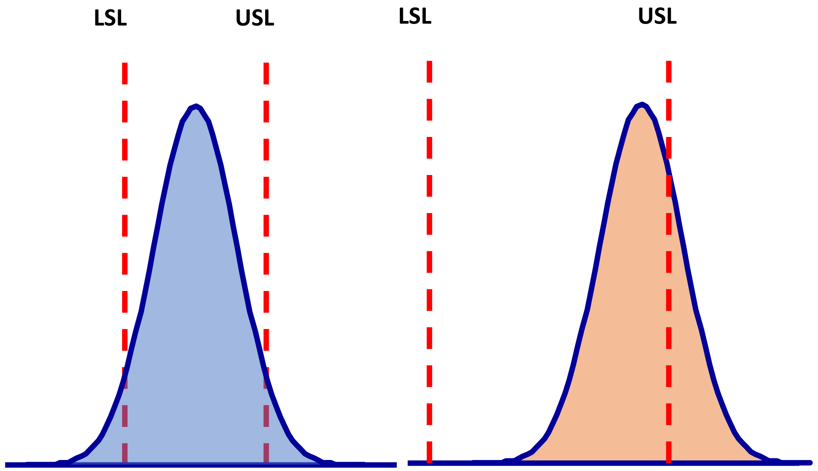


C_{p1} = C_{p2}

- μ, σ = mean, standard deviation
- C_p will only consider process variation:
- Benchmarks:
  - Limit Cp = 1.00
  - OK Cp = 1.33
  - Good Cp = 1.67
- ***C_p* compares process variation to tolerance width, that is, *does the process <u>have the potential</u> to be capable***

Centered capability measure, C_{pk}

$$C_{pk} = minimum\,(C_{pU}, C_{pL}) = \min\left(\left[\frac{USL-\mu}{3\sigma}\right], \left[\frac{\mu-LSL}{3\sigma}\right]\right)$$



C_{pk1} > C_{pk2}

- μ, σ = mean, standard deviation
- C_{pk} consider process both variations and location
- Benchmarks:
    - Limits $C_{pk} = 1.00$ 3 sigma process
    - Standard present processes $C_{pk} = 1.33$ 4 sigma process
    - Demand new processes $C_{pk} = 1.67$ 5 sigma process
- Typically: companies require at least 1.33 of their suppliers, but it varies from case to case and is directly connected to the price

Capability for process, C_p & C_{pk}

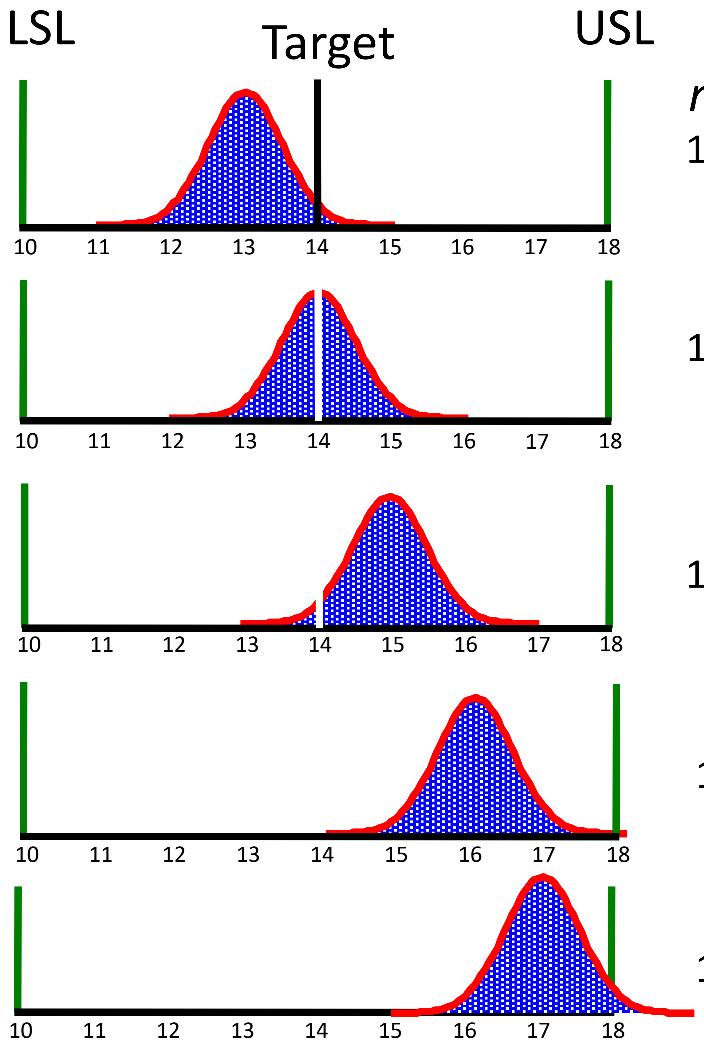
- Cp will only consider process variation:
- Benchmarks:
  - Limit Cp = 1.00
  - OK Cp = 1.33
  - Good Cp = 1.67

- C_{pk} consider process both variations and centre
- Benchmarks:
  - Limits C_{pk} = 1.00
  - Standard present processes C_{pk} = 1.33
  - Demand new processes C_{pk} = 1.67

$$C_p = \frac{Tolerance}{Process\ variation} = \frac{USL - LSL}{6\sigma}$$

$$C_{pk} = min(C_{pU}, C_{pL}) = min\left(\left[\frac{USL - \mu}{3\sigma}\right], \left[\frac{\mu - LSL}{3\sigma}\right]\right)$$

Interplay between C_p and C_{pk}



m	C_p	C_{pk}
13	2	1.5
14	2	2
15	2	1.5
16	2	1
17	2	0.5

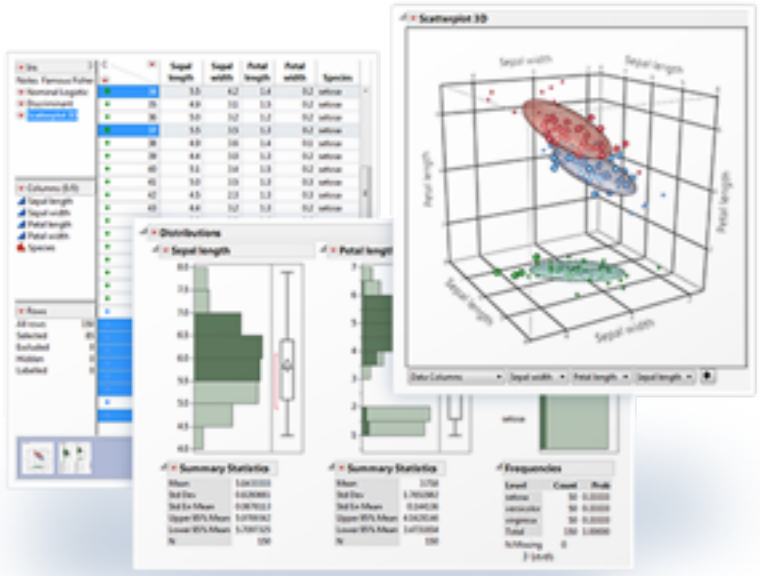
Always:
$C_{pk} \leq C_p$.

Stability is determinating

- **Stability** is required for process capability estimations:
  - Distribution of future products becomes predictable.
  - Almost all products (99,73%) will be within +/- 3 sigma for the process
    - i.e. 399 out of 400 will naturally fall between CL
    - But still 1 of 400 will be odd because of natural reasons – (false alarm?)
    - *How does it relate to your case?*
  - Capability measures become relevant.

- **Without** stability there will be no capability.
  - Unpredictable process.
  - Capability measures meaningless.

JMP Pro



- State-of-the-art program for data visualization, analysis and predictive modelling from experiments: JMP Pro from SAS institute:
  - https://www.jmp.com/en_us/home.html
- Chalmers site license
  - You can down-load it from the student portal or run it in M-computer labs
- To get going with the statistical software package watch the ‘JMP Basics for Professors and Students’. It is located under the headline ‘JMP Basics for Professors and Students’ here:
  - https://www.jmp.com/en_us/academic/academic-webinars.html#basics
- Understanding how to evaluate and monitor a process using JMP Pro:
  - https://community.jmp.com/t5/Mastering-JMP-Videos-and-Files/Evaluating-amp-Monitoring-Your-Process-Using-MSA-and-SPC/ta-p/277447
- Basic on QE, Reliability and Six Sigma
  - https://www.jmp.com/en_us/applications/quality-reliability-six-sigma.html

JMP - one page guides

Pages 26, 68 and 71

Process capability overview
https://www.jmp.com/en_us/applications/quality-reliability-six-sigma.html

General terms and definitions will be parts of the examination. There are much material on internet under the topic of quality and six sigma methodologies. **USE THEM**! For example some general papers:

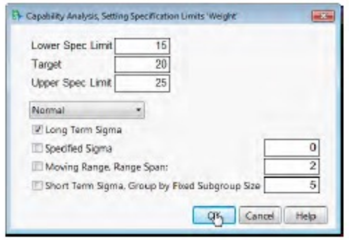
Process Capability: How to understand it
http://www.syque.com/quality_tools/toolbook/Procap/how.htm

Capability Analysis

This page provides information on performing a capability analysis using the Distribution and Control Chart platforms. Capability analysis can also be performed in the **Capability** platform under **Analyze > Quality and Process**.

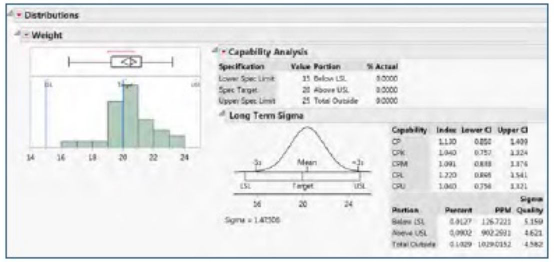
Example: Coating.jmp (Help > Sample Data > Quality Control)

Capability Analysis – Distribution Platform



1. From an open JMP® data table, select **Analyze > Distribution**.
2. Select one or more continuous variables from **Select Columns** (continuous variables have blue triangles), click **Y, Columns**, and click **OK** to generate a histogram and summary statistics.
3. From the **red triangle** for the variable, select **Capability Analysis**.
4. Enter the **spec limits** and **target**.

   Specify the distribution (if the underlying distribution is not normal), and select the estimate(s) to use for sigma. Note: If **moving range** and/or **fixed subgroup size** are selected, data must be sorted in time order.
5. Click **OK** to perform a capability analysis for each estimate of sigma selected.

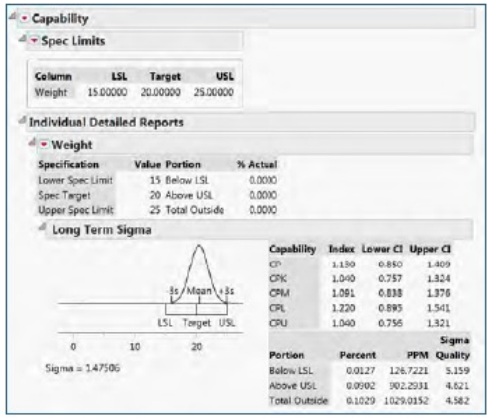


Capability Analysis – Capability Platform

1. Generate a control chart using **Analyze > Quality and Process > Capability**
2. Enter the **spec limits** and **target**, and click **OK**.

   By default, the following will be added to the output:

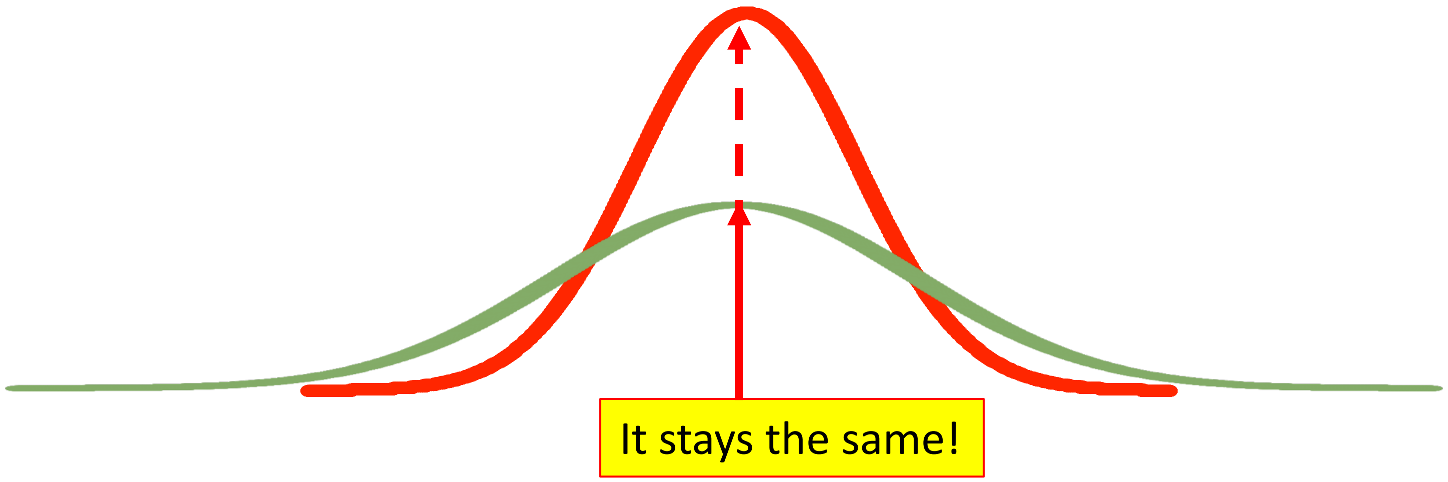
   - The observed (actual) capability.
   - Capability analyses based on the overall standard deviation (**Long Term Sigma**)



Notes: Long term (P_{pK}) capability labeling can be turned on using the JMP Preferences (under **Preferences > Platforms > Distribution**). For information on creating control charts, see the guides under **Quality, Reliability and DOE** at jmp.com/learn. For additional details, search "capability" in the JMP Help or see the book ***Quality and Process Methods*** (under **Help > Books**).

Robustness and non-normal data

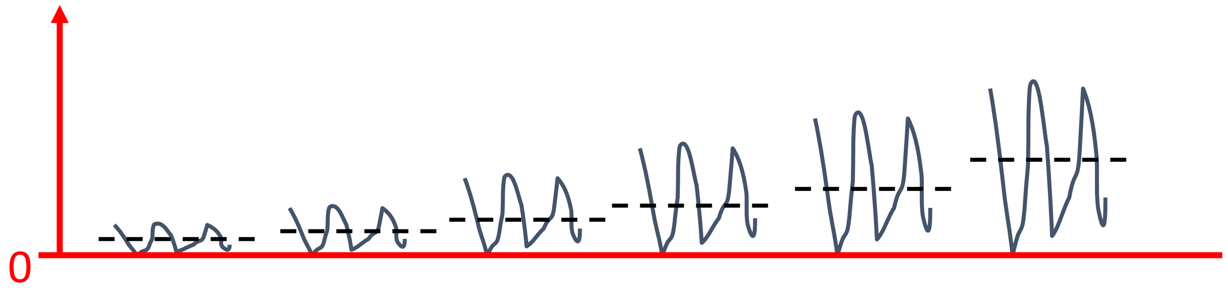
Normal distribution - what happens with the mean when variation increase?



Flaw of averages

- Business and operational data often single sided.
  - Number of products or hours are only positive – *Not Normal distributed!*
  - *What happens when variation increase if there is only one side of the data?*
    - ➢ *mean level will rise!*
    - ➢ *and mean level is connected to business result*

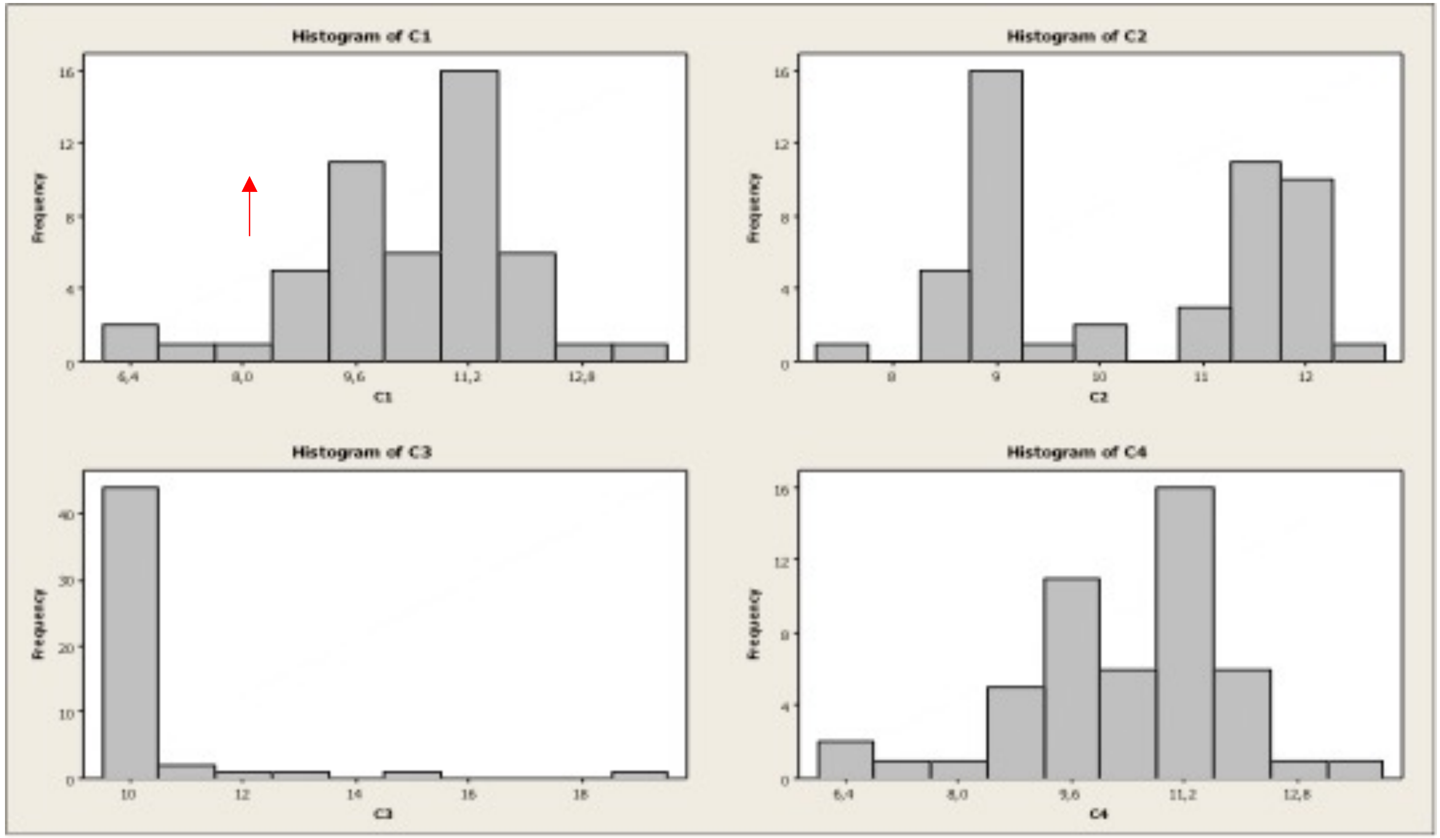
  ➢ *Basic quality improvement philosophy: mitigate influence of variation and get sustainable improvement of mean level*



Why is variation important

$$\bar{x} = 10{,}309; s = 1{,}501$$

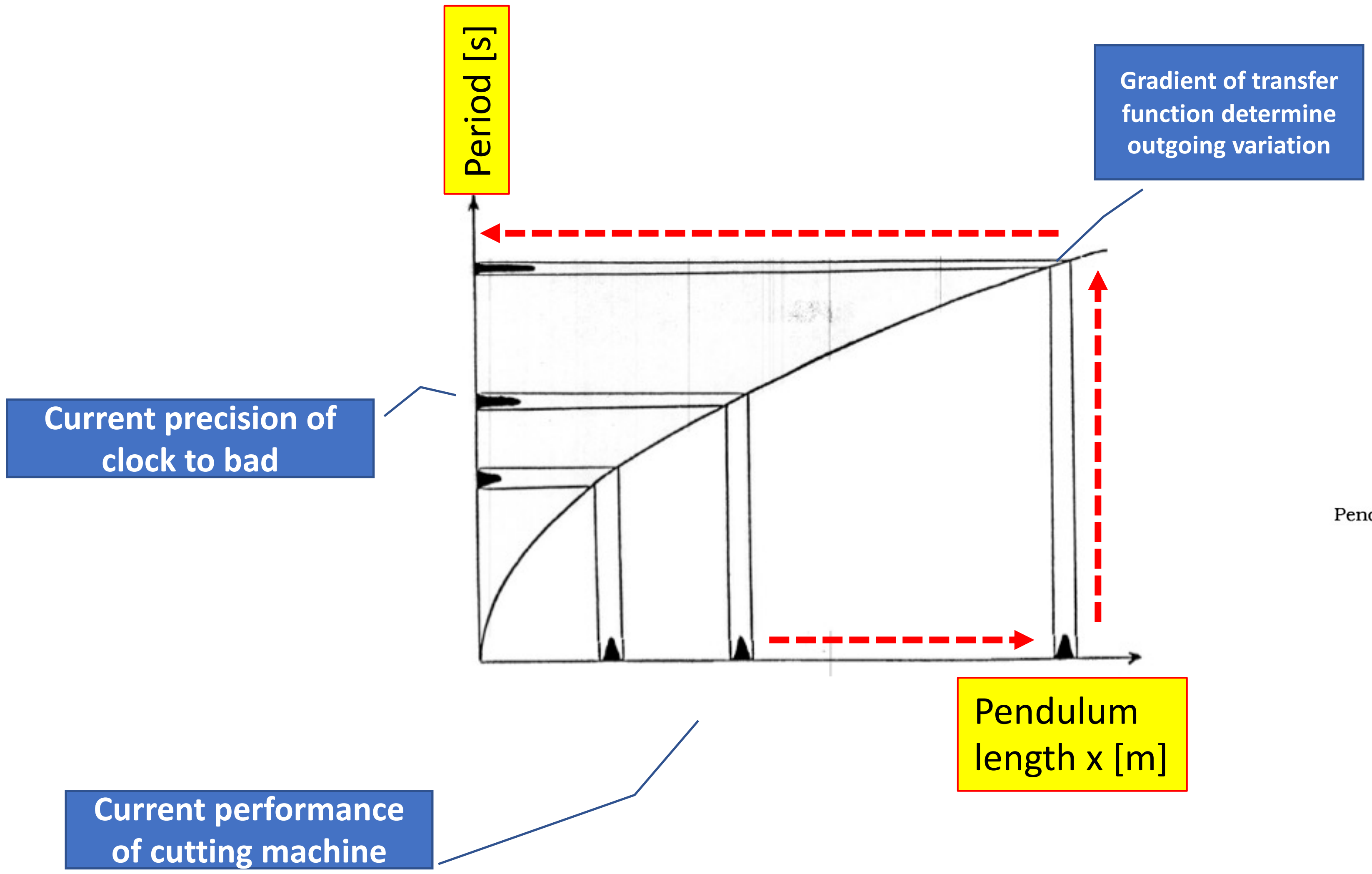
Risk to lose info when condensing into just a number

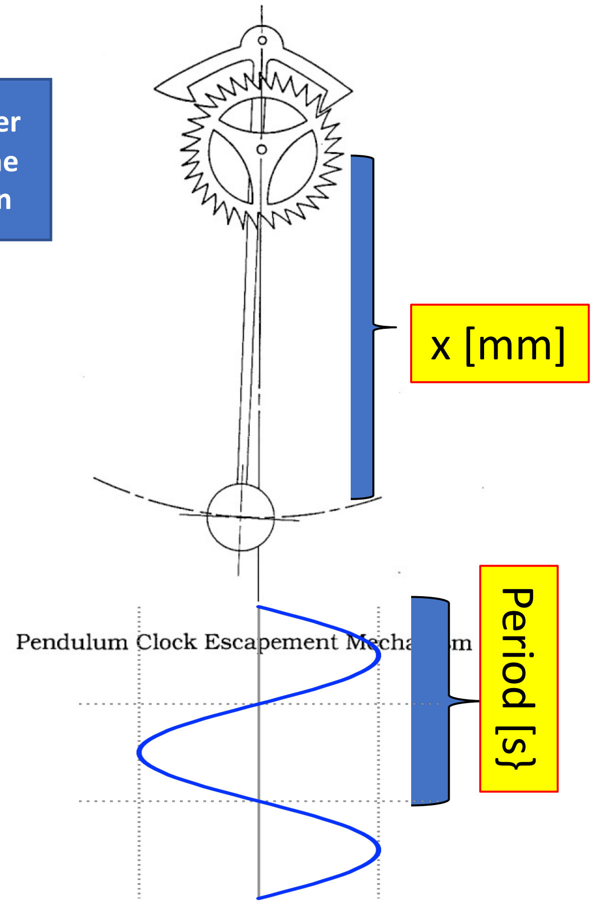


All have the same mean and standard deviation

Longer or shorter pendulum?

Improve output variation without increasing cost



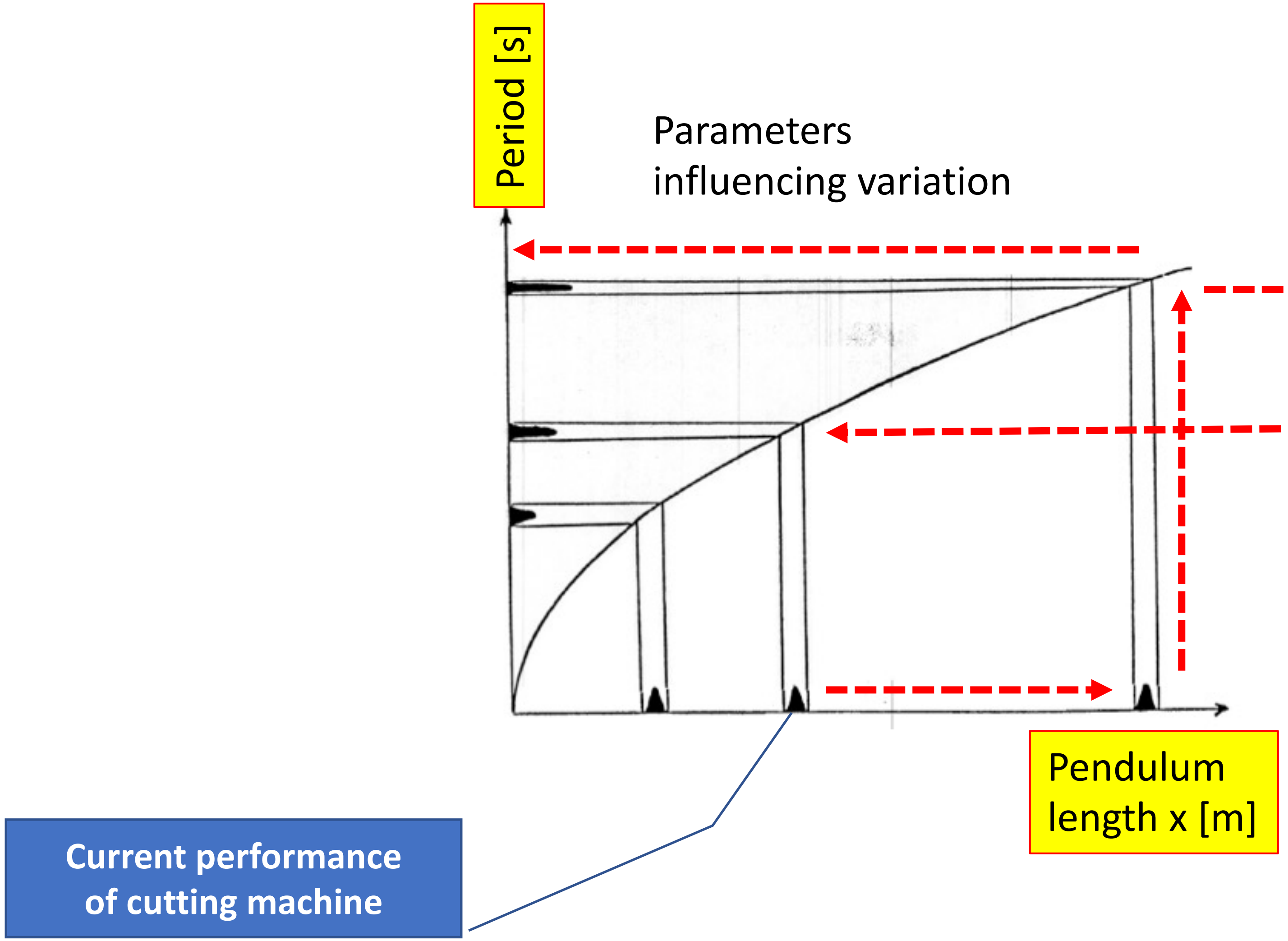


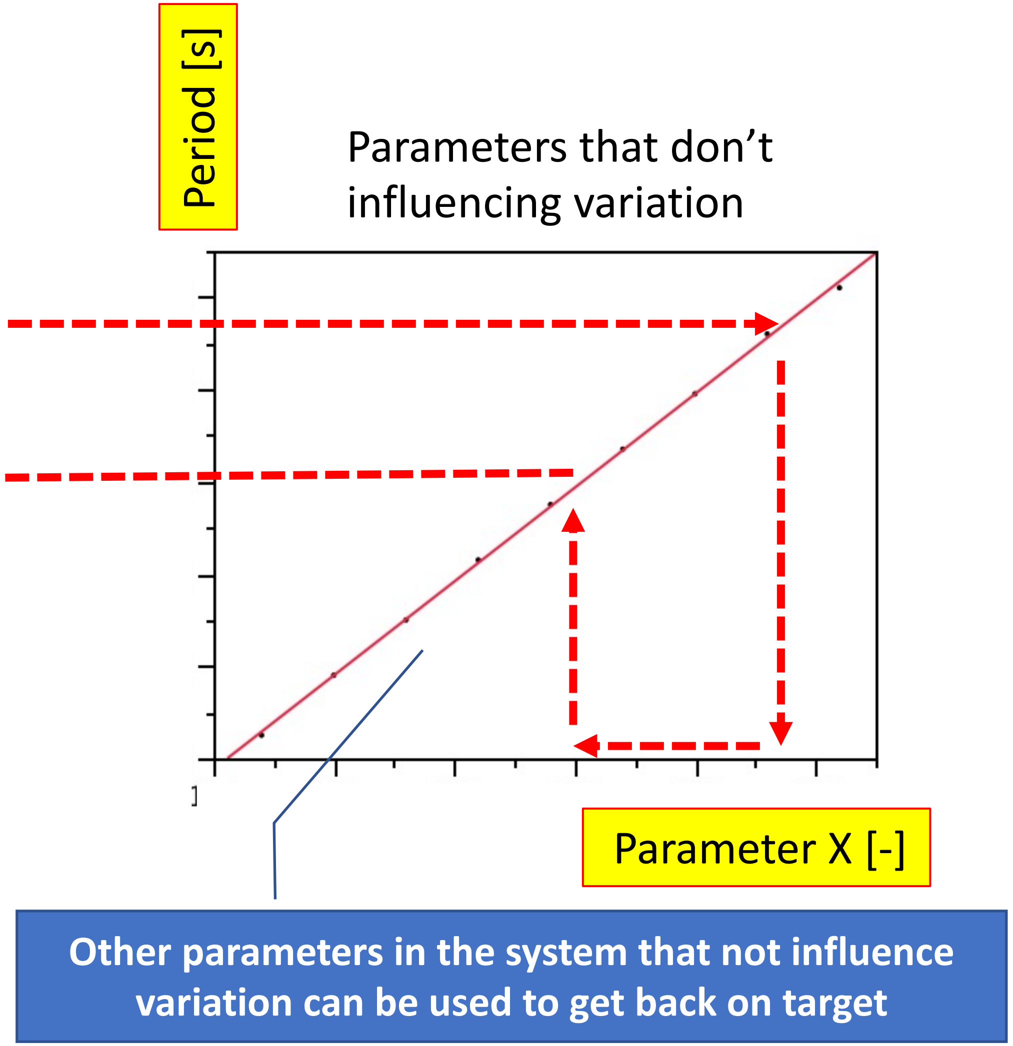
But, we are no longer on target…?

Improve output variation without increasing cost

Robust engineering

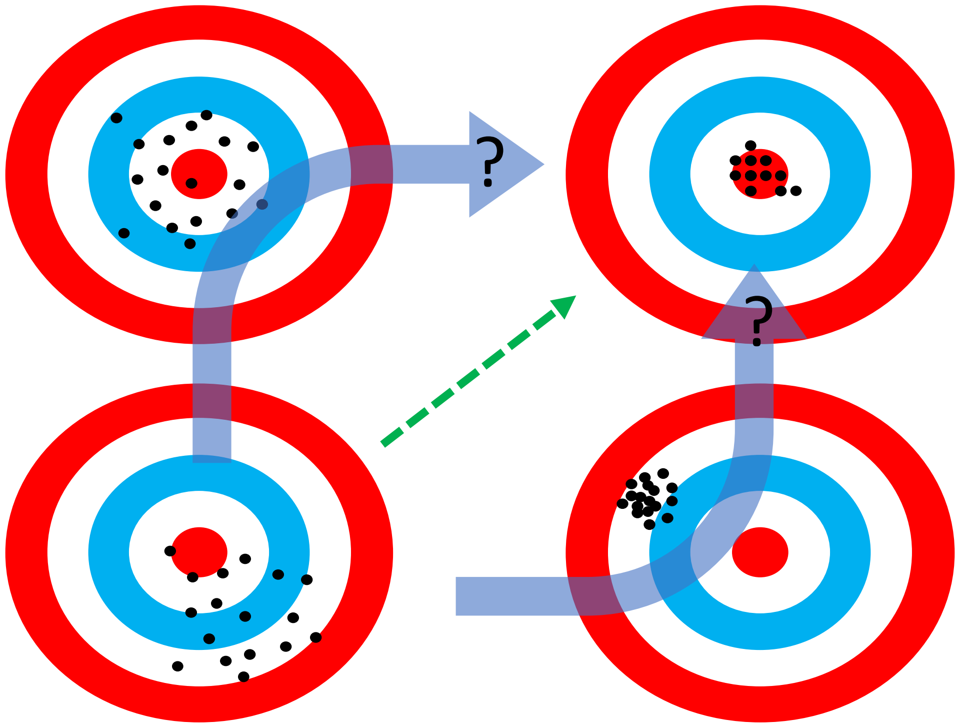
1. First minimize influence of variation
2. Then set performance on target



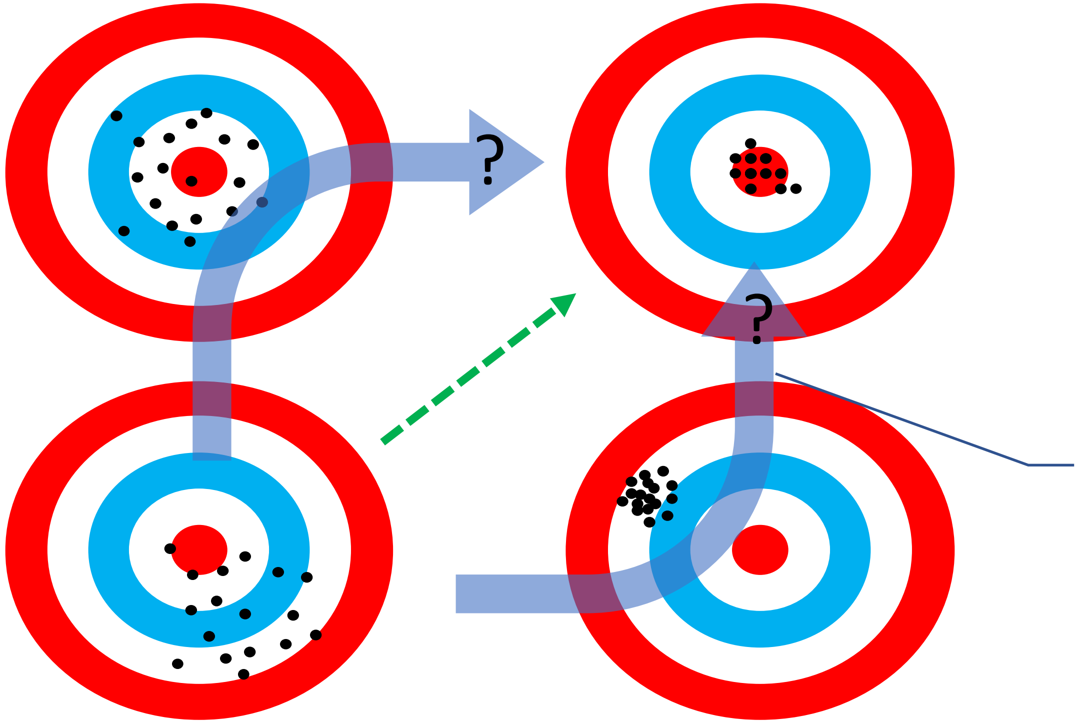


Improving archery

What is the natural behavior when trying to shoot better?



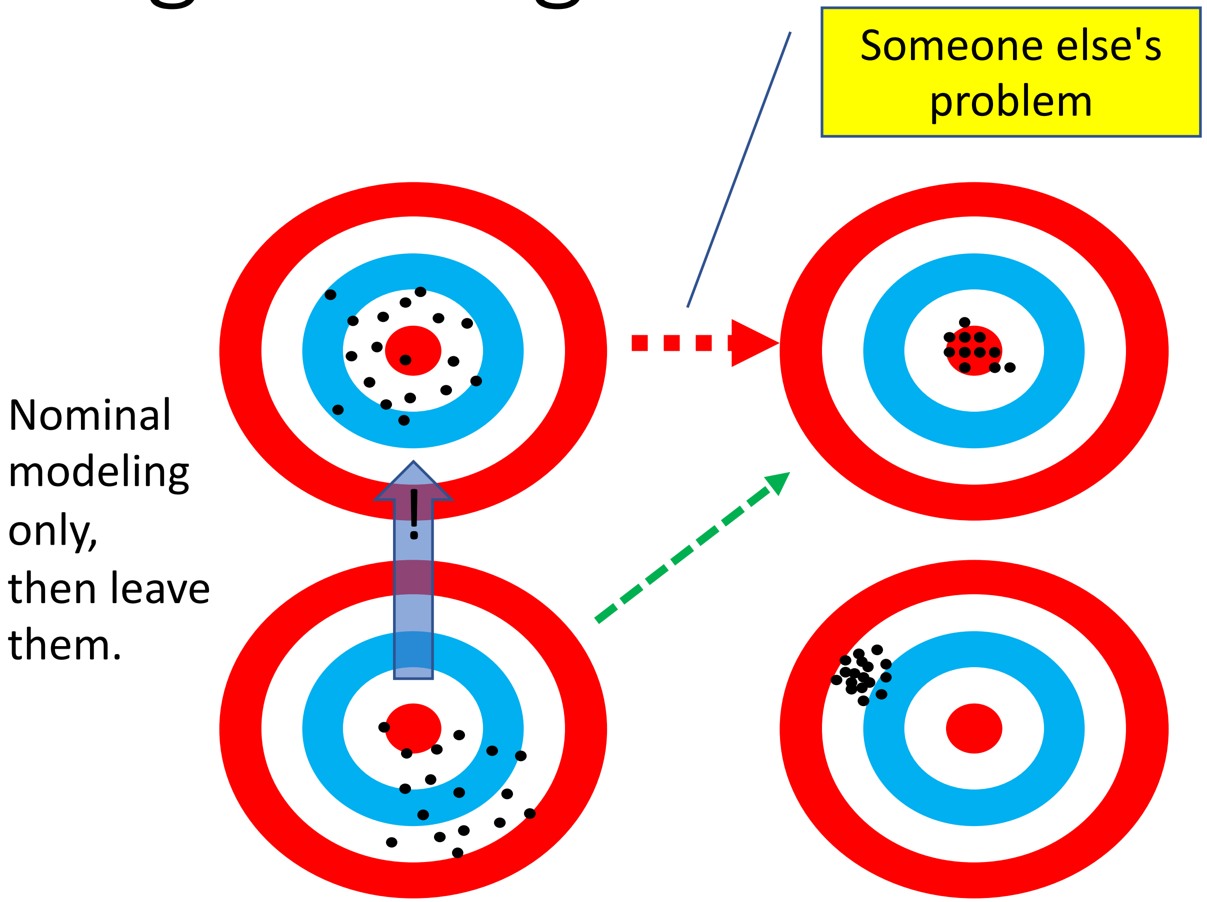
Improving archery



The natural behavior when trying to improve your shooting is the lower route!

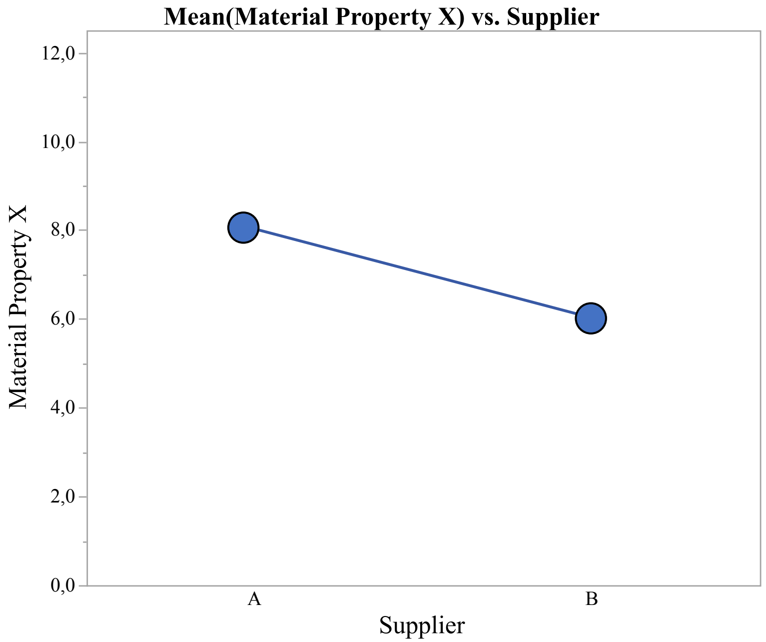
First – get precision under control!
Shifting to target easier.

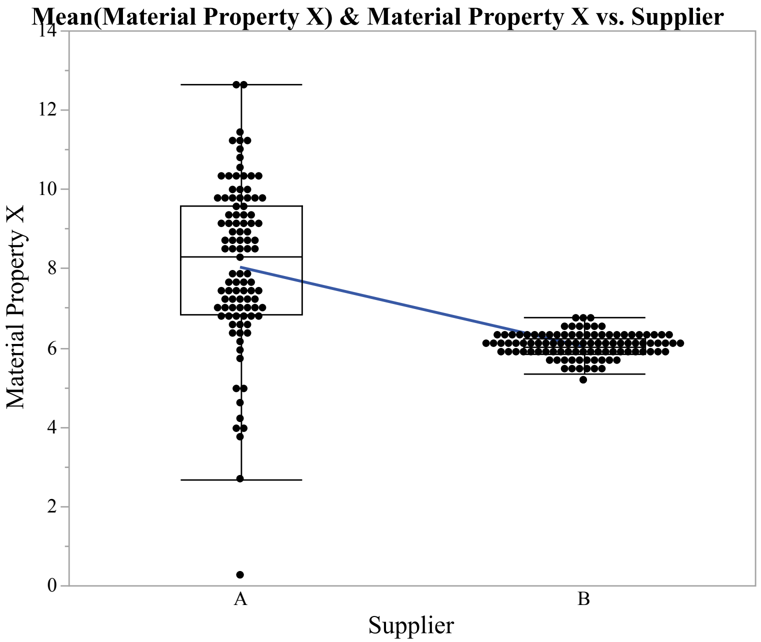
Classical engineering?



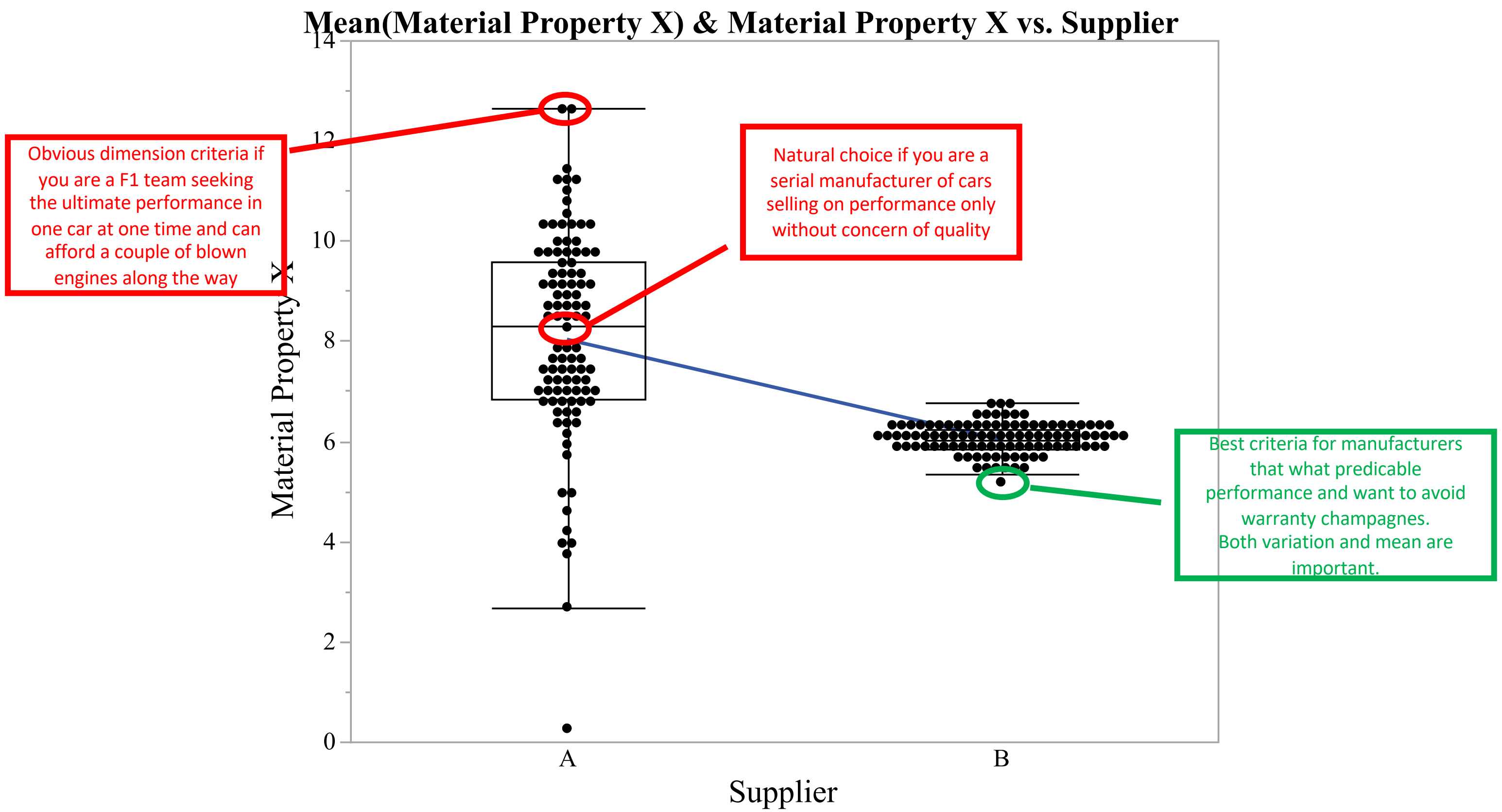
Common, but bad engineering

Comparing two suppliers

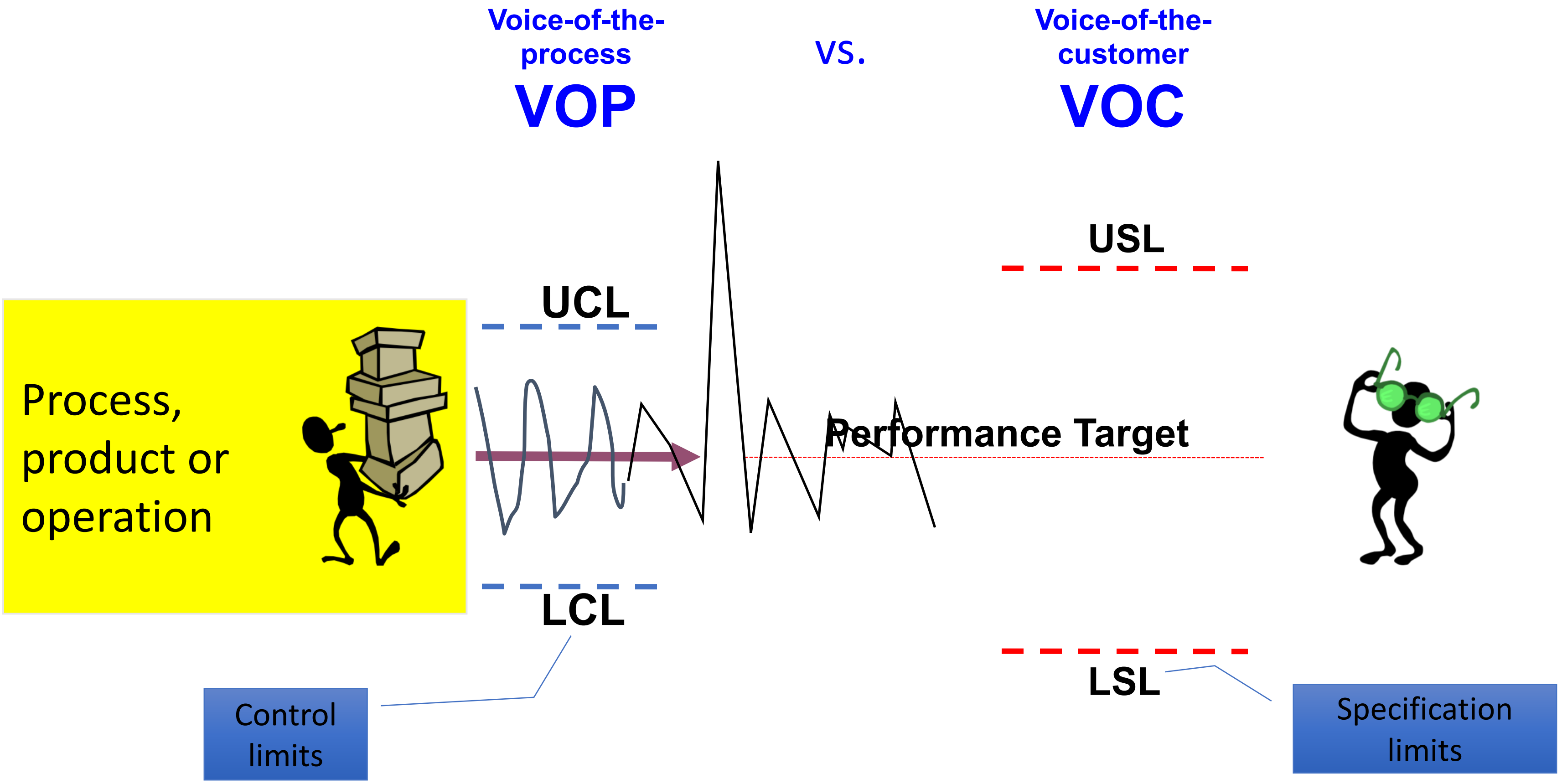




Comparing two suppliers



Control Limits (CL) ≠ Specification Limits (SL)



And nothing is nominal – get used to it

Review questions

What are the purpose with:

- VOP ≠ VOC
- Common vs. special causes of variation
- Process stability
- Observational vs. experimental studies
- SPC, control charts (ImR)
- Control limits based on 3-sigma (mR) vs. standard deviation
    - False alarms vs. missed signal
- Process capability
- Robustness and non-normal data