Lecture 9: Manufacturing cost and process monitoring

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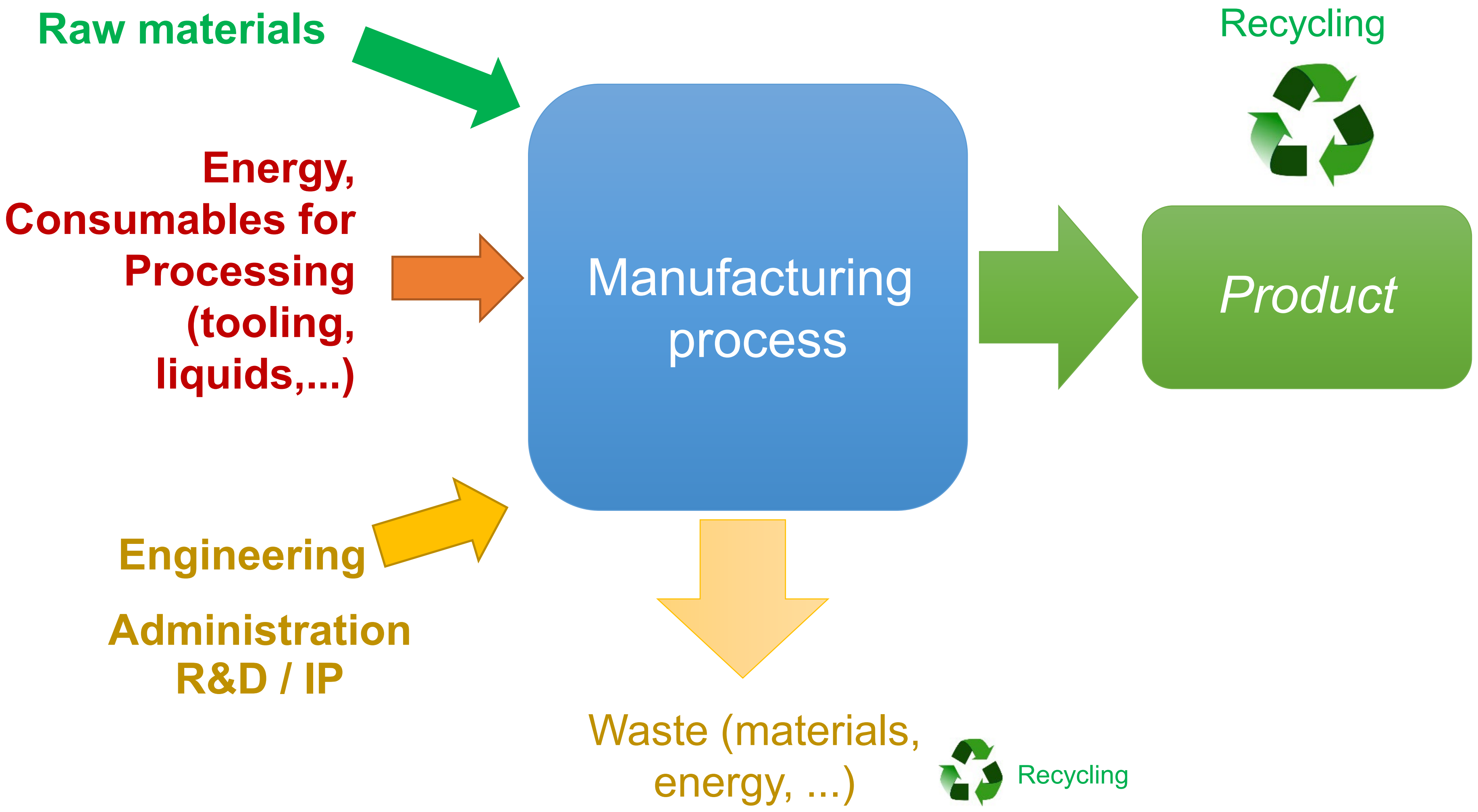
Learning objectives

- **Costs in manufacturing**
- An introduction of quality and variations in processing
- The **normal distribution**
- Understand the quantification of process **limits and capabilities**
- Methods for **process monitoring**

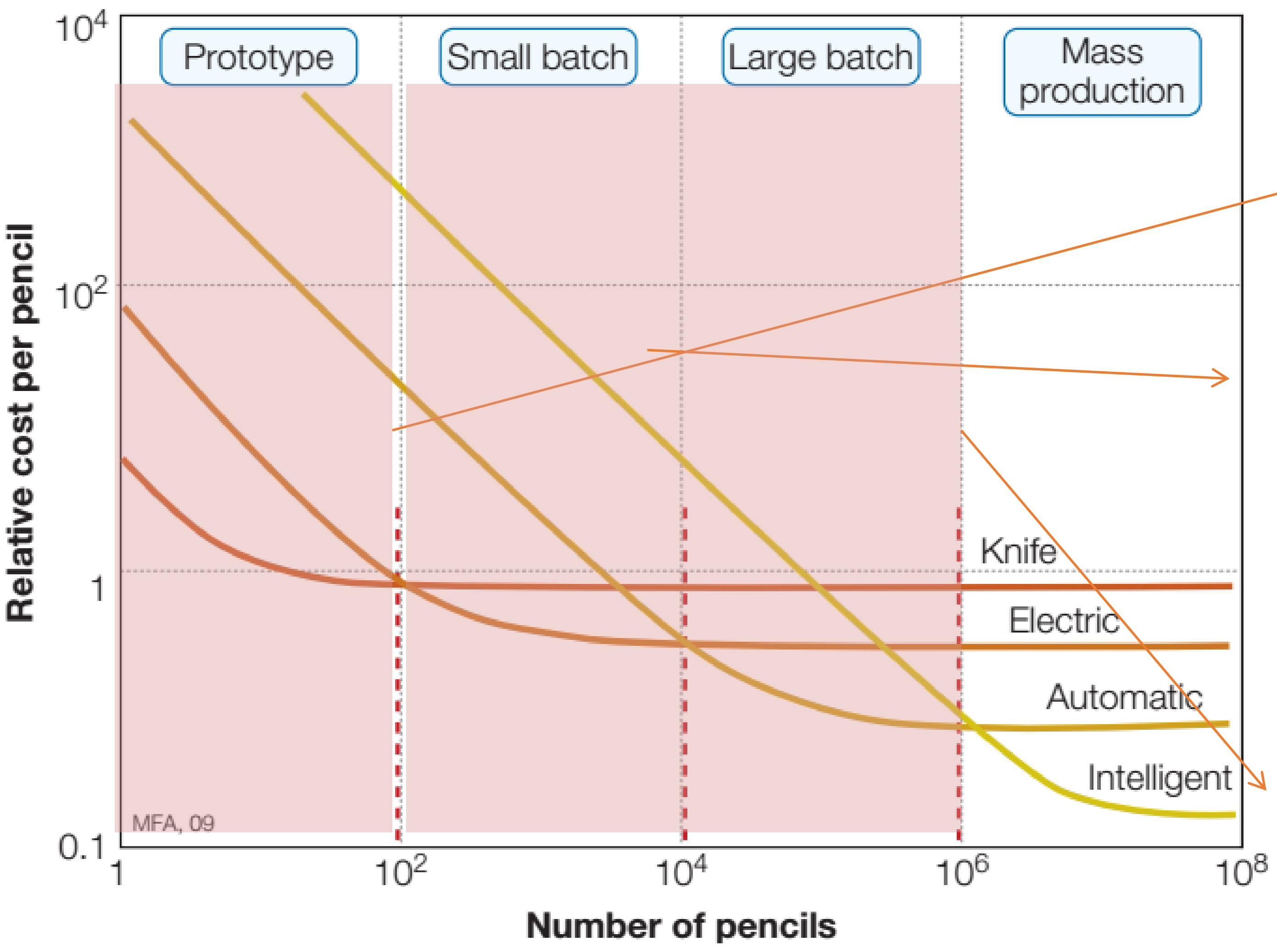
Introductory discussion (in class)

- What defines cost in manufacturing?
- **Exercise:** Suppose you run a machine shop, how would you define the price to ask to your client?

Source of costs in manufacturing



Introduction example: Paper pencil sharpening



(source M.F. Ashby, Materials selection in mechanical design, BH)

(source: Paperstone)

(source: Bureauengros)

(source: Ohmagif)

Raw materials: ‘ready to be processed’

- Cost for the raw material: C_{rm} ($/kg)
- ... *but* ***a fraction f*** *of the material needed to produce the part does not contribute directly to the object is scraped*. (f < 1)
- Real cost:

$$C_{mm} = \left(\frac{1}{1-f}\right) m C_{rm}$$

Real cost of ‘manufactured material’ ($) — C_{mm}

Mass of the final part (kg) — m

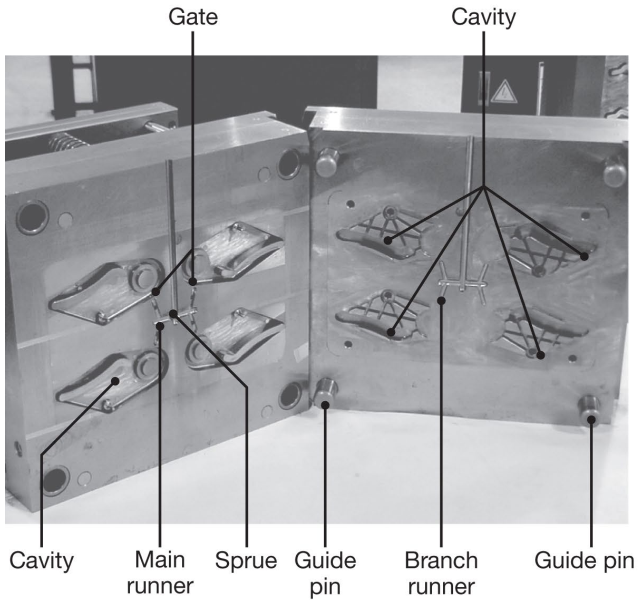
Cost of the raw Material ($/kg) — C_{rm}

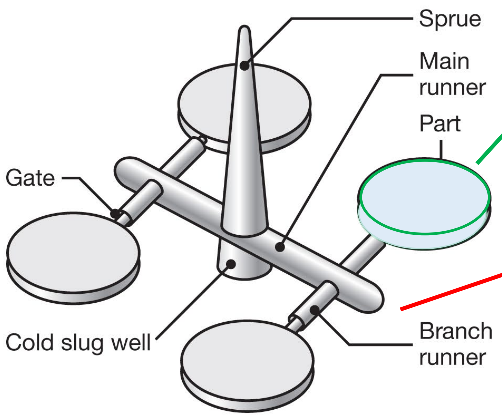
Fraction of the Raw material **effectively used** to produce the final part (>1) — $\left(\frac{1}{1-f}\right)$

f can range from 0% to close to 90%!

Material used to produce a part

- This is not to be confused with the amount of material ***effectively*** in the part volume.
- A fraction of the ***raw*** material is possibly wasted.
- In certain case (when the cost of the material justifies it), scrap material is recycled into production.





(see lecture 6)

Volume of material effectively going into one product

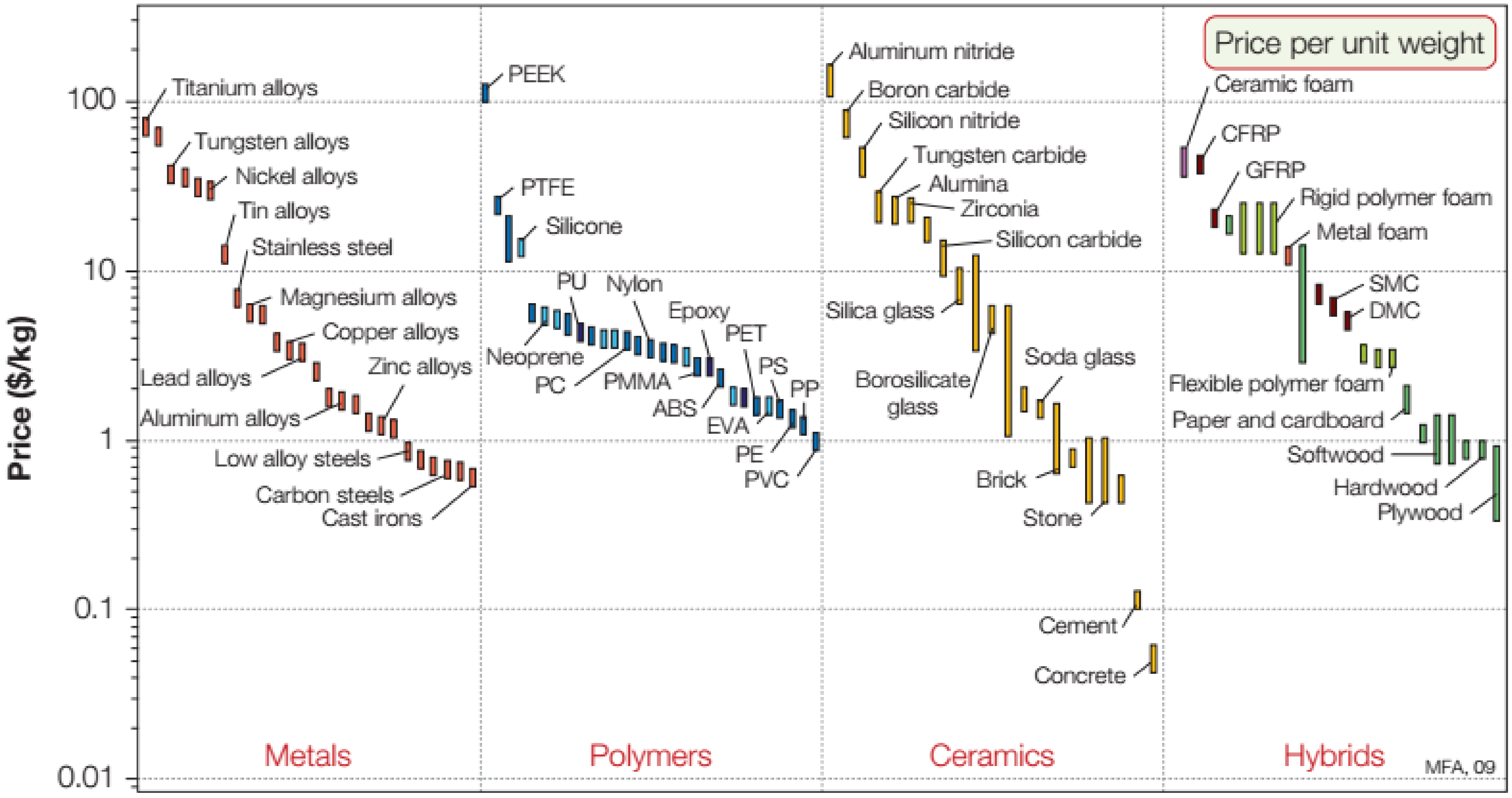
Wasted material (does not go into the final product), *but has to be accounted for...*

About the wasted materials for a given process

- Depends on the process!
  - **1/** Quiz – Can you name a process with (almost) zero material losses?
- Depends also on shape complexity
  - **2/** Quiz – Can you name a process where shape complexity has a strong impact on material losses?
  - **3/** Quiz - Can you name a process where shape complexity has almost no impact on material losses?

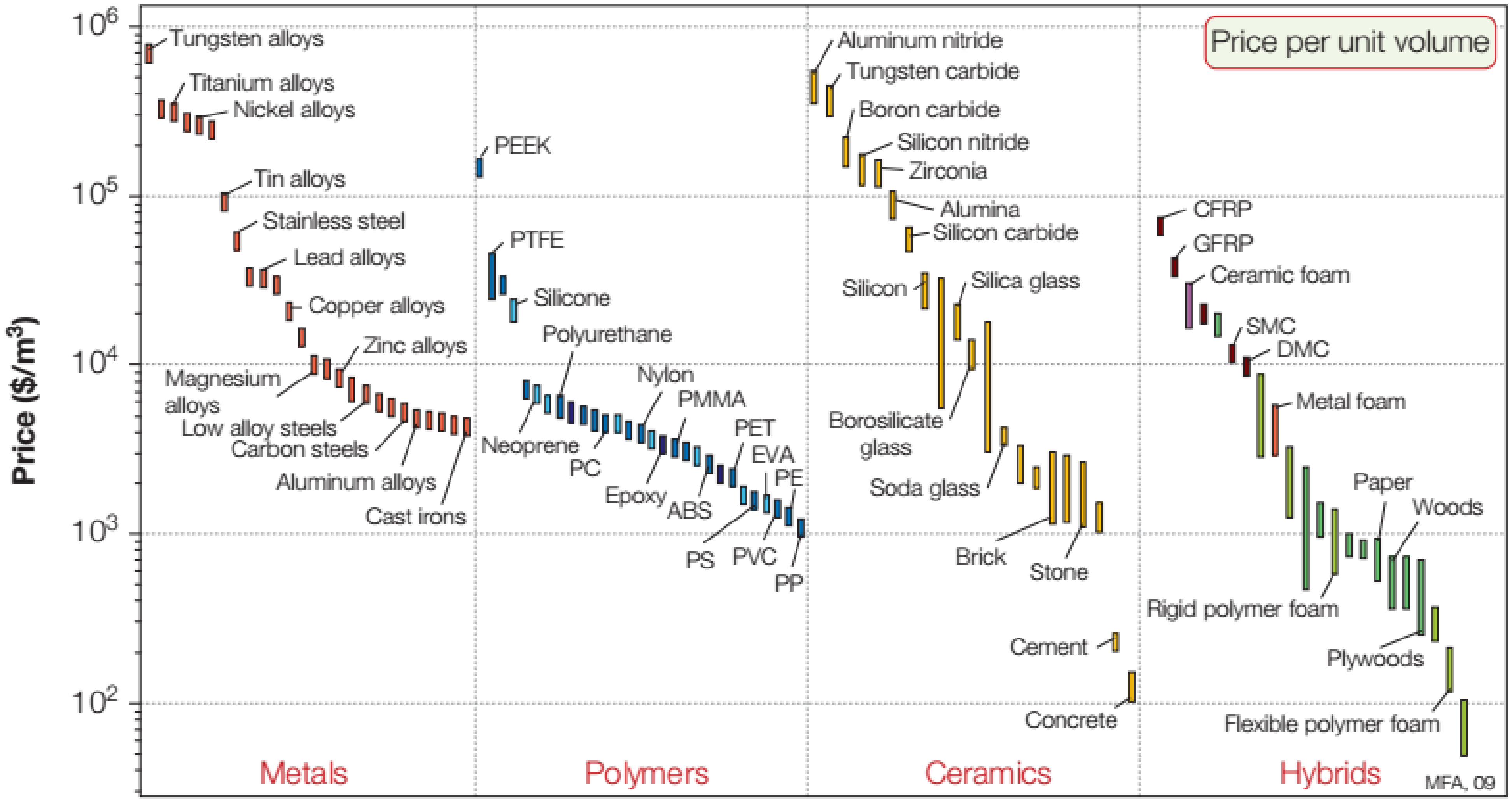
(source: MTM Automation & Aerospace Mfg.)

Typical cost of materials ($/**kg**)



(source M.F. Ashby, Materials selection in mechanical design, BH)

Typical cost of materials ($/m³)



(source M.F. Ashby, Materials selection in mechanical design, BH)

Cost of tooling

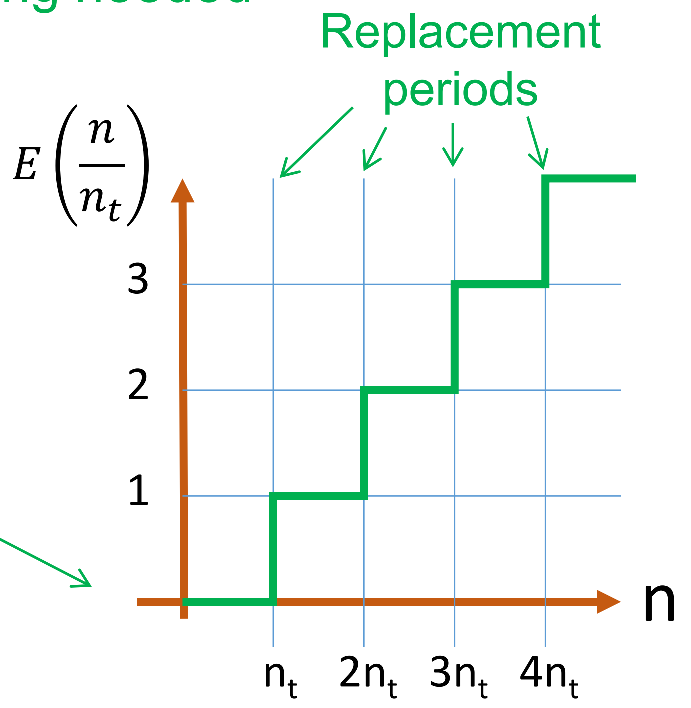
- **Dedicated costs** (i.e. for one type of product)
- Examples: dies, molds, fixtures, jigs,...
- Tools wear... (lifetime = n_t , *'tool need replacement every n_t part'*)

Number of re-tooling needed

Cost of tools

$$C_{tooling} = \left(\frac{C_t}{n}\right)\left\{1 + E\left(\frac{n}{n_t}\right)\right\}$$

Number of parts to produce

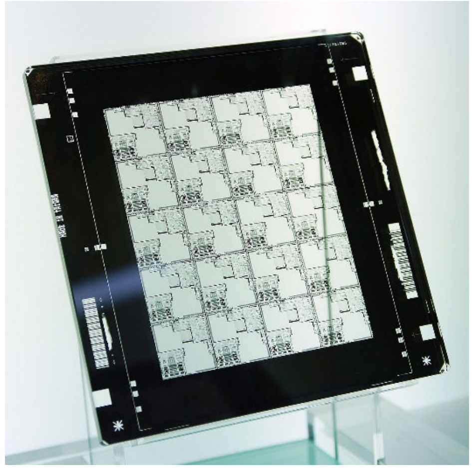


Can you cite examples of tooling cost in some manufacturing process?

Examples of tooling

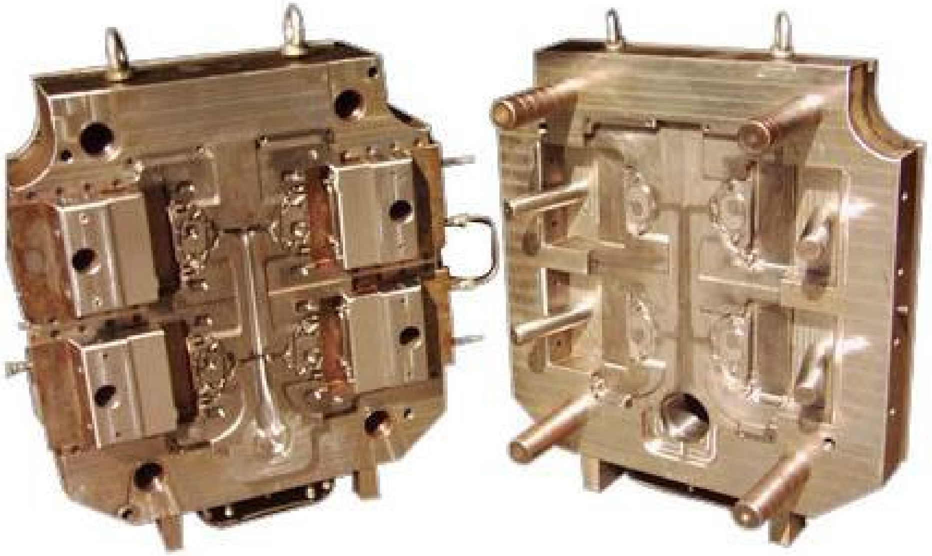
- Drill bits, end-mills, etc.
- **Mold for injection**
- Electrodes for die-sinking EDM
- Masks for lithography,
- etc... *All tools specifically required for a product.*

(source: Allied Express)



(source: Wiki)

(source: Eroda Tools Ltd)



(source: Premouldengineering)

Equipment costs

- **Equipment for processing** [Capital investment (C_c)]
- Usually **non dedicated equipment** (i.e. can be used/re-adapted for other products production)
- May need **specific tooling**

$$C_e = \frac{1}{\dot{n}}\left(\frac{1}{L}\right)\left(\frac{C_c}{t_{wo}}\right)$$

Capital investment (C_c)

Rate of part production ($\dot{n}$)

'Equipment load Per day: 0..100%' (L)

Capital write-off time (ex. 5yrs, 10yrs, etc.) (t_{wo})

Other costs: Labor, engineering, overhead, ...

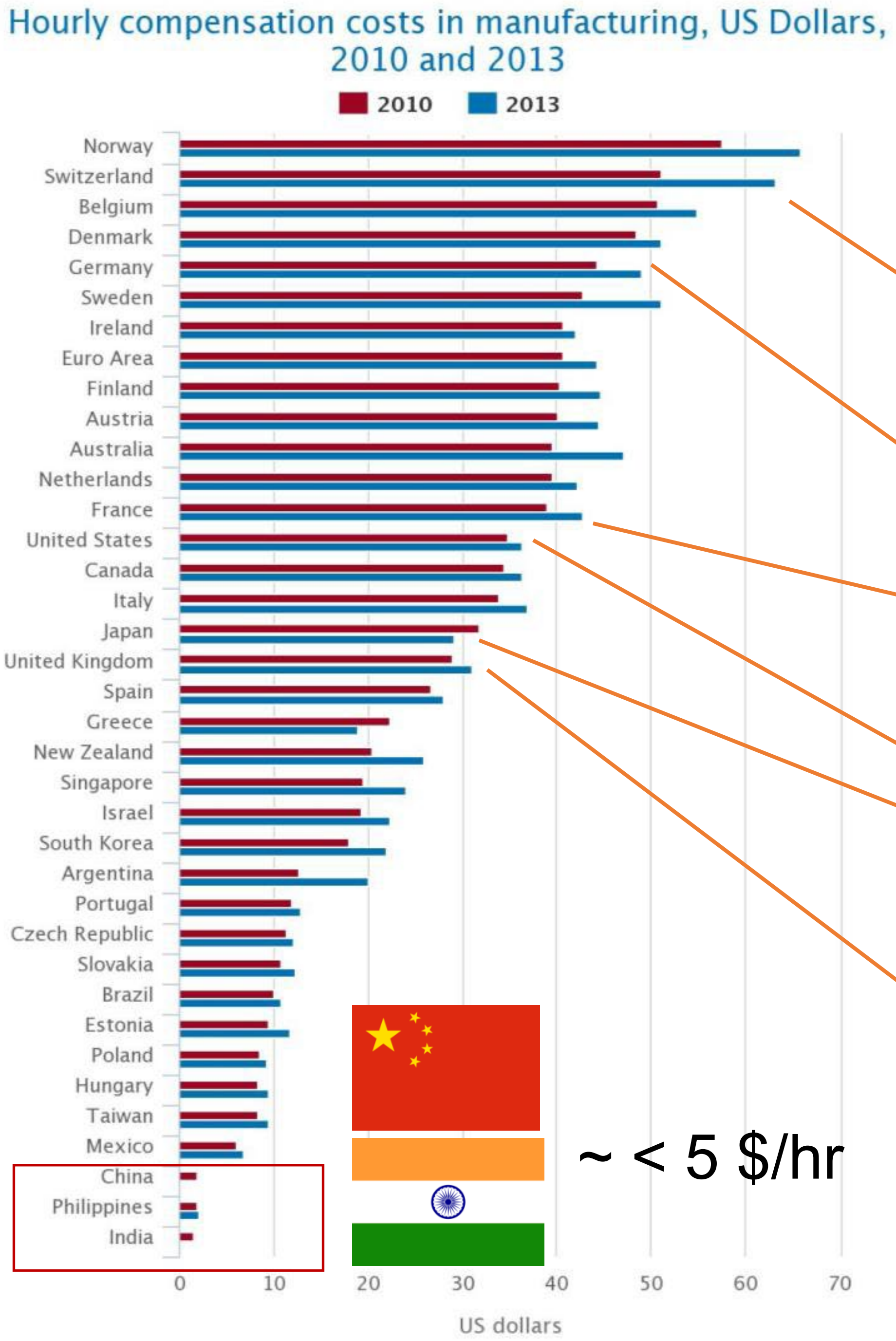
- **Labor** – ex: handling parts, operating, loading machines, ...
- **Administration** – ex: invoicing, marketing, management ...
- **Energy bill**
- **Waste recycling**
- **R&D Costs & Engineering** – ex: process optimization, new development, payback patent royalties, etc.

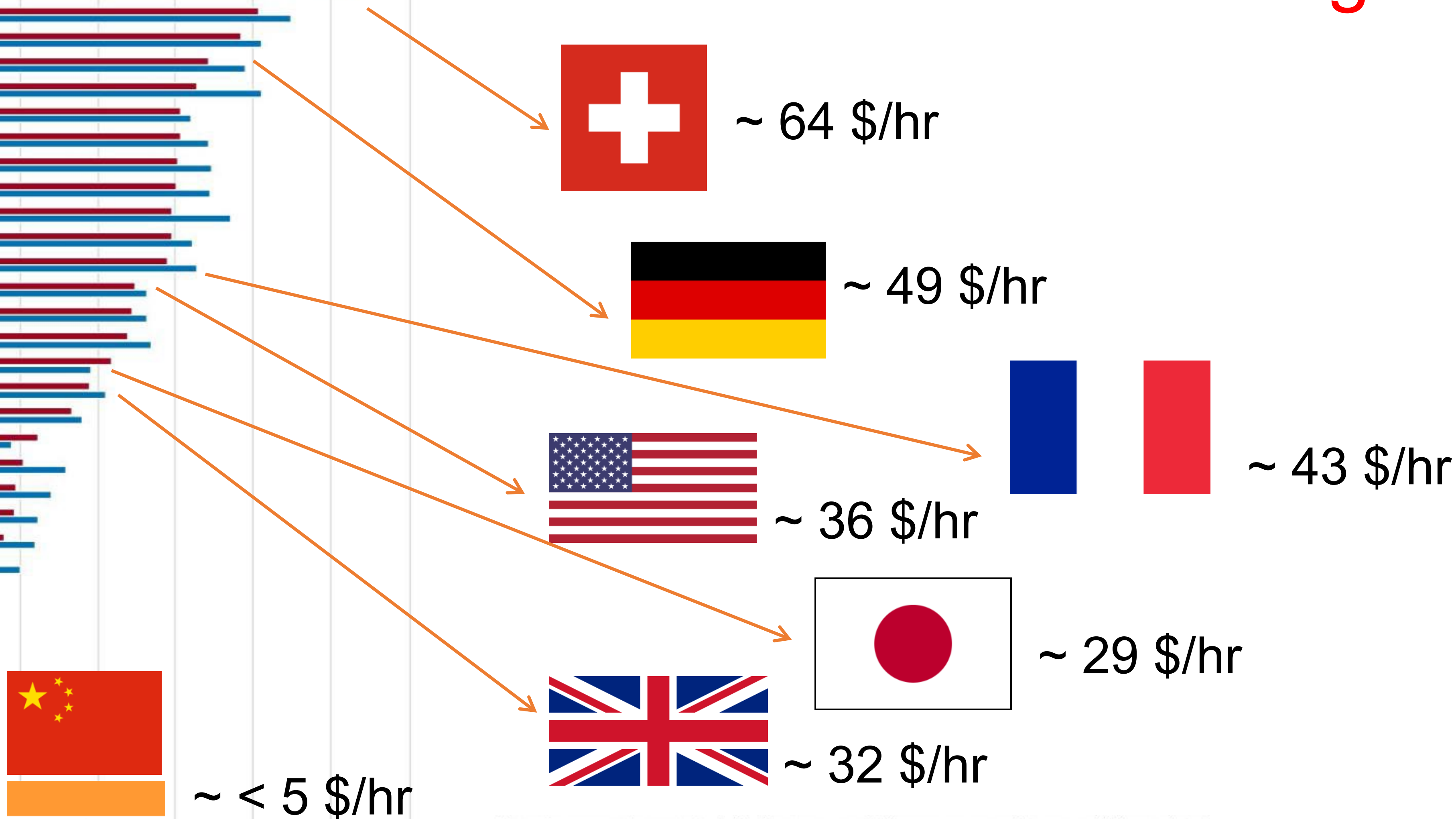
$$C_{others} = \frac{\dot{C}_{oh}}{\dot{n}}$$

$\dot{C}_{oh}$ → All included overhead rate

$\dot{n}$ → Production rate

Labor cost in manufacturing...





Note: Compensation costs include direct pay, social insurance expenditures, and labor-related taxes. Data for China and India are not strictly comparable with each other or with data for other countries. For complete definitions, country information and a description of data limitations associated with estimates for China and India, see the Technical Notes and Country Notes supplementing this report.
Source: The Conference Board, International Labor Comparisons program

Total manufacturing of *a part* cost equation

- Three main terms... (does not include assembly!)

Material cost — Gross overhead — Dedicated cost

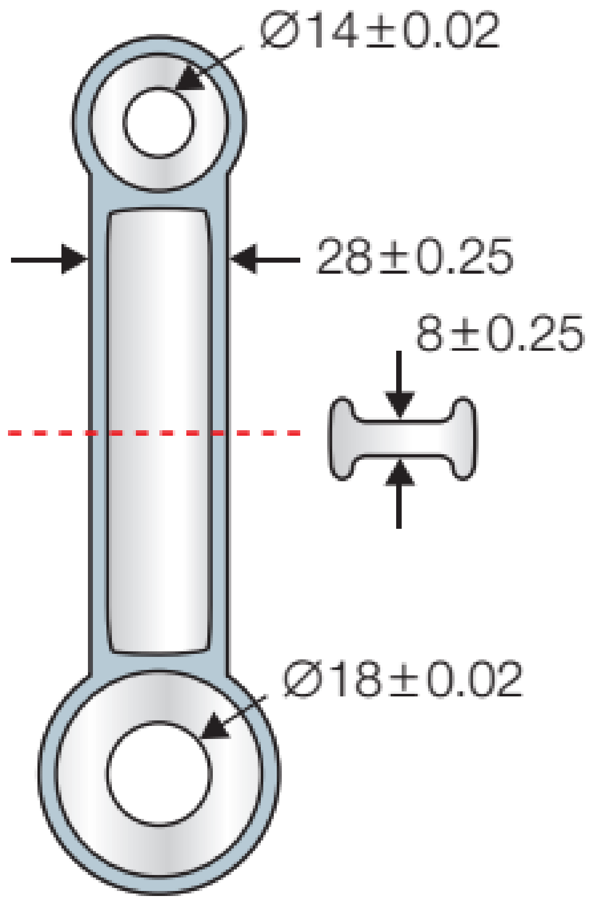
$$C = \left(\frac{m}{1-f}\right)C_{rm} + \frac{1}{\dot{n}}\left[\left(\frac{1}{L}\right)\frac{C_c}{t_{wo}} + \dot{C}_{oh}\right] + \left(\frac{C_t}{n}\right)\left\{1 + E\left(\frac{n}{n_t}\right)\right\}$$

Material cost → *Overall material consumption*

Gross overhead → *Depends on the* ***production rate***

Dedicated cost → *Depends on the* ***production size***

How would make this part? (in class)



- Made of a metal (for instance, aluminium alloys)

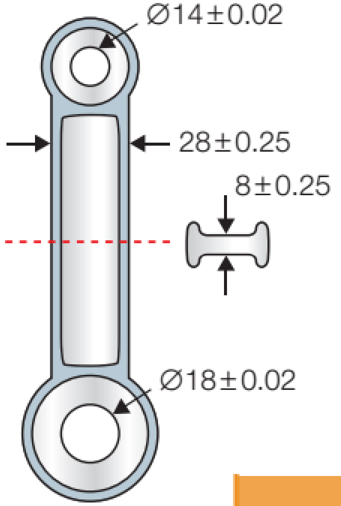
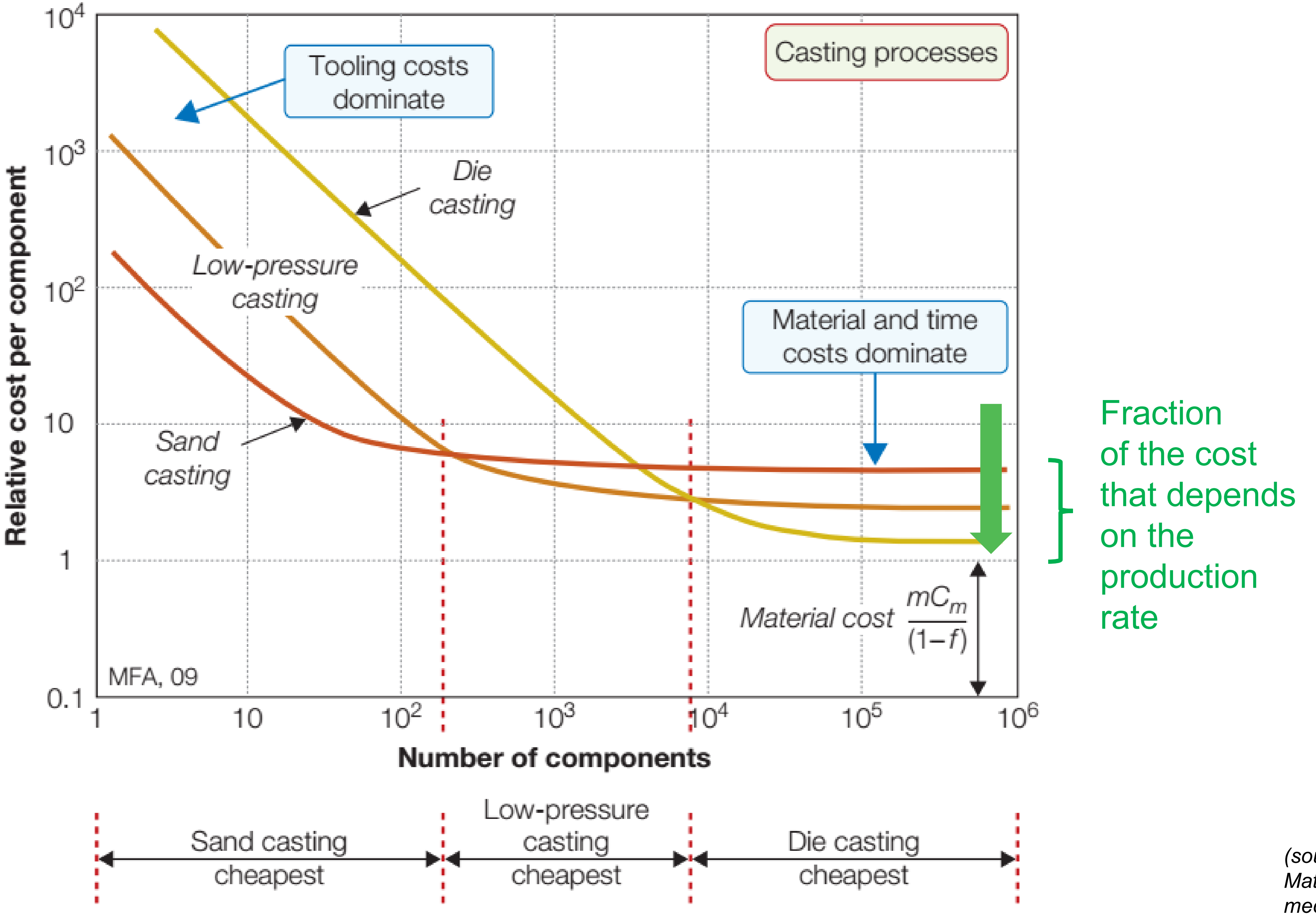


Illustration / Connecting rod

Relative Cost*	Sand Casting	Die Casting	Low-pressure Casting	Comment
Material, $mC_m/(1-f)$	1	1	1	*Process-independent parameters*
Basic overhead $\dot{C}_{oh}$ (hr^{-1})	10	10	10	
Capital write-off time *two* (yrs)	5	5	5	
Load factor	0.5	0.5	0.5	
Dedicated tool cost, C_t	210	16,000	2,000	*Process-dependent parameters*
Capital cost, C_c	1800	30,000	8,000	
Batch rate, $\dot{n}$ (hr^{-1})	3	50	10	
Tool life, n_t (number of units)	200,000	1,000,000	500,000	

* *All costs normalized to the material cost.*

(source M.F. Ashby, Materials selection in mechanical design, BH)



(source M.F. Ashby, Materials selection in mechanical design, BH)

Illustrations of two different ways of producing a same product

- Appel Mac Book
  - https://youtu.be/lJx6cF-H__I
- Lenovo
  - https://youtu.be/Tc0X92fZF1Y

Discussion: source of randomness in manufacturing

- List possible sources of randomness in a manufacturing process (in class)

Possible causes of process variation…

- **The process itself:** inherent capability, change of settings, …
- **Raw material:** defects, inhomogeneity, ...
- **Equipment:** tool wear, calibration, …
- **Environment:** temperature, humidity, vibrations, …
- **Operator:** procedure used, fatigue, …

Illustrative video for discussion

- How nuts & bolts are made...

https://youtu.be/SxEN5wXV-gU

- Discuss the video from a process variability point of view & quality control **(in class)**

Statistical Quality Control: **keywords**

- **Sample size**
  - Number of parts to be inspected in a sample
- **Random sampling**
  - Taking a sample from a lot with equal chance of being included in the final product
- **Population**
  - Total number of individual parts of the same kind
- **Lot size**
  - Subset of the population / production batch

Inspections tools

To control what?

- **Dimensions tolerances**
- **Surface finish**
- **Physical properties** (electrical conductivity, thermal properties, optical, etc.)
- **Mechanical properties** (strength, hardness, etc.)
- **Optical properties** (reflectance, transmittance, etc.)

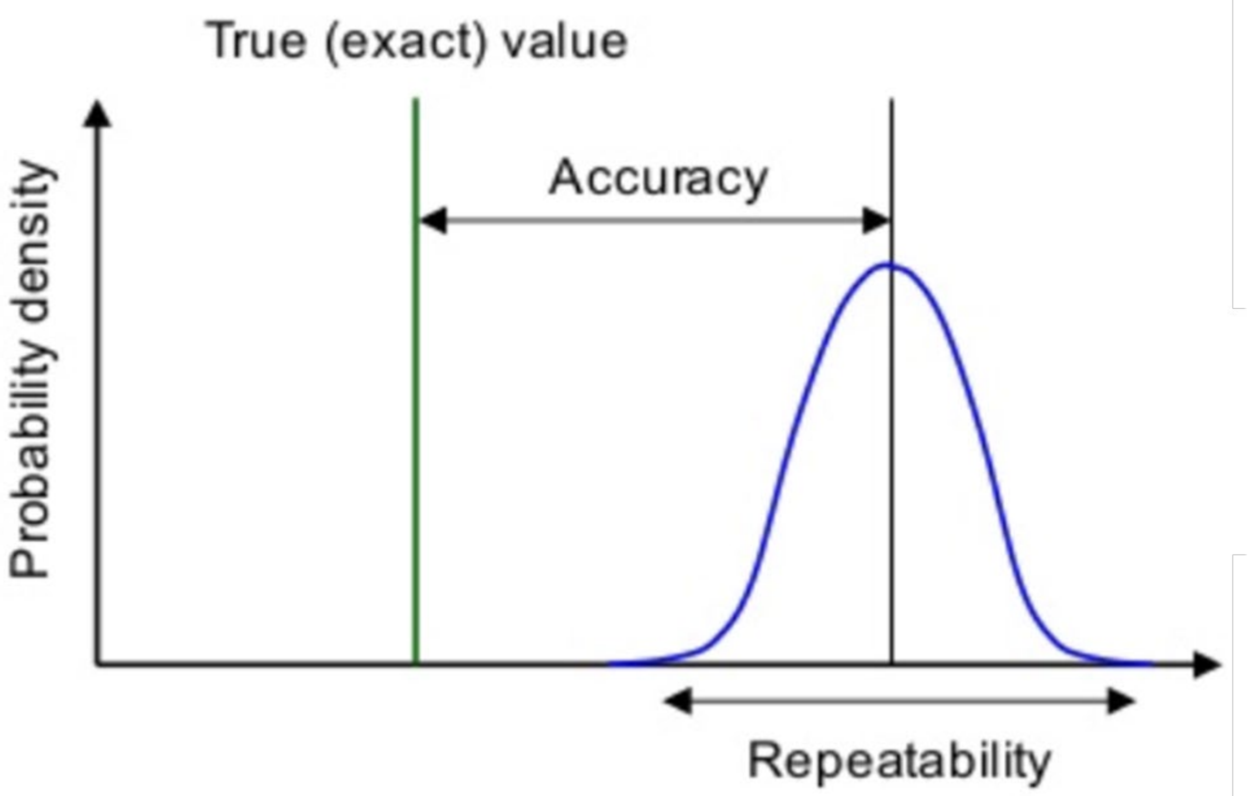
Accuracy, Precision, Resolution...

- **Accuracy**
  - *Difference between the actual physical quantity and its measured value*

- **Precision** (repeatability)
  - *The precision described the spreading of data for the measurement of a same quantity repeated several times.*

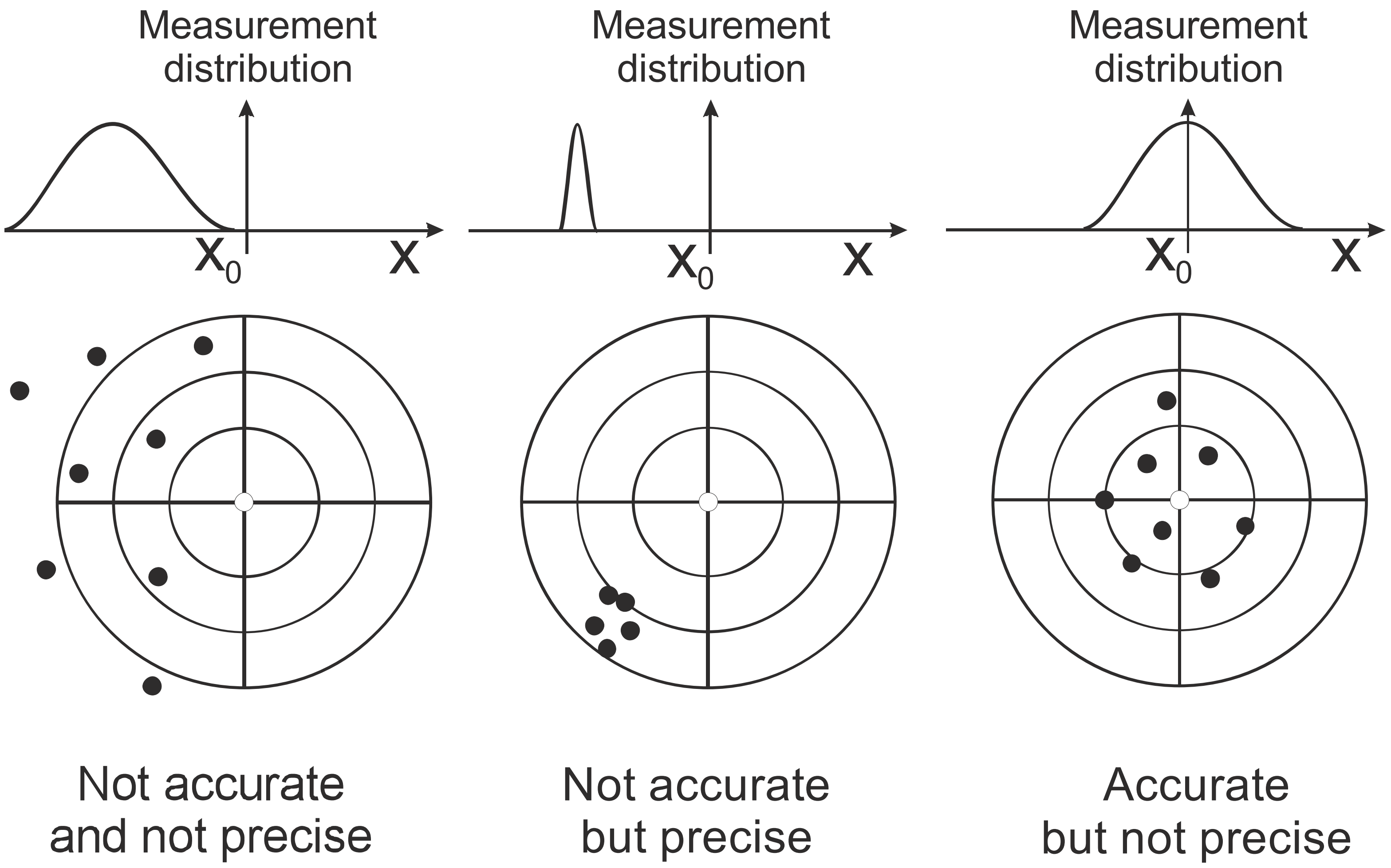
- **Resolution**
  - *Minimum distance between two increments of measurements*

Accuracy, Precision, Resolution...



(sketch: J. Hart, MIT)

Accuracy vs Precision (reminder)



Most common metrology tools in continuous production lines

- Laser triangulation system
- Optical barrier
- Interferometers / profilometers

Online measurements

- Coordinate Measurement Machines
- Calipers

Offline measurements

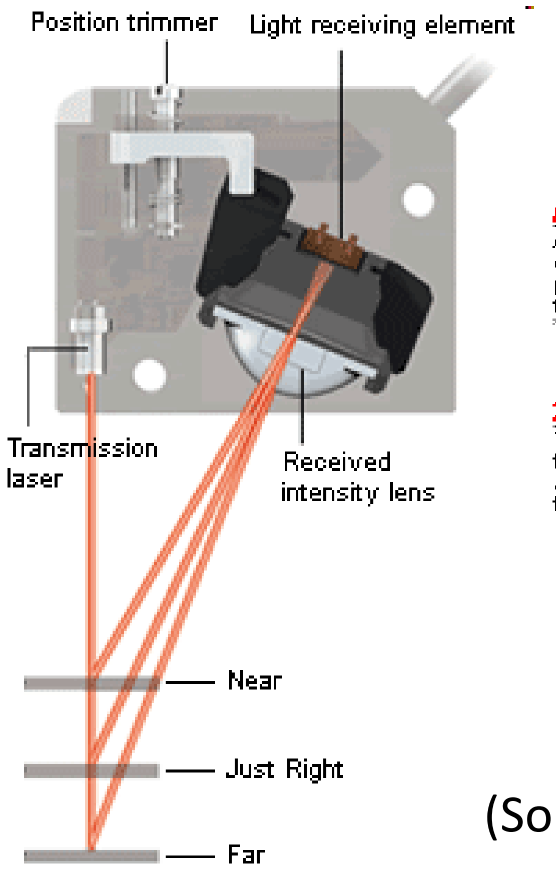
- Torque sensors
- Strain gages and other force sensors

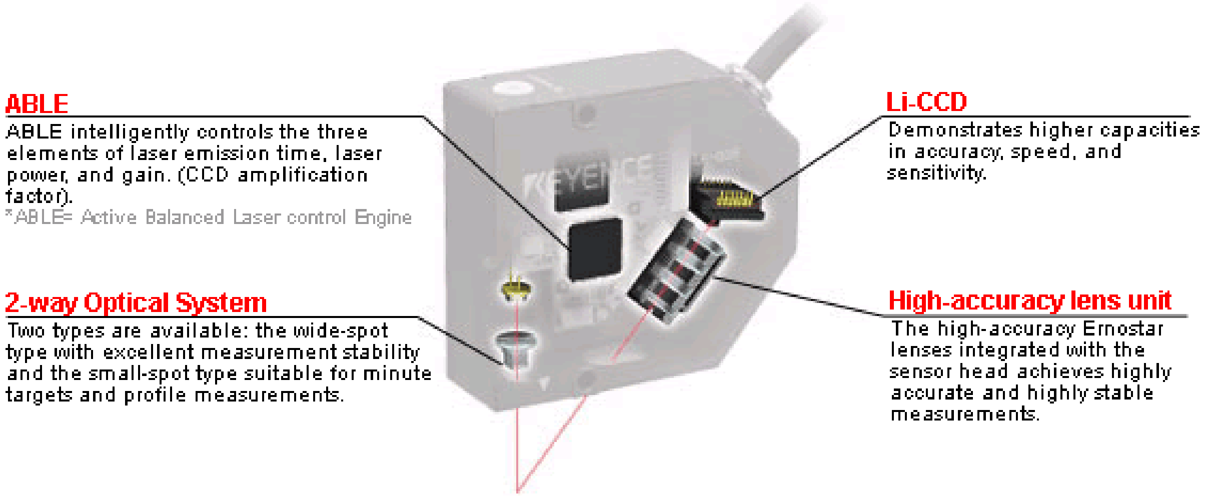
Online measurements

- Accelerometers
- Destructive testing: tensile tester, indenters, etc.

Offline measurements

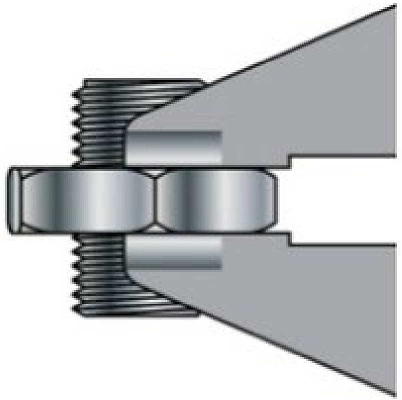
Example of industrial optical non contact sensors for metrology



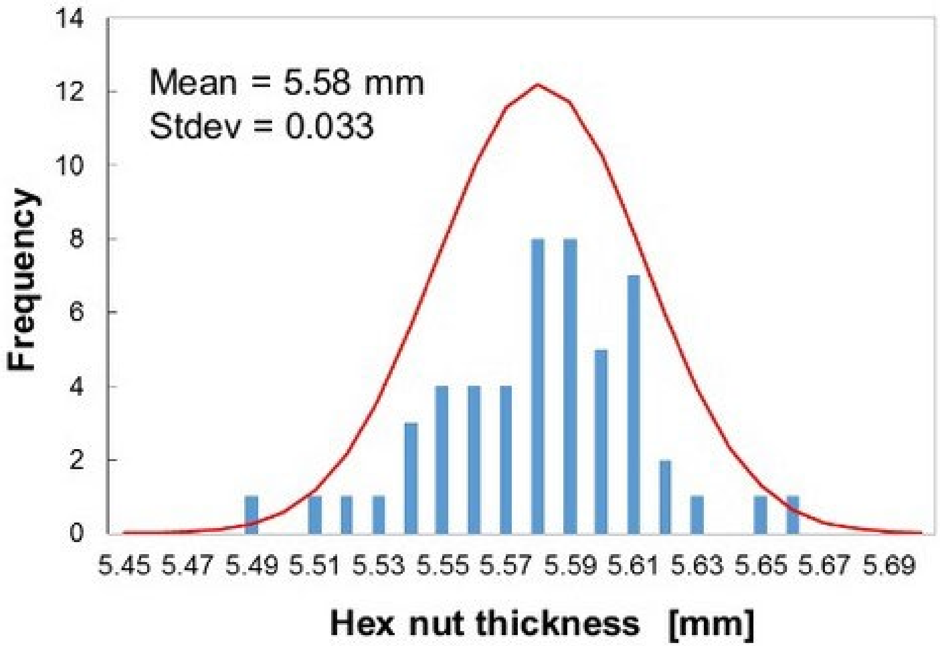


(Source Keyence)

Normal distribution



- **In general:** Assuming we measure *n components* of a same batch, when n goes to infinite, it converges to a *normal distribution*



(Ex: measuring nuts thickness / J. Hart, MIT)

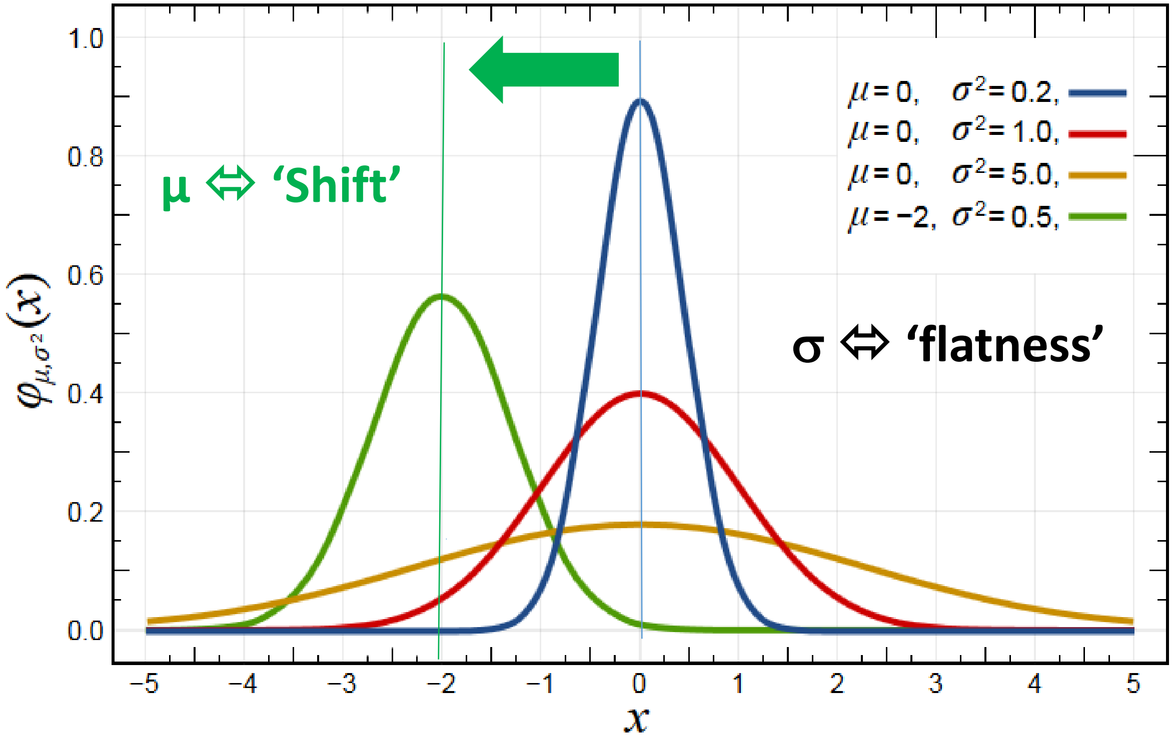
Math parenthesis: the Galton board

More on this topic: https://youtu.be/9QuPHf1xi-4

Normal distribution

- Frequency of occurrence for purely random variable following a normal distribution

$$f(x \mid \mu, \sigma^2) = \frac{1}{\sqrt{2\sigma^2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$



(Image source. Wikipedia)

Normal probability distribution: Important definitions

$$f(x \mid \mu, \sigma^2) = \frac{1}{\sqrt{2\sigma^2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

- μ is the **arithmetic mean** (average value)
- σ is the **standard deviation**

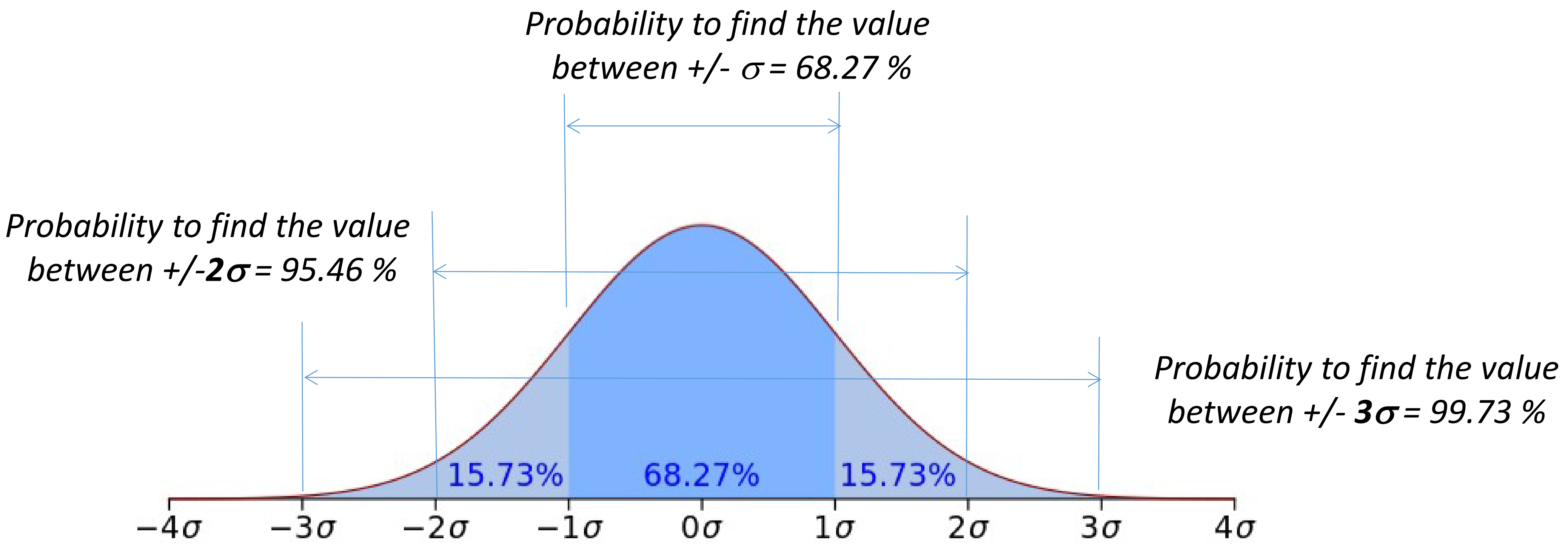
$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \mu)^2}, \text{ where } \mu = \frac{1}{N}\sum_{i=1}^{N} x_i$$

- σ^2 is the **variance**

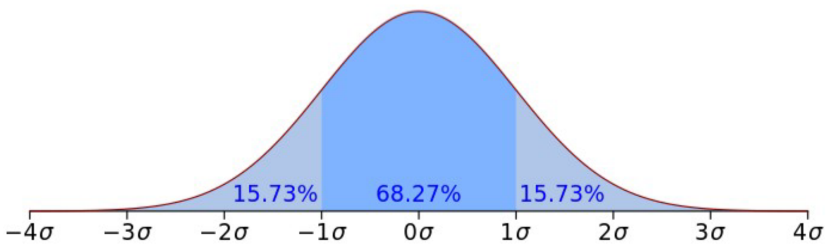
Density of probability

- Definition (for a distribution f_x):

$$\Pr[a \leq X \leq b] = \int_a^b f_X(x)\, dx$$



Cumulative probability



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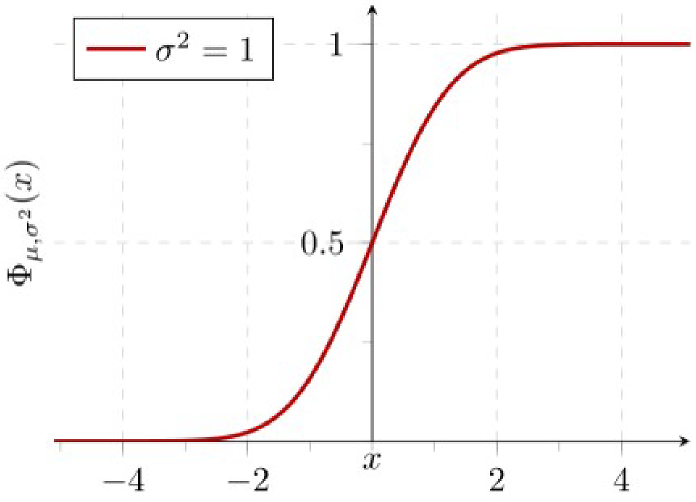


Z-score

- ***Normalized distance*** *of actual data compared to the mean value*

$$z = \frac{x - \mu}{\sigma}$$

- *Useful for calculating the amount of data that fits in a given window of the statistical distribution*

Stacking errors

- If the variable are **independent**:

$$X \sim N(\mu_X, \sigma_X^2)$$
$$Y \sim N(\mu_Y, \sigma_Y^2)$$
$$Z = X + Y,$$

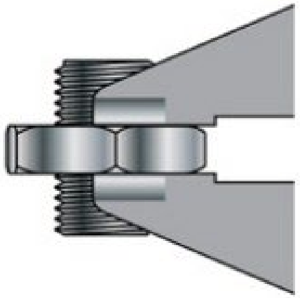
$$\Rightarrow Z \sim N(\mu_X + \mu_Y, \sigma_X^2 + \sigma_Y^2)$$

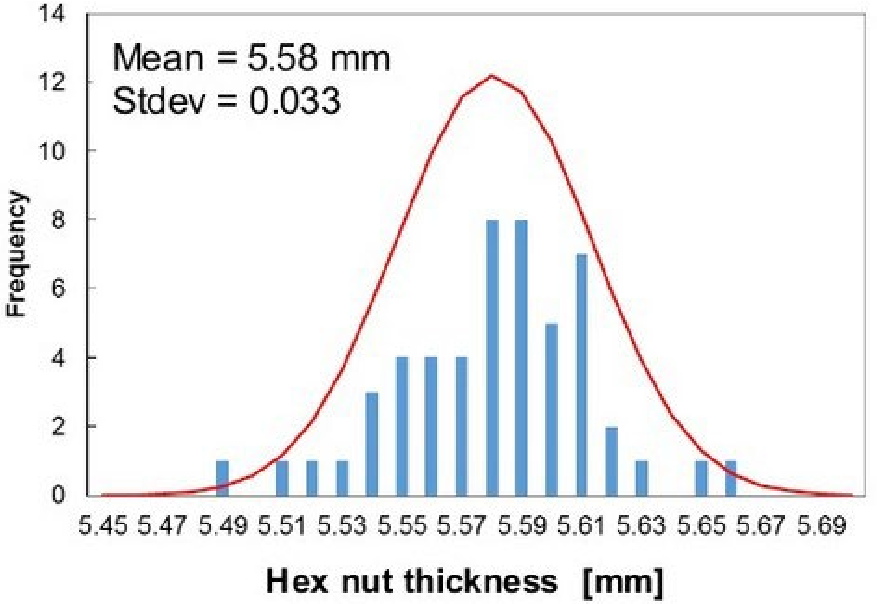
"The sum of two normal distribution for two **independent** variables is a normal distribution"

This can be generalized to n independent variables

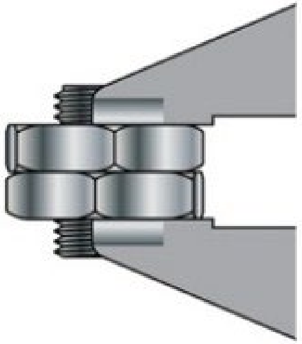
Example

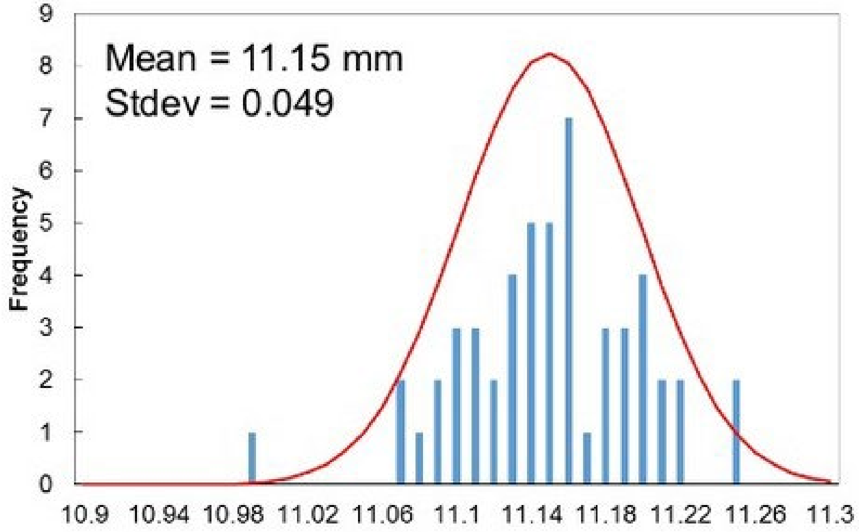
Single hex nut





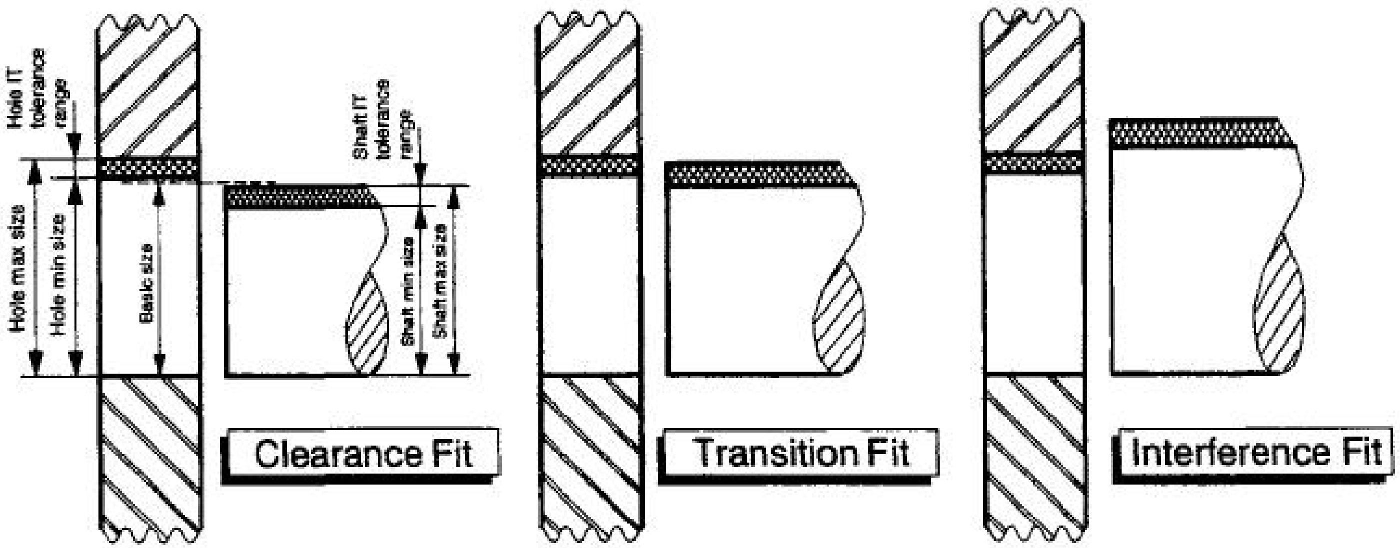
Stack of two hex nuts





(source: J. Hart, MIT)

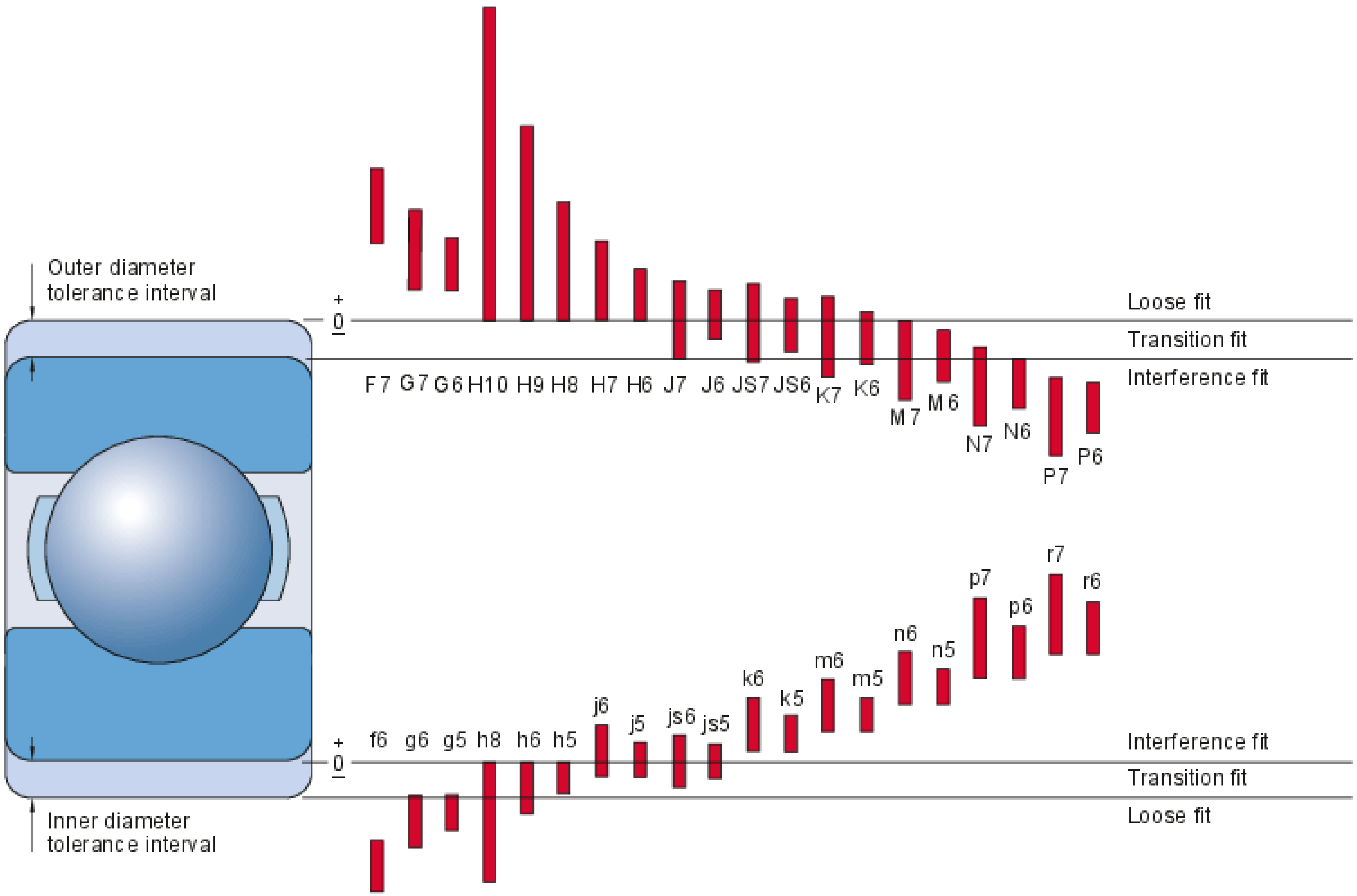
Example: probability of a successful assembly



(source: Manufacturing handbook)

- 'Hole in a shaft'
- Hole diameter : D_H
- Shaft diameter: D_s
- Clearance statistics:
  - $C = D_H - D_s$
  - Distribution of clearance follows a *normal law*

Example (Roller bearing)



(source: skf)

Why process monitoring?

- To verify that a process in **under control**…
- **Identify** problems to improve the process
- **Quality management**
- Monitoring = process evaluation / metrology

A process not in control: (J. Tati, 'Mon oncle')

Process monitoring: statistical process control

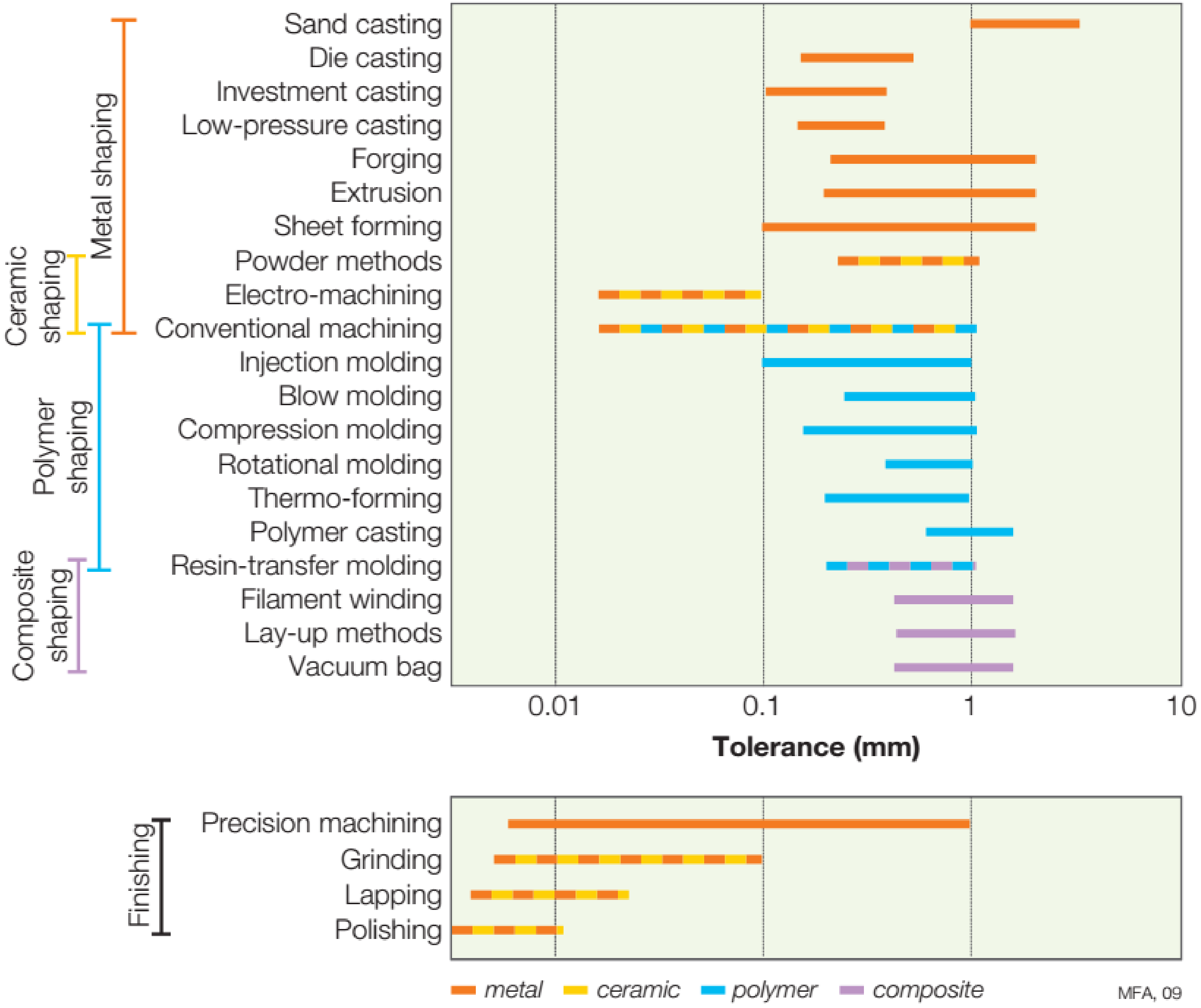
- A **stable** process has intrinsic but supposedly *optimized* and *known variability* => A ‘normal distribution’

- Statistical process control consists of the following:

    - **Knowledge** of the particular manufacturing process
    - **Knowledge** of the machinery, tooling and raw materials potential variability
    - **Define** control charts and control limits

Defining control limits for a process

Process knowledge



Define realistic tolerances

+

Part specifics & operating conditions

=

Control limits

(source M.F. Ashby, Materials selection in mechanical design, BH)

Challenges in choosing tolerances…

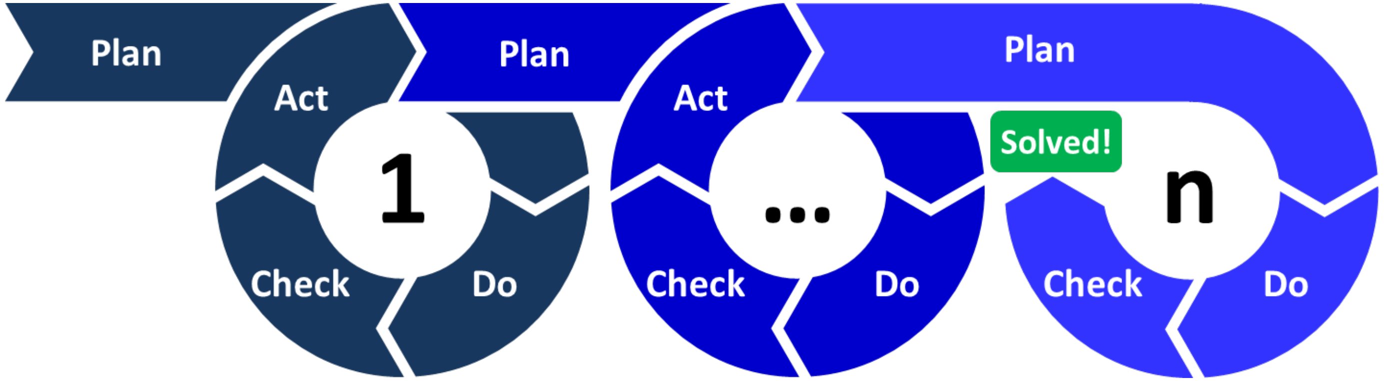
- **Too tight**
  - Extra cost (slower rate of production, additional finishing steps, multiple pass, etc.)
  - Lots of scraps part
  - Extra process control needed
  - Unreasonable expectations
- **Too loose**
  - Not exploiting the process capability
  - Poor quality

Walter A. Shewhart
(1891-1967)

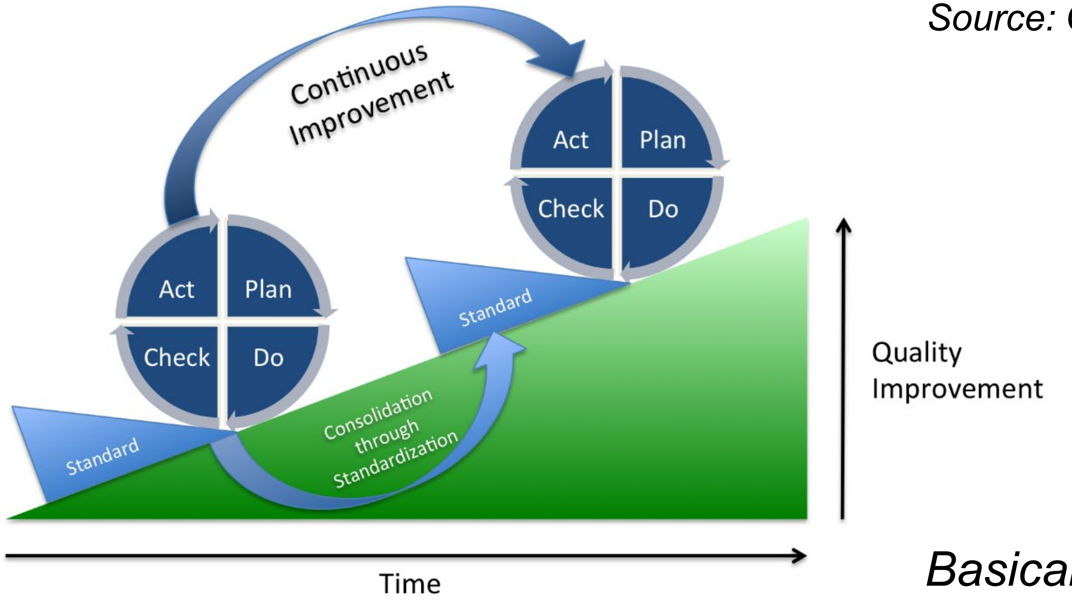
Shewhart cycle for continuous process improvement

- **Plan -** identify what can be improved and what change is needed
- **Do -** implement the design change
- **Study -** measure and analyze the process or outcome
- **Act -** if the results are not as hoped for

Deming/Shewhart continuous improvement cycle



Source: Christoph Roser at Allaboutleans.com



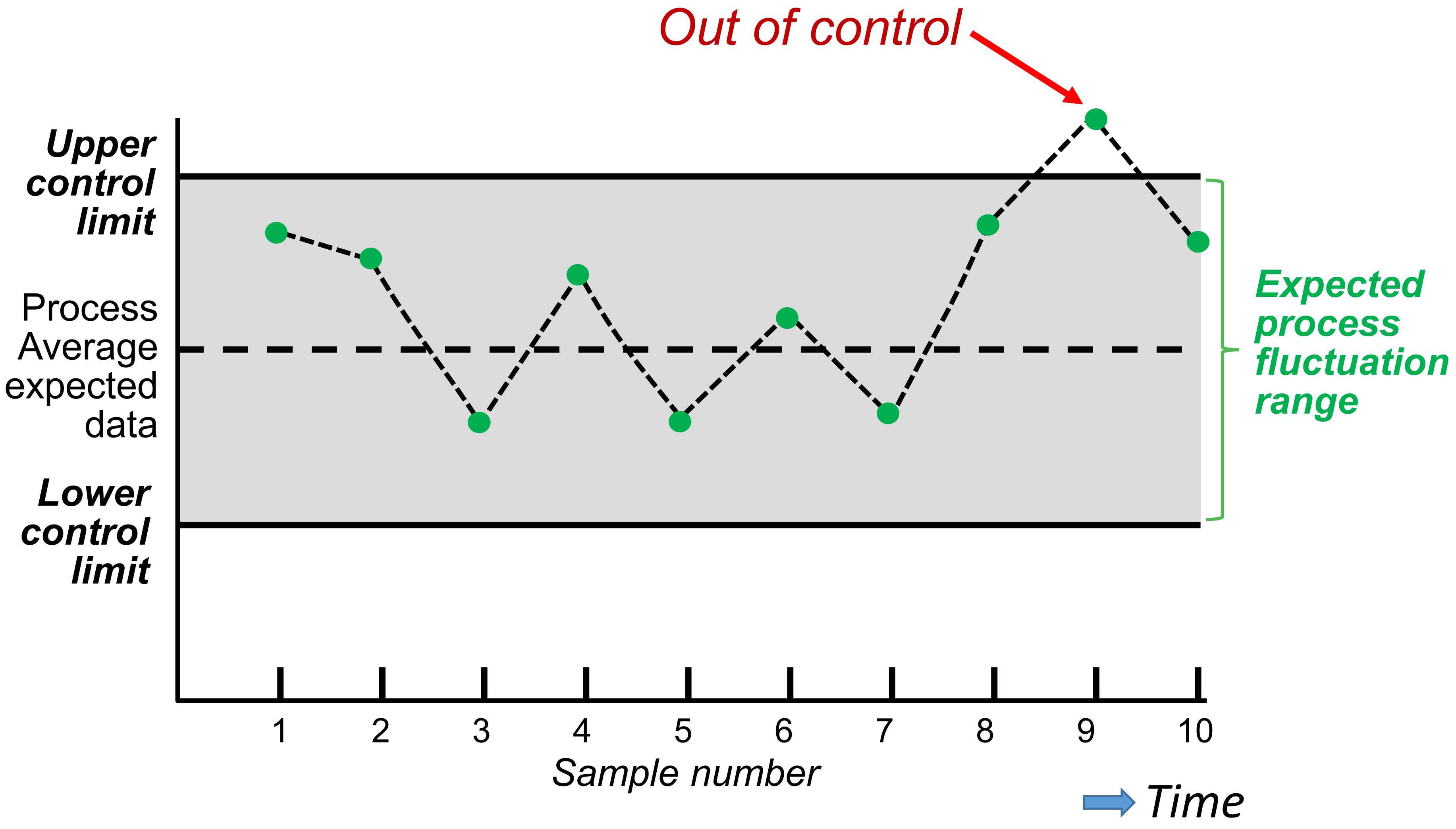
Basically, apply the scientific method...

Control charts (Shewhart)

- **Variations** of a process over time
- Data are taken **while producing by sampling** the production
- Defining **control limits**

- **Two charts**
  - Average charge: fluctuation around a desired value
  - Average range: dispersion of the data

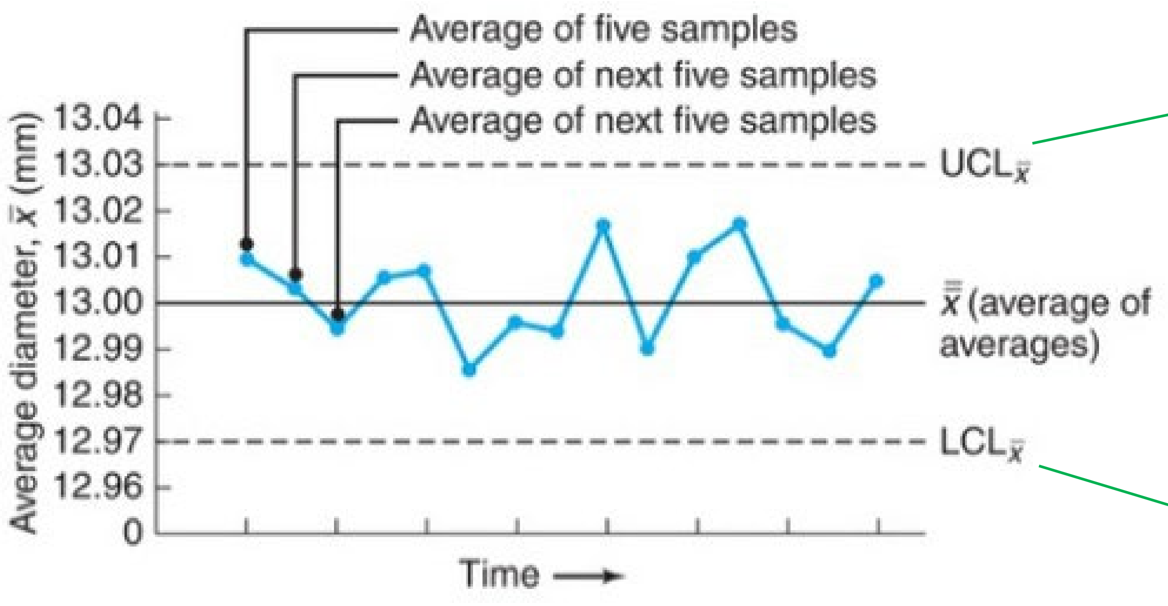
Basic idea of a process monitoring



Average chart

- Variation around the desired value
- Definition of **upper and lower** control values
- UCL and LCL are *not associated* with design tolerances, but **related to the process**

Illustration: machined shaft using a lathe (assume 5 samples)



$UCL_{\bar{x}}$ Upper control limit

$$\bar{\bar{x}} = \frac{\sum_i \frac{\bar{x}_i}{N}}{N}$$

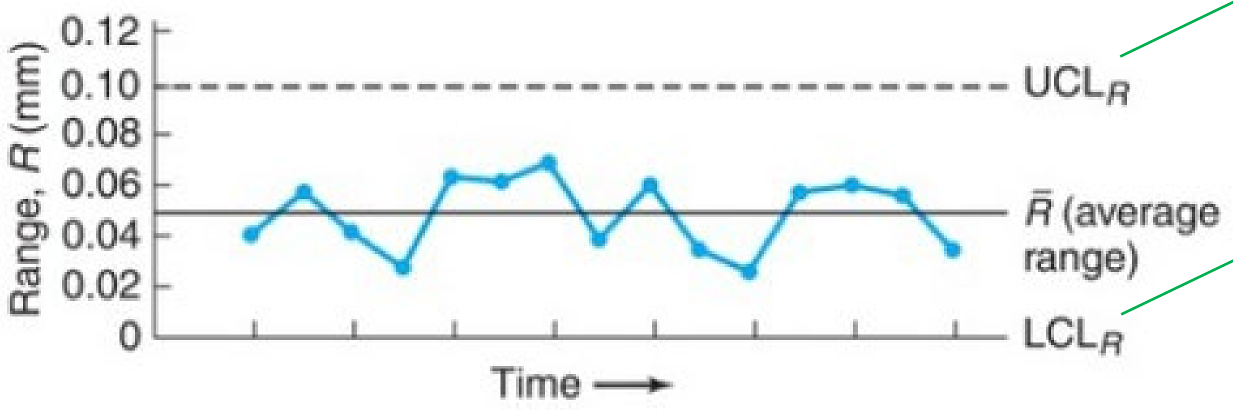
$LCL_{\bar{x}}$ Lower control limit

(Source: S. Kalpakjian/S. Schmid, 'Manufacturing Engineering & Technology, Pearson)

Range chart

- R is the ***average range*** for a variable (linearly related to the standard deviation)
- The value of UCL and LCL for this graph *depends on the sample size* (typ. 2 to 20 sampling)

Illustration: machined shaft using a lathe



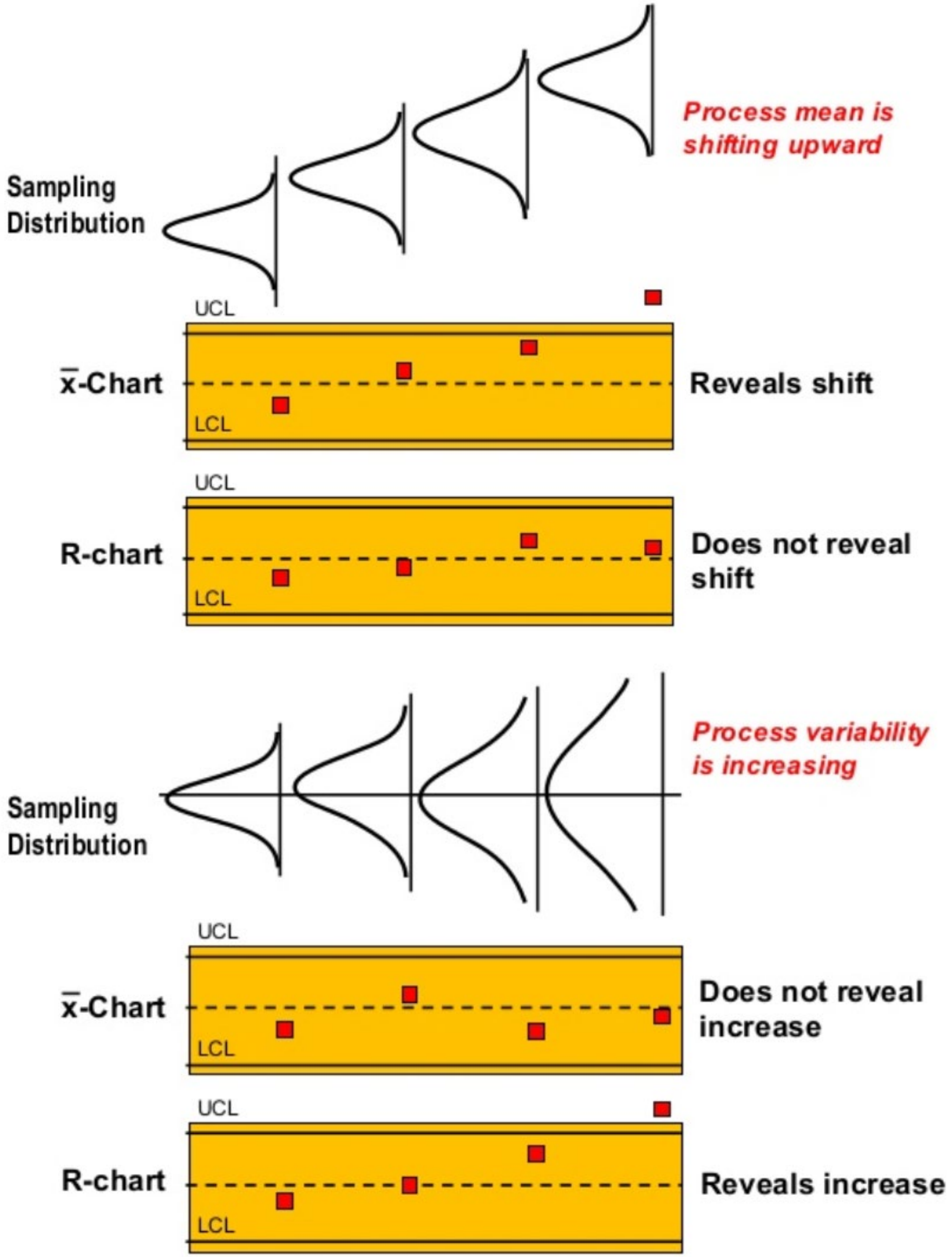
UCL_R Upper control limit

LCL_R Lower control limit

(Source: S. Kalpakjian/S. Schmid, 'Manufacturing Engineering & Technology, Pearson)

Discussion / Questions (in class)

- Why is it useful to monitor **both** graphs?
- How to choose the correct sample size?
- Examples of parts that needs 100% monitoring (all parts are controlled individually)?



Difference between the two graphs

(illustration from J. Hart, MIT)

How to choose the sample size and the frequency sampling?

Trade-off between:

- *Likelihood of unexpected disturbances*
- *Cost of measurement*
- *Cost for defects*

  - Based on the experience and knowledge of the running process

Average & Range charts formalism

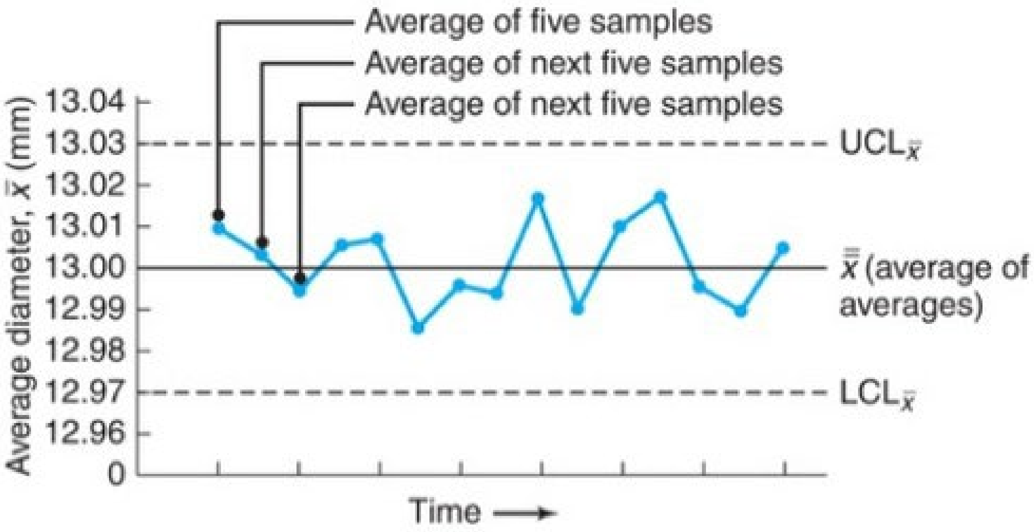
- Assuming a **3σ approach**

$$UCL_{\bar{x}} = \bar{\bar{x}} + 3\sigma = \bar{\bar{x}} + A_2\bar{R}$$

$$LCL_{\bar{x}} = \bar{\bar{x}} - 3\sigma = \bar{\bar{x}} - A_2\bar{R}$$

Constant for a given number specimen (next slide)

'Range chart'

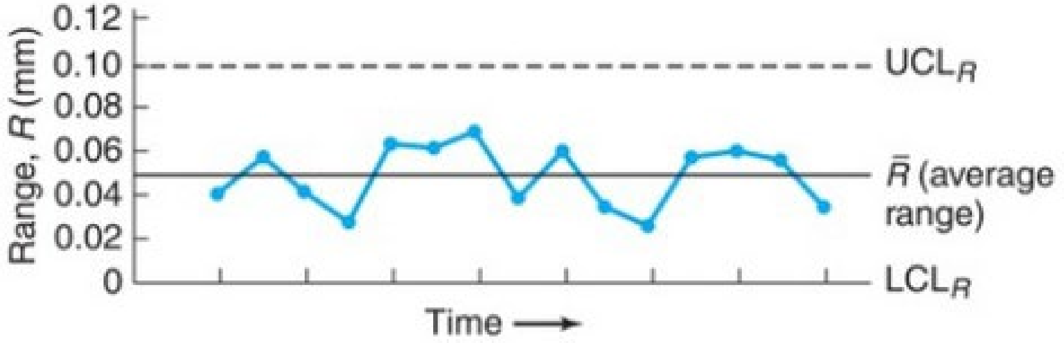


'Average of the average'

$$\bar{\bar{x}} = \frac{\sum_i \bar{x}_i}{N}$$

(Source: S. Kalpakjian/S. Schmid, 'Manufacturing Engineering & Technology, Pearson)

Average & Range charts formalism



$UCL_{\overline{x}}, LCL_{\overline{x}}$

UCL_R, LCL_R

Constants for Control Charts

Sample size	A_2	D_4	D_3	d_2
2	1.880	3.267	0	1.128
3	1.023	2.575	0	1.693
4	0.729	2.282	0	2.059
5	0.577	2.115	0	2.326
6	0.483	2.004	0	2.534
7	0.419	1.924	0.078	2.704
8	0.373	1.864	0.136	2.847
9	0.337	1.816	0.184	2.970
10	0.308	1.777	0.223	3.078
12	0.266	1.716	0.284	3.258
15	0.223	1.652	0.348	3.472
20	0.180	1.586	0.414	3.735

$$UCL_R = D_4 \overline{R}$$
$$LCL_R = D_3 \overline{R}$$

$$\sigma = \frac{\overline{R}}{d_2}$$

Note: $$A_2 = \frac{3}{d_2\sqrt{n}}$$

Sample size

(Source: S. Kalpakjian/S. Schmid, 'Manufacturing Engineering & Technology, Pearson)

Process capability: process control limits vs design tolerances

- **Control limits** in a process depends:
  - Process method and variability
  - Sample size
  - Characteristics of a metrology method and a process

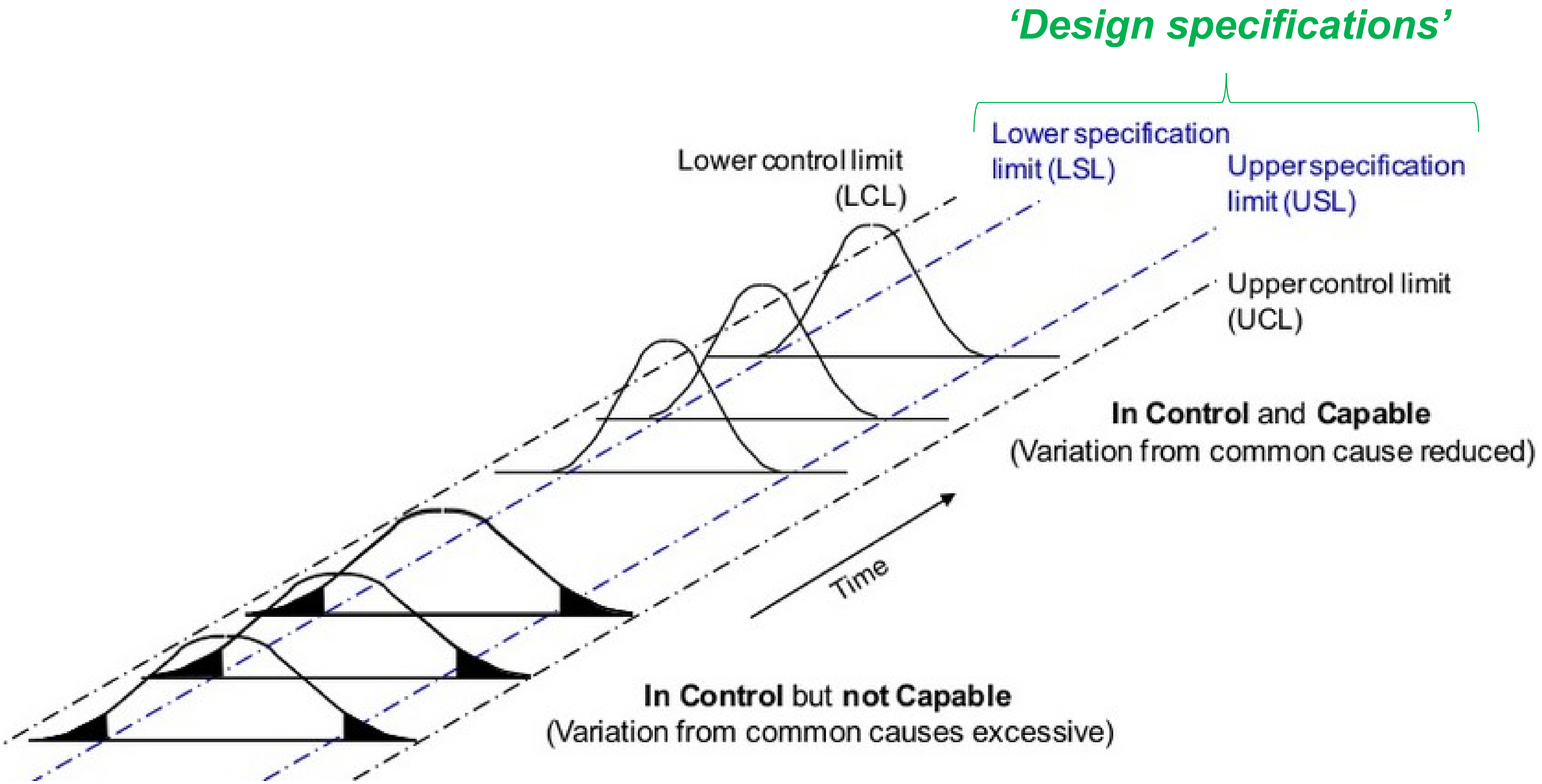
'Process capability'

- **Tolerances**
  - Specified for a given design function
  - Established the conformability of a design to a function

'Design specifications'

Process capability

- A process may be **under control**, but not **capable,** if control values are above specs.



(illustration: Source: J. Hart, MIT)

Comparisons metrics

- C_p is a **metric** comparing *tolerance limits and process standard deviation*

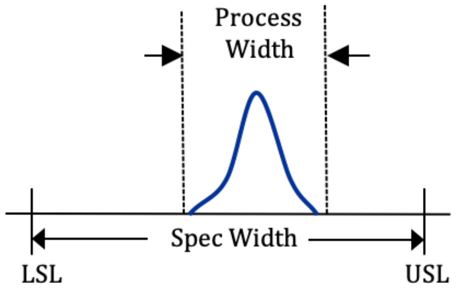
$$C_p = \left[\frac{UCL_{tolerance} - LCL_{tolerance}}{6\sigma_{process}} \right] \geq 1.33$$

- C_{pk} is the **distance** from the mean (process capability index)

$$C_{pk} = \left[\frac{UCL_{tolerance} - \mu_{process}}{3\sigma_{process}} \right]$$

$$C_{pk} = \left[\frac{\mu_{process} - LCL_{tolerance} -}{3\sigma_{process}} \right]$$

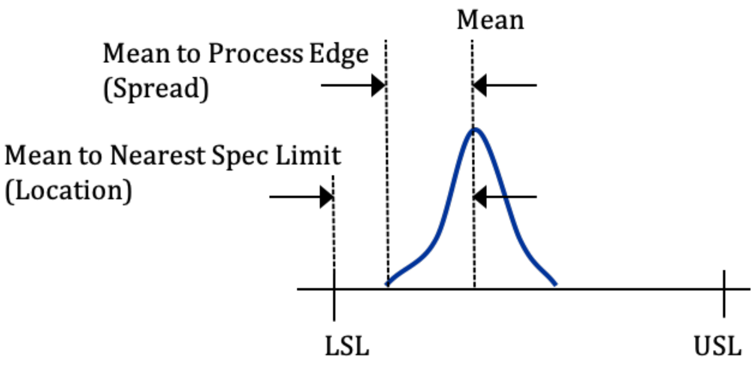
Cp = Specification Width / Process Width



Cp accounts for only the spread (or variation) of the process.

(Adapted from 1factory)

Cpk = Distance from Mean to Nearest Spec Limit / Distance from Mean to Process Edge



Cpk accounts for both the spread and location of the process.

(Adapted from 1factory)

Recommended value (Cp)

	Recommended process capability	Number of parts out of specs (per millions)
Stable process	**1.33**	**63**
New process	1.5	8
Existing process, safety critical	1.5	8
New process, safety critical	1.67	1
Six-sigma quality	**2**	**0.002**

Taguchi loss function

“Quality is related to the financial loss to society caused by a product during its life cycle.”

Genichi Taguchi (1924-2012)

- **Goal:** comparing quality on the basis of minimizing variations.
- Calculates the increasing loss for a company when a component deviates from the design objective.

Taguchi loss function

$$Loss = k\left[(Y - T)^2 + \sigma^2\right]$$

Loss cost

Mean value from manufacturing

Target value From design

Standard deviation of parts from manufacturing

$$k = \frac{R}{(LSL - T)^2}$$

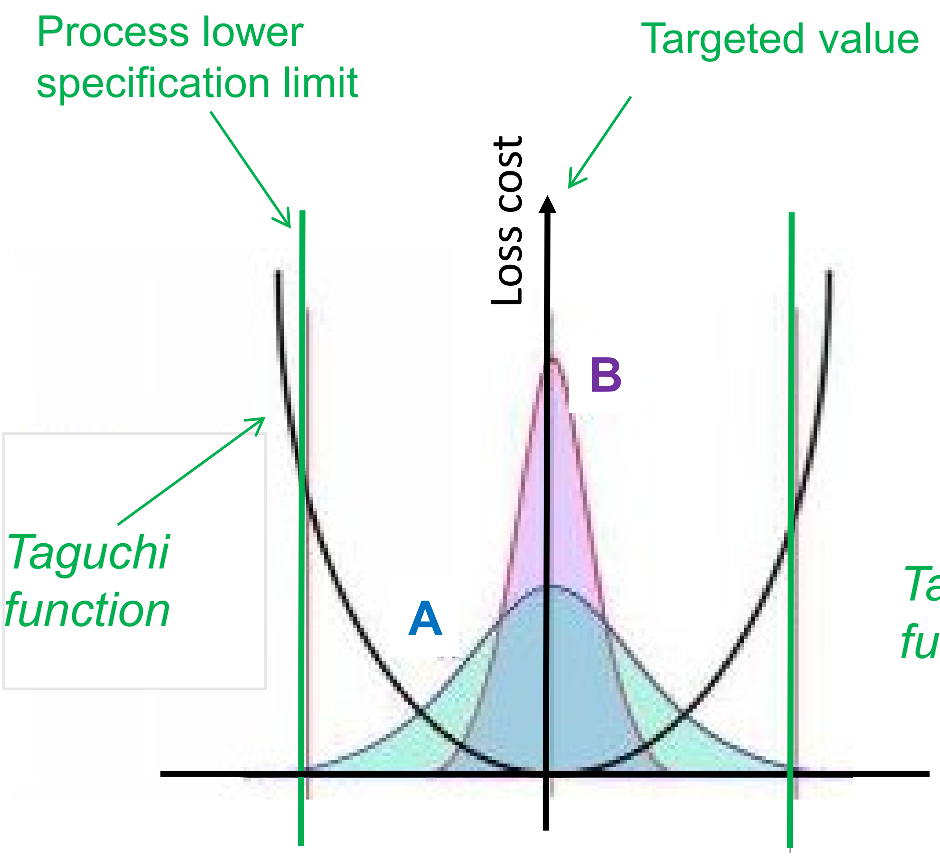
Replacement cost

Lower specification limit (or USL)

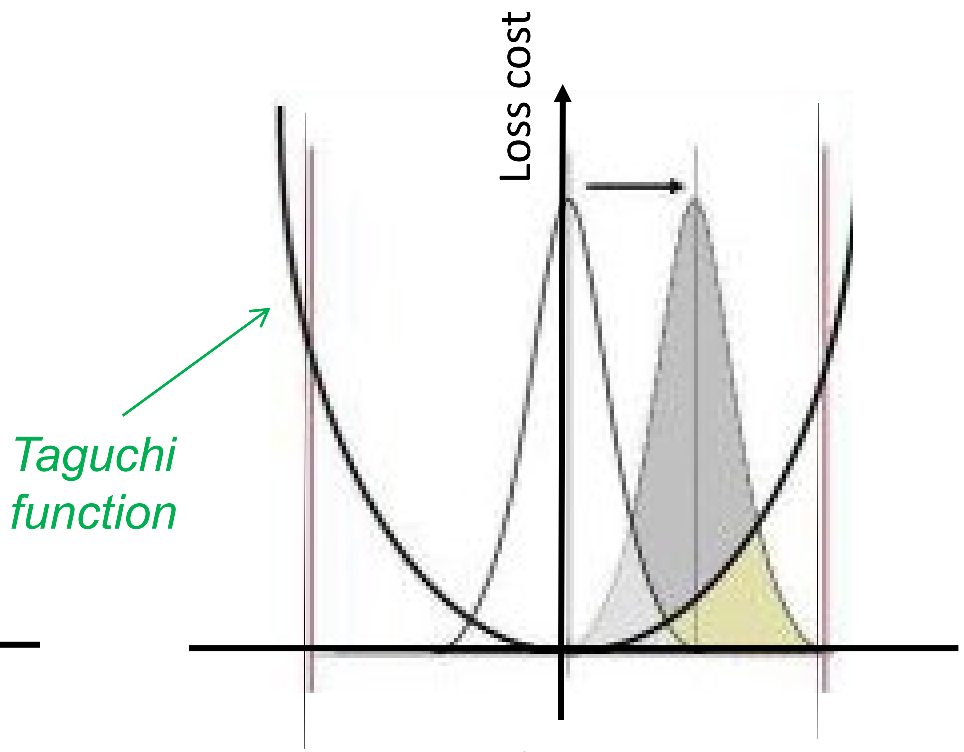
Target value from design

Taguchi loss function: interpretation

'A cost metric of moving away or lowering quality'



Impact of reducing variation from A to B



Impact of moving away from the targeted value

(inspired from R. Stauffer, Process Excellence Network.com)

Interesting videos (for home viewing)

- Packaging lines at Bobst:

  - https://youtu.be/VoxE-FBXNjg
  - https://youtu.be/rJ7irTO7q9E
  - High throughput constant monitoring

- Another example of process monitoring (ball bearing fabrication):
  - https://youtu.be/b6svVy1IYOA

- **Industry 4.0** (a revolution?)
  - https://www.youtube.com/watch?v=DrE0FShBfF4
  - https://www.youtube.com/watch?v=ZCLHojIj7eA