



UNIVERSITÀ DI PISA



Centro E. Piaggio
bioengineering and robotics research center

INGEGNERIA DEI TESSUTI BIOLOGICI: STRESS-STRAIN TEST

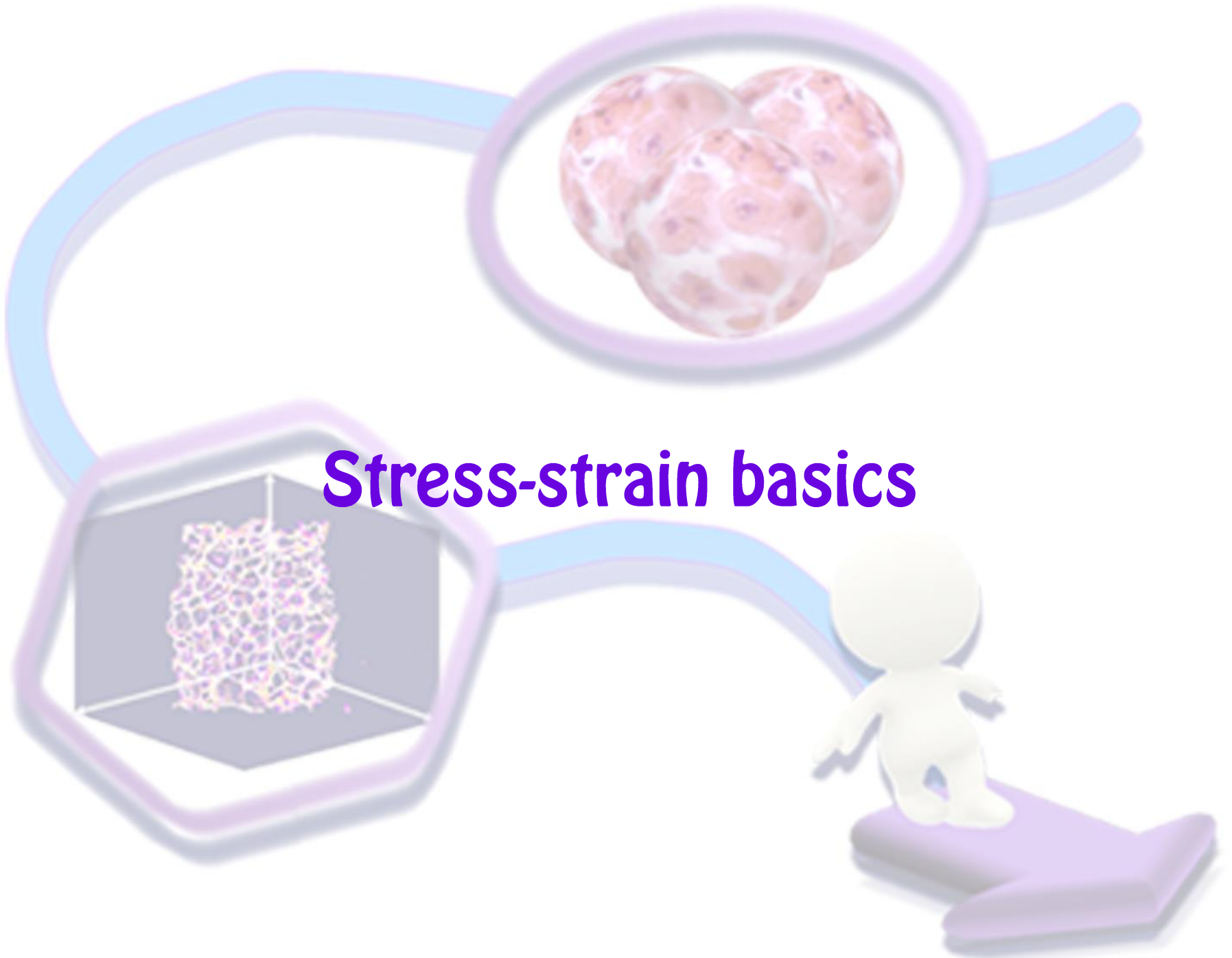
Giorgio Mattei

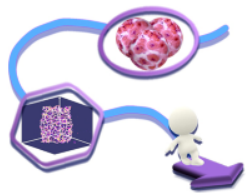
giorgio.mattei@centropiaggio.unipi.it

31 March 2016



Stress-strain basics



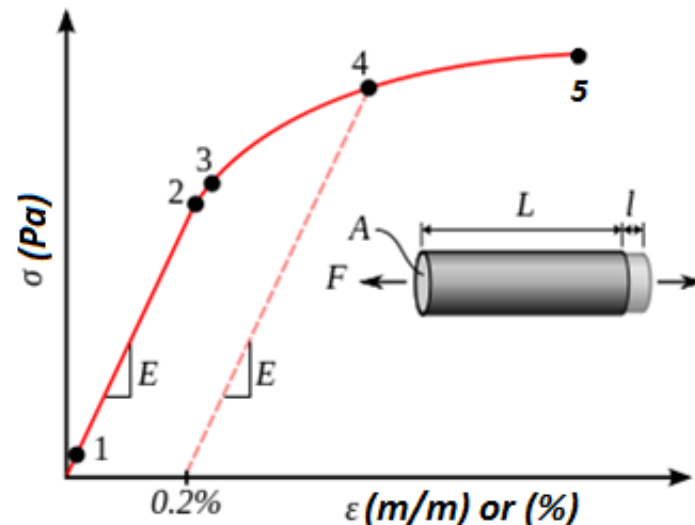


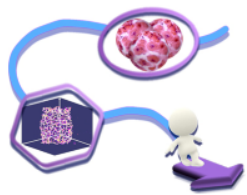
Stress-Strain curve: *definition*

Stress-Strain curve is the relationship between the stress and the strain exhibited by a given material. It is *unique* for each material and is found by recording the amount of deformation (strain) at distinct intervals of tensile or compressive loading (stress). [Wikipedia]

$$\sigma = \frac{F}{A}$$

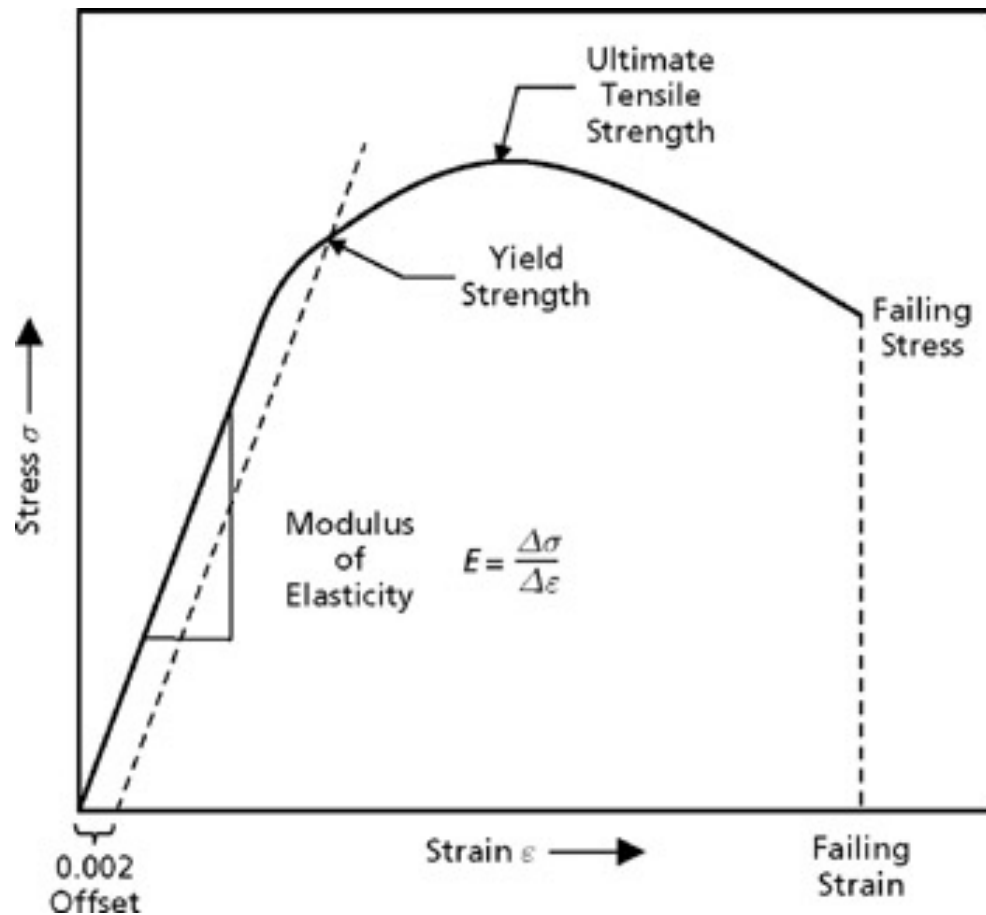
$$\varepsilon = \frac{\Delta l}{l_0}$$

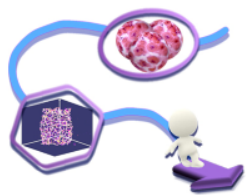




Stress-Strain curve: *utility*

Evaluate material mechanical properties

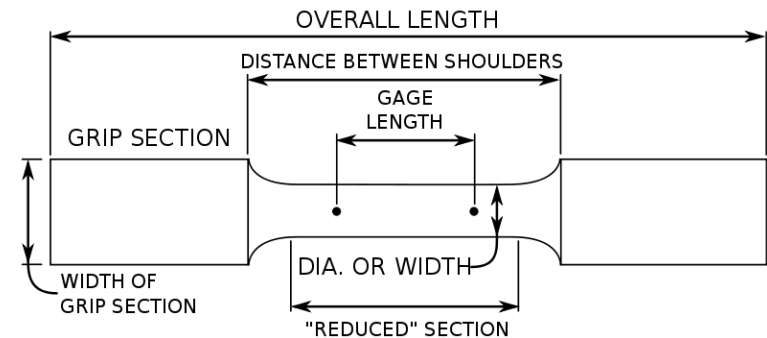




Stress-Strain: *standard vs real sample*

Standard «dog-bone» shaped sample

“...It has two shoulders and a gauge (section) in between. The shoulders are large so they can be readily gripped, whereas the gauge section has a smaller cross-section so that the deformation and failure can occur in this area...” [J. R. Davis, Tensile testing (2nd ed.), ASM International, 2004]



Real Sample

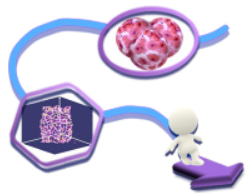
*Depends on what you are testing and typically it is **NOT standard!***

- No sufficient material*
- Heterogeneous (especially tissues or natural materials)*





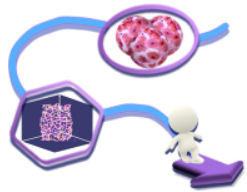
Obtaining experimental data



Zwick/Roell ProLine Z005



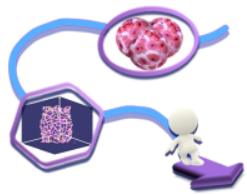
- **Uniaxial testing device**
- **Precision crosshead guidance**
- **Easy change of application:**
 - flexible plug and T-slot system allows **specimen grips/test fixtures** to be changed enabling a wide range of tests to be performed with the same testing machine
 - **load cell can be changed** depending on the required force resolution



Zwick/Roell ProLine Z005



- ProLine is available with **test speeds from 0.0005 to 1500 mm/min**, depending on type. Testing machine speed is independent of the test load.
- The **high test-speed range can be used without restriction**. In addition, **test loads up to 110% of machine nominal load are permissible to compensate for heavy combinations** of test fixtures, accessories etc.
- ProLine is available for **test loads up to 100 kN** and with **test area heights from 1050 mm to 1450 mm**.
- ProLine can be **operated with standard commercial PCs or laptops** and **requires no special expansion card**.



TestXpert II software: wizard

testXpert II - C:\ZWICK\TESTXPRT I\DATA\gelatina_A.zs2

File Machine Specimen management Configuration Options Help

Apri Forza 0 LE Start Stop Muovi Ricalcola Stampa Fine

F2 F3 Shift+F10 F10 F8 Ctrl+D

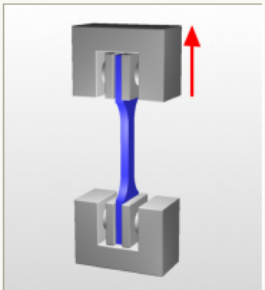
Zwick / Roell

Series layout Specimen layout **Wizard**

Expanded ↻ Parameterise the test method here Help

- Test definition ✓
- Start position ✓
- Pre-load
- Specimen data
- Conditioning phase
- Test phase ✓
- Load application phase
- End of test
- Results
- Actions after test
- Test data memory
- Control parameters
- Parameters for the report

Tipo di test: **Trazione**

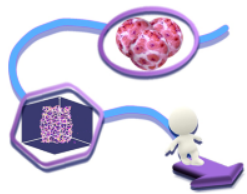


Preselection of the test device for the machine
Identifiers from parameters and results are adapted when changing the type of test

F [N] **0.001** Grip to grip separation [mm] **103.895**

DUUPS - Drive system is ready Test environment name: Default User: Impedenzimetro

start testXpert II - C:\ZWI... 3:30 PM



TestXpert II software: wizard

testXpert II - C:\ZWICK\TESTXPRT I\DATA\gelatina_A.zs2

File Machine Specimen management Configuration Options Help

Apri Forza 0 LE Start Stop Muovi Ricalcola Stampa Fine

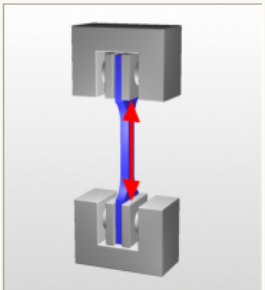
F2 F3 Shift+F10 F10 F8 Ctrl+D

Zwick / Roell

Series layout Specimen layout **Wizard**

Expanded ↻ Parameterise the machine's start position here Help

- Test definition ✓
- Start position ✓
- Pre-load
- Specimen data
- Conditioning phase
- Test phase ✓
- Load application phase
- End of test
- Results
- Actions after test
- Test data memory
- Control parameters
- Parameters for the report



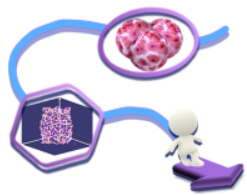
The current value of the machine is accepted by activating the action button

- Grip to grip separation at the start position A 79.70 mm
- Velocità di posizionamento a LE 500 mm/min
- Accetta la posizione corrente della traversa come posizione iniziale
- Percorso di approccio No
- Preselezione per il tratto utile della traversa Distanza tra i tool
- Correzione del tratto utile

F 0.001 Grip to grip separation 103.895
[N] [mm]

DUPS - Drive system is ready Test environment name: Default User: Impedenzimetro

start testXpert II - C:\ZWI... Microsoft PowerPoint ... 3:31 PM



TestXpert II software: wizard

testXpert II - C:\ZWICK\TESTXPRT I\DATA\gelatina_A.zs2

File Machine Specimen management Configuration Options Help

Apri Forza 0 LE Start Stop Muovi Ricalcola Stampa Fine

F2 F3 Shift+F10 F10 F8 Ctrl+D

Zwick / Roell

Series layout Specimen layout **Wizard**

Expanded Test phase Help

- Test definition ✓
- Start position ✓
- Pre-load
- Specimen data
- Conditioning phase
- Test phase ✓
- Load application phase
- End of test
- Results
- Actions after test
- Test data memory
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Selection of the test phase's type

Tipo di fase di misurazione Cicli

Number of cycles 1

Speed of cycles Strain controlled 0.07 mm/min

Point of load application of the cycles Strain 80 mm

Increase at the point of load application of the cycles 1 mm

Holding time at the point of load application of the cycles 5 s

Other speed for load removal at cycles controlled positioning 10 mm/min

Point of load removal of the cycles Strain 0.000 mm

Increase at the point of load removal of the cycles 1 mm

Holding time at the point of load removal of the cycles 1 s

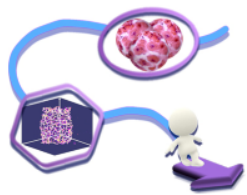
Start cycles at the point of load removal

Record certain cycles only

F 0.001 Grip to grip separation 103.895
[N] [mm]

DUPS - Drive system is ready Test environment name: Default User: Impedenzimetro

start testXpert II - C:\ZWI... Microsoft PowerPoint ... 3:31 PM



TestXpert II software: wizard

testXpert II - C:\ZWICK\TESTXPRT I\DATA\gelatina_A.zs2

File Machine Specimen management Configuration Options Help

Apri Forza 0 LE Start Stop Muovi Ricalcola Stampa Fine

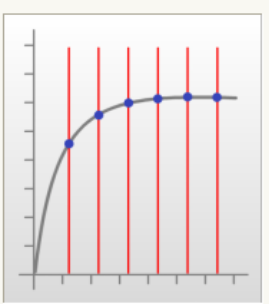
F2 F3 Shift+F10 F10 F8 Ctrl+D

Zwick / Roell

Series layout Specimen layout **Wizard**

Expanded ↻ Parameterise the memory intervals for the single test phases here [Help](#)

- Test definition ✓
- Start position ✓
- Pre-load
- Specimen data
- Conditioning phase
- Test phase ✓
- Load application phase
- End of test
- Results
- Actions after test
- Test data memory ✓
- Control parameters
- Parameters for the report


Interval preselection for test data saving

Travel save interval Standard extensometer 10 μm

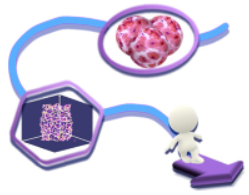
Time save interval 10 ms

Force save interval 1 N

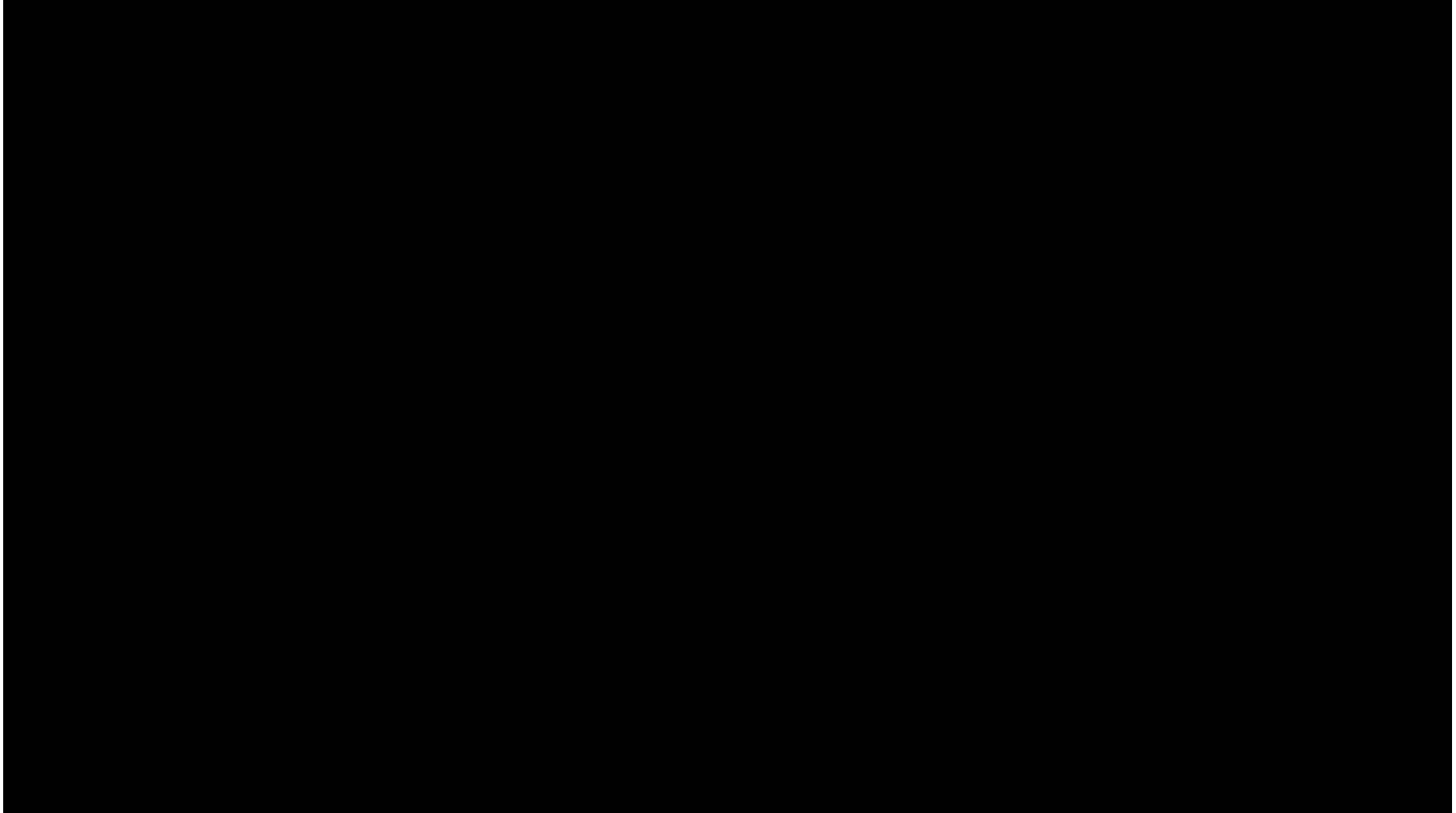
F [N] 0.001 Grip to grip separation [mm] 103.895

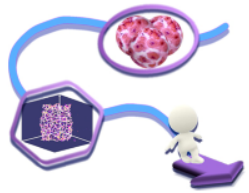
DUPS - Drive system is ready Test environment name: Default User: Impedenzimetro

start testXpert II - C:\ZWI... Microsoft PowerPoint ... 3:32 PM



Zwick/Roell ProLine Z005

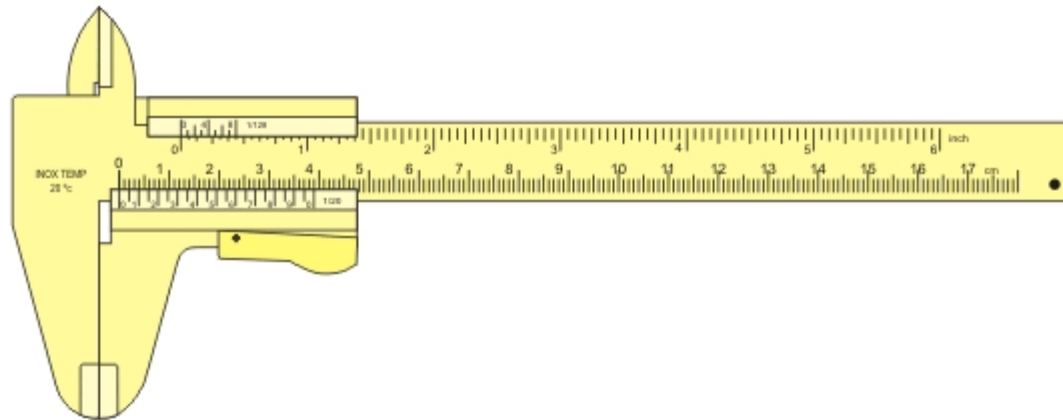


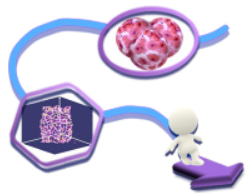


Calliper: *how to use it*

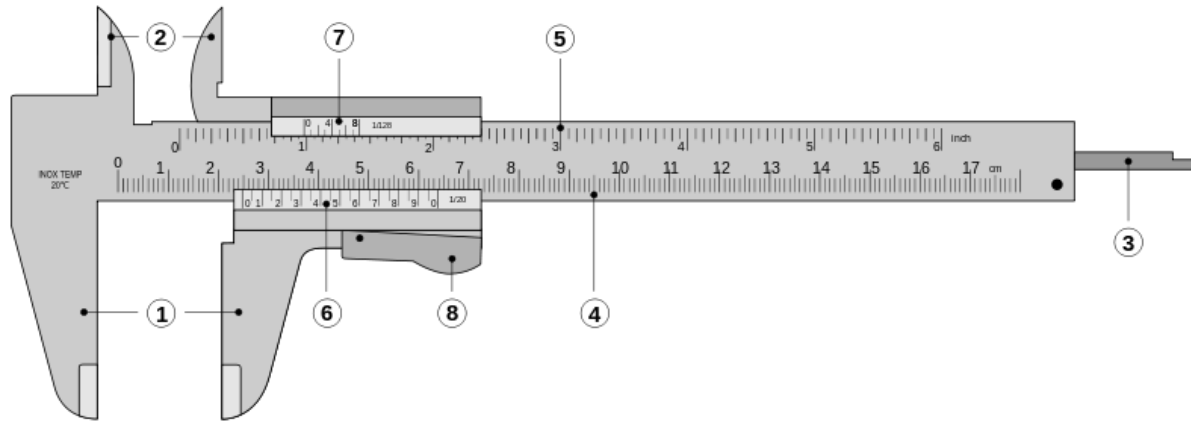


- direct reading of the distance measured with high accuracy and precision
- 0.05 mm resolution

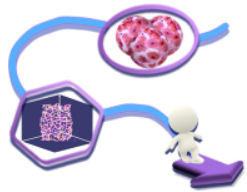




Calliper: *how to use it*



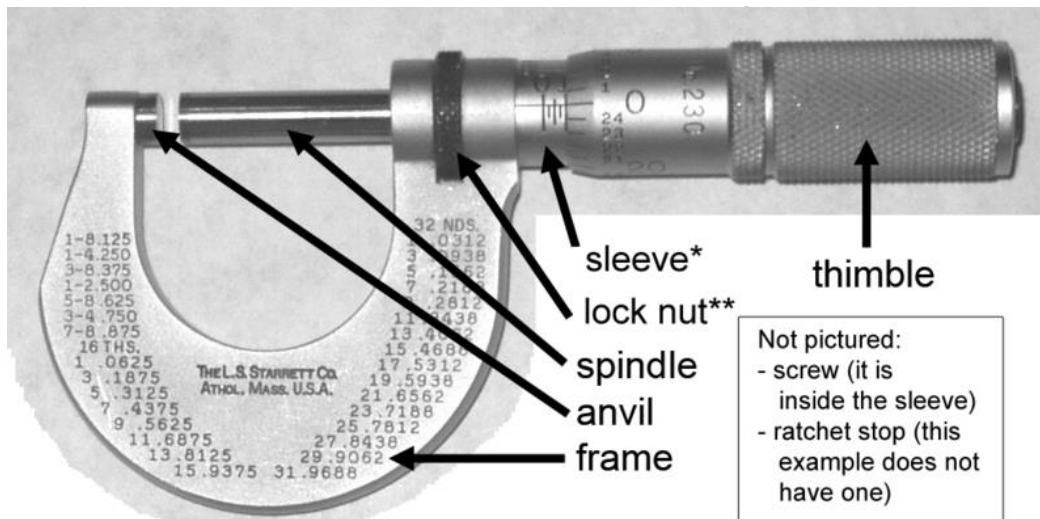
- 1. Outside jaws:** used to measure external diameter or width of an object
- 2. Inside jaws:** used to measure internal diameter of an object
- 3. Depth probe:** used to measure depths of an object or a hole
- 4. Main scale:** scale marked every mm
- 5. Main scale:** scale marked in inches and fractions
- 6. Vernier scale** gives interpolated measurements to 0.1 mm or better
- 7. Vernier scale** gives interpolated measurements in fractions of an inch
- 8. Retainer:** used to block movable part to allow the easy transferring of a measurement



Micrometer: *how to use it*



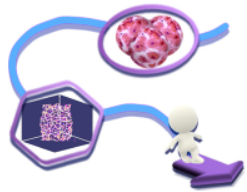
- Micrometers use the principle of a screw to amplify small distances (that are too small to measure directly) into large rotations of the screw that are big enough to read



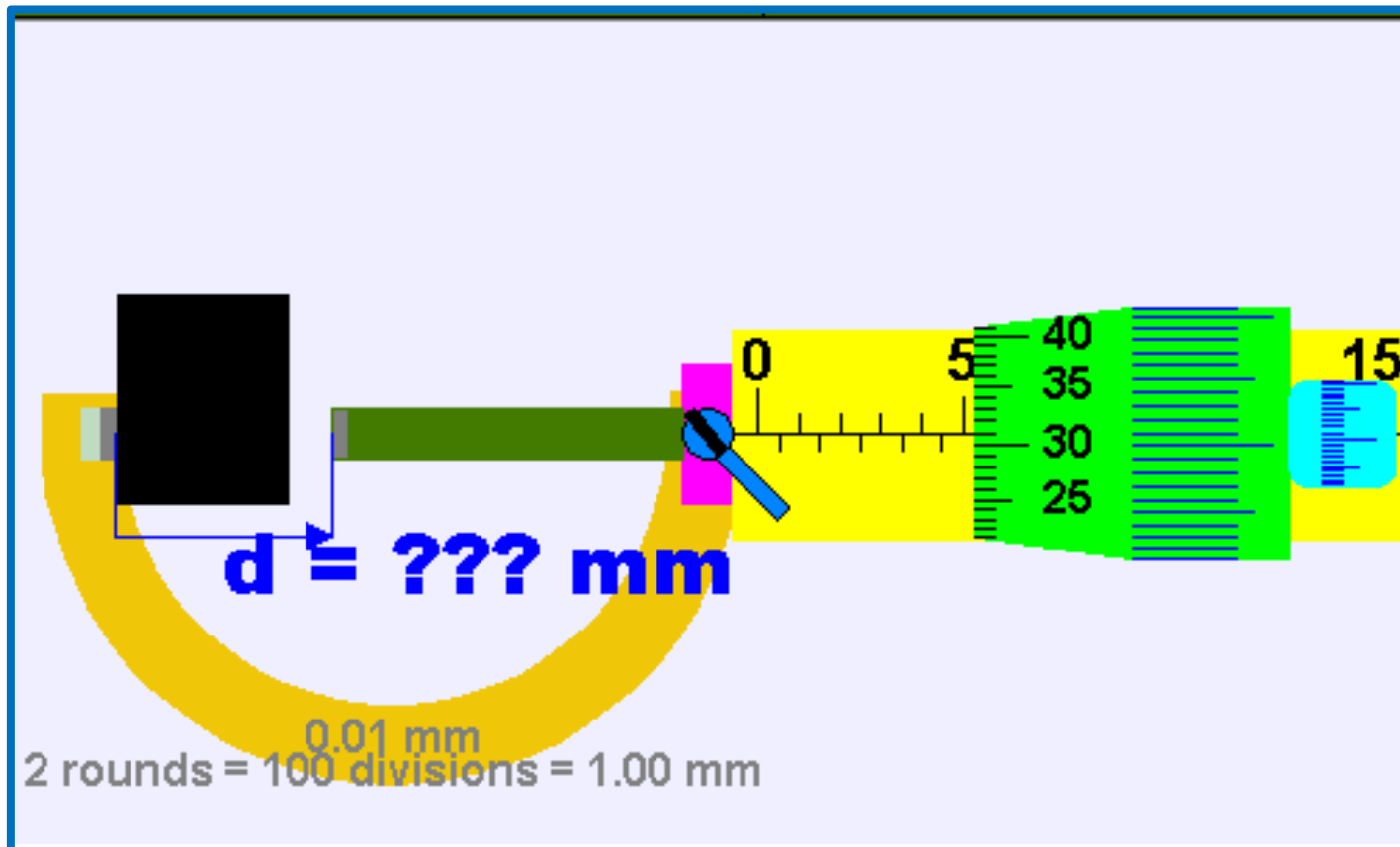
- Resolution 0.01mm (10 μ m)

*Sleeve is the most prevalent name. May also be called the *barrel* or *stock*.

**Aka *lock-ring*. Some mics have a *lock lever* instead.

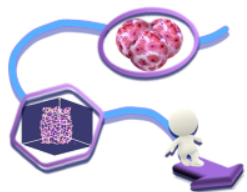


Micrometer: *how to use it*





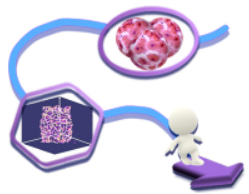
Modelling the linear response



Linear Regression: *Definition*

In statistics, **linear regression** is an approach to modeling the *relationship* between a dependent variable y and one or more independent variables denoted x .

In linear regression, data are modeled using linear predictor functions, and unknown model parameters are estimated from the data.



Linear Regression

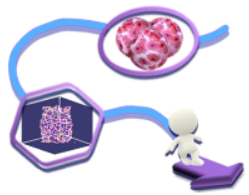
Relationship between **input** and **output** is assumed as:

$$y = \alpha + \beta \cdot x + e$$

where

- **y** is the experimental output observed in response of an input **x**
- **α** and **β** are the unknown parameters to estimate (i.e. intercept and slope of the linear fit)
- **e** is a random error term such that $E\{\varepsilon_i\} = 0$ $\sigma^2\{\varepsilon_i\} = \sigma^2$ $\sigma\{\varepsilon_i, \varepsilon_j\} = 0 \quad \forall i, j \ni i \neq j$



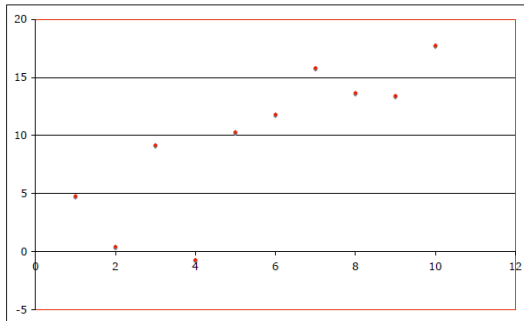


Linear Regression

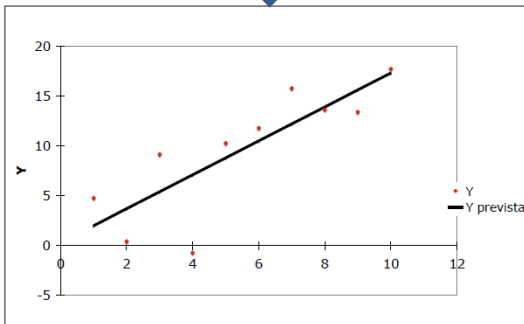
Parameters are estimated by minimizing the of ***sum of squared residual*** (SS_R)

$$y = \alpha + \beta \cdot x$$

$$SS_R = \sum_{i=1}^n (y_i - a - bx_i)^2$$

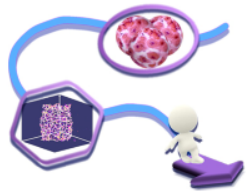


residual = vertical distance between real data and estimated curve



Assumptions:

- (x_i, y_i) are independent and identically distributed observations
- x_i are random and sampled together with y_i

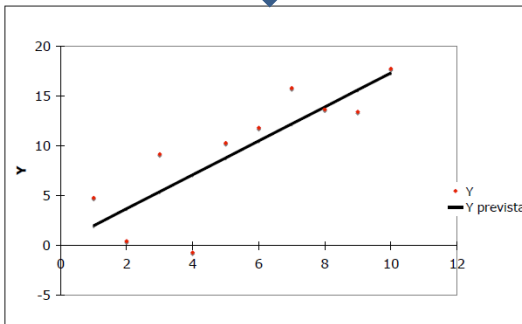
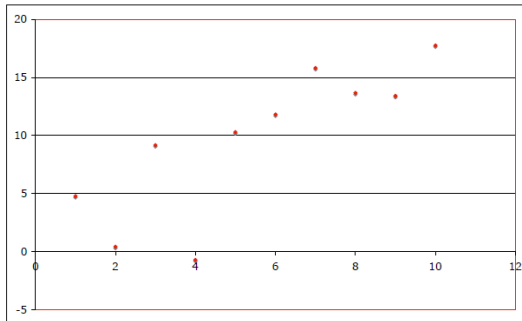


Linear Regression

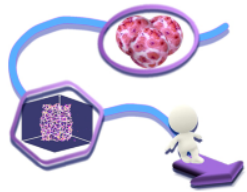
Parameters are estimated by minimizing the of ***sum of squared residual*** (SS_R)

$$y = \alpha + \beta \cdot x$$

$$SS_R = \sum_{i=1}^n (y_i - a - bx_i)^2$$



The SS_R is an index of inherent variability, quantifying how much the fitted line differs from the real output due the error (**e**)



Linear Regression

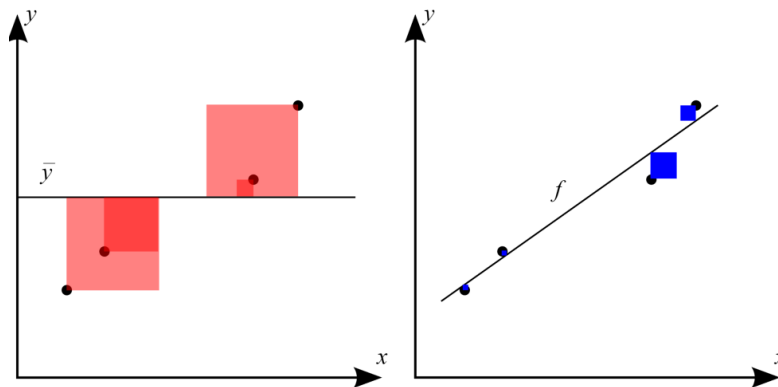
R^2 : a measure of goodness-of-fit of linear regression

$$R^2 := 1 - \frac{SS_R}{S_{yy}}$$

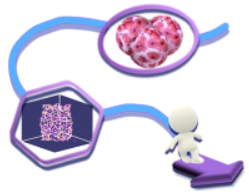
The coefficient of determination (R^2) ranges from 0 (model does not fit the data) to 1 (perfect fit)

$$SS_R = \sum_{i=1}^n (y_i - a - bx_i)^2$$

$$S_{yy} = \sum_i (y_i - \bar{y})^2$$



The **better the linear regression** (on the right) fits the data in comparison to the simple average (on the left), the **closer the value of R^2 is to 1**. The **areas of the blue squares** represent SS_R . The **areas of the red squares** represent the S_{yy} .



Linear Regression

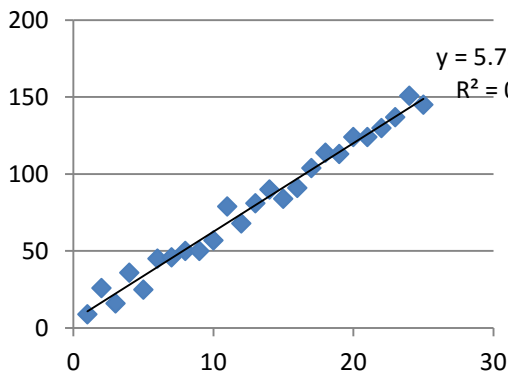
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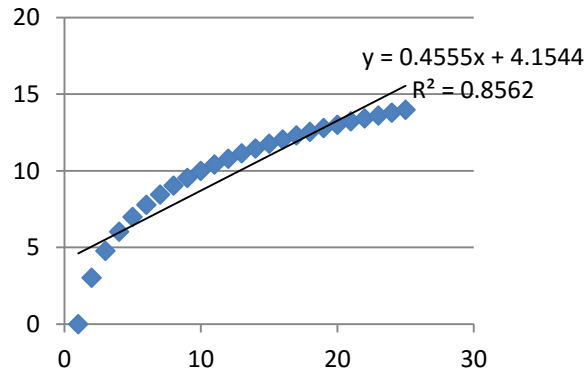
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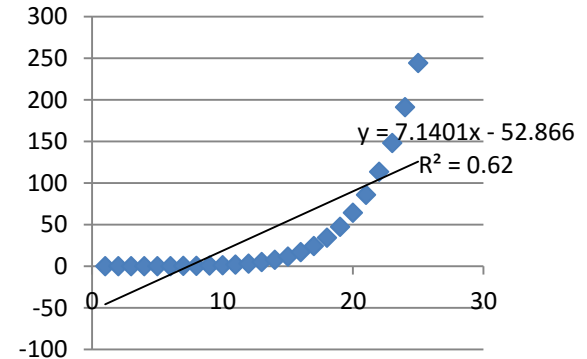
$$S_{yy} = \sum_i (y_i - \bar{y})^2$$



Good fit
($R^2 > 0.9$)



Poor fit
($0.9 > R^2 > 0.8$)



Very bad fit
($R^2 < 0.8$)



Microsoft Excel: Linear Regression

Two ways to evaluate fit parameters

- *Directly on the plot*: add trendline

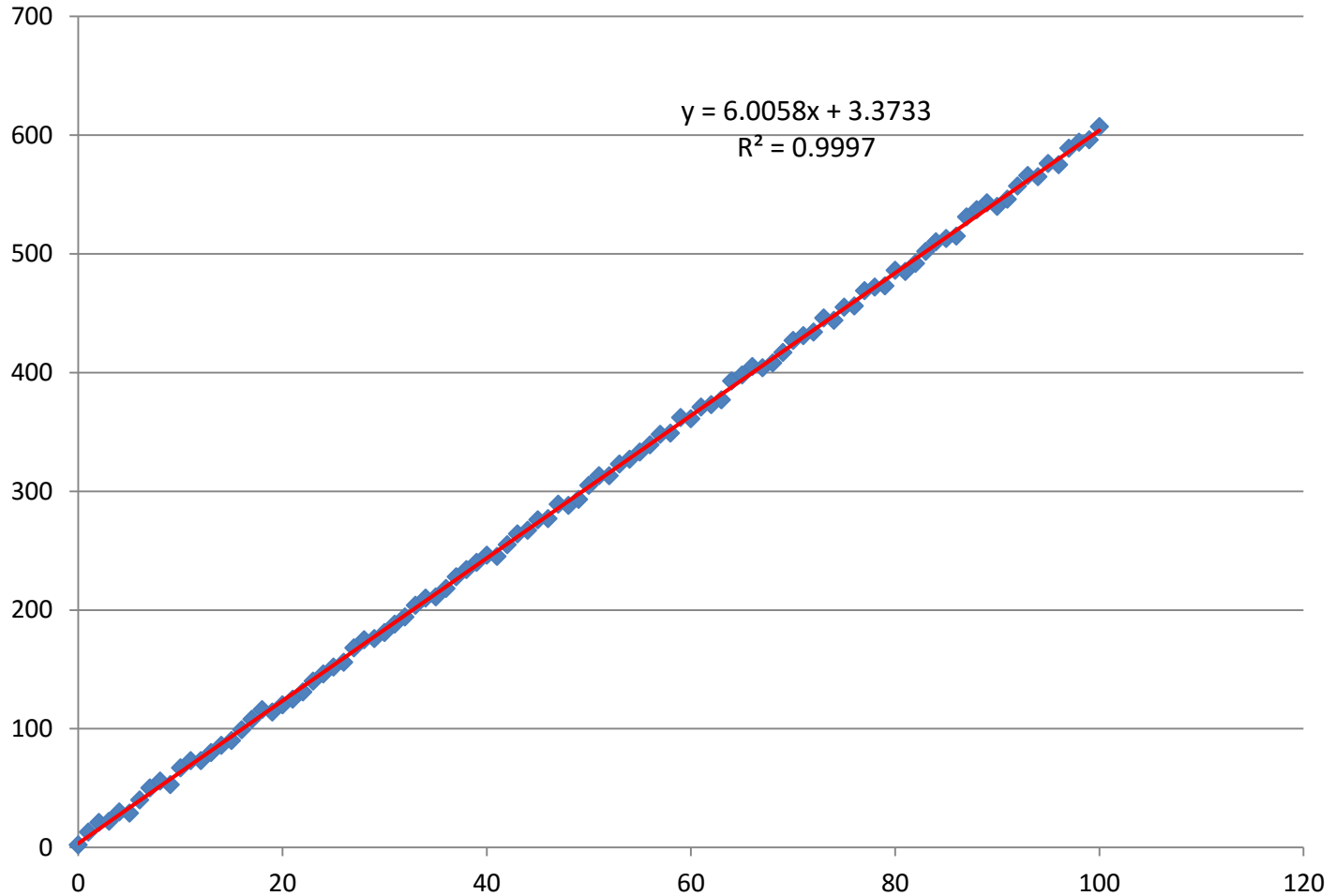
The screenshot shows the Microsoft Excel interface with a scatter plot of data points. A blue linear trendline is fitted to the data, with the equation $y = 6,0088x + 3,5719$ and $R^2 = 0,9997$ displayed on the plot. The 'Formato linea di tendenza' (Format Trendline) dialog box is open, showing the 'Opzioni linea di tendenza' (Trendline Options) tab. The 'Tipo di tendenza/regressione' (Trendline type) section has 'Lineare' (Linear) selected. The 'Nome linea di tendenza' (Trendline name) section has 'Automatico: Lineare (Serie1)' selected. The 'Previsione' (Forecast) section has 'Futura: 0,0' and 'Verifica: 0,0' periods. The 'Visualizza l'equazione sul grafico' (Display equation on chart) and 'Visualizza il valore R quadrato sul grafico' (Display R-squared value on chart) checkboxes are checked.

	A	B
1	0	8
2	1	9
3	2	16
4	3	22
5	4	23
6	5	30
7	6	37
8	7	41
9	8	47
10	9	57
11	10	63
12	11	68
13	12	76
14	13	79
15	14	84
16	15	90
17	16	100
18	17	111
19	18	116
20	19	117
21	20	123
22	21	132
23	22	132
24	23	140
25	24	152

- Easy method
- Data on plot
- GUI help



Microsoft Excel: *Linear Regression*





Microsoft Excel: Linear Regression

Two ways to evaluate fit parameter

- As a cell function: use *linear estimation* function

Known_y's: experimental y values you wish to fit using $y = ax + b$

In Italian...

=REGR.LIN (known_y's, known_x's, const, stats)

Known_x's: experimental x values you wish to fit using $y = ax + b$

Const: a logical value to fix line intercept to 0 (const =0 \rightarrow b=0)

Stats: a logical value to specify whether to return additional regression statistics (stats = 1 returns additional regr. statistics)

	A	B	C	D	E	F
1	m_n	m_{n-1}	...	m_2	m_1	b
2	se_n	se_{n-1}	...	se_2	se_1	se_b
3	r^2	se_y				
4	F	d_f				
5	ssreg	ssresid				

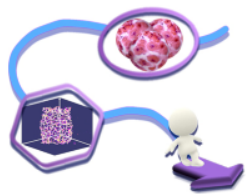


Arrangement of fitted parameters in Excel (select the necessary number of cells then press **CRTL+SHIFT+ENTER** to enter an array formula)



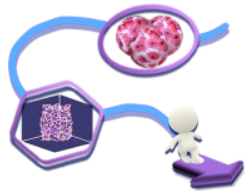
Case of study: the hair

Typical experiment and analysis



Testing the hair: experimental details

1. Measure **hair diameter** using the **micrometre** to evaluate the sample **cross sectional area (A)**
2. **Clamp the hair using acetate sheets**, then measure the **distance between the latter** using the **calliper** to evaluate **sample initial length (l_0)**
3. Assemble the **testing setup**
4. Acquire **force-displacement** curves at a **0.01 s^{-1} strain rate** using the Zwick/Roell ProLine Z005 testing machine
6. **Identify the first loading point**, then **offset force and displacement vectors** to start from 0 in correspondence of the initial loading point and **convert them into stress ($\sigma = F/A$) and strain ($\varepsilon = \Delta l/l_0$)**, respectively
7. **Plot stress-strain curve** of the hair
8. Evaluate the **elastic modulus of the hair** as the **slope of the stress-strain curve** in the **first linear (elastic) tract**

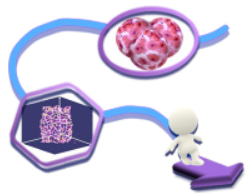


Practical exp: hair mechanical test

When: 6 Apr 2016 – 9.00-13.00

Where: Laboratori Centro di Ricerca “E. Piaggio” – 3° piano
Polo A, Scuola di Ingegneria, Università di Pisa





Contacts

Giorgio MATTEI

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c/o Centro di Ricerca “E. Piaggio” – 3° piano Polo A, Scuola di Ingegneria

<http://www.centropiaggio.unipi.it/research/multi-dimensional-vitro-models.html>

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Website: <http://www.centropiaggio.unipi.it/~mattei>