Introduction to Measurement

for PHYL102

Motivation

Suppose you are given the standard acceleration due to gravity as **10**. Does this value by itself make sense?

First of all, we need **units** to define the type of the quantity. Is it **m/s^2**, **ft/s^2**, or else?

Is **10m/s^2** enough? What might be **wrong** with this value?

Does it mean that standard acceleration due to gravity has as many m/s^2 as we have fingers?

So, somehow can we **count** standard acceleration due to gravity?

What is the difference between **counting** and **measurement**, if any?

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Measurement is a process for determining the size of a physical quantity.

We answer "how much?" via measurement.
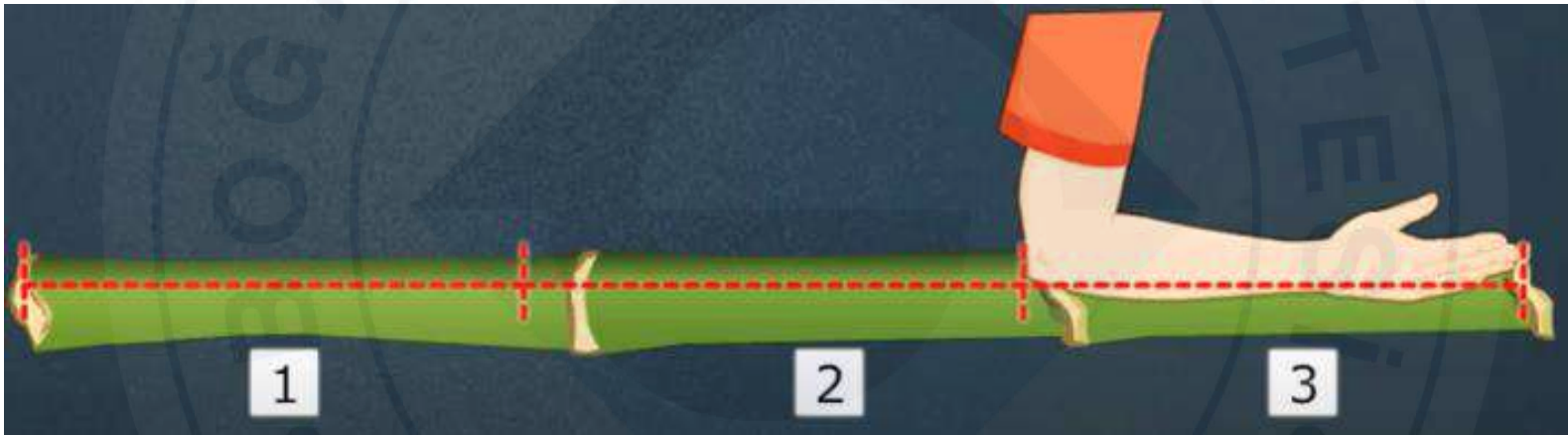
For example, this bamboo stick is three cubits long.

What is Measurement?

A cubit is an example of **non-standard** unit of measurement.

Other non standard units include

- **tablespoon for volume,**

- **grain for weight,**

- **and heart rate for time.**

Though these units are simple to use, they lack **precision**.

For scientific experiments, we need better than that. We need fixed, reliable units such as the **meter, gram, and second**.

Precision and Accuracy

We feel that some measurements are better than others.

Measuring tape is better than human-based units in a length measurement, simply because it is more precise.

Precision is a measure of reproducibility in a measurement.

When precise, repeated measurements give close together results.

Precision is represented by the number of digits given.

For example, 176.3 cm is more precise than 176. cm.
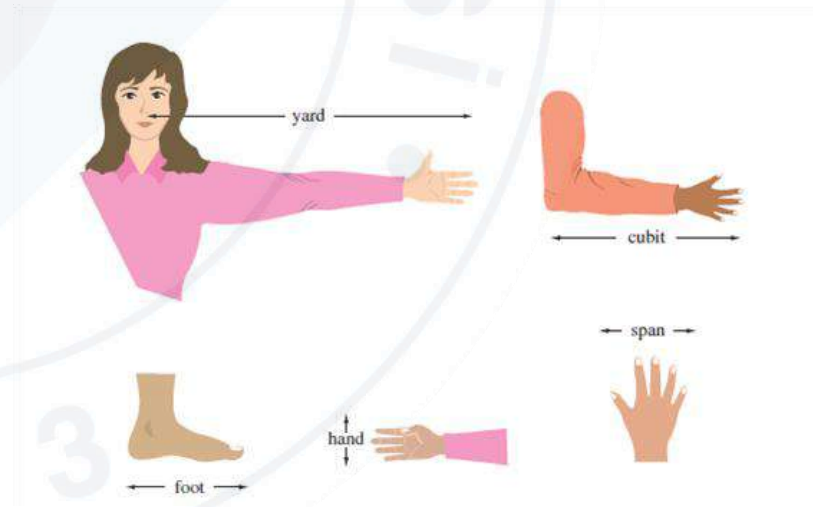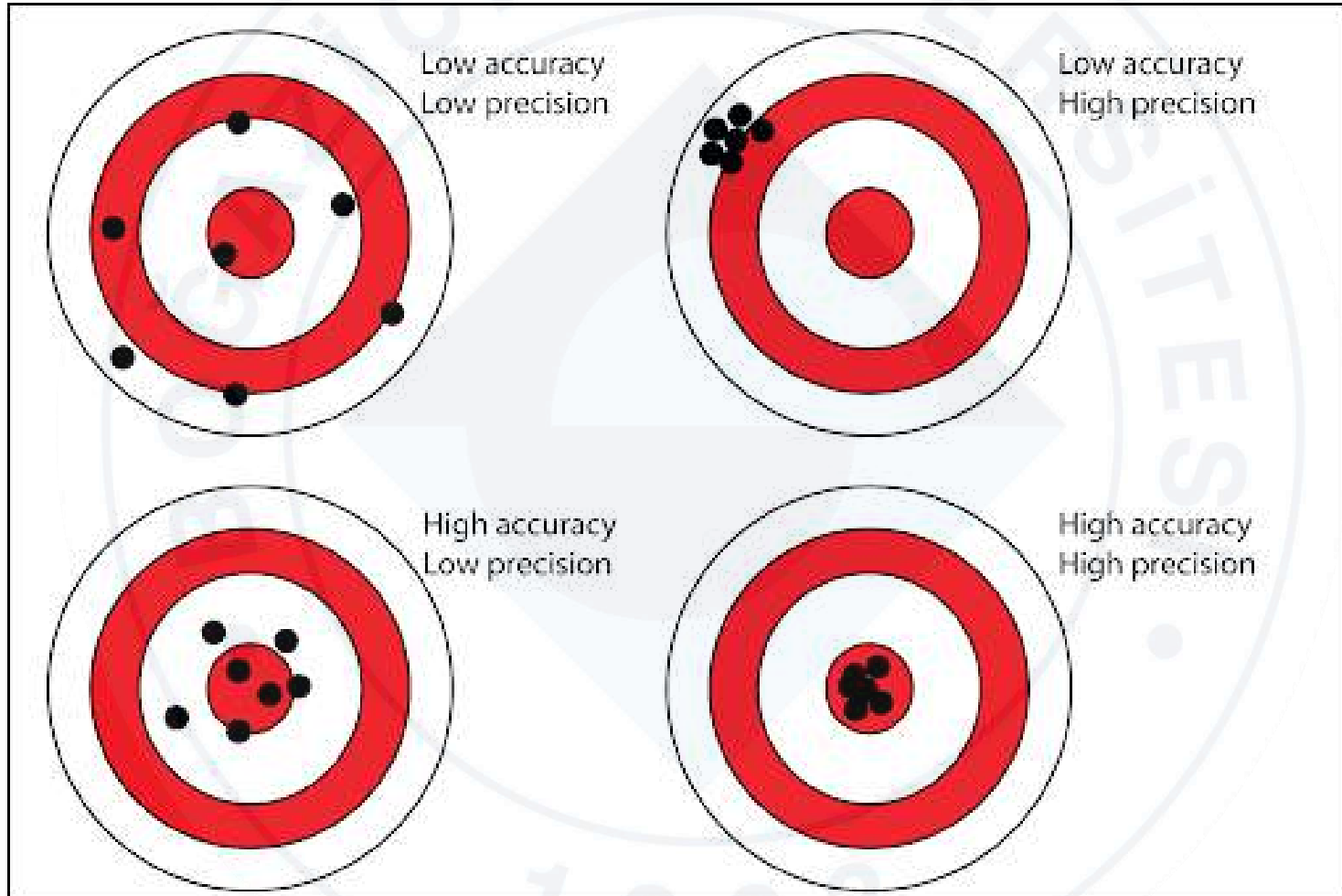
However, precision does not mean accuracy, that is, closeness to the "true" value.

Your weight might appear as 314.15 kg on a broken precision balance. Though that value is more precise than 75. kg on a bathroom balance, say, which one do you think is more accurate?

Precision and Accuracy

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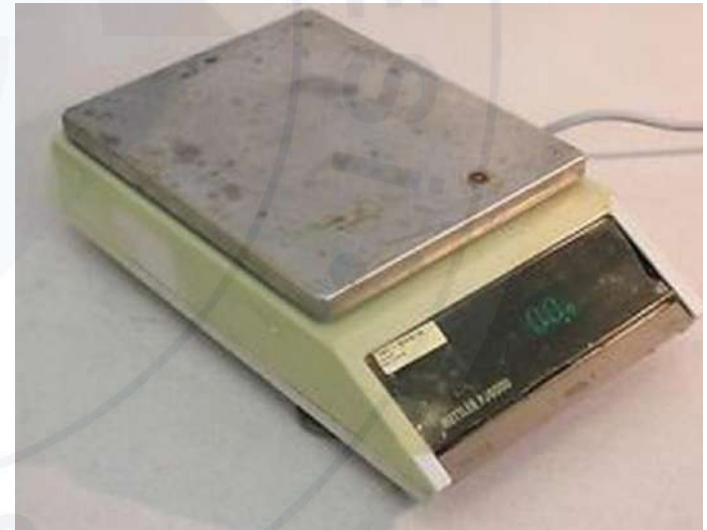
Precision and Accuracy

A good measurement is both **precise** and **accurate**.

For precision, we use "better", more precise equipment.

For example, a **micrometer** is more precise than a **vernier scale**, which is more precise than a **meterstick**.

A meterstick reads up to **0.1 cm**. It measures a barley grain as, say, **1.3 cm**.
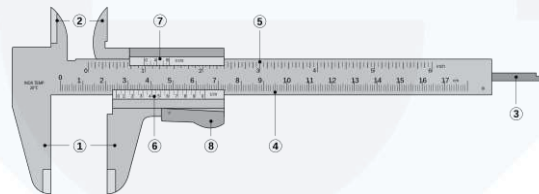
A vernier scale reads up to **0.01 cm**. It measures the same grain as, say, **1.34 cm**.

A micrometer reads up to **0.001 cm**. It measure the same grain as, say, **1.343 cm**.

For accuracy though, better equipment is not enough. First of all, we can never be sure if our result is close enough to the "true" value. After all, what is true value?

Say, we measure our height ten times using a measuring tape. These ten measurements will not exactly match.

Height (cm)
173.4
173.2
173.6
173.4
173.5
173.5
173.1
173.7
173.2
173.4

So, which one is the true value, if any?

Is it the most frequent reading (the mode)?

Is it the average, or median?

If so, how do we explain when these statistical measures change by different measurements?

It is clear that we can never know what true value is. We can only hope to approach it. For this, we need to take many measurements and take their average. The average of many measurements is our best shot at the "true value", or rather the accepted value.

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Precision and Accuracy

Although, repeated measurements do not match, they follow a pattern.

They seem to distribute about a value. Their distribution is known as normal distribution.

Repeated measurements form a Gaussian curve (or bell curve).
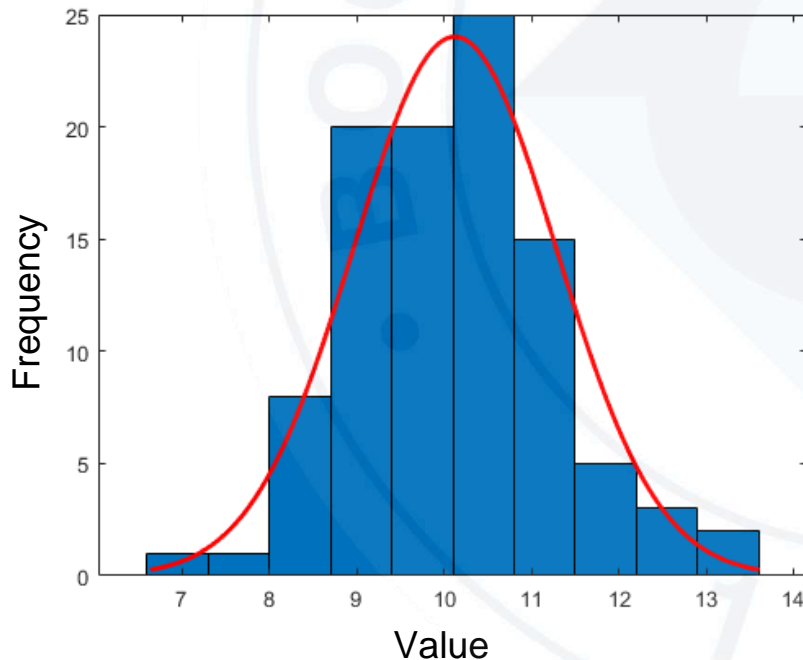
This histogram shows a distribution of repeated measurements.

For example, a value between 10 and 11 is obtained 25 times.

Precision and Accuracy
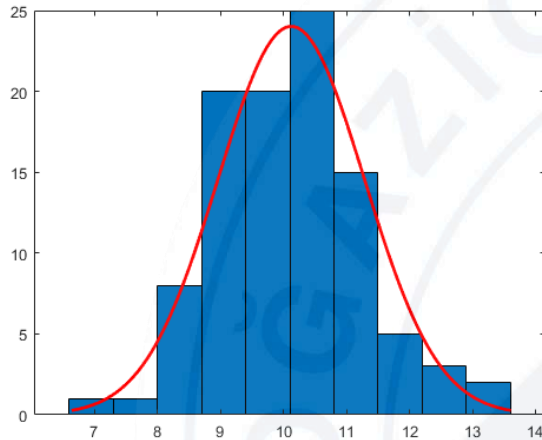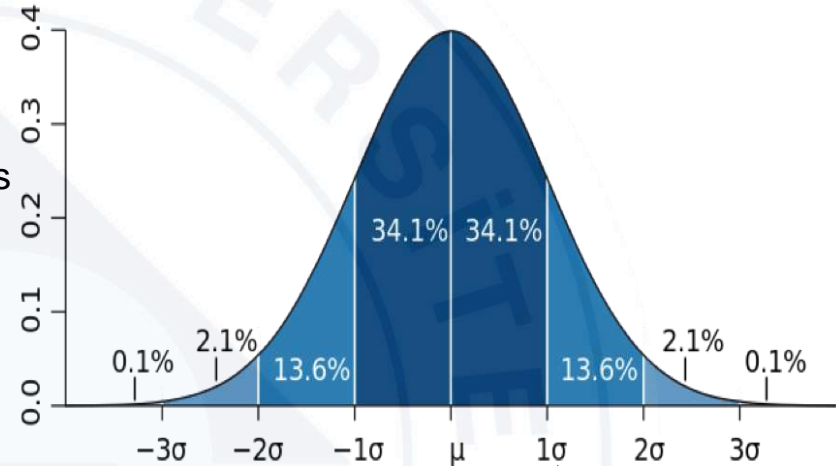
On the right, we see a normal distribution.

What we call "true value" is the average.

The idea is that the more measurements we take, the closer we get to the true value.

Standard deviation is a measure of spread and it represents error.

Many measurements

Average   Standard Deviation

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Error is inherent in measurements.

There are many sources of error. In measuring your height, for example,

- **you may use a faulty measure tape,**

- **measure while lying down,**

- **or your hands may be shaking.**

Sources of error are typically classified into three groups: instrumental error, systematic error and random error.
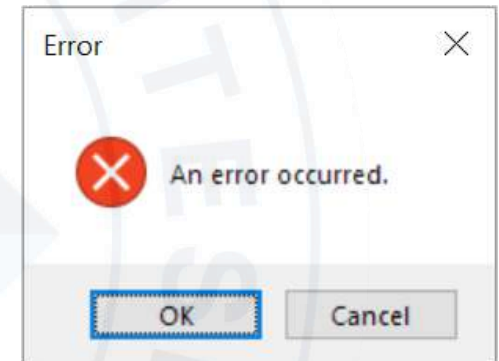
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Instrumental error is when you use bad equipment. To reduce instrumental error, simply use better, more precise measuring instruments.

Systematic error, also bias error, is when you follow a **faulty procedure**, use **poorly calibrated equipment**, or **disregard environmental conditions**. To reduce systematic errors, be careful and mindful of your measurement procedure.

- For example, any measurement you take with this ruler will be off by **1.0** cm because of end-point bias. So you should record the length of the pencil not as **11.0** cm. but as **10.0** cm.

Random error, also statistical error, is **due to chance**, and we cannot control it.

Random error causes fluctuation in repeated measurements. To reduce random error, we simply take many measurements and then take their average.

- Random error is responsible for **normal distribution**.

Error

Error

As error is inherent in measurement, we need a way to describe error in our results.

One common way of describing error is to introduce an error window using the $\pm$ sign, as in 176.3 $\pm$ 0.1 cm.

Such a result means more than a pure number. It means that if we measure the same length, the result will most likely be within 0.1 cm of 176.3 cm.

As you may guess, 176.3 $\pm$ 0.1 cm is more precise a measurement than, say, 176.3 $\pm$ 0.6 cm.

A bare result such as 176.3 cm lacks its measure of precision and therefore is meaningless.

Significant Figures

However, we assign a meaning to such values as 176.3 cm.

Our convention is that, in a result, when not stated explicitly, the error is in the **last digit**, and its size is determined by the measuring instrument.

So, 176.3 cm really means 176.3 $\pm$ 0.1 cm.

Consider you step on a digital bathroom scale and read 72.0 in kilograms.

If you report your result as 72. kg, it is implied that your weight is within 1. kg of 72. kg.

Yet, you actually know better than that; your weight is within 0.1 kg of 72.0 kg.

So, the last digit in 72.0 kg is **significant**. You cannot take it off without changing the meaning of the measured value.

Significant Figures

Significant figures are important because

- **they tell precision,**

- **they help determine the precision of calculated, not directly measured, values such as standard acceleration due to gravity.**

Suppose you want to find the area a rug covers.

You measure the sides, and multiply them.

Knowing the errors of side measurements, what can we say about the error in area?

We will talk more about significant figures.

85.6 cm

124.2 cm

A Digression on Error

When we say error, we usually mean the precision of a result. For example, 176.3 $\pm$ 0.1 cm has an error of 0.1 cm.

However, error can also indicate accuracy.

When we compare the experimental value, with the true value, their difference is also known as error.

This error shows how accurately we have carried out the experiment.

For example, suppose standard gravity, g, in Istanbul is given as 9.808 m/s^2. We accept this value as the true value (TV).

Then we carry out an experiment and determine g as 9.78 m/s^2. We call this the experimental value (EV).

The difference between the two values will be called error, as well.

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Generally, we talk of **percentage error** in this context. It is calculated as

$$\% \text{ Error } = \frac{|TV - EV|}{TV} \times 100$$

where TV and EV denote true value and experimental or evaluated value, respectively.

Suppose now all we have is two experimental values, EV_1 and EV_2

Then we calculate the error as

$$\% \text{ Error } = \frac{|EV_1 - EV_2|}{(EV_1 + EV_2)/2} \times 100$$

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Recording Measurement

In general, to what precision we should record our measurement is dictated by the measuring instrument.

For example, a typical ruler has a resolution of 1 mm. Therefore, a typical ruler scale enables us to read up to 1 mm, no more, no less.

How should we record the length of this pencil?

Both 10 cm and 10. cm are incorrect. Our result must echo the resolution of the instrument: 10.0 cm.

Recording Measurement

Digital readings work the same way as analog readings.

What does this stopwatch read?

It is 303.00 seconds.

Although there is no difference between 303.00 and 303. to a calculator, these two values are quite different from the standpoint of physics. In other words, the last two zeroes are significant.

So, make sure you record up to the resolution of your measuring instrument. Otherwise you risk misperception.

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Two Rules of Thumb

Consider the following measurement.
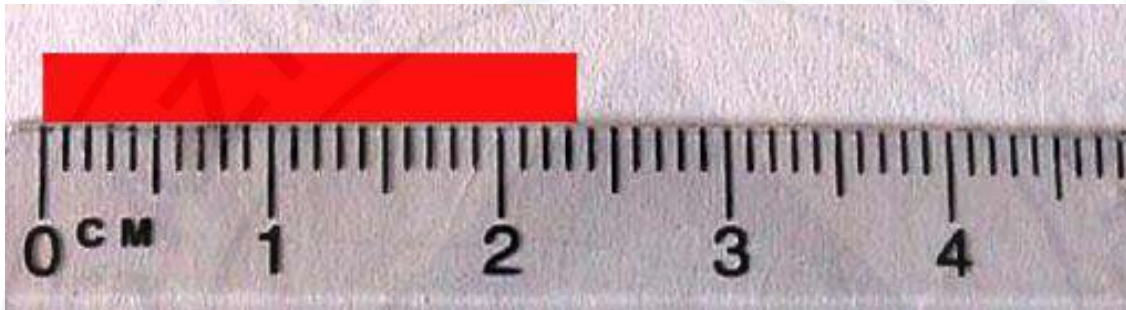
The red strip stretches from **0.0** to somewhere in between **2.3** and **2.4**. In such cases, as a rule of thumb, we should record **the nearest tick**, in this case **2.3 cm**.

Another issue is about the precision of given values of lab equipment.

Say, you are given a washer of **100 g**, or a resistor of **50 Ω**.

If you do not measure these yourself and there is no indication that these are measured and given to you, you should accept and record these values **as they are**.

In this case, all 0's are significant, and these values are no more precise than their last digit. So they are **not** 100.0 g or 50.00 Ω, but **100. g** and **50. Ω**.

Few Common Mistakes

Measurements done with a single instrument do not have to share the same number of significant figures.

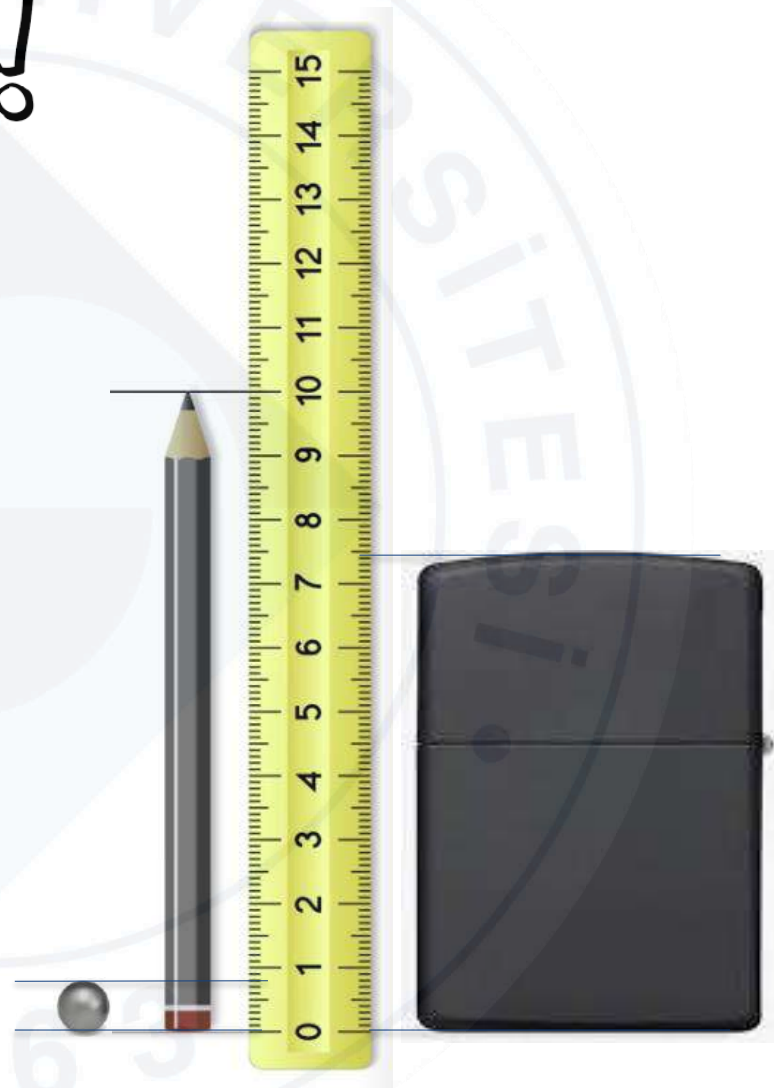**For example, consider the three measurements shown on the right.**

The pencil is 10.0 cm. It has 3 s.f.

The lighter is 7.4 cm. It has 2 s.f.

The steel ball is 0.8 cm. It has 1 s.f

Consider this stack of coins.

A stack of 37 coins is 12.1 cm tall.

Dividing 12.1 cm by 37, we get 0.327 cm.

If we measured a single coin, we could measure only up to 0.1 cm precision; we would get 0.3 cm.

But measuring many at once and dividing by the total number gives more significant figures.

We will see more about significant figure arithmetic later on.

- **Physical values are dimensionful, so they require units.**

- **Error is inherent in measurements. Physical values without error are meaningless.**

- **Rigor in measurement corrects systematic error, and repetition reduces random error. Multiple measurements done carefully is the best we can do about error.**

- **We imply error with significant figures. Typically, error is in the last digit.**

- **Precision of a measurement is dictated by the measuring instrument. The precision of a measured value should be the same as the resolution of the instrument. For example, you can read on a regular meterstick 176.3 cm, but not 176. cm or 176.30 cm.**

Significant Figures

Significant Figures

Significant figures are the 'meaningful' digits that account for the precision of measurements or values derived from those measurements.

Benefiting from these figures, we can be consistent while reading measurements in devices and noting the values in an experiment.

We find these significant figures to show the values properly.

• We count the number of significant figures in measurements, since they will determine the precision or the number of significant figures of calculated values.

So, how can we find and count these significant figures?

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Rules for Counting Significant Figures (sf)

Nonzero integers are always significant

If a digit has a nonzero value, we can say that the digit has a meaningful contribution

to the measurement.

3456. cm	4 sf
12.97 cm	4 sf
1.11278 cm	6 sf

Rules for Counting Significant Figures (sf)

Leading zeros are always insignificant

If a measurement begins with zeros, we can say that those zeros do not contribute to the precision of that measurement and they can be written in a more scientific notation.

0.0034 ms   2 sf   ➡️ 3.4×10^{-3} ms

0.123 ms   3 sf   ➡️ 1.23×10^{-1} ms

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Zeros between nonzero integers are always significant

Since there will be at least a nonzero value after those zeros and

the last nonzero value will determine the precision of the measurement,

we can say that zeros in the middle are significant.

0.003004 kg   4 sf   ➡ 3.004×10^{-3} kg

102.003 g   6 sf

Rules for Counting Significant Figures (sf)

Trailing zeros are significant if a decimal point exists

⚬ **If zeros exist after the decimal, it must be significant since it indicates the precision on that digit.**

⚬ **However, if there is no decimal and you know that *this is a measurement* (poorly reported one), trailing zeros will be insignificant.**

1.600 A	4 sf		
1200 mA	2 sf	➡	1.2×10^3 mA

Significant Figures

- **Operations with values that have no significant figures do not change the significant figure of the result, i.e., averaging.**

$$\frac{11.\ s + 33.\ s}{2} = 22.\ s \qquad \text{not 20 s}$$

- **Rounding**

  Round numbers to 2 sf

  37.2793 ⟶ 37.
  37.9793 ⟶ 38.
  37.5793 ⟶ 38.
  38.5793 ⟶ 38.

- **Handling 0's in measurement devices while reporting**

  0 at the end is also significant since the device can measure that digit

  Example: A ruler with units of cm

  … 127 128 129 130 131 132 133 …
    3 sf 3 sf 3 sf ??? 3 sf 3 sf 3 sf

  130 cm

  13.0×10^1 cm
  1.30×10^2 cm
  130. cm

  Also report the other measurements like **127** and **128** with a decimal point as **127.** and **128.** so as not to confuse them with integers.

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Calculations with Significant Figures

Calculations with Significant Figures

Addition and Subtraction (A&S)

In addition and subtraction, the precision of a result is determined by the last significant digit of the least precise value used within the operation.

```
   12.1    g                                          12.1????? g
    1.11   g          Put ?'s for                      1.11???? g
+ 111.235 g          non-significant        +       111.235??? g
_____            digits               _____
  124.445 g  →   124.4 g                            124.4????? g
```

Put **?'s** for non-significant digits

This is what a calculator would give you

Round the number up **if necessary**

124.4 g

Note: As seen in this example, the result has 4 significant figures, even though none of the terms added has 4 significant figures.

Calculations with Significant Figures

Addition and Subtraction (A&S)

In addition and subtraction, the precision of a result is determined by the last significant digit of the least precise value used within the operation.

More Examples:

3×10^1 mg

$$3\textbf{0} \text{ mg}$$
$$+ \quad 142.1 \text{ mg}$$
$$\overline{17\underline{2}.1 \text{ mg}}$$

"0" in "30" is not significant

17**0** g

3.0×10^1 mg

$$3\textbf{0.} \text{ mg}$$
$$+ \quad 142.1 \text{ mg}$$
$$\overline{17\underline{2}.1 \text{ mg}}$$

"0" in "30." is significant

17**2** g

$$\textbf{2}0 \text{ mg}$$
$$30. \text{ mg}$$
$$+ \quad 142.0 \text{ mg}$$
$$\overline{1\underline{9}2.0 \text{ mg}}$$

? 1**9**0 g

Calculations with Significant Figures

Addition and Subtraction (A&S)

➢ **An Exception: If you are instructed to make some number of independent measurement of a quantity and just find the average value, report the average with the precision of the measurement with the least s.f.**

If you round off your result by regarding the s.f. of the sum, realize that the precision can increase indefinately when you increase the number of measurements.

6.21	m	
6.18	m	
6.25	m	} 5
6.21	m	
+ 6.23	m	
31.08	m	

$$\frac{31.08 \text{ m}}{5} = 6.216 \text{ m} \quad ✗$$
$$= 6.22 \text{ m}$$

6.22	m	
6.19	m	
6.21	m	} 20
⋮		
+ 6.25	m	
124.15	m	

$$\frac{124.15 \text{ m}}{20} = 6.2075 \text{ m} \quad ✗$$
$$= 6.21 \text{ m}$$

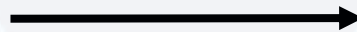|		
6.19	m	
6.24	m	
6.22	m	} 200
⋮		
+ 6.17	m	
1241.67	m	

$$\frac{1241.67 \text{ m}}{200} = 6.20835 \text{ m} \quad ✗$$
$$= 6.21 \text{ m}$$

Calculations with Significant Figures

Multiplication and Division (M&D) (also valid for powers and roots)

The number of significant figures in the result is equal to the least significant figure of a measurement within the operation.

12.1 cm ➡ 3 sf

✕ 4.0 cm ➡ 2 sf

48.4 cm² ➡ 48 cm²

➡

12.1? cm

✕ 4.0? cm

.????

0.000

+ 48.4?

48.???? cm²

➡ 48 cm²

Calculations with Significant Figures

Logarithm

$$\text{Log} (1.71 \times 10^1) = 1.233$$

mantissa (the part after the decimal point: 233)

characteristic (the part before the decimal point: 1)

The part of a logarithm after the decimal point is called *mantissa*, while the part before the decimal point is called *characteristic*.

When taking the logarithm of a number, the **mantissa** of the logarithm should have **the same number of significant figures as the number** whose log is being taken.

The **characteristic** of a logarithm indicates the exponent when the number is expressed as a **power of ten**.

$$\log 2.53 = \log (2.53 \times 10^0) = 0.403$$

$$\log 25.3 = \log (2.53 \times 10^1) = 1.403$$

$$\log 253 = \log (2.53 \times 10^2) = 2.403$$

$$\log 253.3 = \log (2.533 \times 10^2) = 2.4036$$

$$\log 253.34 = \log (2.5334 \times 10^2) = 2.40370$$

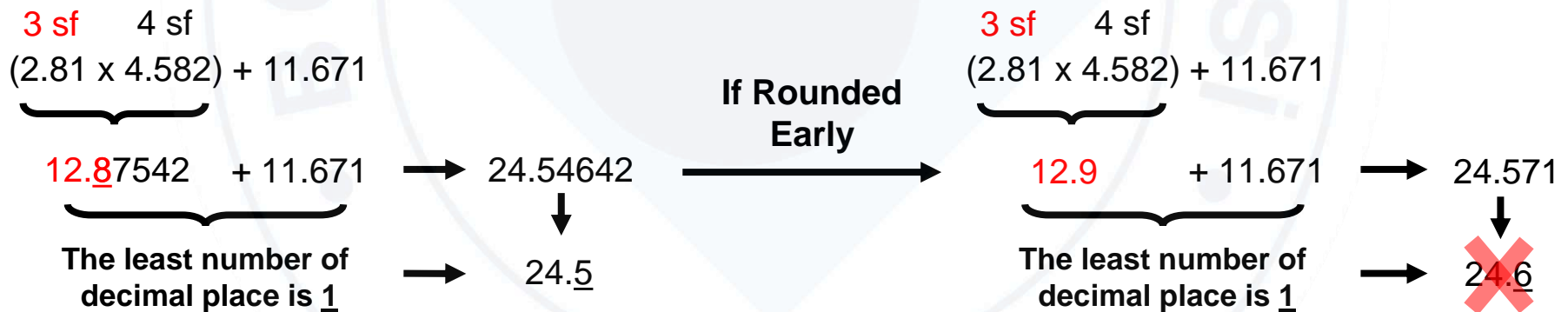**BOĞAZİÇİ UNIVERSITY**
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Calculations with Significant Figures

Mixed Operations

The previous rules for A&S and M&D still apply, but order of operations should additionally be taken into account. It is as follows:

Parentheses, **E**xponents, **M**ultiplication, **D**ivision, **A**ddition, and **S**ubtraction
(**P**lease **E**xcuse **M**y **D**ear **A**unt **S**ally)

While applying rules according to the order of operations, keep a track of what the limiting significant figure is in each step without rounding in intermediate steps.

3 sf   4 sf
(2.81 x 4.582) + 11.671

12.8̲7542   + 11.671 → 24.54642

The least number of decimal place is 1̲ → 24.5̲

If Rounded Early

3 sf   4 sf
(2.81 x 4.582) + 11.671

12.9   + 11.671 → 24.571

The least number of decimal place is 1̲ → ❌ 24.6̲

__Keep in mind that you should always round off your result at the end of your calculations.__

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Dimensions and Units

Dimensions and Units

A dimension is a measure of a physical quantity without numerical values, while a unit is the way of assigning a value to that dimension.

Whereas a physical quantity has one type of dimension, it may have more than one unit.

DIMENSION	VALUE
Length	7 meters = 700 centimeters = 7×10^{-3} kilometer
Mass	5 kilograms = 5×10^3 grams
Time	1 hour = 60 minutes = 3600 seconds

Dimensions and Units

- **In physics, there are 7 base or fundamental quantities.**

- **The rest of the physical quantities are called derived quantities and expressed in terms of the base quantities.**

- **The following table shows these 7 base quantities. The orange ones are the base quantities you will encounter in the introductory physics labs.**

Base Quantity	Dimension	International System of Units (SI Units)	Unit Symbol
Length	L	Meter	m
Mass	M	Kilogram	kg
Time	T	Second	s
Electric current	I	Ampere	A
Absolute Temperature	Θ	Kelvin	K
Amount of substance	N	Mole	mol
Luminous intensity	J	Candela	cd

Dimensions and Units

Dimensional analysis is the way of expressing the dimension of a derived quantity as a product of the dimensions of the base quantities.

Examples:

DERIVED QUANTITY	DIMENSION
Velocity	Length / Time = L / T = L T^{-1}
Frequency	1 / Time = 1 / T = T^{-1}
Density	Mass / (Length)^3 = M / L^3 = M L^{-3}

Dimensional Analysis

More examples:

Dimension of force

To find its dimension what we need is a force formula. We know that

$F = m\ a$ where F, m and a are force, mass and acceleration respectively. So,

$[F] = M \times L\ /\ T^2 = M\ L\ T^{-2}$.

Dimensional Analysis

More examples:

Dimension of energy

Although it does not matter which energy formula is chosen, let's take kinetic energy formula into consideration first. Then we can also consider the potential energy and can check that their dimensions are really the same as stated.

The kinetic energy is given by $E_k = \frac{1}{2} m v^2$, so the dimension of energy is

$[E] = M \times (L / T)^2 = M L^2 T^{-2}$.

The potential energy is given by $E_p = m g h$, so the dimension of energy is

$[E] = M \times L/T^2 \times L = M L^2 T^{-2}$.

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Why is the dimensional analysis important?

Let's say you are confused with the formula for the period of simple harmonic motion and can't remember its correct form. Was it T=2$\pi\sqrt{g/L}$ or T=2$\pi\sqrt{L/g}$?

How to figure it out?

We know that

the period T must have the dimension of time that is T ,

the length of the pendulum L has the dimension of length that is L ,

the gravitational acceleration g has the dimension of acceleration that is L T^{-2}

and 2π is a dimensionless constant. So,

$$[T] = [2\pi\sqrt{g/L}] = (L^{1/2}\,T^{-1})\,/\,L^{1/2} = T^{-1} \qquad\qquad [T] = [2\pi\sqrt{L/g}] = L^{1/2}\,/\,(L^{1/2}\,T^{-1}) = T$$

incorrect **correct**

Unit Systems

MKS

M for meter

K for kilogram

S for second

CGS

C for centimeter

G for gram

S for second

Examples:

Force:

5 Newton = 5 kg m s^{-2}

5×10^5 dyne = 5×10^5 g cm s^{-2}

Energy:

7 Joule = 7 kg m^2 s^{-2}

7×10^7 erg = 7×10^7 g cm^2 s^{-2}

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Plotting a Graph

Plotting a Graph

Graph plotting enables us to see what kind of relation exists between two physical quantities in an experimental setup. So, in order to see that relation we need to

- **collect data by doing the experiment,**

- **mark data on a graph paper,**

- **draw best fit line or curve based on the trend presented by data points,**

- **analyse the line or the curve.**

Collecting Data

Let's say in order to find the velocity of a car (i.e. the relation between the position and the time),

- **we have done an experiment**

- **and collected the data for the position of a car at successive time intervals as in the table below.**

Time: t (second)	Position: x (meter)
0.00	1.2
0.10	1.6
0.20	1.9
0.30	1.8
0.40	2.5
0.50	2.9
0.60	3.4
0.70	3.6

Marking Data Points

Since we will draw position vs time graph, we should

- **label the axes and write the units accordingly,**

- **scale the axes based on the data range and the resolution of the data points (while the position data has 0.1 meter resolution, the time data has 0.01 second resolution in our case),**

- **mark the data points.**

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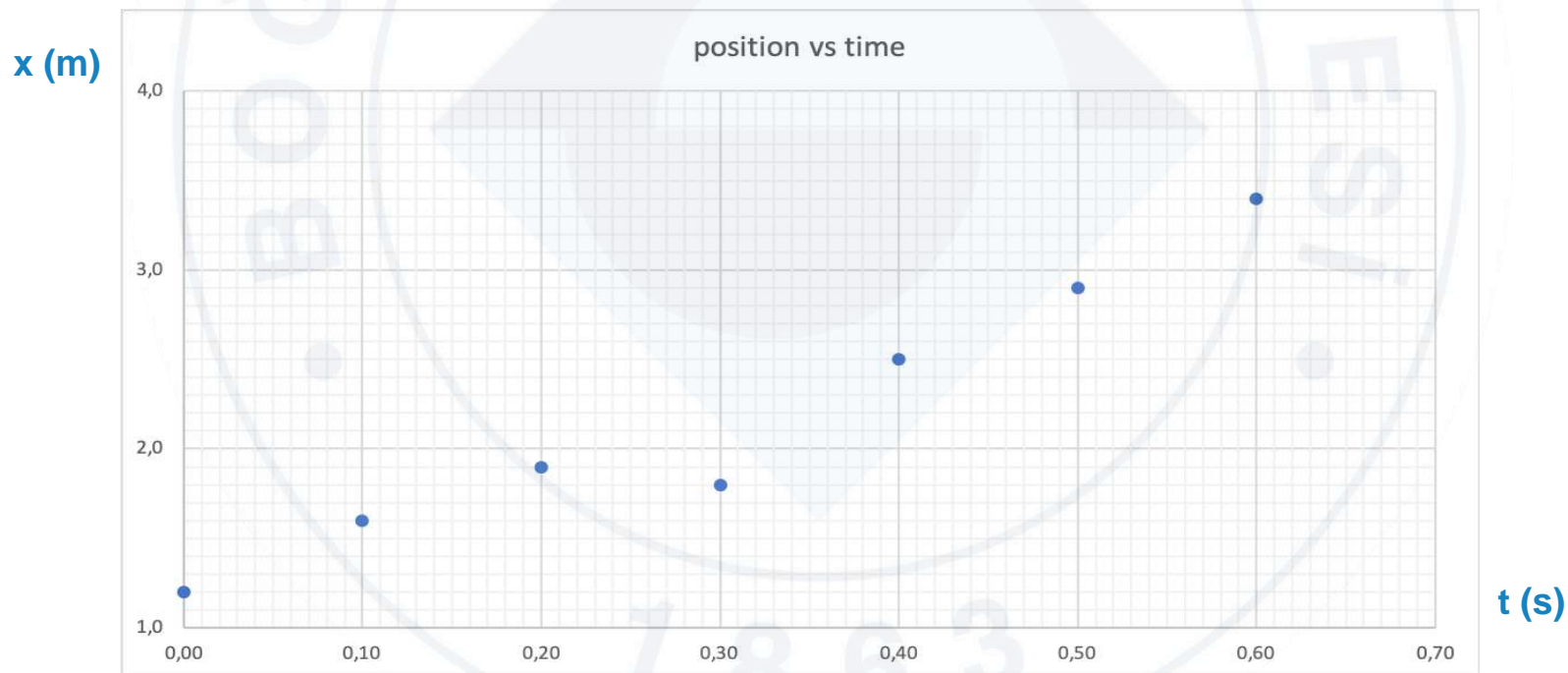
Drawing Best-fit Line

How to draw the best-fit line

- Before drawing the line or the curve, we should consider the distribution of the data points to decide the trend between two physical quantities.

- In our case, based on the data it is obvious that there is a linear relation betwen the position and the time.

- So, we should draw a best-fit line as below, not a curve!

Keep in your mind that since the experimental error is always present and inevitable, our best-fit line does not necessarily have to pass through all data points.

Drawing Best-fit Line

Wrong way of drawing the best-fit line

Do not connect your data points by making zigzag as below !!! Instead, use a ruler to draw a straight line.

WRONG!!!

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Analysing the Best-fit Line : Slope

Once we draw the best-fit line, we accept that the most accurate position values for every time coordinate lie along that line. Thus, we should forget about the data points and focus on the best-fit line.

Since we are looking for the velocity of the car which is, by definition, the change in the position in unit time, we should calculate the slope of the best-fit line which is equal to the velocity in our case.

- **Select two slope points on the best-fit line.**

- **Determine the X and Y coordinates of these two slope points.**

$$\text{Slope} = \frac{|Y2-Y1|}{|X2-X1|}$$
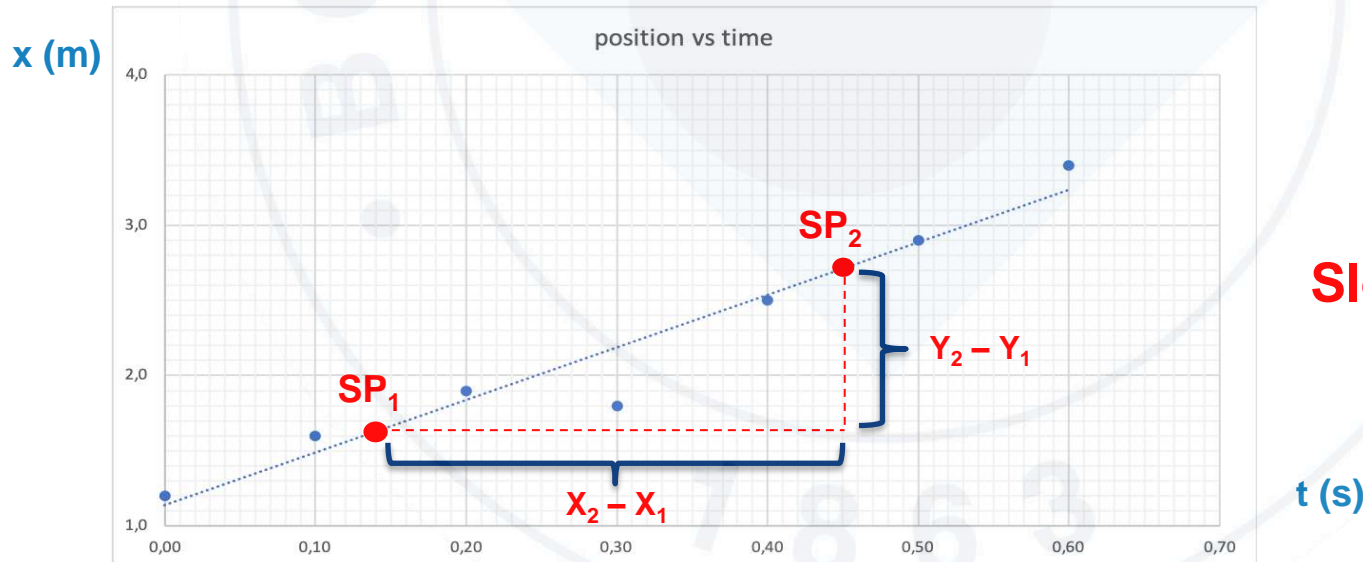
APPENDIX

for PHYL102

METER STICK (with Jaws):

For all kinds of length measurements, one may take advantage of using metal jaws attached to a meter stick for a more precise measurement.

How to measure the inner diameter of a ring:

- Attach the metal jaws to the meter stick in such a manner that the unangled sides of the jaws stay outside as in the image below.

- Make the measurement and read the values at the unangled sides of the jaws.

Since the unangled side of this jaw is aligned with the beginning of the meter stick, it is enough to read the value only for the other jaw.

Read here.

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METER STICK (with Jaws):

How to measure the outer diameter of a ring:

- **Attach the metal jaws to the meter stick in such a manner that the unangled sides of the jaws stay inside as in the image below.**

- **Make the measurement and read the values at the unangled sides of the jaws and take the difference.**

Read these two values and take the difference.

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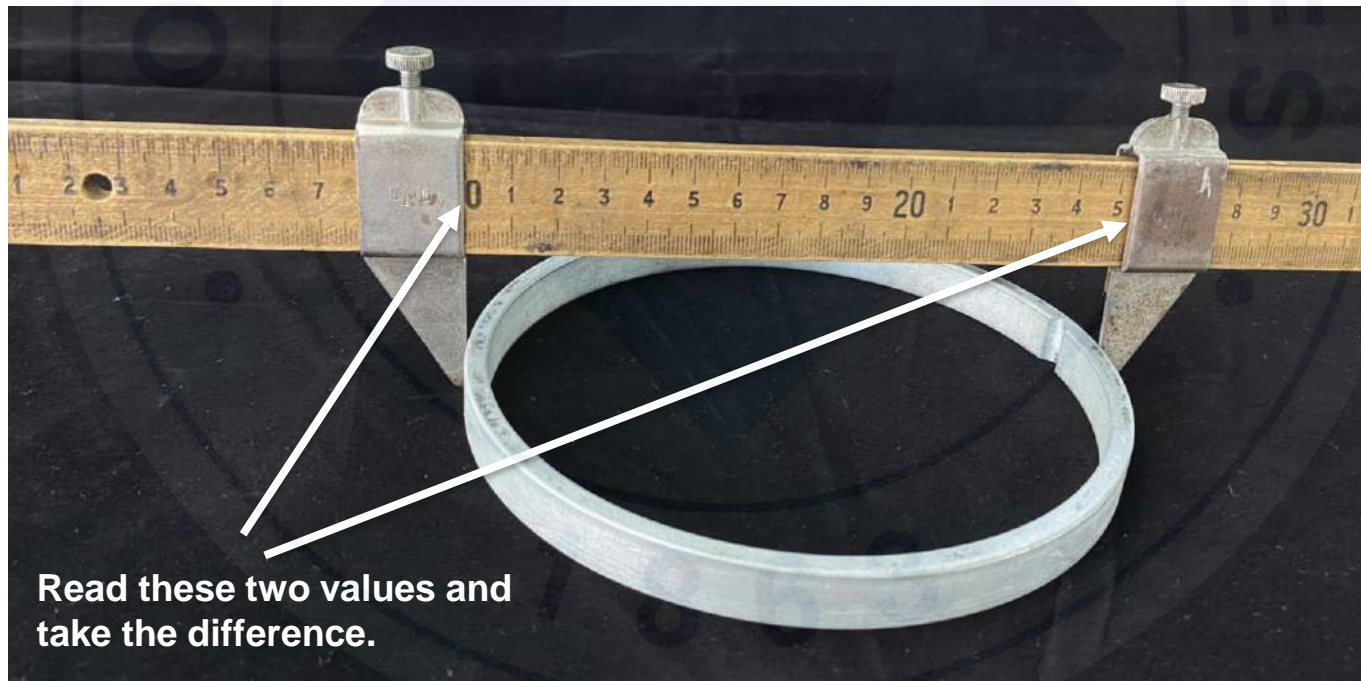
VERNIER CALIPER:

A vernier caliper is a length measurement tool that allows us to measure up to 0.01 cm precision.

jaws for measuring inner dimensions
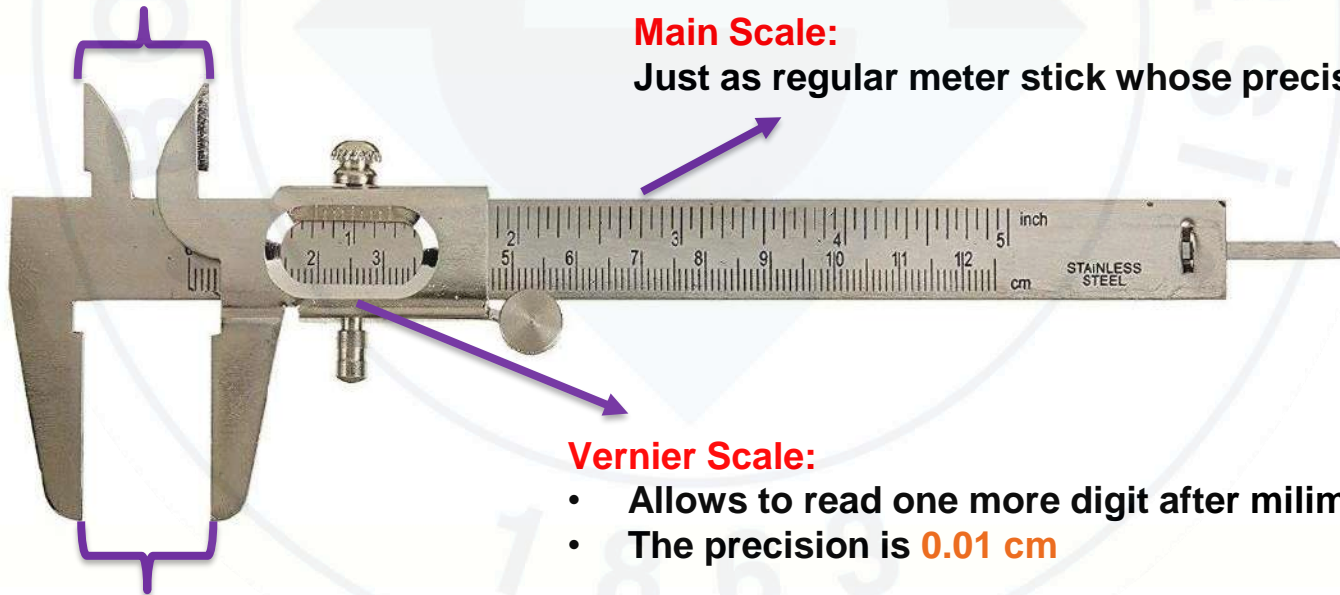
Main Scale:
Just as regular meter stick whose precision is 0.1 cm

Vernier Scale:
- **Allows to read one more digit after milimeter**
- **The precision is 0.01 cm**

jaws for measuring outer dimensions

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VERNIER CALIPER

jaws for measuring inner dimensions →

jaws for measuring outer dimensions →

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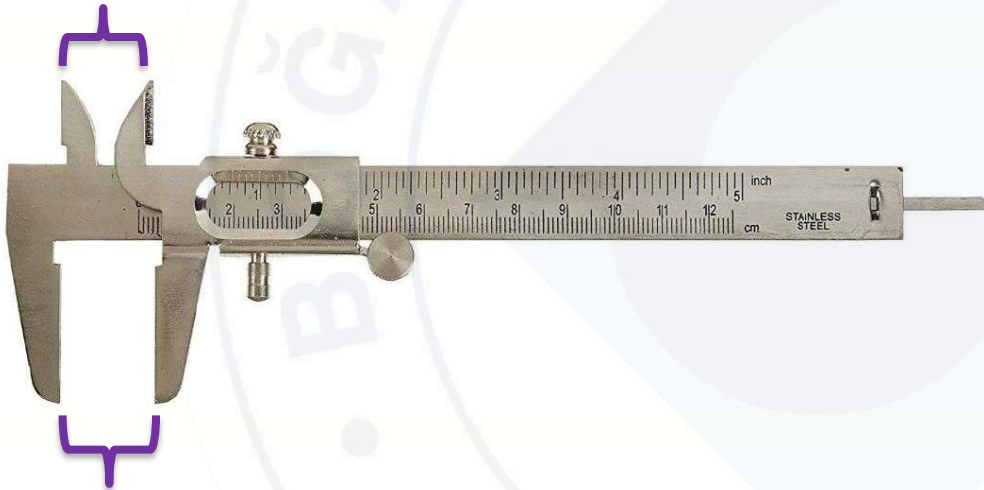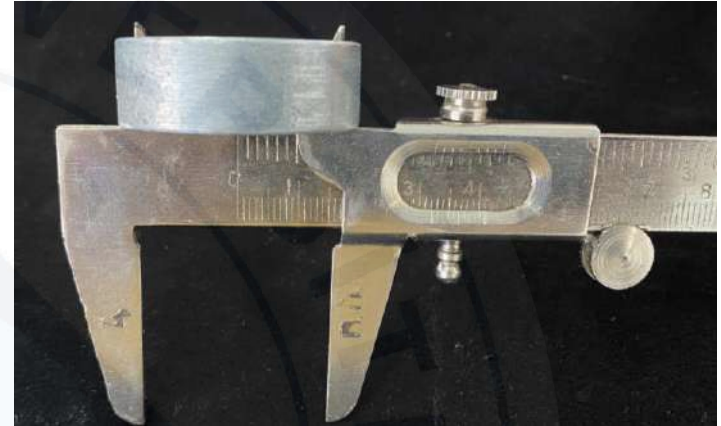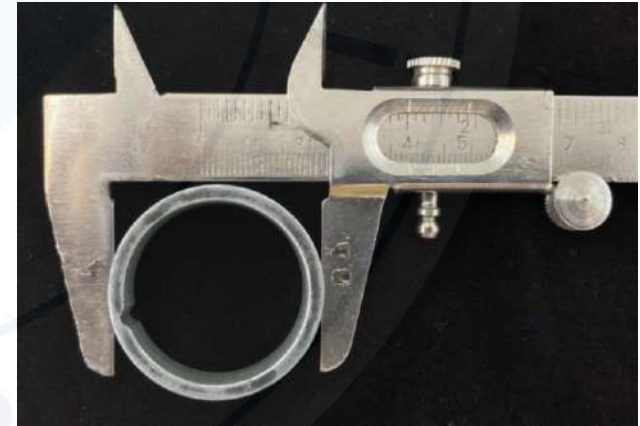
VERNIER CALIPER:

How to measure with a vernier caliper:

If a vernier caliper output a measurement reading of **2.13 cm**, this means that:

- **The main scale contributes the main number(s) and one decimal place to the reading (E.g. 2.1 cm, whereby 2 is the main number and 0.1 is the one decimal place number)**

- **The vernier scale contributes the second decimal place to the reading (E.g. 0.03 cm). Look at the image below and look closely for an alignment of the scale lines of the main scale and vernier scale. The aligned line corresponds to 3.**

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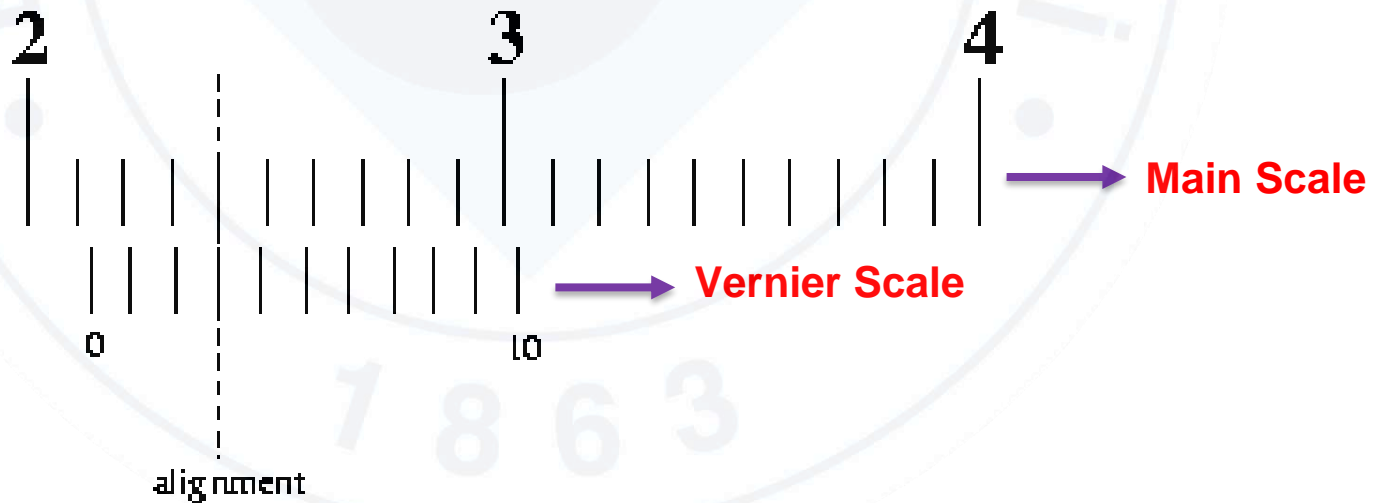
VERNIER CALIPER
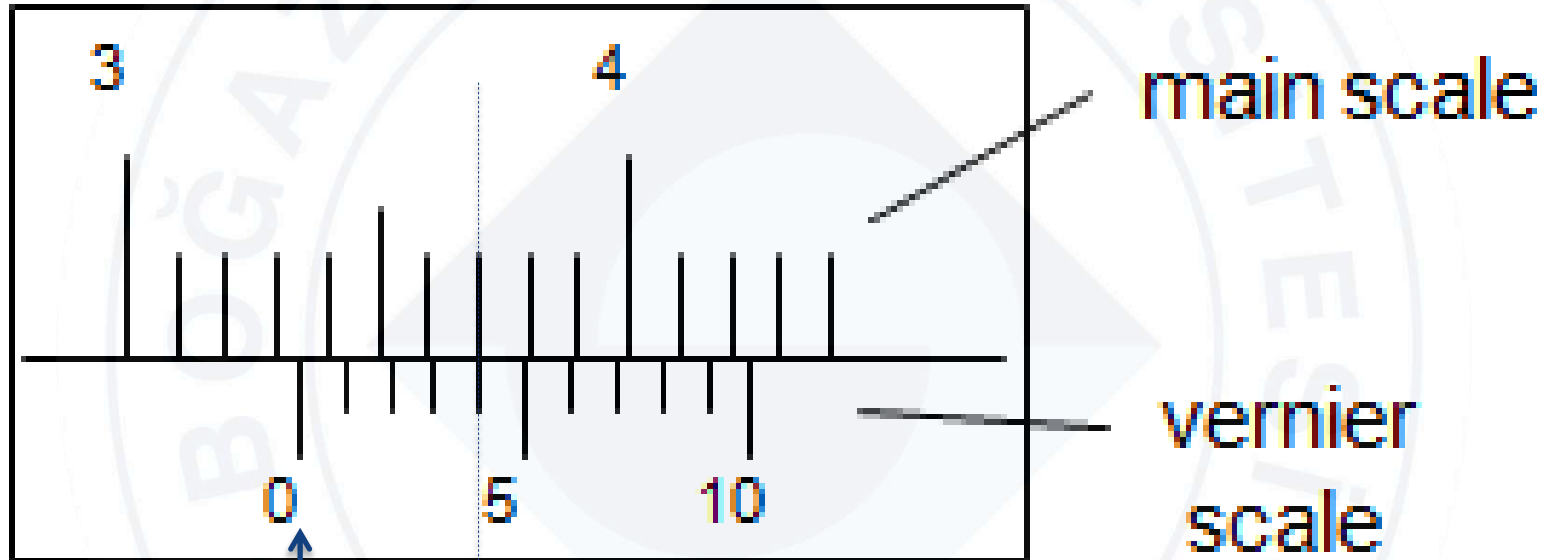
Example:

Main number: 3
One decimal: 3
3.3

The aligned line
corresponds to 4.
0.04

RESULT: 3.34 cm

VERNIER CALIPER

Example:

Main number: 10
One decimal: 0
10.0

The aligned line corresponds to 2.
0.02

RESULT: 10.02 cm
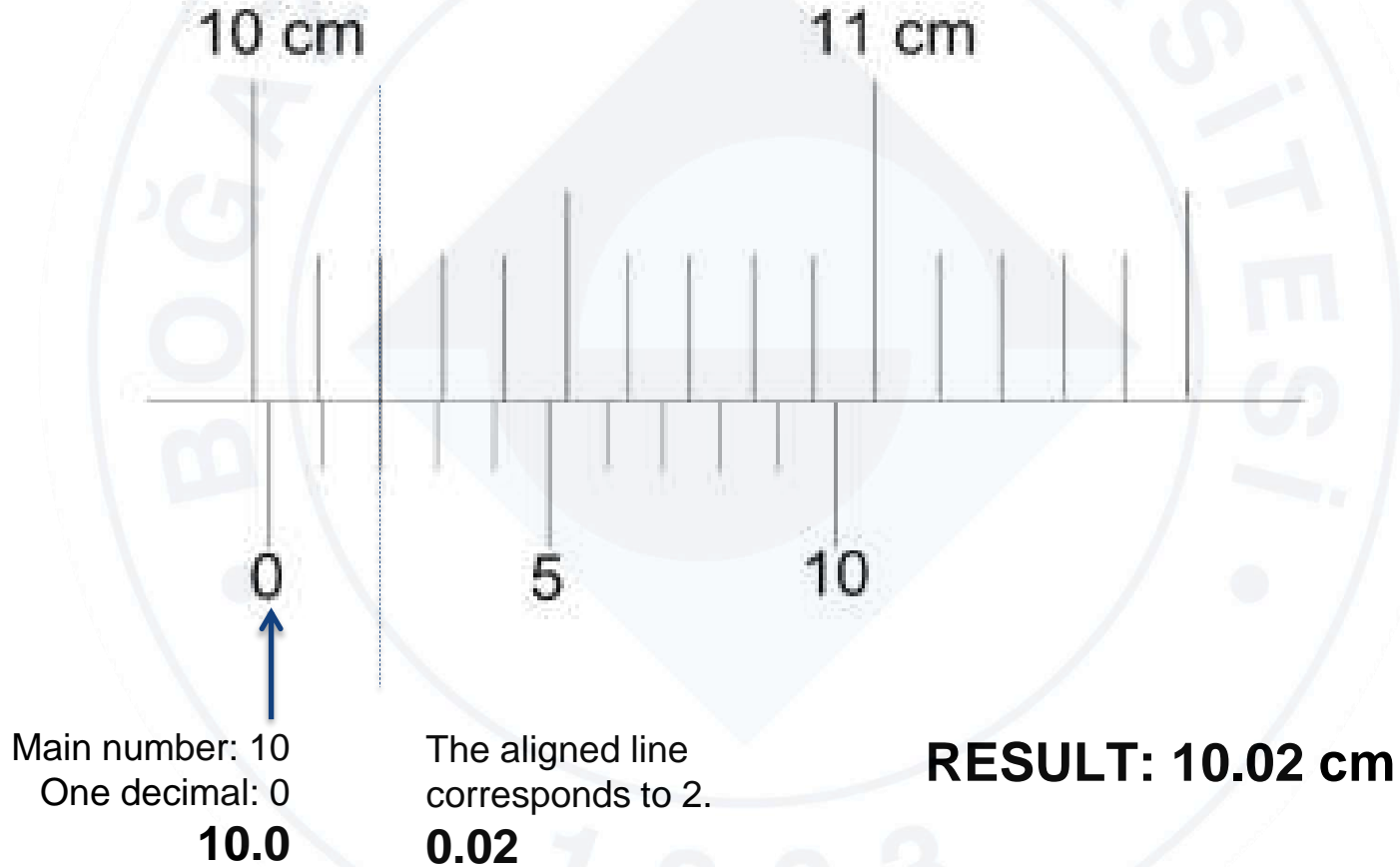
VERNIER CALIPER

Example:
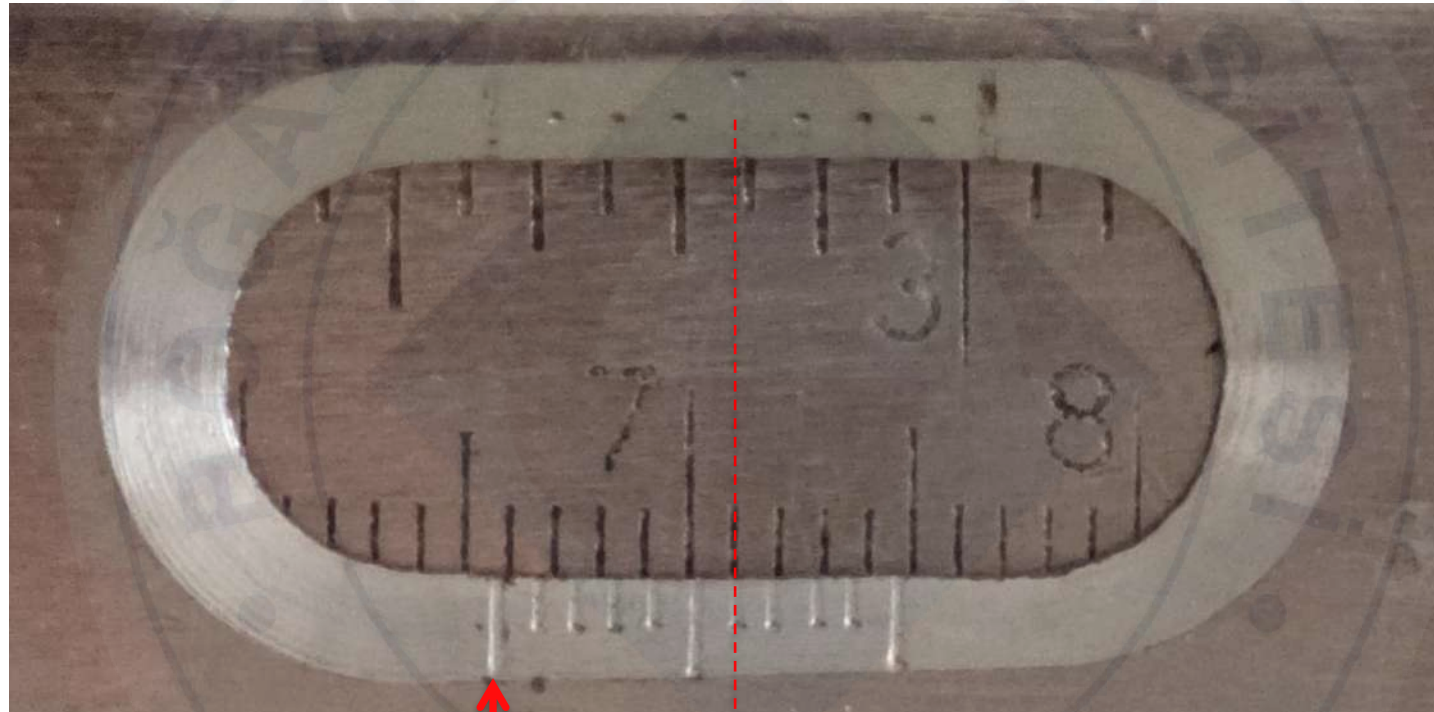
Main number: 6
One decimal: 5
6.5

The aligned line corresponds to 6.
0.06

RESULT: 6.56 cm

PROTRACTOR: A tool to measure the angle between two lines which intersect.

How to use a protractor to measure an angle:

- **Place the vertex of the intersected lines at the mid-point of the protractor.**

- **By rotating the protractor about the mid-point, align one of the lines with the zero angle line of the protractor.**

- **Read the angle value that the other line crosses.**
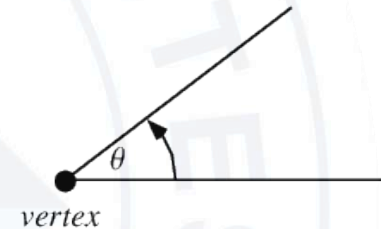
Examples:
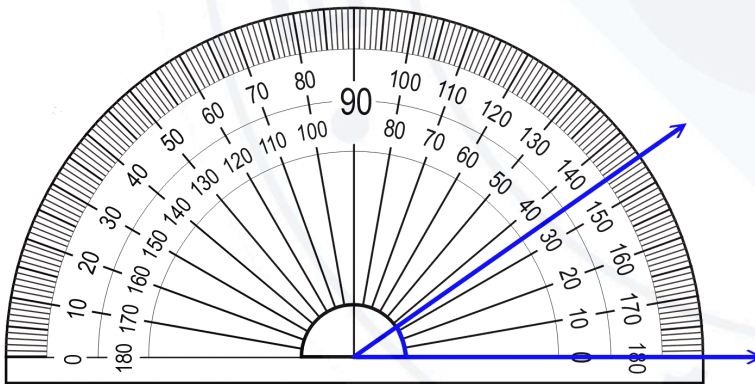
Since the angle goes in counter-clockwise direction, look at the inner scale.
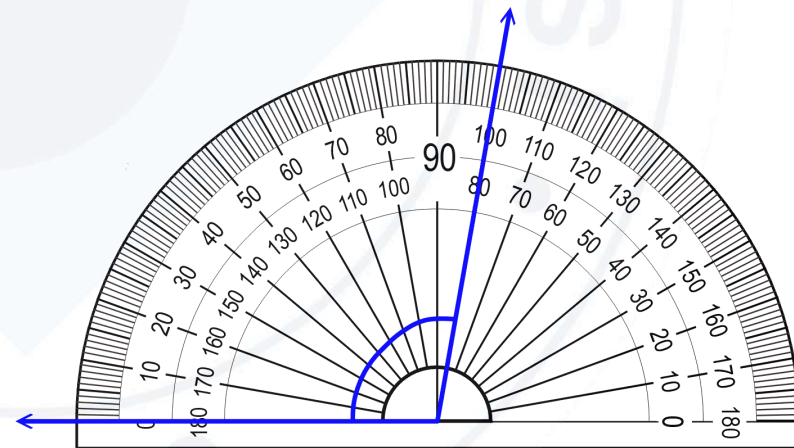
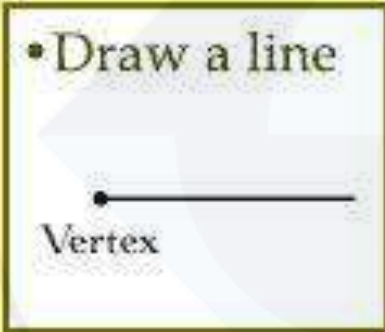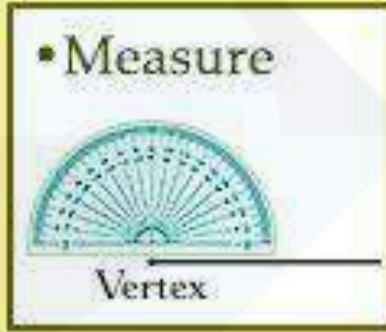Since the angle goes in clockwise direction, look at the outer scale.

PROTRACTOR:

How to use a protractor to draw an angle:

Example: **Let's say you want to draw a 40 degree angle**