NUST

SCHOOL OF ELECTRICAL ENGINEERING & COMPUTER SCIENCE

- Course: **EE383 Instrumentation and Measurements**
- Session: Fall 2022
- **Lectures: Week 2**
- Course Instructor: Dr. Shahzad Younis

INSTRUMENTATION
& MEASUREMENT

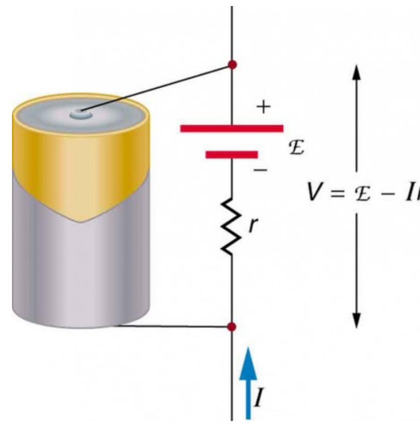
Week 2

- **Chapter 2**

  Static Characteristics of Instruments

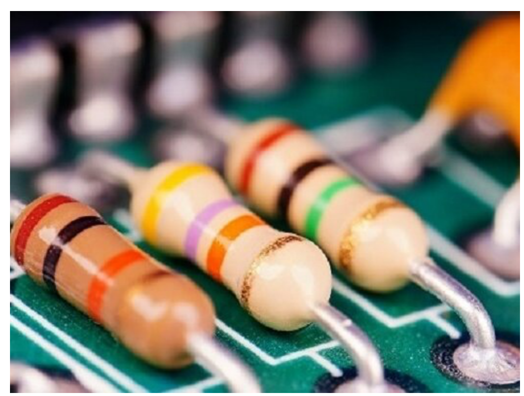
Static Characteristics Of Instrument?

- The attributes of an instrument which are constant or vary very slowly with time.



→EMF of a battery

→Resistance of a resistor (at constant temp.)



What are the Static Characteristics of Instrument?

Magnification.

Scale Interval.

Readability.

Calibration.

Repeatability.

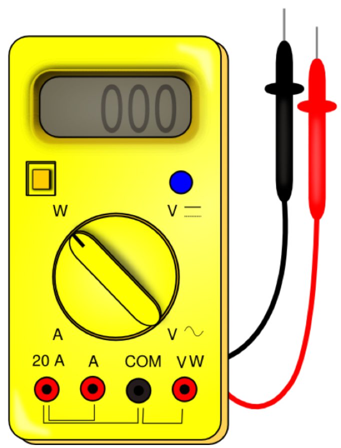
Discrimination.

Precision.

Accuracy.

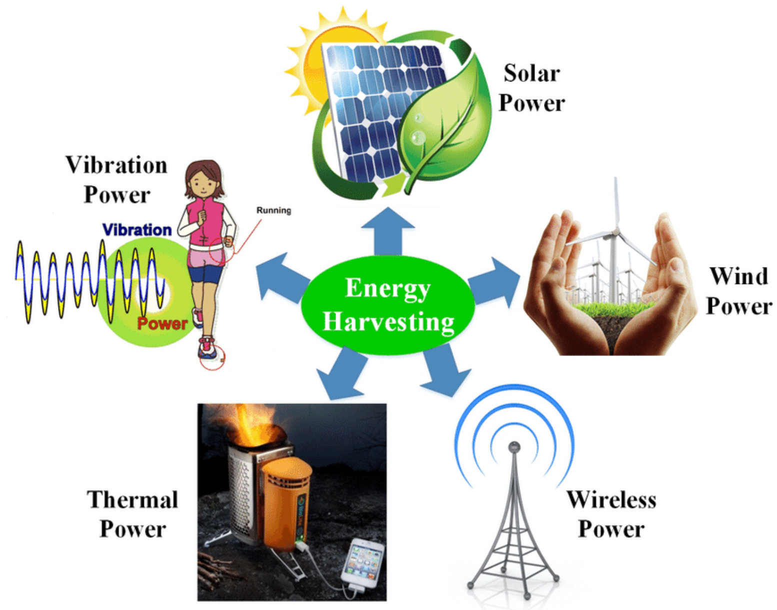
Static Characteristics Of Instrument

❑ **Choice of an instrument for a particular application**



Electrometer: voltage and current measurements

✓ **Range, operating conditions,…**



N. Zhao et al., Exploiting Interference for Energy Harvesting: A Survey, Research Issues and Challenges, IEEE Access, Vol. 5, 2017

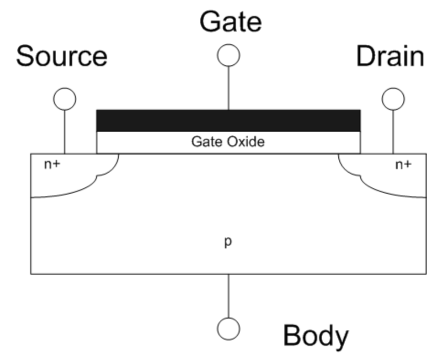
Static Characteristics Of Instrument

- **Choice of an instrument for a particular application**

Thermal camera: Temperature measurement

- ✓ **Hot-spot detection**
- ✓ **Range, resolution…**

PCB



MOSFET

Static Characteristics Of Instrument

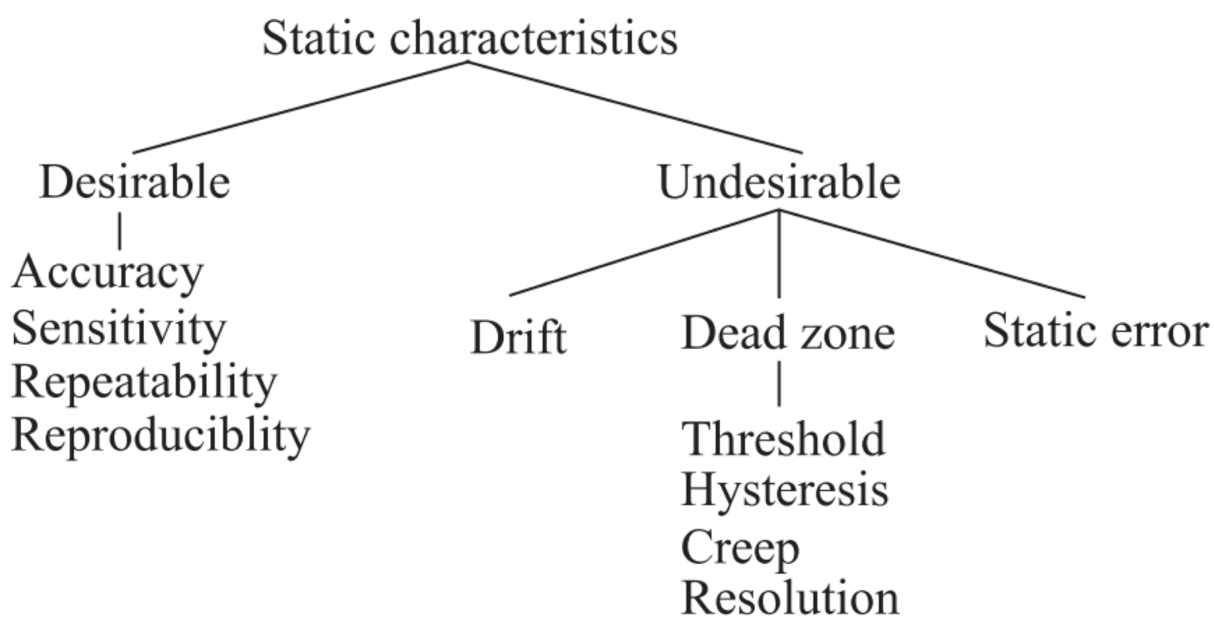
- **Choice of an instrument for a particular application**
- **Temperature measurement**
  - **An accuracy of $\pm$0.5℃ may not be crucial for the temperature regulation in a room**
  - **An accuracy of $\pm$0.5℃ may be crucial for a chemical process**

Static Characteristics Of Instrument

- Choice of an instrument for a particular application
- Temperature measurement
  - An accuracy of $\pm 0.5^{\circ}C$ may not be crucial for the temperature regulation in a room
  - An accuracy of $\pm 0.5^{\circ}C$ may be crucial for a chemical process
- Accuracy is one consideration
- Other parameters: sensitivity, linearity etc. are further considerations

Static Characteristics Of Instrument

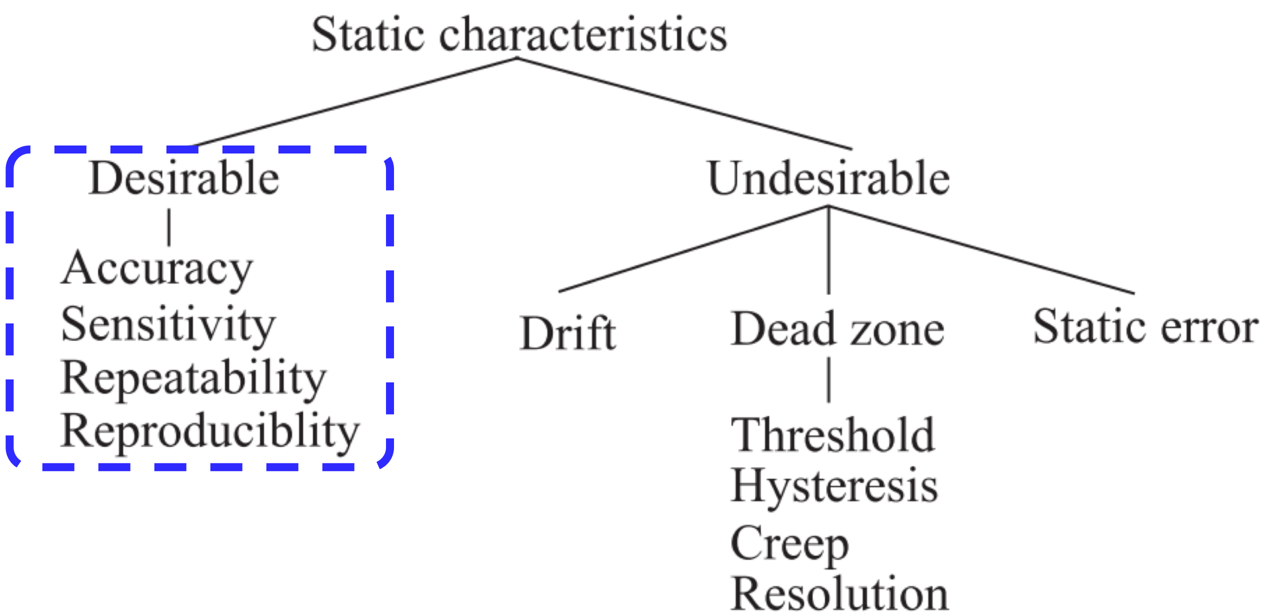
- **Characteristics relating the steady-state (achieved) of an instrument**
- **Measurement of quantities which are constant or vary very slowly with time**
- ***Example: EMF, resistance at constant T***



Ch. 2: Introduction to Measurements and Instrumentation, Arun K. Ghosh

Static Characteristics Of Instrument

- **Characteristics relating the steady-state (achieved) of an instrument**



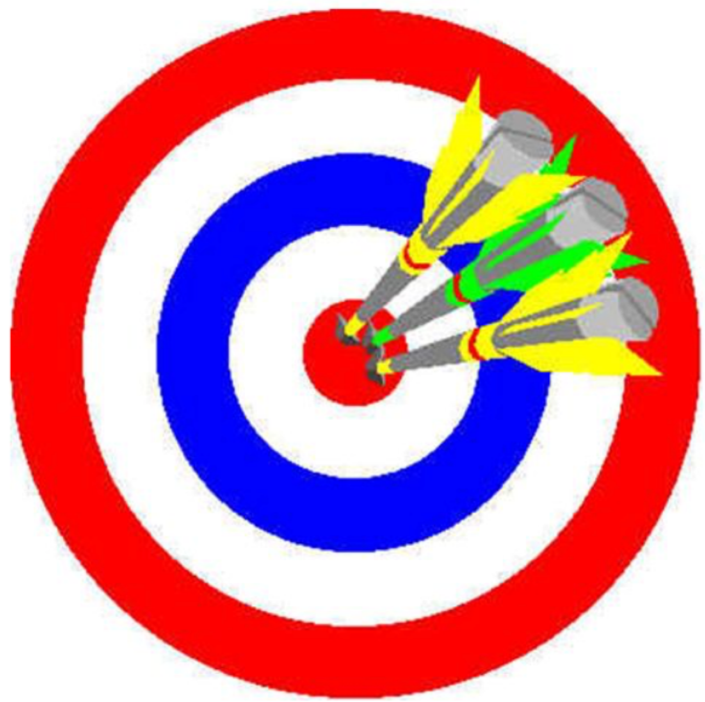
Desirable Characteristics

- Accuracy
  - Precision
  - Significant figures
- Sensitivity
  - Linearity & Non linearity
- Repeatability
- Reproducibility

Accuracy

❑ **Measure of closeness of the output reading of an instrument to the true value of the measurand**

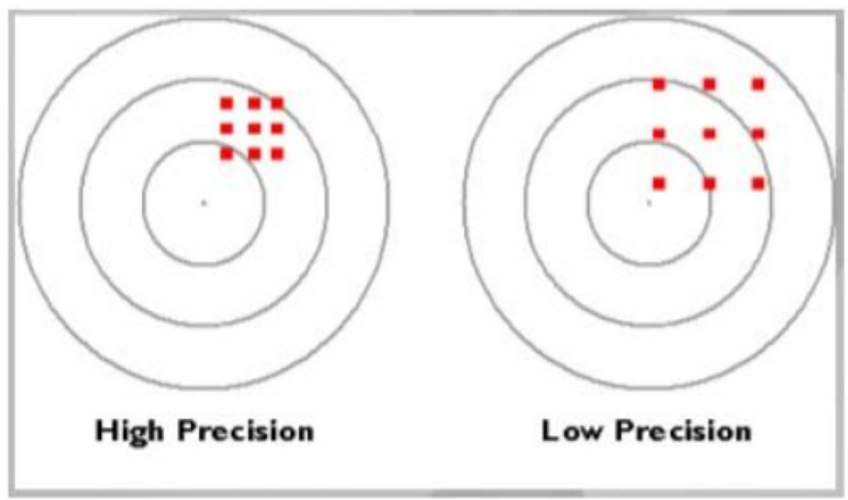
- When doing an experiment we want to find the true value
- This is an accurate value



Precision

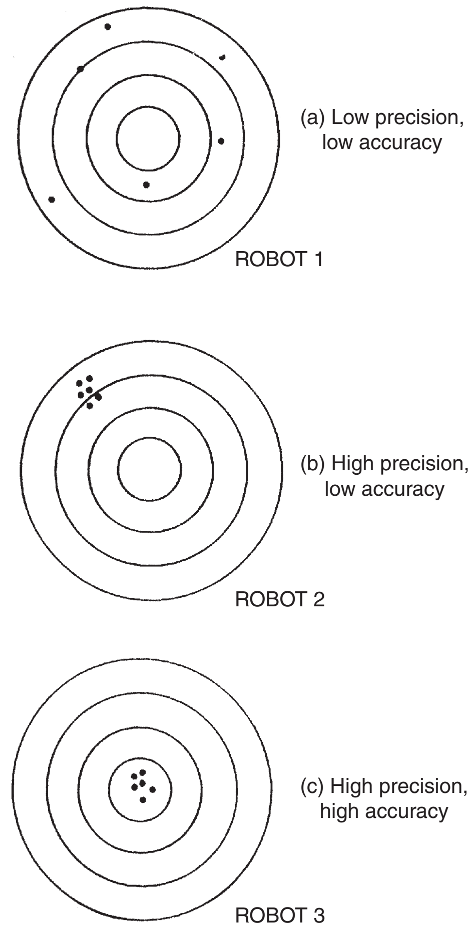
- How close are the measured values to each other

It is the ability of a measuring instrument to give identical responses for repeated applications of the same value of the measured quantity under the same conditions of use.

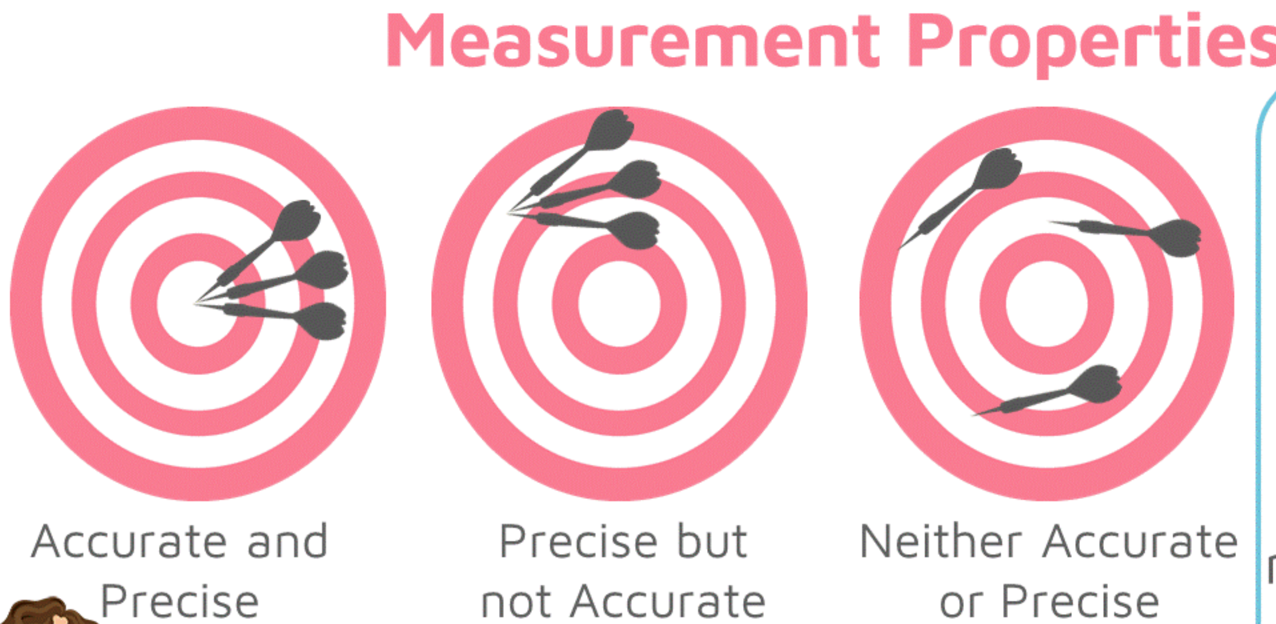


Comparison of Accuracy and Precision?

❑ **Example: Three industrial robots programmed to place components at a particular point on a table**



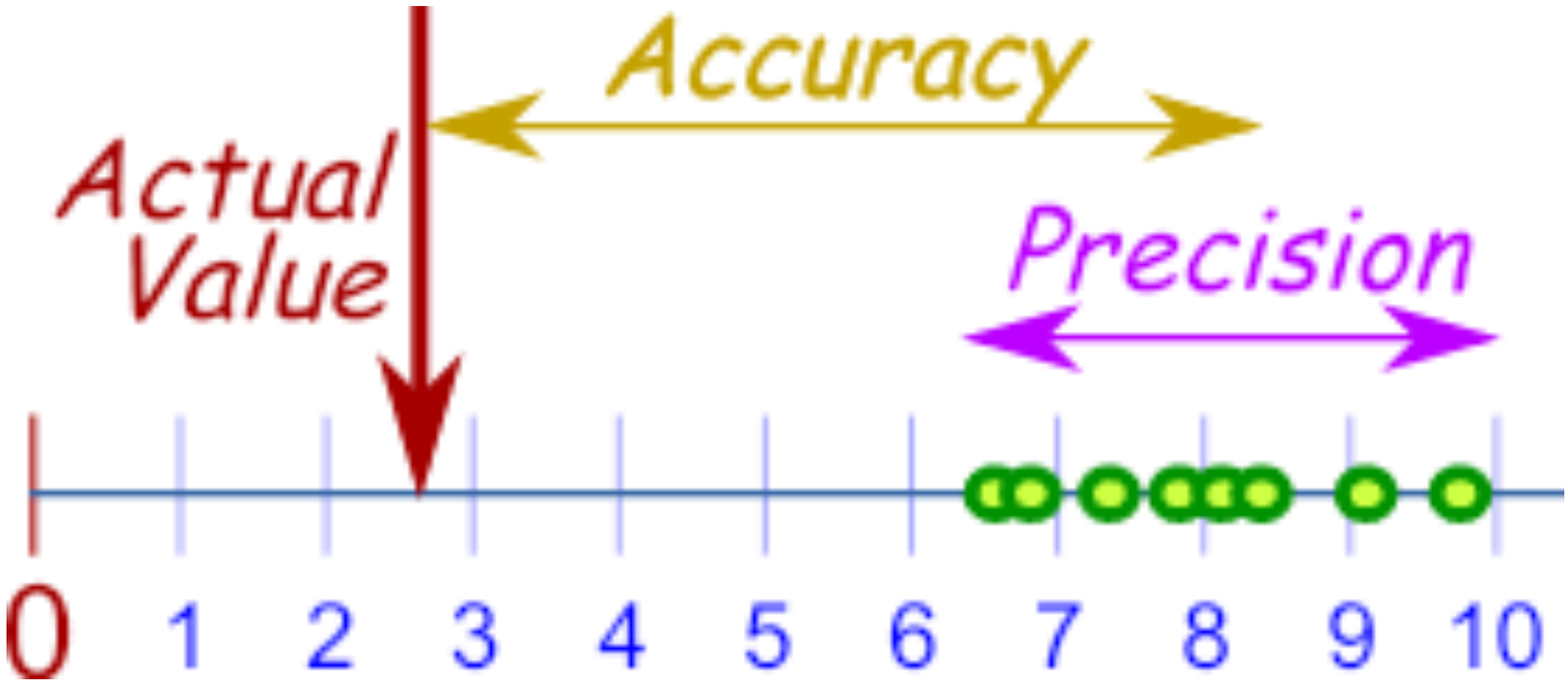
Accuracy and Precision



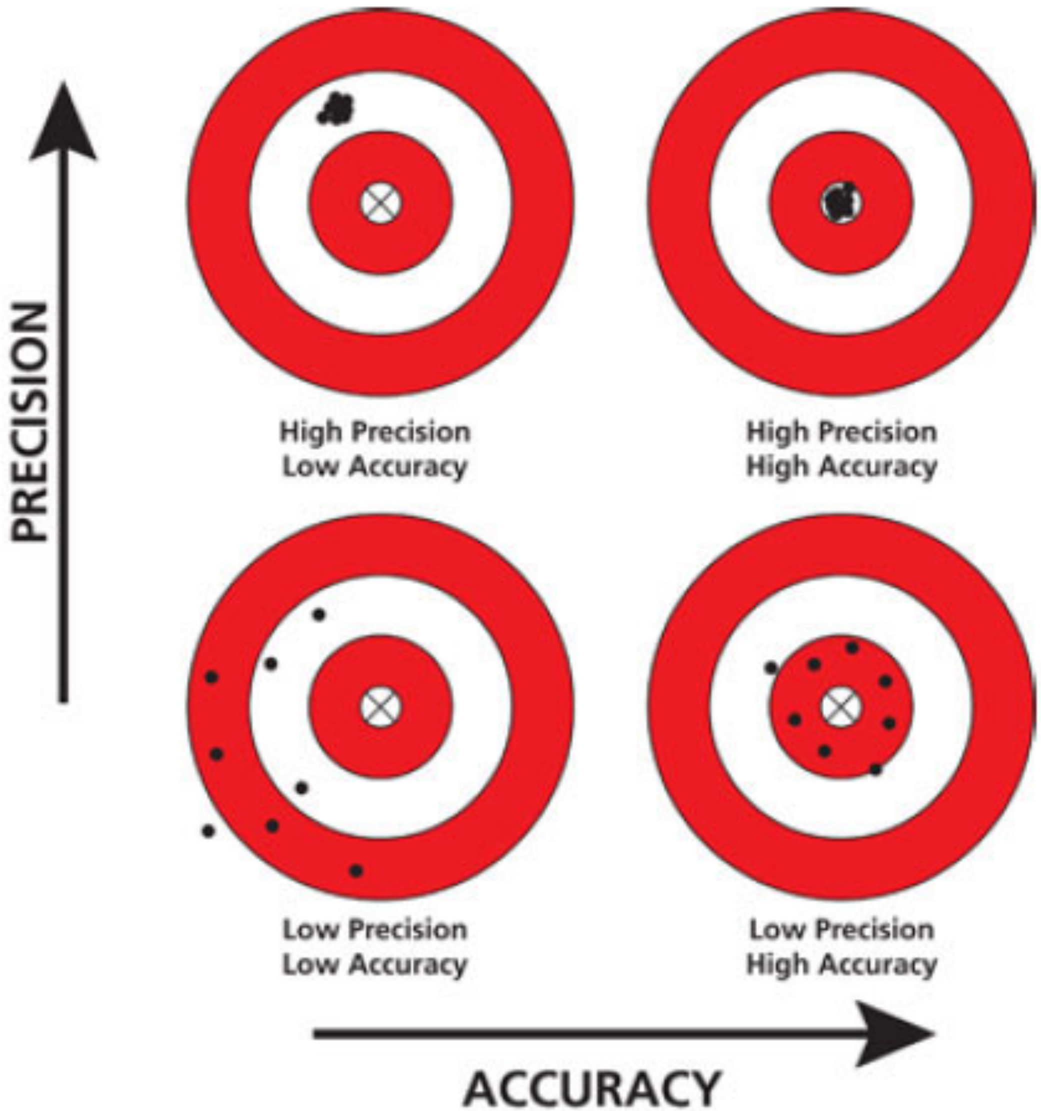
Accurate: Close to the true value.

Precise: Several measurements are close together.

Accuracy and Precision



Accuracy and Precision



Concept Checks

Concept Checks

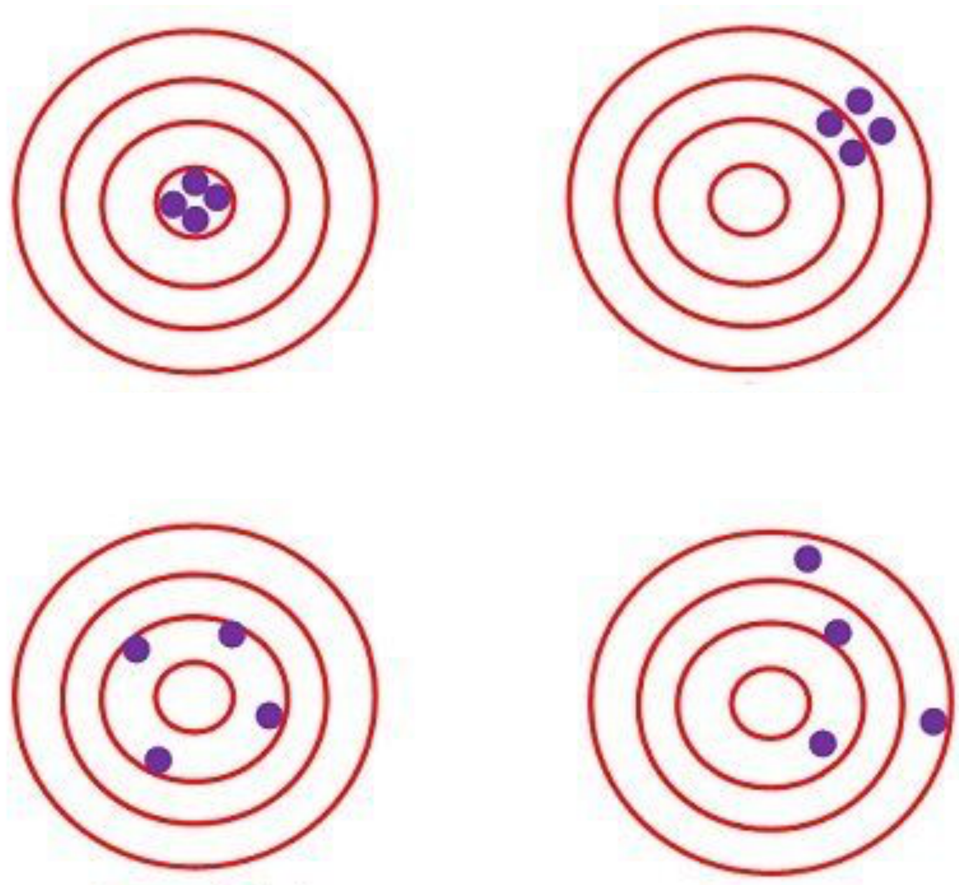
GOOD ACCURACY
GOOD PRECISION

Concept Checks

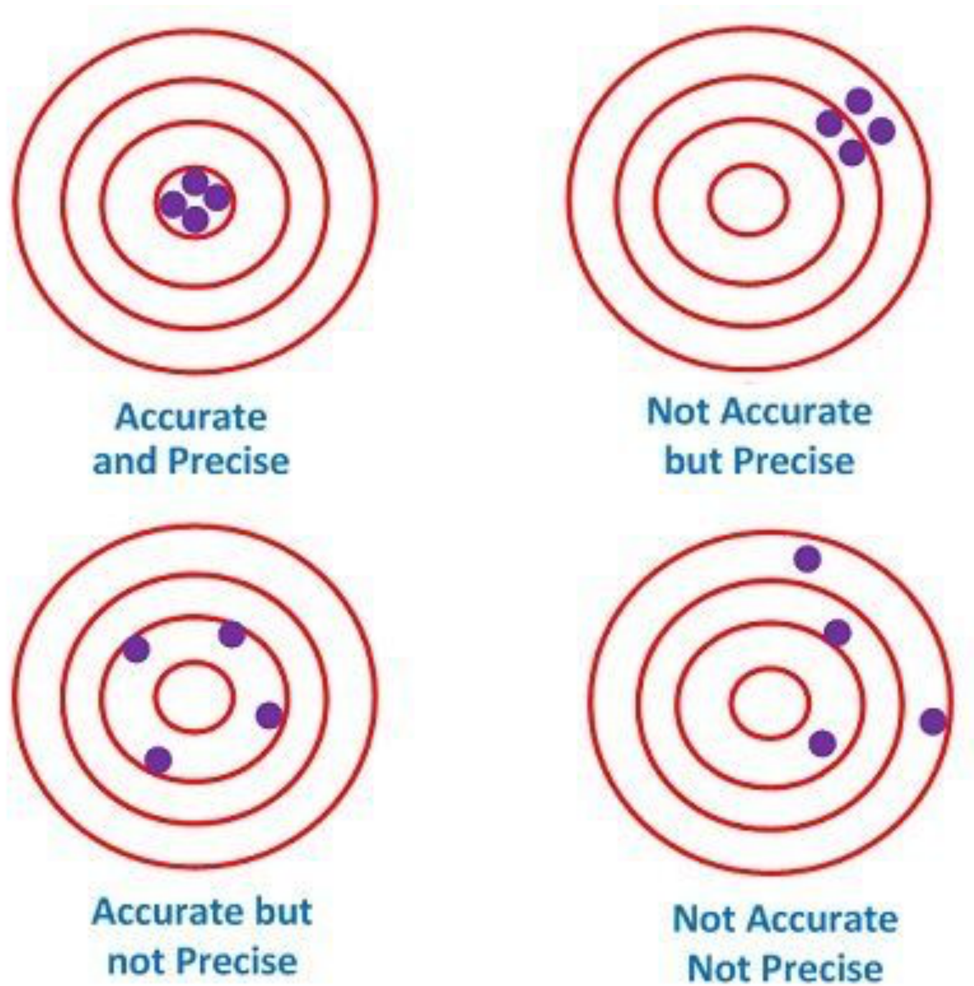
Concept Checks

POOR ACCURACY
POOR PRECISION

Concept Checks



Concept Checks



Accuracy, precision and calibration error

- **Example**
  - **True value: 200V**
  - **Voltmeter readings: 204, 205, 203, 203 and 205 volts**
    - **Accuracy ~2.5%**
    - **Readings: 204 ± 1 V; the precision ~0.5%**
      - **There is a bias of 4V, to be removed by calibration**

- **If "a" denotes accuracy, "p" the precision and "c" the calibration error**

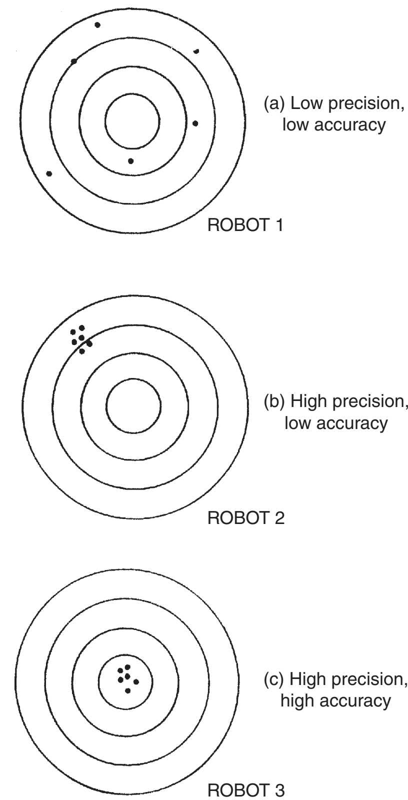
$$\boxed{a = p + c}$$

To calculate a percentage accuracy, subtract the observed value from the true value, divide by the true value, multiply by 100

Accuracy = (205-200)/200*100

Precision

- Precision does not imply measurement accuracy
- Characteristic of an instrument
  - For a high-precision instrument
    - Design and construction has to be improved



Precision

- Precision has two characteristics
  - Conformity
  - Significant figures

Conformity: It is the ability of an instrument to produce the same reading, or it is the degree of similarity between the individual measurements.

- **Depends upon number of "significant figures"**

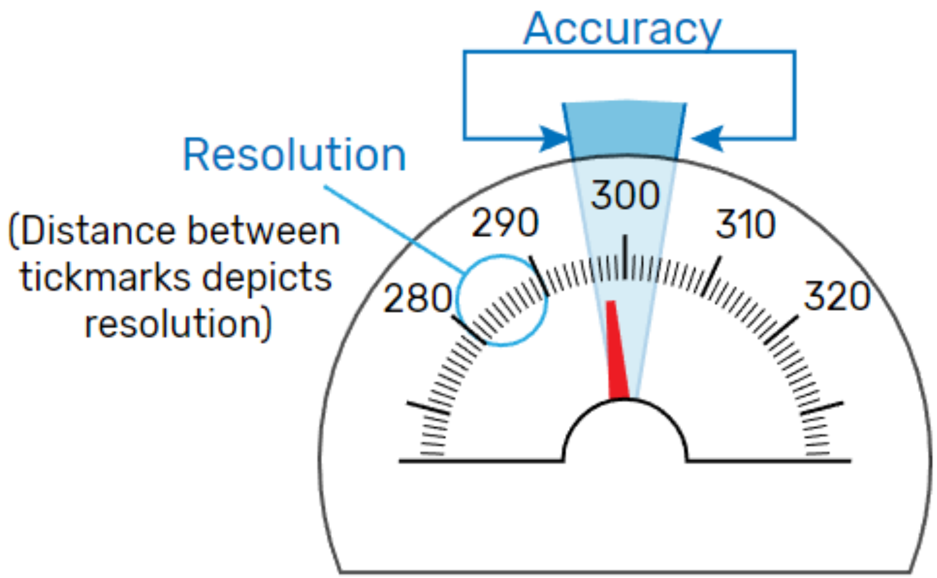
Imprecise

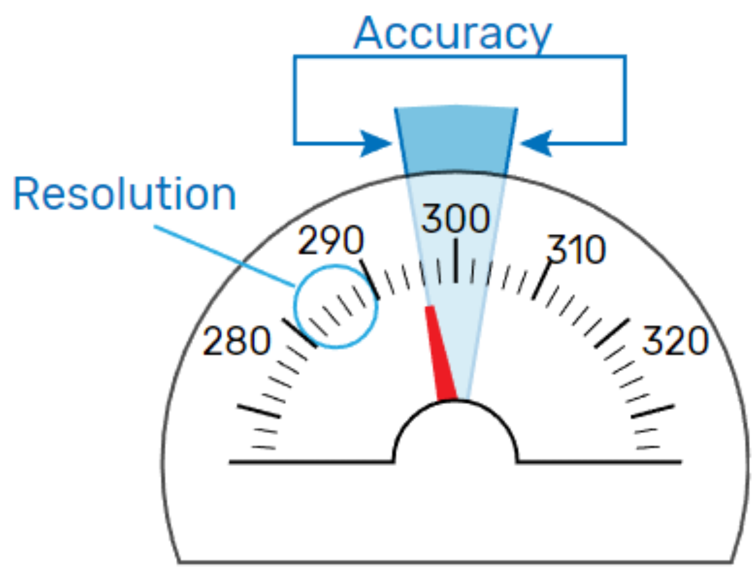
Relatively Precise

Instrument maybe measuring accurately.

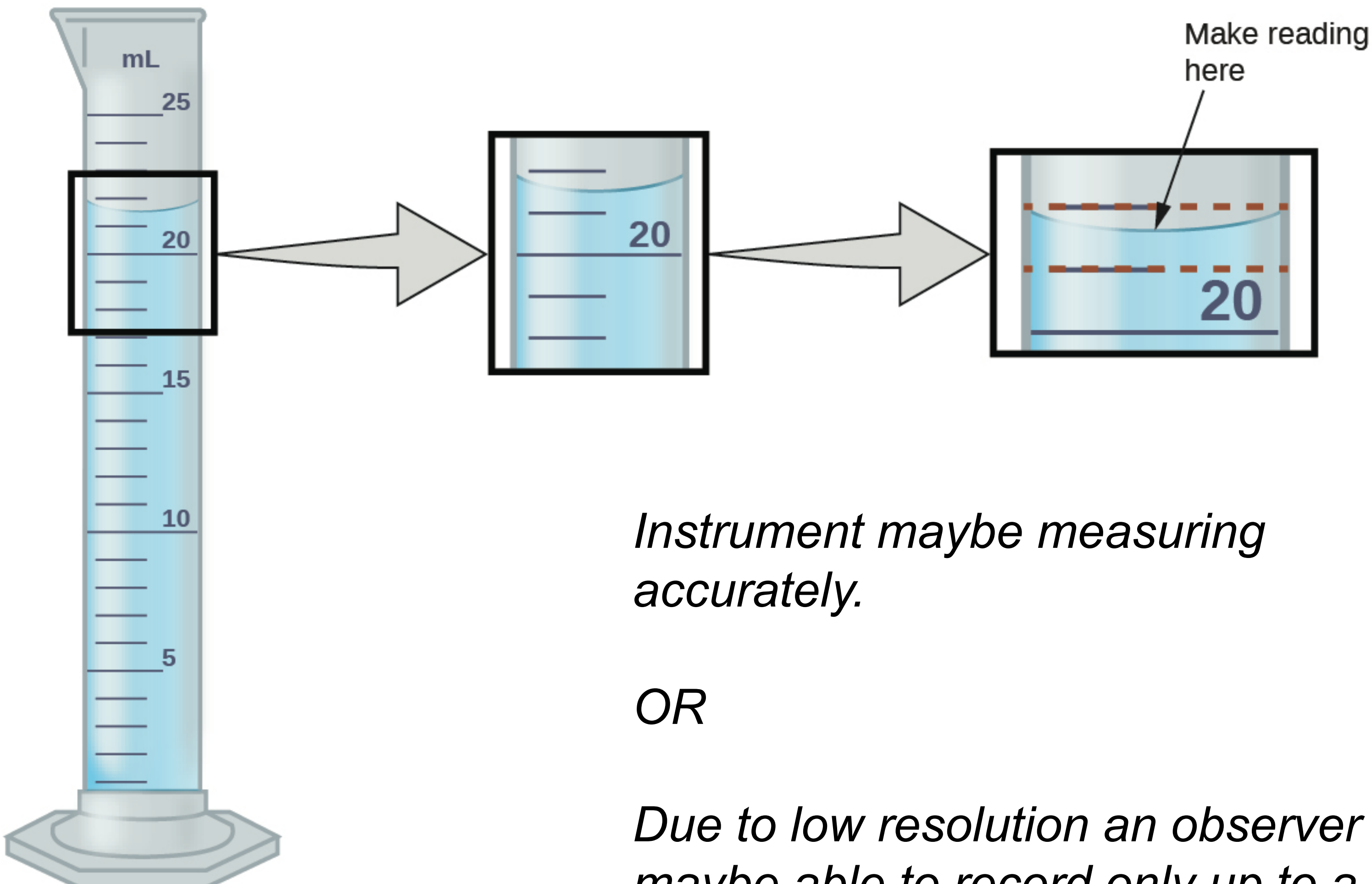
*Due to low resolution an **observer** maybe able to record only up to a certain number of significant figures.*

Example: on an analog voltmeter with a resolution of 1 V, an observer wont be able to tell difference between 1.6V and 1.7 V reading


Accuracy
Resolution
(Distance between tickmarks depicts resolution)
280
290
300
310
320


Accuracy
Resolution
280
290
300
310
320

Precision

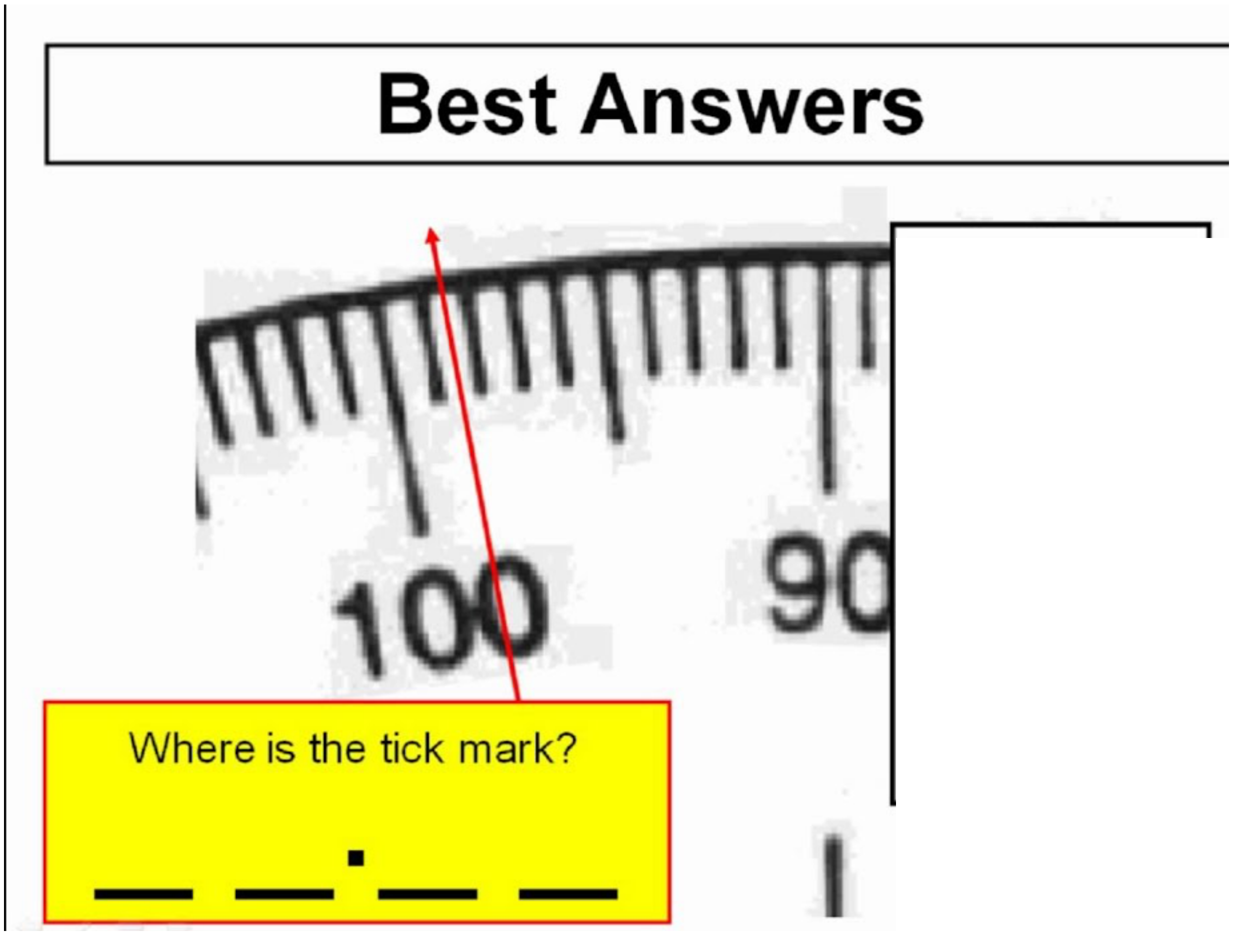


Instrument maybe measuring accurately.

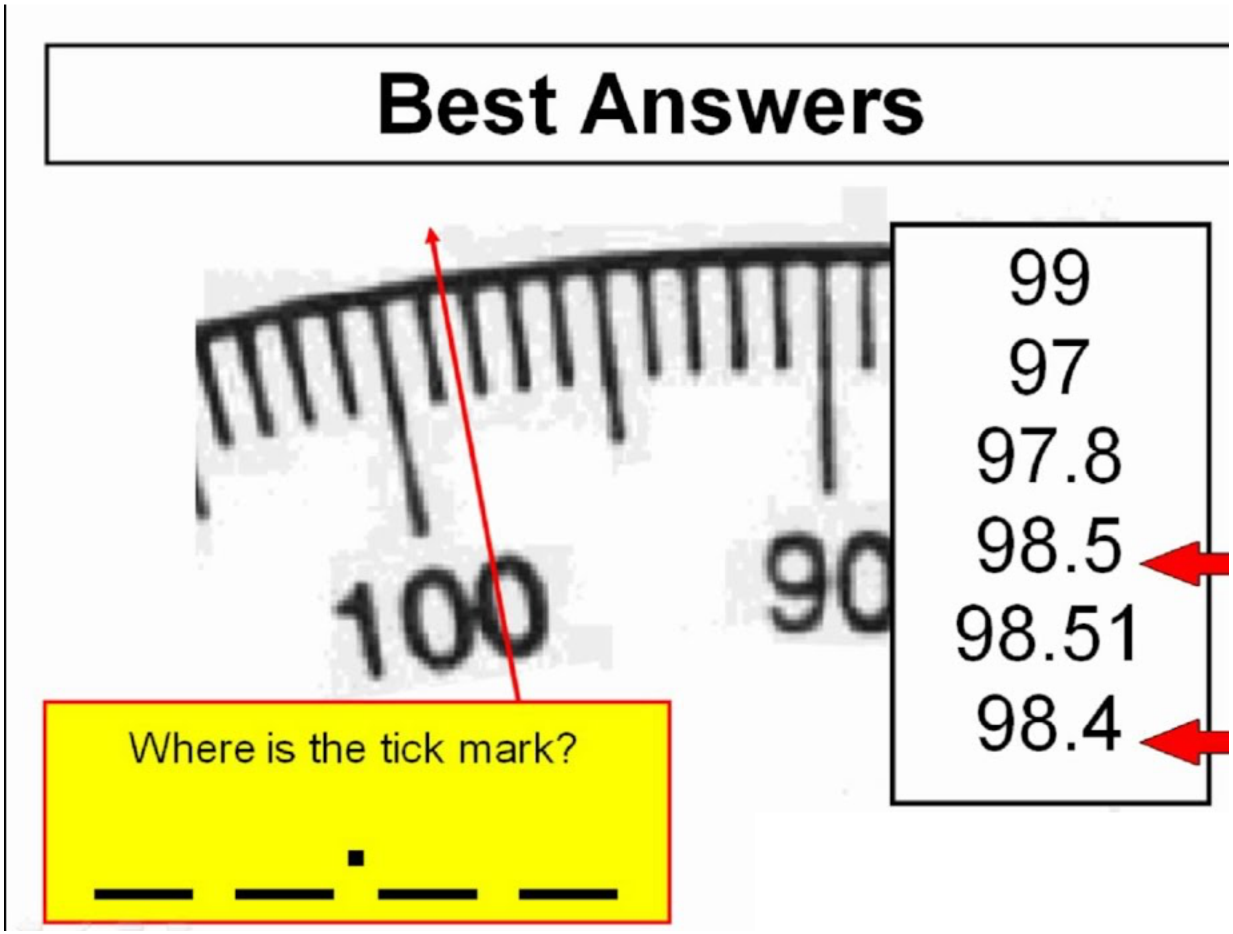
OR

Due to low resolution an observer maybe able to record only up to a certain number of significant figures.

Concept Checks



Concept Checks



Significant Figures

- **Significant figures**
  - What they signify in a reading?
    - 220 V → closer to 220 V than 219 or 221 V **< 3 significant figures>**
    - 220.0 V → closer to 220.0 V than 219.9 or 220.1 V **<4 significant figures>**

  - How to perform involved measurements with varying number of significant figures?

resistors of values 28.4, 4.25, 56.605 and 0.76 ohms are connected in series.

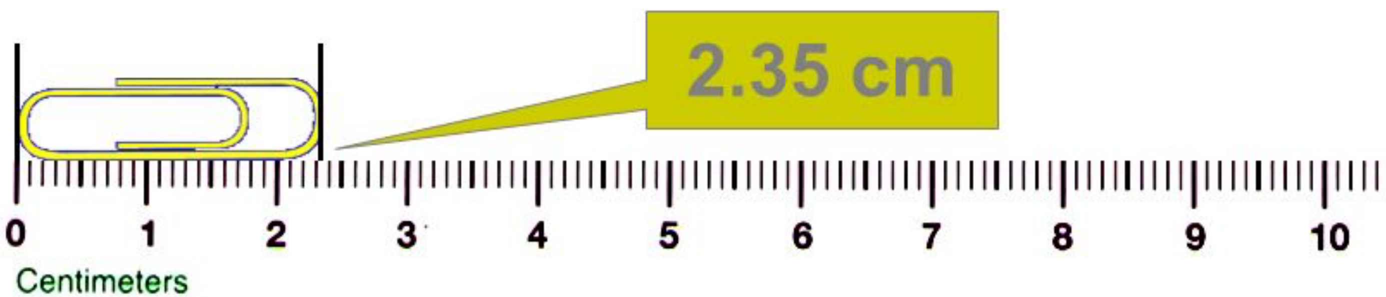
$$\begin{array}{r} 28.\mathit{4} \\ 4.2\mathit{5} \\ 56.60\mathit{5} \\ 0.7\mathit{6} \\ \hline 90.\boxed{\mathit{015}} \end{array}$$

Doubtful figures

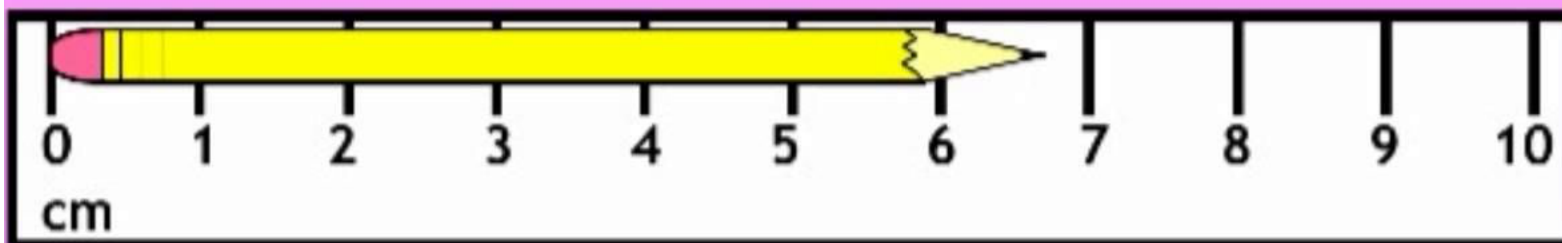
*90.0 ohms convey right information about precision of this involved measurement***.**

Why Significant Figures?

- **Indicate precision of a measurement.**
- Recording Sig Figs
  - Sig figs in a measurement include the known digits plus a final estimated digit



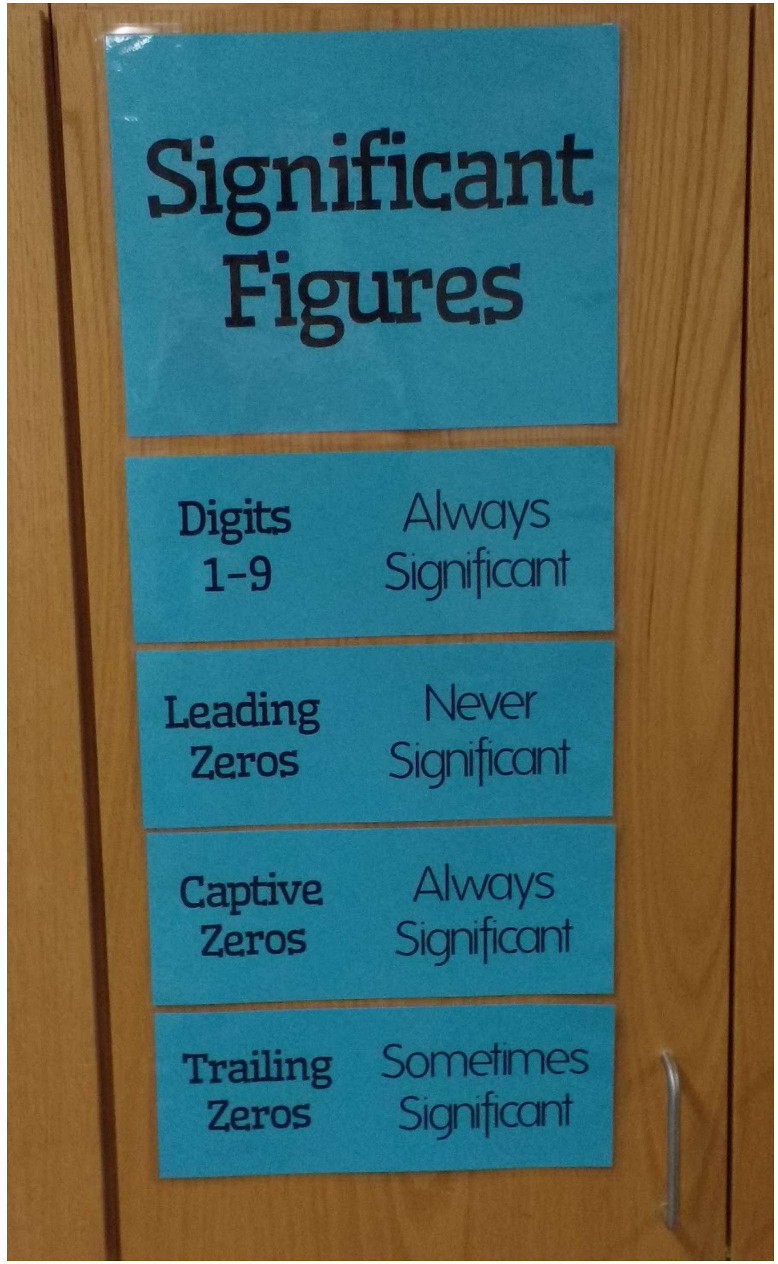
Significant figures (or sig figs) include all known digits plus one estimated digit



6.7 cm

This measurement has 2 significant figures.

Few Rules for



Few Rules for Significant Figures?

Significant figures are the digits in a number that indicates reliability of a measurement. These are identified by following rules

1. All non-zero digits are significant.
2. Zeros between non-zero digits are significant.
3. Trailing zeros (the right most zeros) are significant when there is a decimal point in the number.

Significant figures: Rules for zeros

Leading zeros are not significant.

Leading zero | 0.421 – three significant figures

Captive zeros are significant.

Captive zero | 4012 – four significant figures

Trailing zeros are significant.

Trailing zero | 114.20 – five significant figures

Example

0.00001230004560000

Leading zeros
are *never* significant

Captive Zeros
Are *always* significant

Trailing Zeroes
Are *only* significant
if a decimal is
present

Rules

Counting Significant Digits

If a measurement has already been made and provided, then we can determine how many significant digits are present by following a few simple rules.

1. All non-zero numbers are significant.

For example, the number 843 would have three significant digits are they are all non-zero.

2. Zeros between non-zero numbers are significant.

The number 307 would also have three significant digits as the zero is sandwiched between the non-zero numbers 3 and 7.

3. Leading zeros before a number are not significant.

In the number 0.0025, the leading zeros (those to the left of the non-zero numbers) are not significant. Therefore, only the 2 & 5 are counted meaning it has two significant digits. The leading zeros are known as *placeholder zeros* as they do not add to the precision of the measurement, they simply occupy the ones, tenths, and hundredths places. This will become more clear in our lesson on Scientific Notation as 0.0025 could also be written as 2.5×10^{-3}, completely eliminating the leading zeros.

Rules

4. Trailing zeros after a number are not significant unless there's a decimal point.

Consider three different measurements: 250 versus 250. versus 250.0

250 – The trailing zeros (those to the right of the non-zero numbers) are also placeholders and thus do not add to the precision of the measurement. Thus, there are only two significant digits from the 2 & 5. Again, as we'll see in our lesson on Scientific Notation, this could be written 2.5×10^2 completely eliminating the final placeholder zero.

250. – The decimal point indicates the measurement is precisely 250. not *around* 250 as in the previous example. This number would have three significant digits.

250.0 – Again, the decimal point indicates that the trailing zeros are significant and should be counted meaning there are four significant digits.

Let’s Practice..

1. **23.5** –

Let's Practice..

1. **23.5** – Three significant digits as all are non-zero numbers (see rule #1 above).

2. **23.50** –

decimal place (see rule #4 above).

Let's Practice..

1. **23.5** – Three significant digits as all are non-zero numbers (see rule #1 above).

2. **23.50** – Four significant digits. The final zero is significant because the number contains a decimal place (see rule #4 above).

3. **402** –

Let's Practice..

1. **23.5** – Three significant digits as all are non-zero numbers (see rule #1 above).

2. **23.50** – Four significant digits. The final zero is significant because the number contains a decimal place (see rule #4 above).

3. **402** – Three significant digits. The zero is between non-zero numbers (see rule #2 above).

Let’s Practice..

1. **23.5** – Three significant digits as all are non-zero numbers (see rule #1 above).

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4. **5,200** –

Let's Practice..

1. **23.5** – Three significant digits as all are non-zero numbers (see rule #1 above).

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3. **402** – Three significant digits. The zero is between non-zero numbers (see rule #2 above).

4. **5,200** – Two significant digits. There is no decimal place so the trailing zeros are simply placeholders and not-significant (see rule #4 above).

5. **0.030** –

Let’s Practice..

1. **23.5** – Three significant digits as all are non-zero numbers (see rule #1 above).

2. **23.50** – Four significant digits. The final zero is significant because the number contains a decimal place (see rule #4 above).

3. **402** – Three significant digits. The zero is between non-zero numbers (see rule #2 above).

4. **5,200** – Two significant digits. There is no decimal place so the trailing zeros are simply placeholders and not-significant (see rule #4 above).

5. **0.030** – Two significant digits. Leading zeros are never significant (see rule #3 above). The trailing zero *is* significant because the number contains a decimal place (see rule #4 above).

Let’s Practice..

1. **23.5** – Three significant digits as all are non-zero numbers (see rule #1 above).

2. **23.50** – Four significant digits. The final zero is significant because the number contains a decimal place (see rule #4 above).

3. **402** – Three significant digits. The zero is between non-zero numbers (see rule #2 above).

4. **5,200** – Two significant digits. There is no decimal place so the trailing zeros are simply placeholders and not-significant (see rule #4 above).

5. **0.030** – Two significant digits. Leading zeros are never significant (see rule #3 above). The trailing zero *is* significant because the number contains a decimal place (see rule #4 above).

6. **0.0070080** –

Let's Practice..

1. **23.5** – Three significant digits as all are non-zero numbers (see rule #1 above).

2. **23.50** – Four significant digits. The final zero is significant because the number contains a decimal place (see rule #4 above).

3. **402** – Three significant digits. The zero is between non-zero numbers (see rule #2 above).

4. **5,200** – Two significant digits. There is no decimal place so the trailing zeros are simply placeholders and not-significant (see rule #4 above).

5. **0.030** – Two significant digits. Leading zeros are never significant (see rule #3 above). The trailing zero *is* significant because the number contains a decimal place (see rule #4 above).

6. **0.0070080** – Five significant digits. Leading zeros are never significant (see rule #3 above). The two zeros between 7 and 8 are significant because they are between non-zero numbers (see rule #2 above). The trailing zero is significant because the number contains a decimal place (see rule #4 above).

Significant Figures (Rounding)

Numbers can be rounded to 1,2, 3 or more significant figures. We count the number of figures from the first non-zero digit.

Rounding to 1 s.f

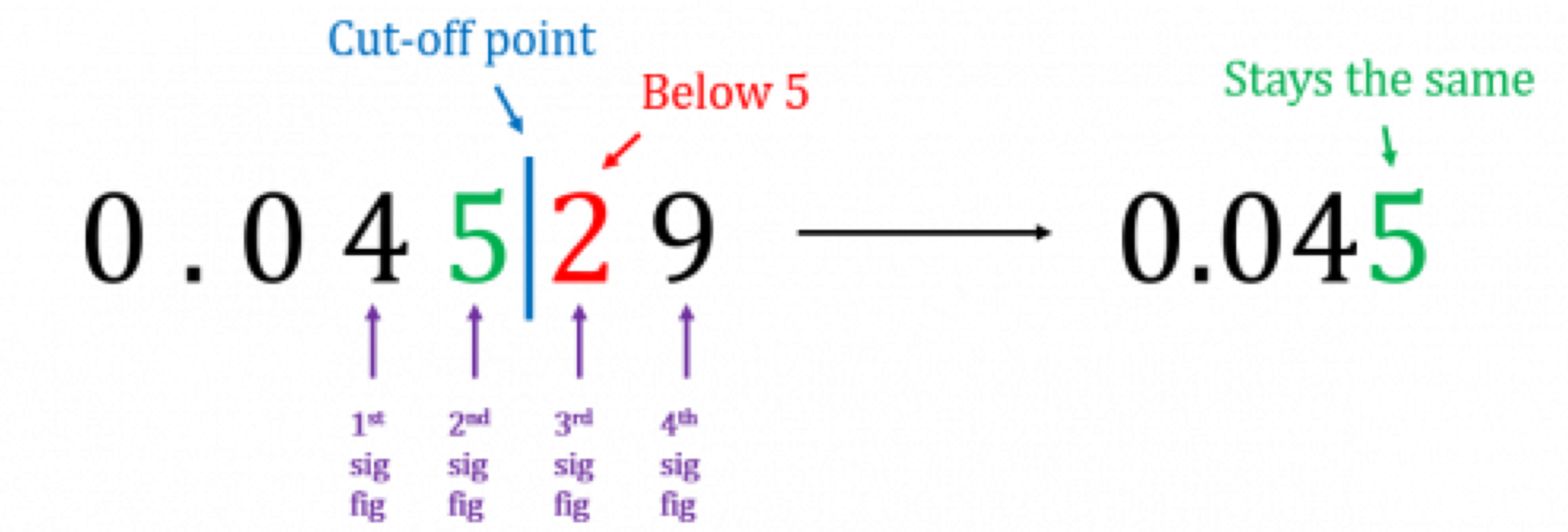
4.3325	5.7425	0.0425
5 or bigger ?	5 or bigger ?	5 or bigger ?
No	Yes	No
4	6	0.04

First non-zero digit.

Concept Checks:
Significant Figures (Rounding)

0.045|29 ⟶

Significant Figures (Rounding)



Rounding decimals

When **rounding** decimals look at the first digit past the number of decimal places required.

- If this number is *less than 5*, write the number with the required number of decimal places.
- If this number is *5 or more*, add 1 to the last decimal place being kept.

Significant Figures (Rounding): Convention

1. If it is less than 5, drop it and all the figures to the right of it.
2. If it is more than 5, increase by 1 the number to be rounded, that is, the preceeding figure.
3. If it is 5, round the number so that it will be even. Keep in mind that zero is considered to be even when rounding off.

Example #1 - Suppose you wish to round 62.5347 to four significant figures. Look at the fifth figure. It is a 4, a number less than 5. Therefore, you will simply drop every figure after the fourth, and the original number rounds off to 62.53.

Example #2 - Round 3.78721 to three significant figures. Look at the fourth figure. It is 7, a number greater than 5, so you round the original number up to 3.79.

Example #3 - Round 726.835 to five significant figures. Look at the sixth figure. It is a 5, so now you must look at the fifth figure also. That is a 3, which is an odd number, so you round the original number up to 726.84.

Example #4 - Round 24.8514 to three significant figures. Look at the fourth figure. It is a 5, so now you must also look at the third figure. It is 8, an even number, so you simply drop the 5 and the figures that follow it. The original number becomes 24.8.

When the value you intend to round off is a five, you MUST look at the previous value ALSO. If it is even, you round down. If it is odd, you round up. A common question is "Is zero considered odd or even?" The answer is even.

Significant Figures

- **An indication of the precision of a measurement**
  - **More the significant figures, greater the precision**

Significant Figures

- **Involved measurement?**

Significant Figures

- Involved measurement
  - Multiple measurands have to be combined for output
    - The number of significant figures plays a crucial role to determine the precision of the ultimate measurement
- Addition and subtraction
  - The result is rounded to the same number of decimal places as the least accurate number

Significant Figures

Addition and subtraction. After performing the operation write the result rounded to the same number of *decimal places* as the least accurate figure.

Multiplication and division. After the operation round the result to the same number of *significant figures* as the least accurate number.

Example 2.1
Four capacitors of values 45.1, 3.22, 89.309 and 0.48 μF, are connected in parallel. Find the value of the equivalent capacitor to the appropriate number of significant figures.

Example 2.2
A current of 3.12 A is flowing through a resistor of 53.635 Ω. Find the value of the voltage drop across the resistor to the appropriate number of significant figures.

Significant Figures

- **Addition and subtraction**
  - **The result is rounded to the <u>same number of decimal places</u> as the least accurate number**

- **Example 2.1**
  - **Four capacitors in parallel: 45.1, 3.22, 89.309 and 0.48 μF**
    - **Sum: 138.109 μF**
    - **Acceptable value (rounding): 138.1 μF**

Example: 1 (Addition)

Addition and subtraction. After performing the operation write the result rounded to the same number of *decimal places* as the least accurate figure.

23.4567g
2.2g
12.112g

37.7687g

37.8 g

They have the same number of digits after the decimal

37.7687 is rounded off in such a manner that that there's only 1 digit after the decimal. When 6 is removed, it added 1 to 7, because it is greater than 5

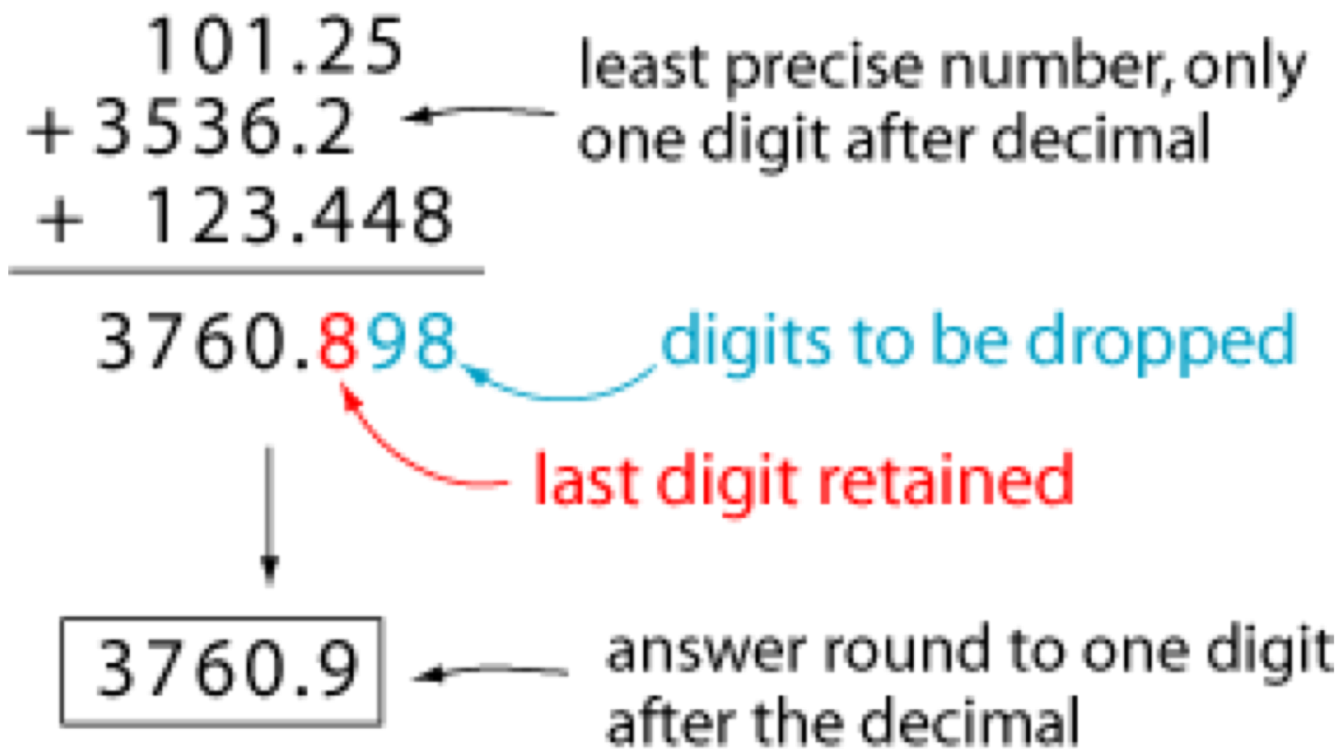
Example 2 (Addition)

Addition and subtraction. After performing the operation write the result rounded to the same number of decimal places as the least accurate figure.

$$
\begin{array}{r}
101.25 \\
+3536.2 \\
+\ 123.448 \\
\hline
\end{array}
$$

Example 2 :Addition

Addition and subtraction. After performing the operation write the result rounded to the same number of *decimal places* as the least accurate figure.



Significant Figures

- **Multiplication and division**
  - **The result is rounded to the same number of significant figures as the least accurate number**

- **Example**

A current of 3.12 A is flowing through a resistor of 53.635 Ω. Find the value of the voltage drop across the resistor to the appropriate number of significant figures.

Solution
The straightforward multiplication yields 167.3412 V. Rounding it off to three significant figures—the same as that of 3.12—the value to be reported is 167 V.

Significant Figures

- **Multiplication and division**
  - **The result is rounded to the same number of significant figures as the least accurate number**

Example 1:

$$\frac{22.91_{(4\ significant\ figures)} \times 0.152_{(3\ significant\ figures)}}{16.302_{(5\ significant\ figures)}} = 0.213613 \approx 0.214$$

Example 2 : Multiplication

Multiplication and division. After the operation round the result to the same number of *significant figures* as the least accurate number.

$34.6 \times 12.1 \times 1.2 =$

Example 2 : Multiplication

Multiplication and division. After the operation round the result to the same number of *significant figures* as the least accurate number.

least number of significant figures

last digit retained

digits to be dropped

$$34.6 \times 12.1 \times 1.2 = 502.392$$

$$\boxed{5.0 \times 10^2}$$

answer round to two significant figures

Example 3 : Multiplication

- **Multiplication and division**
  - **The result is rounded to the same number of significant figures as the least accurate number**

Example:

```
 123.4
x   23
------
```

```
 123.4     4 Sig. figures
x   23     2 Sig. figures
------
  3702
 2468
------
2838.2
```

Retain

Digits to be dropped

= 2.8 x 10^3 *{rounded to scientific notation}*

Example: 2 (Multiplication)

Multiplication and division. After the operation round the result to the same number of *significant figures* as the least accurate number.

39.2
403.45

15815.24 ➡ ***Round the result to 3 significant figures***

$39.2 \times 403.45 = 1.58 \times 10^4$

3 significant figures.

5 significant figures.

3 is smaller than 5. Answer should be rounded to 3 significant figures.

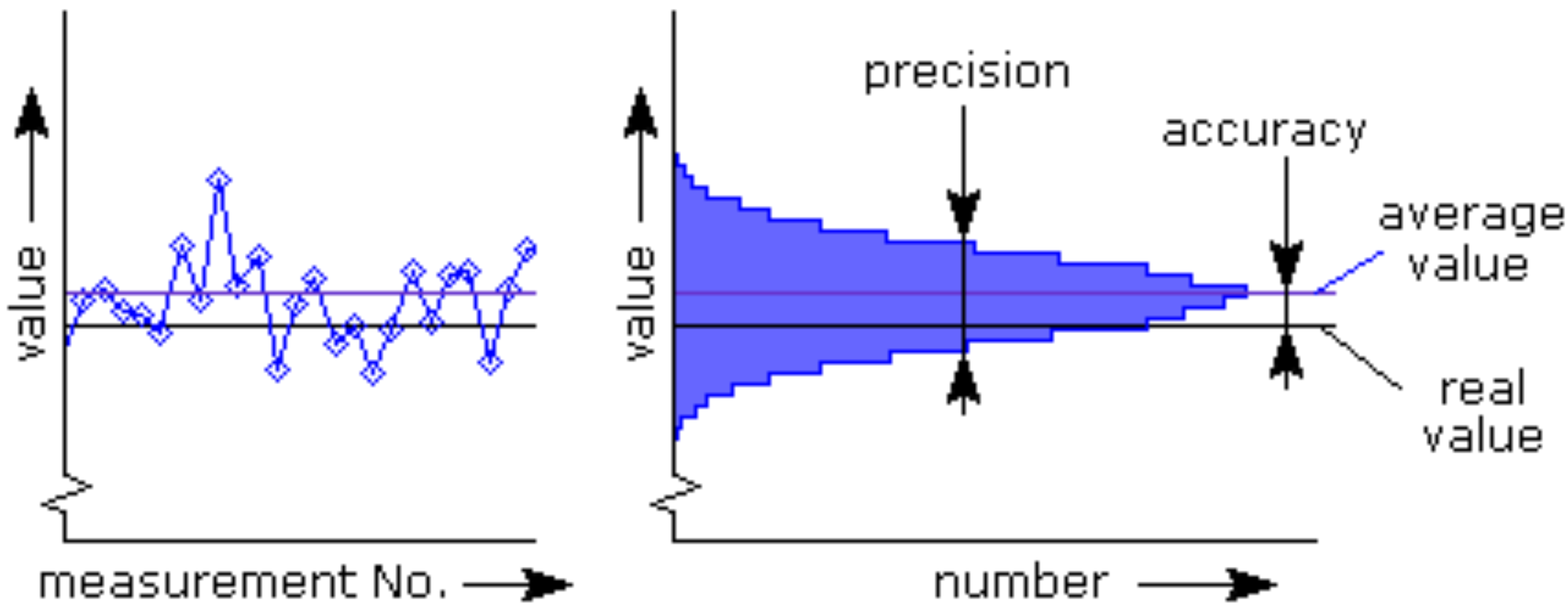
Count the number of significant figures when multiplying or dividing.

$2.90 \times 1.8 = 5.2$
$490 \div 6 = 80$

No decimal. Only the 8 is significant.

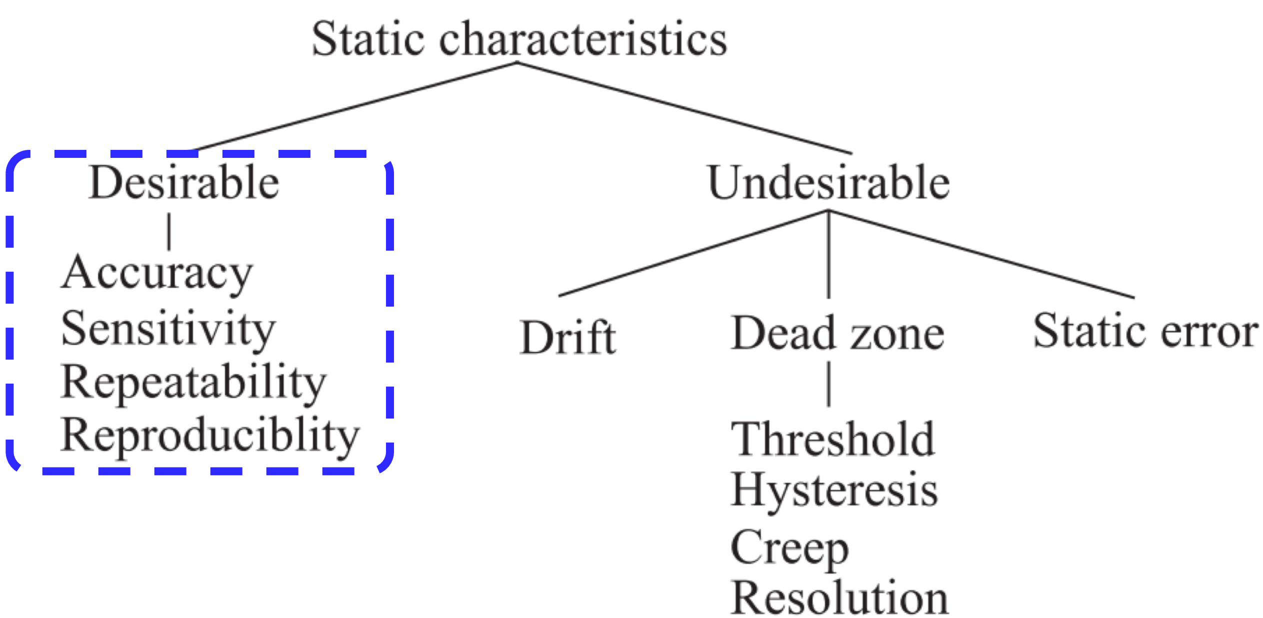
For multiplying and dividing, round answers to the least number of significant figures.

Summarizing: Accuracy and Precision



Static Characteristics Of Instrument

- **Characteristics relating the steady-state (achieved) of an instrument**



Desirable Characteristics

- Accuracy
  - Precision
  - Significant figures
- Sensitivity
  - Linearity & Non linearity
- Repeatability
- Reproducibility

Precision

- **Repeatability and reproducibility ?**

Precision

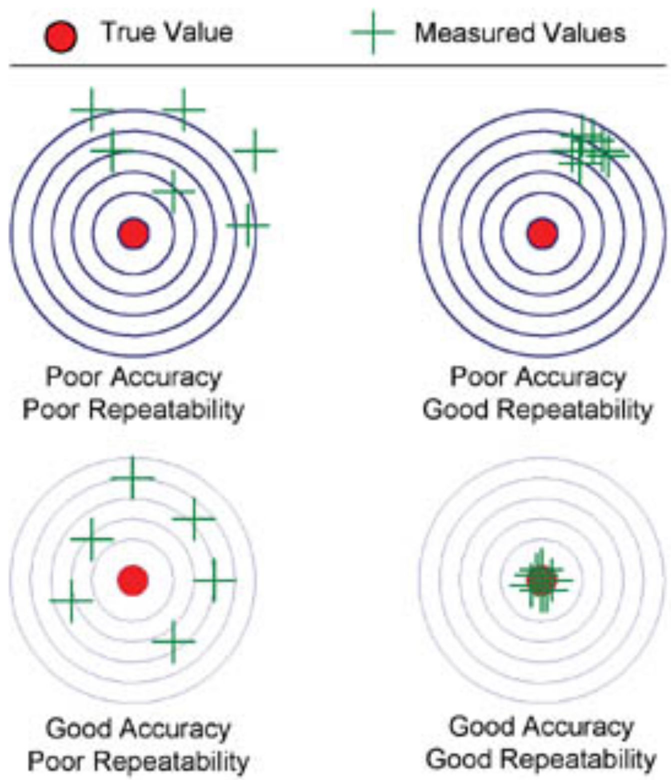
ACCURATE = CORRECT

PRECISE = CONSISTENT

- Repeatability and reproducibility
  - closely related to precision

Repeatability and Reproducibility

- **Repeatability**
  - **Closeness/spread of output readings for the same input**
  - **Same measurement conditions: time, observer, location, measuring equipment, calibration conditions etc.**



Repeatability and Reproducibility

- **Reproducibility**
  - **Closeness/spread of output readings for the same input**
  - **Different measurement conditions: changes in measurement method, observer, location, equipment, conditions of use and time of measurement etc.**

Repeatability and Reproducibility

- **Repeatability**
  - **Closeness/spread of output readings for the same input**
  - **<u>Same</u> measurement conditions: time, observer, location, measuring equipment, calibration conditions etc.**
- **Reproducibility**
  - **Closeness/spread of output readings for the same input**
  - **<u>Different</u> measurement conditions: changes in measurement method, observer, location, equipment, conditions of use and time of measurement etc.**
  - **Reproducibility, therefore, determines precision of an instrument.**
- **Why repeatability and reproducibility**

Desirable Characteristics

- **Repeatability vs Reproducibility**

Repeatability	Reproducibility
Measure of agreement between results of successive measurements under *unchanged conditions* of measurement	**Measure of agreement between results of successive measurements under *changed conditions* of measurement**
→Made by same observer	**→Maybe made by different observers**
→Measuring instrument is unaltered	**→The instrument maybe dismantled and reassembled**
→Same occasion	**→Maybe made months or years apart**

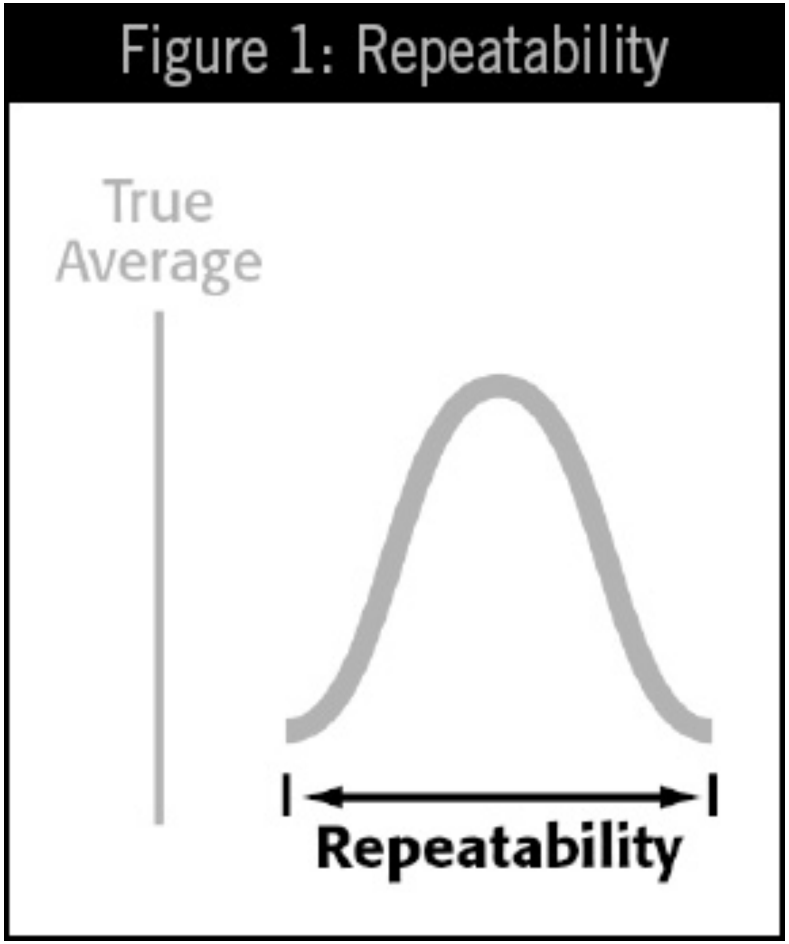


Figure 1: Repeatability
True
Average
Repeatability

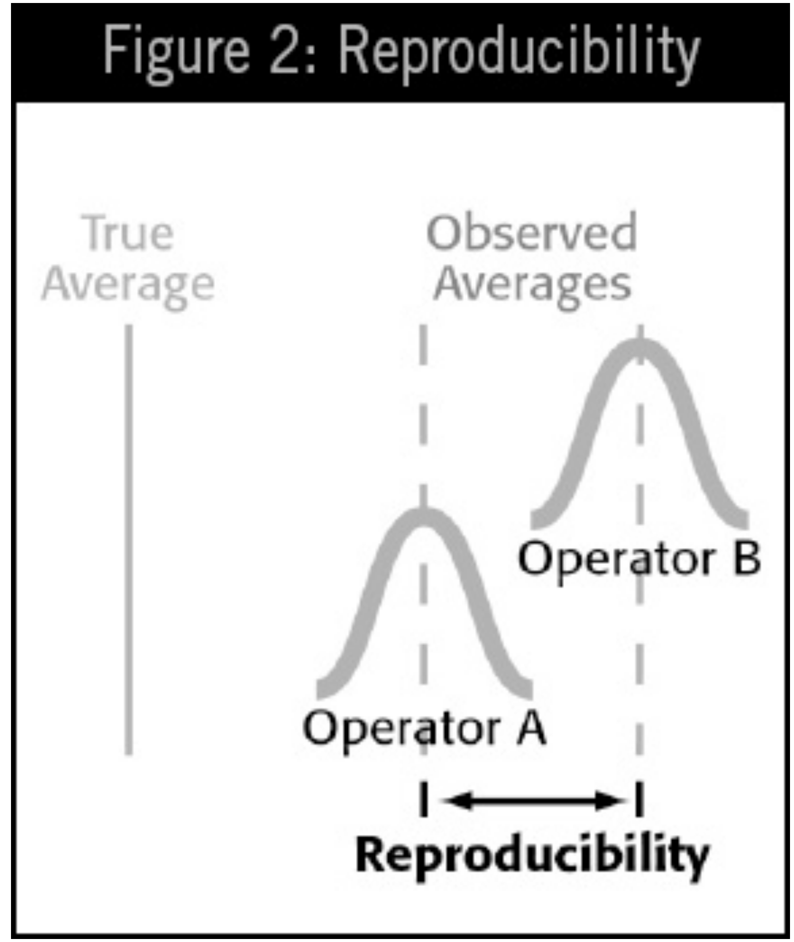
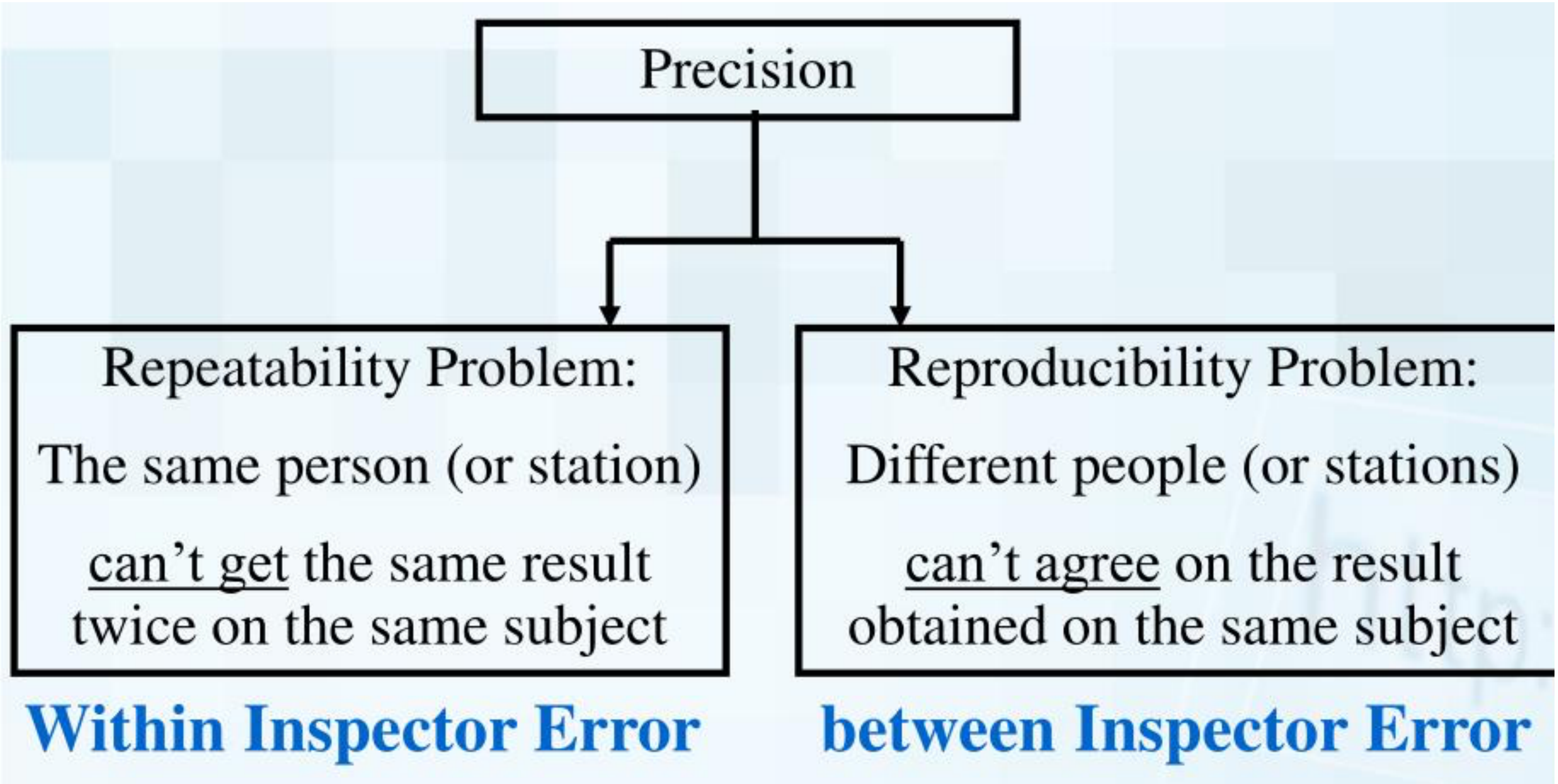


Figure 2: Reproducibility
True
Average
Observed
Averages
Operator B
Operator A
Reproducibility


Precision
Repeatability Problem:
The same person (or station)
can't get the same result
twice on the same subject
Reproducibility Problem:
Different people (or stations)
can't agree on the result
obtained on the same subject
Within Inspector Error
between Inspector Error

Repeatability and Reproducibility

- For high precision
  - **Repeatability or Reproducibility**

Repeatability and Reproducibility

- ❑ **For high precision:**

  - ❑ **Repeatability or Reproducibility?**

  - ✓ **Reproducibility**

Figure 1: Repeatability

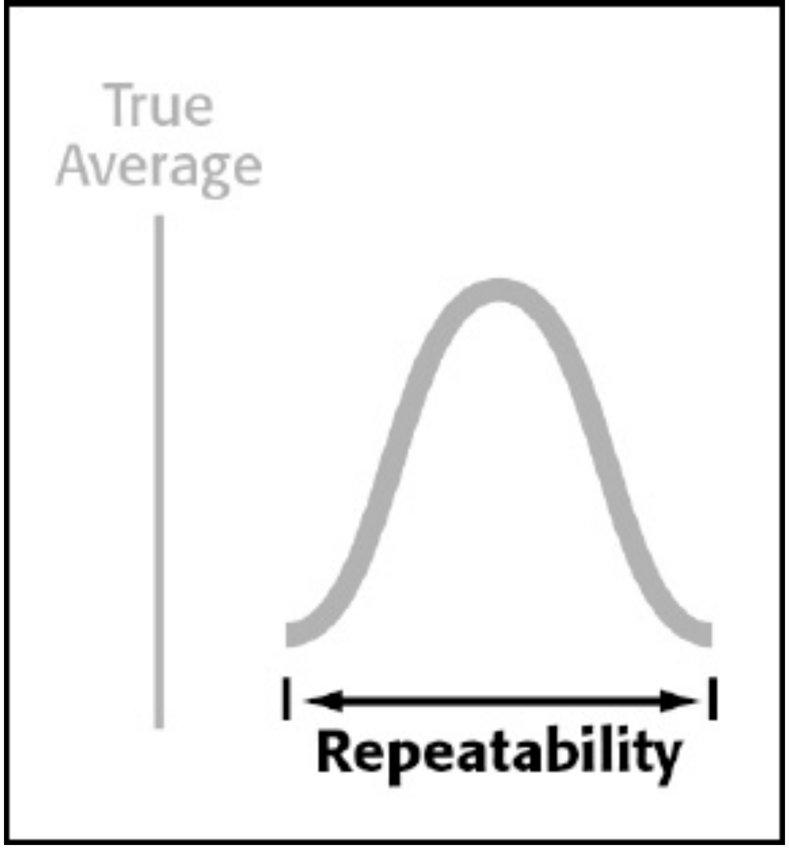
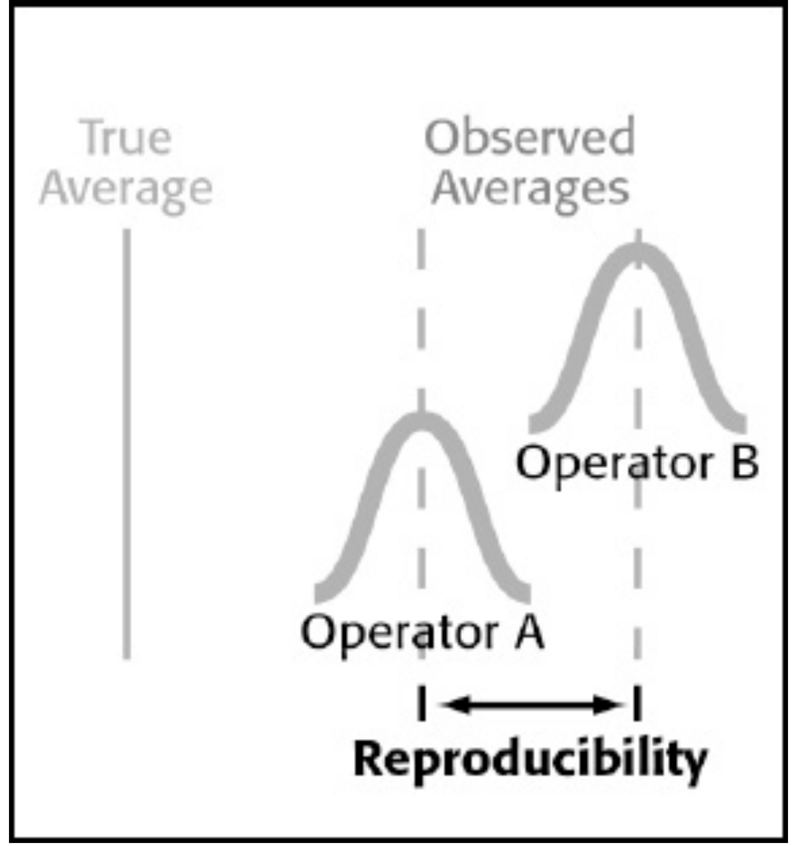
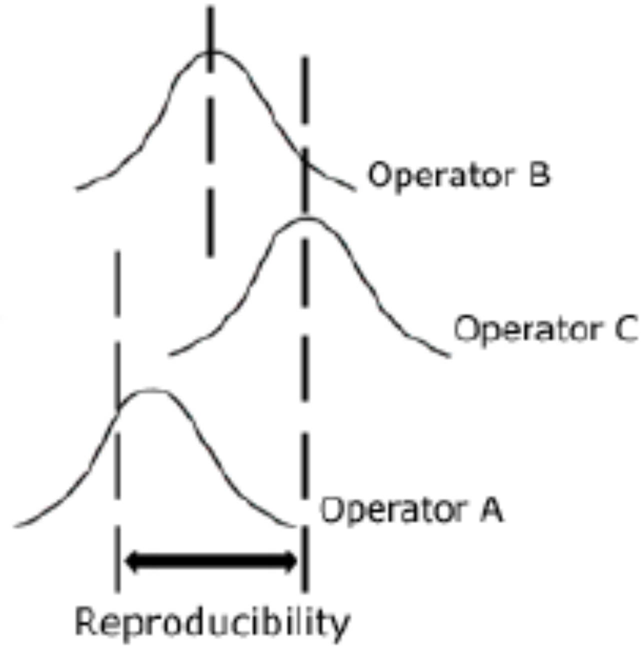


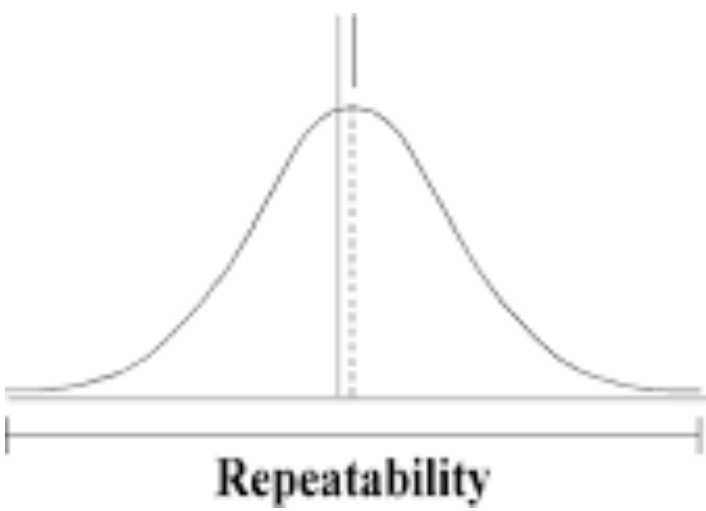
Figure 2: Reproducibility

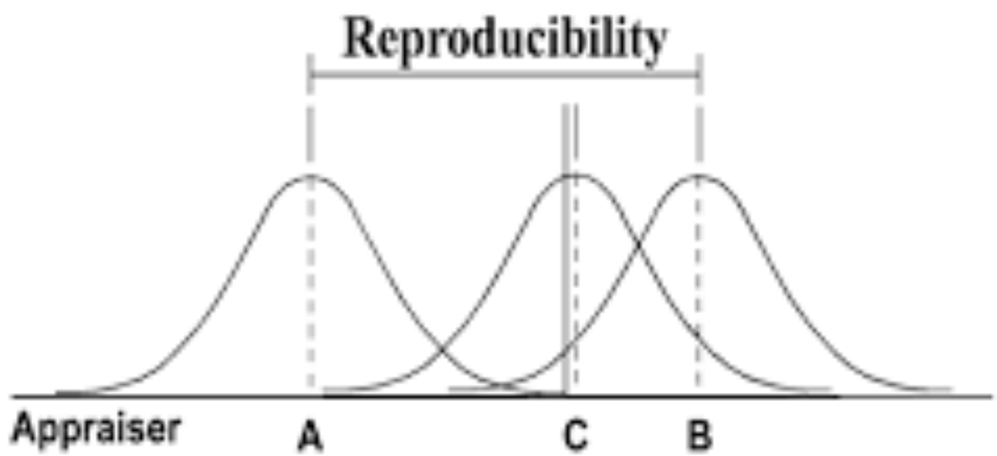


Precision:

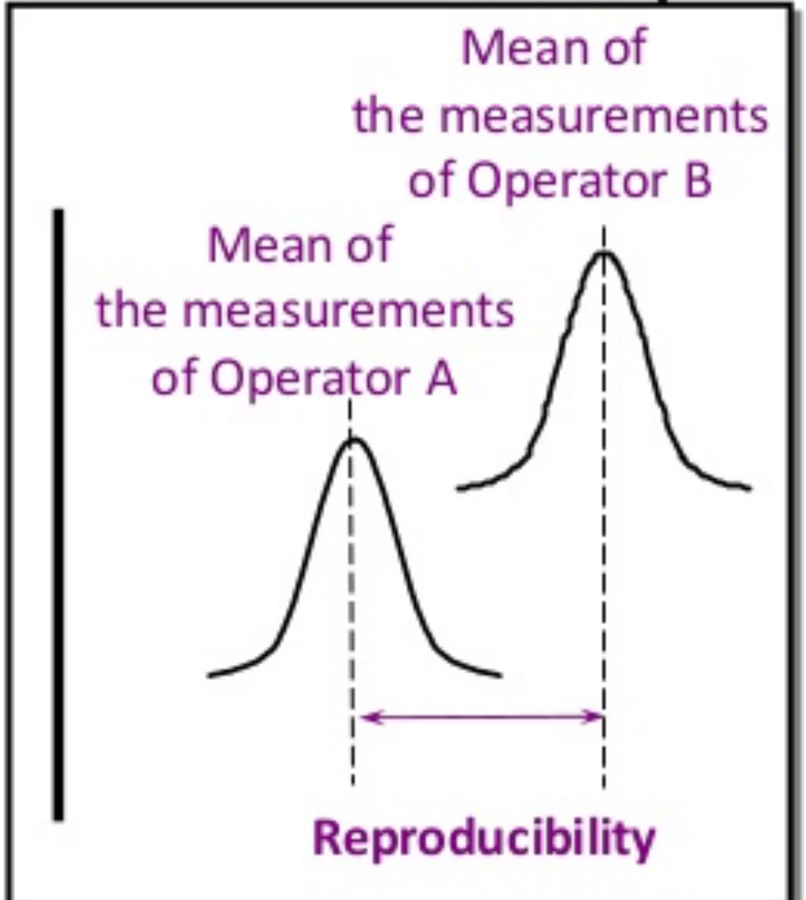
- Repeatability - within an operator or piece of equipment
- Reproducibility - operator to operator or attribute gage to attribute gage







Reproducibility



Possible Causes of Poor Reproducibility

- Measurement procedure is not clear
- Operator is not properly trained in using and reading gage
- Operational Definitions not established

Static Characteristics Of Instrument

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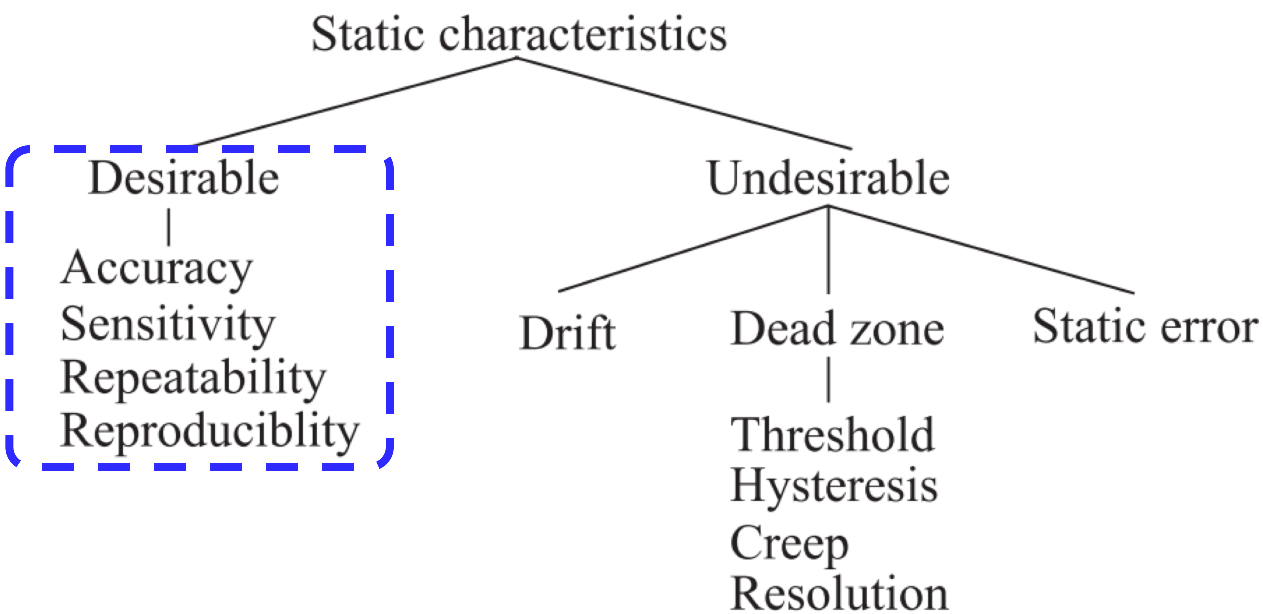

Desirable Characteristics

- Accuracy
  - Precision
  - Significant figures
- Sensitivity
  - Linearity & Non linearity
- Repeatability
- Reproducibility

Sensitivity

- **Absolute ratio of the increment of the output signal (or response) to that of the input signal (or measurand)**
- **Ratio of the output signal (measurement/response) to that of the input signal (measurand)**

Sensitivity

- **Absolute ratio of the increment of the output signal (or response) to that of the input signal (or measurand)**
  - **If q_i and q_o are input and output quantities, respectively**

$$S = \frac{\Delta q_o}{\Delta q_i}$$

Sensitivity

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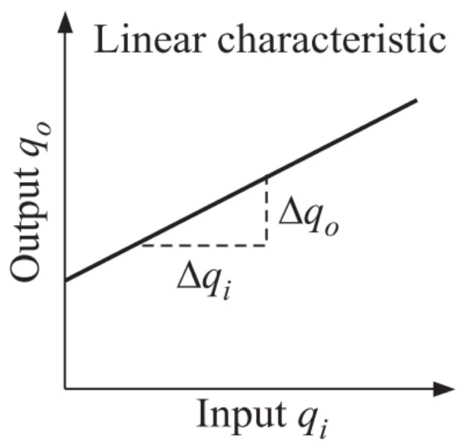
$$S = \frac{\Delta q_o}{\Delta q_i}$$

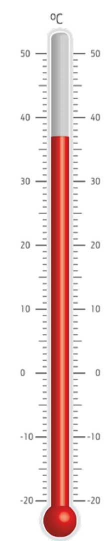
  - **Slope of the instrument's response curve**



Sensitivity of Thermometer?

Example:

- In a mercury in glass thermometer, meniscus moves by 1 cm when a temperature changes by 10 ° Celsius.
  - Sensitivity of the thermometer will be?

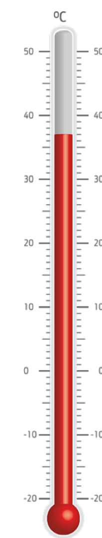


Sensitivity

- **Absolute ratio of the increment of the output signal (or response) to that of the input signal (or measurand)**
  - **If q_i and q_o are input and output quantities, respectively**

$$S = \frac{\Delta q_o}{\Delta q_i}$$

  - **Mercury-in-glass thermometer**
    - **Meniscus movement: ΔH=1 cm for ΔT=10 ℃**
    - $S = \frac{\Delta H}{\Delta T}$ **= 1 mm/ ℃**



Temperature

Sensitivity

- What is the sensitivity of a **voltmeter**?

Sensitivity

- ❑What is the sensitivity of a **voltmeter**?

  - ❑How does it work?

Sensitivity

- ❑ Voltmeter: how does it work?

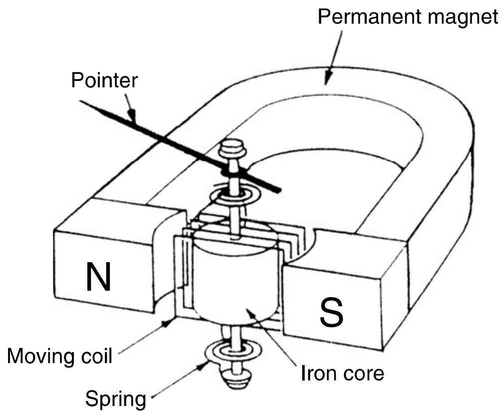


Figure 7.3
Mechanism of a moving coil meter.

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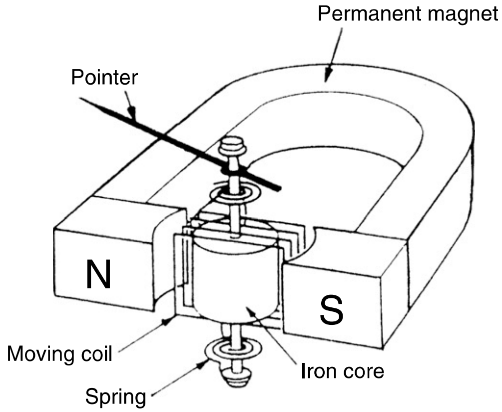
- Interaction of the induced field with permanent magnet's filed causes deflection
  - Rectangular coil draws current from the circuit

Sensitivity

- Voltmeter: how does it work?
  - it draws the current from the measurand's circuit



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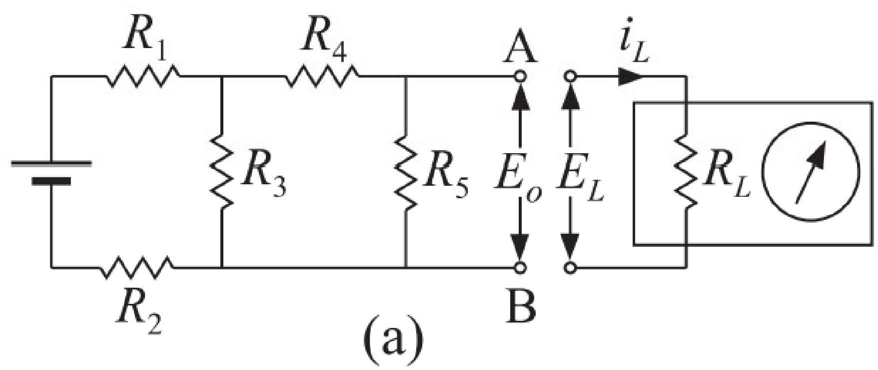
Mechanism of a moving coil meter.



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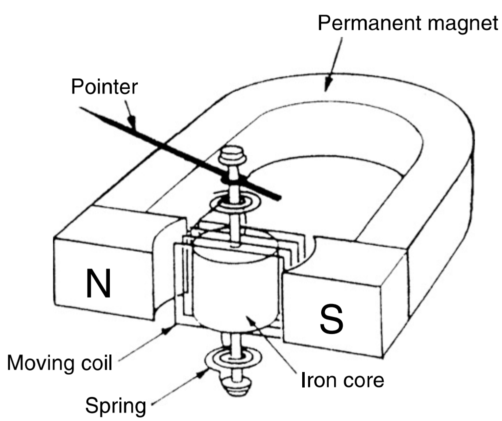
Sensitivity

- Voltmeter: how does it work?
  - it draws the current from the measurand’s circuit
  - more sensitive, if it draws less current from the circuit
    - high resistance to be connected in parallel



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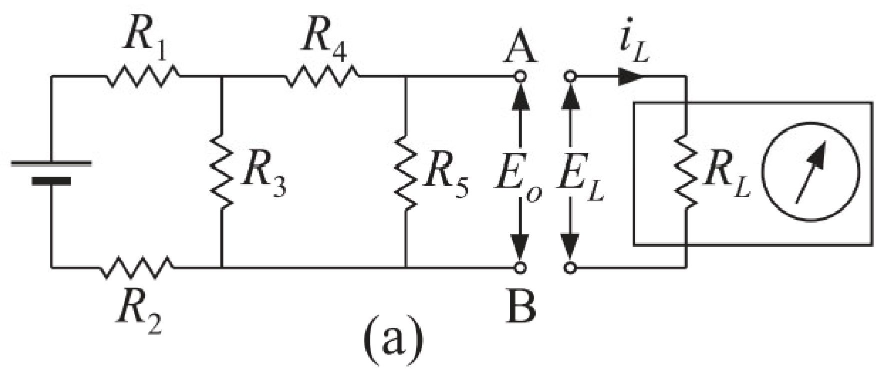

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Sensitivity

- **Sensitivity of a voltmeter**
  - varies inversely with the current required for full-scale deflection (FSD)
  - If I_{FSD} is the current required for the full-scale deflection (FSD)

$$S = \frac{1}{I_{FSD}} \, ohm/volt$$

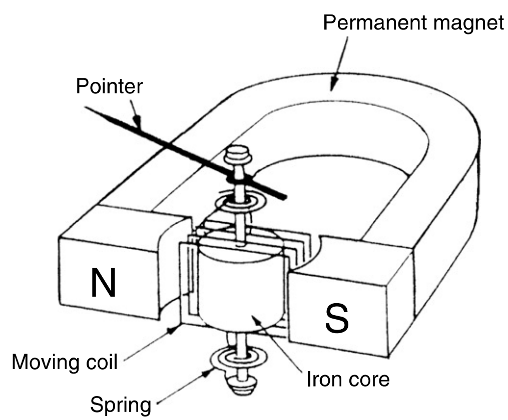

Figure 7.3
Mechanism of a moving coil meter.

Sensitivity

Example 2.3

What is the sensitivity of a voltmeter having 50 μA FSD?

Solution

The required sensitivity is given by

$$\text{Sensitivity} = \frac{1}{50 \times 10^{-6}} = 20,000 \text{ ohm/volt}$$

Lab quality voltmeters should have a minimum sensitivity of 20 kΩ/volt.

Queries

Thanks!