Electrical and Electronic Measurements:

Measurement and Testing

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Electrical and Electronic Measurements

WEEK 1	Introduction
WEEK 2-4	Measurements / Analysis / Errors
WEEK 5	Indicating instruments
WEEK 6-7	Component measurements
WEEK 8	Midterm exam
WEEK 9-10	Digital meters
WEEK 11	Power and energy measurements
WEEK 12	Oscilloscopes
WEEK 13	Special measurements
WEEK 14	Safety in measurement
WEEK 15	Final exam

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Grading Criteria

- **Quizzes & Homeworks** **30%**
- **Midterm exam** **30%**
- **Final exam** **40%**
- **Your letter grade is based on your final score relative to your classmates'**

A general guideline:
To avoid F, you should score ≥ 30%.

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Measurement

- **Measurement** is to determine the value or size of some quantity, e.g. a voltage or a current.
- **Analogue measurement** gives a response to a continuous quantity.
- **Digital measurement** is for the quantity at sampled times and quantized values.
- **Comparison measurement** is to compare the quantity with standards, e.g. null method, in which the resultant effect of the comparison is zero.

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Testing

- **Testing** is to measure to ensure that a product conforms to its specification.
- **Manual testing** proceeded by human
- **Automatic testing** by a machine for reducing human error and increasing the performance.

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A Conceptual Basis of Measurements

Quality

↓ is based upon

Valid decisions

↓ are based upon

Correct numerical data

↓ are based upon

Accurate measurements

↓ are based upon

Calibrated instruments

↓ are based upon

Traceable standards

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Measurement Standards

- **International standards**, for comparison with primary standards, are defined by international agreements and mentioned at *the International Bureau of Weights and Measures* in France.
- **Primary (absolute) standards** are sufficiently accurate such that it is not calibrated by or subordinate to other. They are for checking the accuracy of secondary standards and are maintained at institutions in various countries around the world.
- **Secondary standards** are very close approximations of primary reference standards. They are for verifying the accuracy of working standards and are employed in industry as references for calibrating high-accuracy equipment and component.
- **Working standards** are the principal tools of a measurement laboratory.

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Electrical Measurement Standards

- Electrical measurement standards are precise resistors, capacitors, inductors, voltage sources, and current sources, which can be used for comparison purposes when measuring electrical quantities.
- For example, the primary standard for resistance, the mercury ohm was initially defined in 1884 in as a column of mercury 106.3 cm long and 1 mm^2 in cross-section, at 0 °C. It is quite difficult to reproduce! Since 1990 the international resistance standard has been based on the quantized Hall effect discovered by Klaus von Klitzing.
- At the present time, Fluke 742 series working standard resistors are available in values ranging from 1 Ω - 19 MΩ used at ambient room temperatures (18-28 °C) with resistance changes ranging from ±1.5 (10 kΩ) to ± 4 (19 MΩ) ppm.

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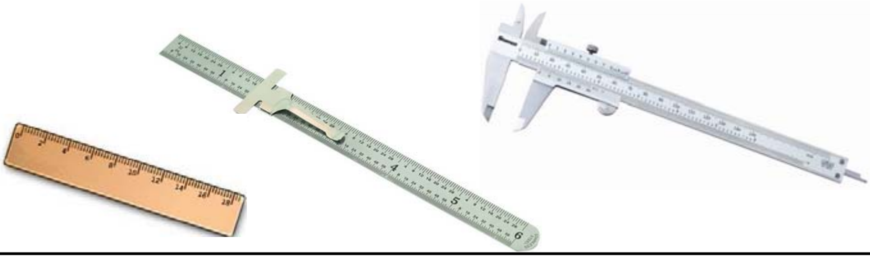
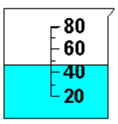
Exact and Measured Numbers

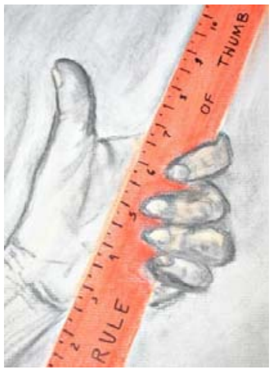
- Exact numbers e.g.
  I have exactly 10 fingers and 10 toes.
- Any measurements e.g. a pen's length
  Quickly measure → It is about 15 cm.
  More precise → It might be 15.5 cm.
  Even more precise → It would be 15.55 cm.



Significant and Estimated Digits

- In any measurements, the number of significant digits is the number of digits believed to be correct.
- It includes one estimated digit.
  A rule of thumb → read 1/10 of the smallest division for base-10 numeral system.





- e.g. Is the volume in this beaker 47 mL, 48 mL or 49 mL?
  All the answers are correct within the reading error ±1mL. We know the "4" for sure, but the trailing have to be estimated.

Significant Digits

- Each recorded measurement has a certain number of significant digits or significant figures.
- Calculations done on these measurements must follow the rules for significant digits.
- Placeholders, or digits that have not been measured or estimated, are not considered significant.

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Rules for Significant Digits

- Leading zeros are never significant. The leftmost non-zero digit called the most significant digit, e.g. 00**145** 0.00**52**
- Imbedded zeros are always significant, e.g. 1020.045
- Trailing zeros are significant only if the decimal point is specified, e.g. 12.2300 1500 120.0 90.
- A mark may be placed on the last trailing zero if it is significant, e.g. 54<u>0</u>00

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Uncertainty in Calculation

- Measured quantities are often used in calculations. The precision of the calculation is limited by the precision of the measurements on which it is based.
- For adding or subtracting, the answer can only show as many decimal places as the measurement having the fewest number of decimal places,
  e.g. 4.7832 + 1.234 + 2.02 = 8.04 (not 8.0372)
  Sometimes significant figures are lost while performing calculations.
- For multiplying and dividing, the answer may only show as many significant digits as the multiplied or divided measurement showing the least number of significant digits, e.g. 2.8723 × 1.6 = 4.6 (not 4.59568)

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Rounding, Truncating and Averaging

- The usual method is to round numbers with digits less than 5 down and numbers with digits greater than 5 up.
- If there is a 5, there is an arbitrary rule,
  if the number before the 5 is odd, round up, else let it be.
  Of course, if we round off 2.459 to 2 significant digits, the answer is definitely 2.4, since 2.459 is closer to 2.5 than 2.4!
- In some instances numbers are truncated, or cut short, rather than rounded.
- Sometimes numbers used in a calculation are exact rather than approximate, e.g. the average height of 30.1 cm, 25.2 cm and 31.3 cm is 86.6 / 3 = 28.9 cm. There are 3 significant digits in the heights even though you are dividing the sum by a single digit (3 is the exact number).

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Scientific Notation

- Scientific notation is the way that scientists easily handle very large numbers or very small numbers, e.g. $100 = 1\times10\times10 = 1\times10^2$.

Number	Number of Significant Digits	Scientific Notation
0.00682	3	6.82×10^{-3}
1.072	4	1.072×10^{0}
300	1	3×10^{2}
300.	3	3.00×10^{2}
300.0	4	3.000×10^{2}

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Metric Prefixes

e.g.	Abbreviation	Meaning
• Pico	p	$\times10^{-12}$
• Nano	n	$\times10^{-9}$
• Micro	µ	$\times10^{-6}$
• Milli	m	$\times10^{-3}$
• Centi	c	$\times10^{-2}$
• Deci	d	$\times10^{-1}$
• Deca	da	$\times10^{1}$
• Hecto	h	$\times10^{2}$
• Kilo	k	$\times10^{3}$
• Mega	M	$\times10^{6}$
• Giga	G	$\times10^{9}$
• Tera	T	$\times10^{12}$

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SI Unit System

Le Système International d' Unités
(7-Base in 1960)

- Mass (kilogram, kg)
- Length (meter, m)
- Time (second, s)
- Current (Ampere, A)
- Temperature (Kelvin, K)
- Luminous Intensity (Candela, cd)
- Amount of Substance (mole, mol)

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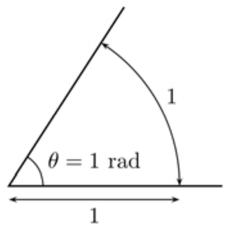
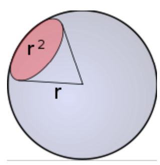
Supplementary Units

- Plane Angle (radian, rad)
  θ = Arc Length / Radius   m/m
- Solid Angle (steradian, sr)
  Ω = Surface Area / Radius^2 m^2/m^2





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Derived Units

e.g.

- Area (m^2)
- Velocity (m/s)
- Frequency (Hertz, Hz = 1/s)
- Force (Newton, N = $kg{\cdot}m/s^2$)
- Energy (Joule, J = N·m = $kg{\cdot}m^2/s^2$)
- Power (Watt, W = J/s = $kg{\cdot}m^2/s^3$)
- Pressure (Pascal, Pa = N/m^2)
- Celsius temperature (°C = K – 273.15)
- Luminous flux (Lumen, lm = cd·sr)
- Illuminance (Lux, lx = lm/m^2)

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Electrical Units

e.g.

- Electric Charge (Coulomb, C = A·s)
- Potential Difference (Volt, V = J/C = W/A)
- Capacitance (Farad, F = C/V)
- Resistance (Ohm, Ω = V/A)
- Conductance (Siemens, S = A/V)
- Magnetic flux (Weber, Wb = V·s)
- Inductance (Henry, H = Wb/A)

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Definition of Electric Current

An electric current (Ampere) is a flow of electric charge (Coulomb per second).

In electric circuits this charge is often carried by moving electrons in a wire.

It can also be carried by ions in an electrolyte, or by both ions and electrons such as in a plasma.

The charge of an electron is approximately -1.602×10^{-19} C.

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Amount of Electric Current

How electrical current affects the human body?

An approximate general framework for shock effects is as follows:

Electric Current (1 second contact)	Physiological Effect of Electric Shock
1 mA	Threshold of feeling, tingling sensation.
10-20 mA	"Can't let go!" current - onset of sustained muscular contraction.
100-300 mA	Ventricular fibrillation, fatal if continued.

http://hyperphysics.phy-astr.gsu.edu/hbase/electric/shock.html

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Definition of Potential Difference

Electric potential (Volt) is the amount of work (Joule) needed to move a unit charge (Coulomb) from a reference point to a specific point against an electric field.

Voltage is the difference of electric potentials between those two given points in the space.

Amount of Voltage

The numerical definition of voltage depends on context. For example, this is in the context of building wiring and the safety of electrical apparatus (IEC 60038 Voltage Standard).

IEC Voltage Range (for Supply System)	AC (V_{rms})	DC (V)	Defining Risk
Extra-low voltage	< 50	< 120	low risk
Low voltage	50-1000	120-1500	electrical shock
High voltage	> 1000	> 1500	electrical arcing

IEC stands for *the International Electrotechnical Commission.*

Definition of Electrical Resistance

The electrical resistance (Ohm) of a circuit component or device is defined as the ratio of the voltage (Volt) applied to the electric current (Ampere) which flows through it.

Whether or not a material obeys Ohm's law, its resistance can be described in terms of its bulk resistivity.

The resistivity, and thus the resistance, is temperature dependent.

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Amount of Resistivity

Electrical resistivity or volume resistivity is an intrinsic property that quantifies how strongly a given material opposes the flow of electric current.

resistivity

$$\rho = R\frac{A}{\ell}$$

cross-sectional area of the specimen

length of the piece of material

resistance

At 20 °C

Material	Example	Resistivity (Ω·m)
Superconductors	Mercury	0
Metals	Copper, Gold, Aluminium	$> 10^{-8}$
Semiconductors	Up to degree of doping	Variable
Electrolytes	Salt water, Nitric acid	Variable
Insulator	Wood, Air, Teflon	$> 10^{16}$

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Dimensional Analysis

Dimensional analysis, also called unit factor method, is a problem-solving method that uses the fact that any number can be multiplied by one without changing its value, e.g.

- Time in minutes, 1 min = 60 s
- Length in inches, 1″ = 2.54 cm
- Weight in pounds, 1 lb = 0.45359237 kg
- Volume in litres, 1 L = 1000 cc = 1000 cm^3

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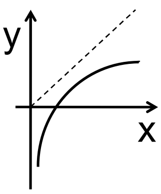
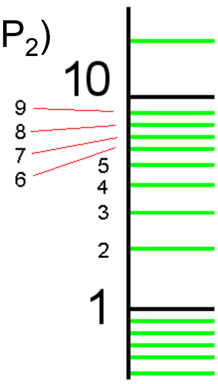
Decibels

The ratio between two values expressed on a logarithmic scale,
e.g. to the base-10 → $y = \log_{10}x$ or $x = 10^y$.

$$N_{bel} = \log(P_1/P_2)$$
$$N_{dB} = 10\log(P_1/P_2)$$



e.g. $10\log(10^{-1}) = -10$ dB
↓ ↓
$10\log(10^{0}) = 0$ dB
↓ ↓
$10\log(10^{1}) = 10$ dB
↓ ↓
$10\log(10^{2}) = 20$ dB



Note: Natural log, ln = $\log_e$ where e = 2.718281...

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Decibel to Voltage Gain and Loss

In electrical circuits, dissipated power is typically proportional to the square of voltage or current when the impedance is held constant.

If V_1 is the voltage being measured and V_2 is a specified reference voltage, the power gain expressed in decibels is as follows:

$$G_{dB} = 20 \log(V_1/V_2)$$

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Error of a Measurement

- Errors are present in every experiment! If an experiment is well designed and carefully performed, the errors can be reduced to an acceptable level (their effects are not significant).
- Error = Measured Value – True Value
- Percentage Error = $\dfrac{\text{Error}}{\text{True Value}} \times 100\%$
- Degree of Uncertainty = $\pm$ %Error

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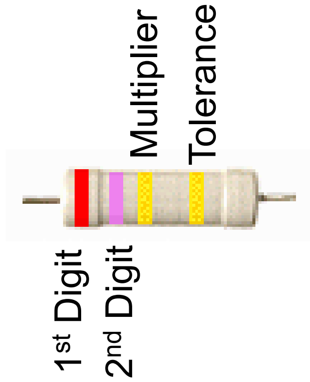
Error of a Measurement (2)

e.g. Resistor codes

None		(±20%)
Silver	-2	(±10%)
Gold	-1	(±5%)
Black	0	
Brown	1	(±1%)
Red	2	(±2%)
Orange	3	
Yellow	4	
Green	5	(±0.5%)
Blue	6	(±0.25%)
Violet	7	(±0.1%)
Grey	8	(±0.05%)
White	9	



$27\times10^{-1}\ \Omega \pm 5\%$

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Random Error

- **Random error** is unpredictable for a successive reading of the same quantity.
- **Operating error** from the measurement situation leading to small variations.
- **Environmental error** such as a temperature or a humidity.
- **Stochastic error** e.g. electrical noise.

Electronic noise generated by the thermal agitation of the charge carriers inside an electrical conductor was first measured by John B. Johnson and explained by Harry Nyquist at Bell Labs in 1926.

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Systematic Error

- **Systematic error** remains constant with repeated measurements.
- **Construction error** from manufacture of an instruments
- **Calibration error** from an incorrect setting.
- **Approximation error** e.g. for a linear scales
- **Ageing error** for the old instrument.
- **Loading error** for inserting a quantity affecting its value.

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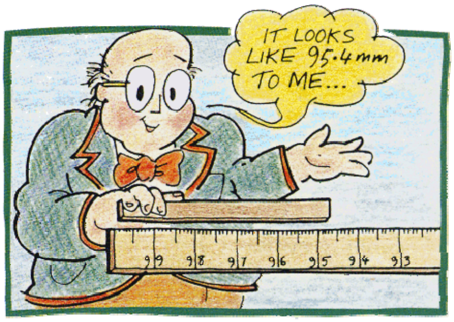
Human Error

- **Human error** or gross error, the most common of errors, is the mistake made by humans in using instruments and taking the readings.
- **Misreading** of the operator.
- **Calculation error** of the operator.
- **Incorrect instruments** chosen by the operator.
- **Incorrect adjustment** of any conditions.



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Accuracy

- Accuracy refers to how closely a measured value agrees with the correct value.

- Error = Measured Value – Expected Value

$$e = x_{measured} - x_{expected}$$

- Percent Error = (Error / Expected Value)×100

$$\%e = |\,(x_{measured} - x_{expected}) / x_{expected}\,| \times 100$$

- Accuracy = 100 – Percent Error

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Precision

- Precision refers to how closely individual measurements agree with each other.

- Deviation = Measured Value – Average Value

$$d = x_{measured} - x_{average}$$

- Percent Deviation = (Deviation / Average Value) ×100

$$\%d = |\,(x_{measured} - x_{average}) / x_{average}\,| \times 100$$

- Precision = 100 – Percent Deviation

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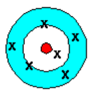
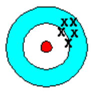
Accuracy Vs Precision

e.g. When a meter is said to be accurate to 1%, this means that a reading taken anywhere along one of its scale will not be in error by more than 1% of the full-scale value.



Accurate
(the average is accurate)
but not precise



Precise
but not accurate
(calibration needed)

Accurate
and precise

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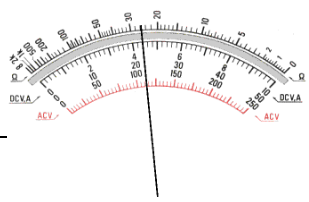
Resolution and Sensitivity

- Resolution is the significance of the least significant digits, e.g. the range of ammeter is 199 mA with a resolution of 0.1 mA. The range would be 000.0, 000.1, 000.2, …, 199.9 mA
  or 3½ meter (the most significant digits can only be either a 0 or 1.)



- Sensitivity = $\dfrac{\text{Change in the Output}}{\text{Change in the Input}}$

e.g. $\dfrac{\text{Change in instrument scale reading}}{\text{Change in the quantity being measured}}$

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Reading Resolution of Digital Multimeter (DMM)

For 3½ digits display

- 0 0 0.1 ➔ 0.1 V for each step
- 0 0.0 1 ➔ 0.01 V for each step
- 0.0 0 1 ➔ 0.001 V for each step

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Accuracy of DMM

- For example
  ± (0.5% Reading + 1 Digit LSB)
- when you read a voltage 1.8 V

$$\text{error} = \pm (0.5\% \text{ of } 1.8V + 0.001V)$$
$$= \pm 0.01V$$
$$\approx \pm 0.56\% \text{ of reading}$$

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Range and Bandwidth

- The range of an instrument refers to the minimum and maximum values of the input variable for which it has been designed. The range chosen should be such that the reading is large enough to give close to the required precision.
- The bandwidth of an instrument is the difference between the minimum and maximum frequencies for which it has been designed. If the signal is outside the bandwidth, it will not be able to follow changes in the quantity being measured.

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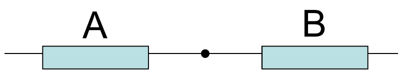
Summation of Error



Relative Error

$100\Omega \pm 10\%$ $\quad$ $200\Omega \pm 5\%$

$90\Omega \leftrightarrow 110\Omega\ (\pm 10\Omega)$ $\quad$ $190\Omega \leftrightarrow 210\Omega\ (\pm 10\Omega)$

Absolute Error

$$X = A + B$$

$$\begin{aligned} X \pm \Delta X &= A \pm \Delta A + B \pm \Delta B \\ &= (A+B) \pm (\Delta A + \Delta B) \\ &= (100\Omega + 200\Omega) \pm (10+10) \\ &= 300\Omega \pm 20 \end{aligned}$$

$280\Omega \leftrightarrow 320\Omega \quad \Rightarrow$ Extreme!

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Summation of Error (Cont'd)

In case of summation,

$X = A + B$

$X \pm \Delta X = A \pm \Delta A + B \pm \Delta B$

$= (A+B) \pm \sqrt{(\Delta A)^2 + (\Delta B)^2}$

$= 300\Omega \pm 14.14$

$285.86\Omega \leftrightarrow 314.14\Omega \quad \Rightarrow \quad$ Better

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Product of Error

In case of multiplying,

$X = AB$

$X \pm \Delta X = (A \pm \Delta A)(B \pm \Delta B)$

$= AB \pm A\Delta B \pm B\Delta A \pm \cancelto{0}{\Delta A \Delta B}$

$\Delta X = \pm A\Delta B \pm B\Delta A$

$\Delta X/X = (\pm A\Delta B \pm B\Delta A) / AB \ \% \quad \Rightarrow \quad$ %Error

$= \pm \Delta B/B \pm \Delta A/A \ \%$

$= \pm (\Delta B/B + \Delta A/A) \ \%$

or $\Delta X/X = \pm \sqrt{(\Delta B/B)^2 + (\Delta A/A)^2} \ \%$

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References

- Science Help Online Chemistry, http://www.fordhamprep.org/gcurran/sho/sho/index.htm
- Math Skill Reviews: Significant Figures: http://www.chem.tamu.edu/class/fyp/mathrev/mr-sigfg.html

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