南京邮电大学
Nanjing University of Post & Telecom

物理实验教学中心

Physics Expeiment Center

Introduction to college physics experiments

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NJUPT

List of experiments

- 0. Introduction, J2-532
- 1. Torsional Pendulum, J2-427
- 2. Spectrometer, J2-532
- 3. Michelson Interferometer, J2-534
- 4. Oscilloscope, J2-418
- 5. Double Bridge, J2-417
- 6. Wheatstone Bridge, J2-416
- 7. Dielectric constant measurement, J2-429

https://github.com/bliseu/phylab

Part 1

Rules of this course

1. Preparations

Key-points：

- Reference books, Handouts
- Goals, methods, principles
- Experimental conditions
- Preparation reports

Preparation report includes：

1. Title；
2. Your name, student ID, date;
3. Experimental goals；
4. Experimental principles;
5. Experimental apparatus (models, specifications) ;
6. Data Tables

2 . Experiments

At the beginning of the class, I will :

- ➢Check your preparation reports of this lesson;
- ➢Ask for your previous experiment reports;
- ➢Show the experimental principles and the operation.

During the experiments, you should:

- ➢Follow the operating rules;
- ➢Observe experimental phenomena;
- ➢Record the data.

➢Experimental data and phenomenon；

Record: date, time, place, temperature, pressure, instrument serial number, title, specifications, original data and phenomenon…

- Requirement: smooth writing, plotting (when necessary), data, results.
- Good habit: process experimental data and submit reports in time.

3、Contents of experimental reports：

1、Title

2、Goals

3、Instruments

4、Principles

Before class

5、Contents & steps

6、Data processing

7、Discussions and analysis

after class

Part 2

Measurement error and instrumental error range in physics experiments

1、Measurement data & unit

- **data = value+unit**

e.g.： ***175.0*** **cm**

value **unit**

The international system of units (SI)：meter (m)、kilogram (kg)、second (s)、ampere (A)、Kelvin (K)、mole (mol)、candela (cd)

2、Measurement classification

direct

passive

e.g.

The cylinder's density

$$\rho = \frac{4m}{\pi D^2 h}$$

3、 Significant digit and more…

(1). Significant digit： total digit number from first non-zero digit to the last one.

4.60cm≠4.600cm

(2). Significant digit's nature

a). Significant digit tells the precision of measuring instrument

length measurement with different precision

steel ruler： L=46.0mm, $\Delta_{仪}$= 0.1mm,

E_r=0.13%

Vernier calipers: L =46.00mm, $\Delta_{仪}$= 0.02mm ,

E_r=0.026%

micrometer: L=46.000mm, $\Delta_{仪}$= 0.004mm ,

E_r=0.006%

b) Significant digit have nothing to do with decimal point's location and unit

e.g. 4.60 cm   0.0460m   46.0mm

measurement results

0.0125m=1.25cm   1.0900cm≠ 1.09cm

8.88m=8880mm?

(3). Scientific notation

Scientific notation : $a \times 10^n$ (单位)

$8.88\text{m} = 8.88 \times 10^3\text{mm}$

80.30g=0.0803kg?=80300mg?

$80.30\text{g} = 8.030 \times 10^1\text{g} = 8.030 \times 10^4\text{mg}$

$= 8.030 \times 10^{-2}\text{kg}$

(4). rules for rounding

- If the last digit of a number is less than 5, drop it;
- If it is more than 5, the number to be rounded add 1;
- If it is 5, make the last digit be even.

e.g.： if m=3.065kg, u_{cm}=0.042kg

m=(3.06±0.05)kg

e.g.

7.146 rounded to two digits	7.1
0.086 rounded to one digits	0.09
2.4352 rounded to three digits	2.44
17.415 rounded to four digits	17.42
17.425 rounded to four digits	17.42

(5). algorithms

a) addition and subtraction

e.g.

$$A+B+C=14.7\overline{\boxed{8}}+0.004\overline{7}-1.50\overline{3}$$

$$=13.2\overline{8}\,\overline{1}\,\overline{7}=13.2\overline{\boxed{8}}$$

Shortest decimal

b) Multiplication and division

e.g.

$$A \times B \times C = 24.56\bar{8} \times \boxed{3.4\bar{5}} \times 128.\bar{4}$$

$$= 10883.13264 = \boxed{1.09} \times 10^{4}$$

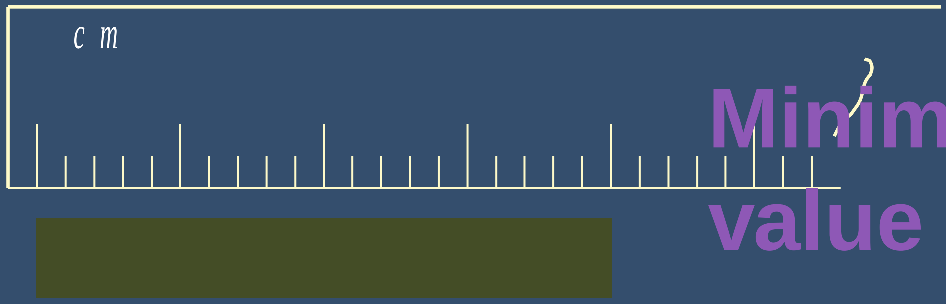
Shortest digit

(6)、the rule to read data(direct)

instrumental error or minimum graduation value

a：ruler

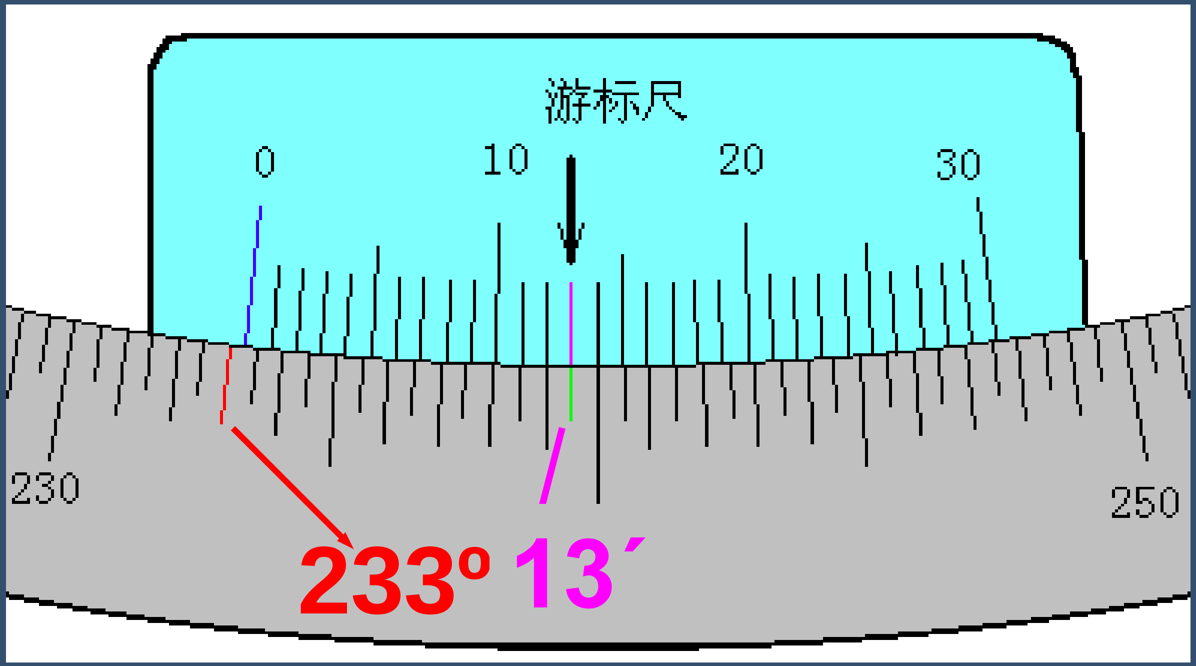
2cm or 20mm?



Minimum graduation value 1/5 ~ 1/2

2.00cm or 20.0mm

b：angular vernier



e.g. vernier calipers

c： reading of digital meter

reading :23.9℃

4、 error and uncertainty

Error and true value

true value： a

measured value: x

error： ε $\quad \varepsilon = x - a$

Classification of error

error $\Rightarrow$ $\left\{ \begin{array}{l} \text{Systematic error} \\ \text{Random error} \\ \text{gross error} \end{array} \right.$

Systematic error

uncertainty

★**uncertainty:** range of fluctuation

the uncertainty *u*

1. *A* uncertainty : u_A
2. *B* uncertainty : u_B
3. Synthetic uncertainty:

$$u = \sqrt{u_B^2 + u_A^2}$$

A uncertainty

$$u_A = \frac{st}{\sqrt{n}} = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{x})^2}{(n-1)}} \cdot \frac{t}{\sqrt{n}}$$

t distribution factor， n measurement times， probability P=0.95：

n	2	3	4	5	6	7	8	9	10
t	12.71	4.30	3.18	2.78	2.57	2.45	2.36	2.31	2.26
$\frac{t}{\sqrt{n}}$	8.99	2.48	1.59	1.24	1.05	0.93	0.84	0.77	0.72

B uncertainty

instrument error ,Limit error

instrument error： Δ

instrument error =Level × range

***B* uncertainty**

$$u_B = \Delta_{ins}$$

Synthetic uncertainty

$$u = \sqrt{u_B^2 + u_A^2}$$

measurement result：

$$N = N_M \pm u \quad \text{(unit)}$$

u=Synthetic uncertainty,

N_M= best estimation of measurement data

Single measurement, Multiple/Repeated measurement

1、result of single direct measurement

single direct measurement

estimated true value： result of single measurement

$$u = u_B = \Delta_{仪}$$

$$N = N_m \pm \triangle \ \text{(unit)}$$

N_m have same decimal as $\triangle$

2、result of repeated measurement

$$N = \overline{N} \pm u \text{ (unit)}$$

estimated true value： $\overline{N}$

uncertainty：

$$u = \sqrt{u_A^2 + u_B^2}$$

$$\mu_A = \sqrt{\frac{\sum (N_i - \overline{N})^2}{(n-1)}} \cdot \frac{t}{\sqrt{n}} \qquad \mu_B = \Delta_{仪}$$

Example 1: Vernier caliper(division:50), cylinder diameter, 10 times.

times	1	2	3	4	5	6	7	8	9	10
d_i(cm)	19.78	19.80	19.70	19.78	19.74	19.76	19.72	19.68	19.80	19.72

$$\bar{d} = \frac{\sum_{i=1}^{10} d_i}{10} = 19.75mm$$

$$u_A = S_{\bar{d}} \cdot \frac{t}{\sqrt{n}} = \sqrt{\frac{\sum_{i=1}^{10} (d_i - \bar{d})^2}{9}} \cdot 0.72 = 0.0108mm$$

$$u_B = \Delta_{仪} = 0.02mm$$

uncertainty

$$u = \sqrt{u_A^2 + \Delta_{仪}^2} = \sqrt{0.0108^2 + 0.02^2}$$

$$\approx 0.0227mm \approx 0.023mm$$

diameter

$$d = \bar{d} \pm u_d = 19.750 \pm 0.023(mm)$$

Same decimal

relative uncertainty

L_1=(170.0 ± 0.3) (cm) E_{r1}=0.18%

L_2=(17.0 ± 0.3) (cm) E_{r1}=1.8%

relative uncertainty, E_r

$$E_r = \frac{u}{\overline{N}} \times 100\%$$

(3) percentage error

$$E_0 = \frac{|N - N_0|}{N_0} \times 100\%$$

$E_r=1.54\% \longrightarrow E_r=1.\underline{6}\%$

$E_r=3.82\% \longrightarrow E_r=3.\underline{9}\%$

$E_0=5.04\% \longrightarrow E_0=\underline{6}\%$

Indirect measurement

if， $N = f(x, y, z\ldots.)$

$x, y, z\ldots.$ direct measurement

if $\bar{x}, \bar{y}, \bar{z}\cdots\cdots$ best estimates of direct measurement

best estimates of indirect measurement

$$\bar{N} = f(\bar{x}, \bar{y}, \bar{z}\cdots\cdots)$$

Estimate of uncertainty（indirect measurement）

N uncertainty

$$u_N = \sqrt{\left(\frac{\partial f}{\partial x}\right)^2 u_x{}^2 + \left(\frac{\partial f}{\partial y}\right)^2 u_y{}^2 + \cdots}$$

N relative uncertainty

$$E_r = \frac{u_N}{N} = \sqrt{\left(\frac{\partial \ln f}{\partial x}\right)^2 u_x{}^2 + \left(\frac{\partial \ln f}{\partial y}\right)^2 u_y{}^2 + \cdots}$$

Result of indirect measurement

$$N = \bar{N} + \mu_N$$

$$\bar{N} = f(\bar{x}, \bar{y}, \cdots)$$

★calculation processing （uncertainty）

1、direct measurement $(x, y, \cdots)$ uncertainty $(u_x, u_y, \cdots)$

2、function $N = f(x, y, \cdots)$

N total derivative $dN = \frac{\partial f}{\partial x} dx + \frac{\partial f}{\partial y} dy + \cdots$

3、N uncertainty u_N

$$\boxed{u_N = \sqrt{(\frac{\partial f}{\partial x})^2 u_x{}^2 + (\frac{\partial f}{\partial y})^2 u_y{}^2 + \cdots}}$$

★calculation processing （relative uncertainty)

1、 direct measurement uncertainty u_x， u_y， …;

2、function $N = f(x, y, \cdots)$

logarithm $\ln N = \ln f(x, y, \cdots)$

ln N total derivative $\dfrac{dN}{N} = \dfrac{\partial \ln f}{\partial x}dx + \dfrac{\partial \ln f}{\partial y}dy + \cdots$

3、relative uncertainty of *N*

$$E_r = \frac{u_N}{N} = \sqrt{(\frac{\partial \ln f}{\partial x})^2 u_x{}^2 + (\frac{\partial \ln f}{\partial y})^2 u_y{}^2 + \cdots}$$

Example 2: **Using pendulum to measure acceleration of gravity:** $g=4\pi^2 l/T^2$,

$T=2.000 \pm 0.002s, l=100.0 \pm 0.1cm$, **try to write a gravitational acceleration** g **expression.**

answer:

$$g=\frac{4\pi^2 l}{T^2}, \ln g=\ln 4\pi^2+\ln l-2\ln T$$

$$\frac{\partial \ln g}{\partial l}=\frac{1}{l}, \frac{\partial \ln g}{\partial T}=-\frac{2}{T}$$

$$E_r=\frac{u_g}{g}=\sqrt{\left(\frac{\partial \ln g}{\partial l}\right)^2 u_l^{\,2}+\left(\frac{\partial \ln g}{\partial T}\right)^2 u_T^{\,2}}$$

Thus:

$$E_r = \sqrt{\left(\frac{u_l}{l}\right)^2 + 4\left(\frac{u_T}{T}\right)^2} = \sqrt{\left(\frac{0.1}{100}\right)^2 + 4\left(\frac{0.002}{2.000}\right)^2}$$

$$= 2.24 \times 10^{-3} = 0.23\%$$

$$g = \frac{4\pi^2 l}{T^2} = \frac{4 \times 3.1416^2 \times 100.0}{2.000^2} = 987.0(cm/s^2)$$

$$u_{cg} = E_r \cdot g = 2.24 \times 10^{-3} = 2.3(cm/s^2)$$

Round to the nearest tenth , carry only!

acceleration of gravity **$g=(987.0 \pm 2.3)\ (cm/s^2)$**

align

Part 3
Methods of data processing

1. Tabulation

Notes:

a. Table design: reasonable， straightforward， complete.

b. Title bar: physical quantity’s name、 mark,unit.

c. Data: effective number.

d. instruction and parameter （table name, measuring instrument specifications, environment condition).

e. main->original data, important intermediate result.

Table　Data of wire diameter measurement

Instrument：micrometer caliper，Level：1，range：0～25mm，error：±0.004mm,initio data:-0.005mm

Order	data（mm）	diameter D_I(mm)	$D_i - \bar{D}$ (mm)	$(D_i-\bar{D})^2(\times 10^{-8}mm^2)$
1	0.280	0.285	0.0022	484
2	0.278	0.283	0.0002	4
3	0.275	0.280	-0.0028	784
4	0.284	0.289	0.0062	3844
5	0.272	0.277	-0.0052	2704
6	0.278	0.283	0.0002	4
Average		0.282 8		$\sum(D_i-\bar{D})^2=7824$

$$S_{\bar{D}} = 1.7\times10^{-3}mm, \sigma_{仪} = \frac{\Delta_{仪}}{\sqrt{3}} = \frac{0.004mm}{\sqrt{3}} = 2.3\times10^{-3}mm,$$

$$u_{cD} = \sqrt{S_{\bar{D}}^{\ 2} + \sigma_{仪}^{\ 2}} = 2.9\times10^{-3}mm = 0.003mm,$$

$$D = \bar{D} \pm u_{cD} = (0.283\pm0.003)mm$$

2. Graphical method

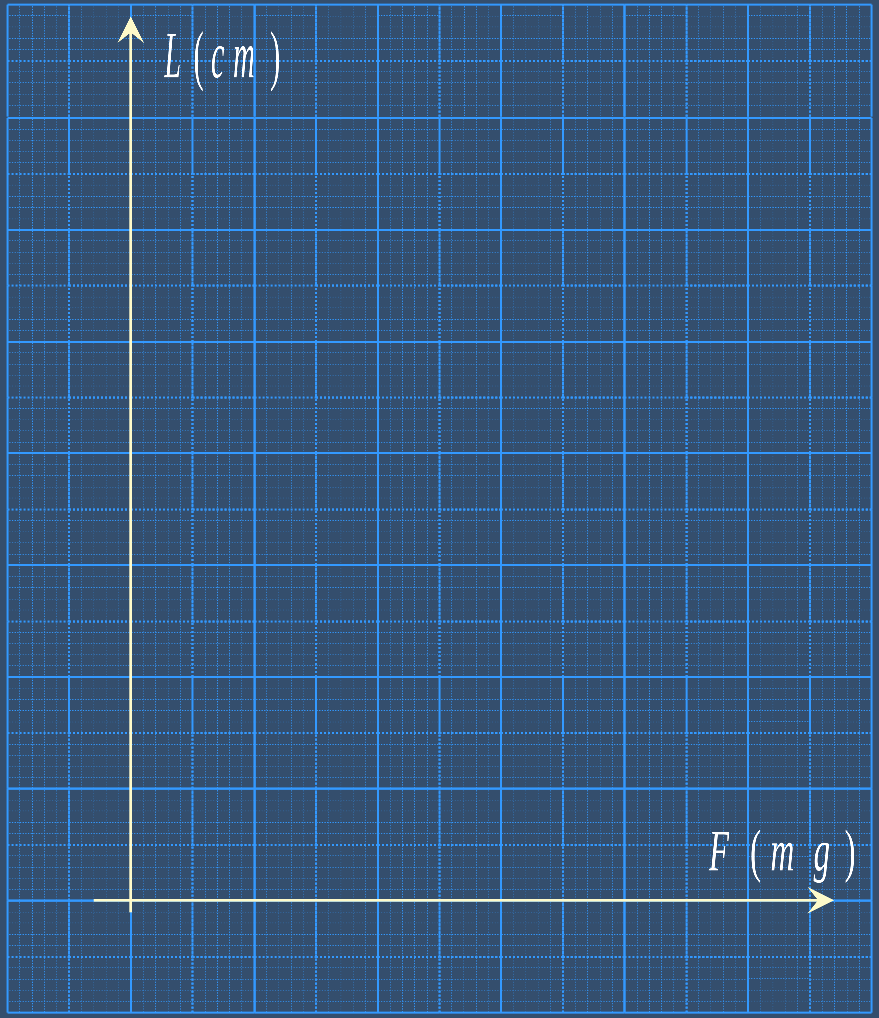
- Numbers, Lines
- Mapping rules

Mapping rules

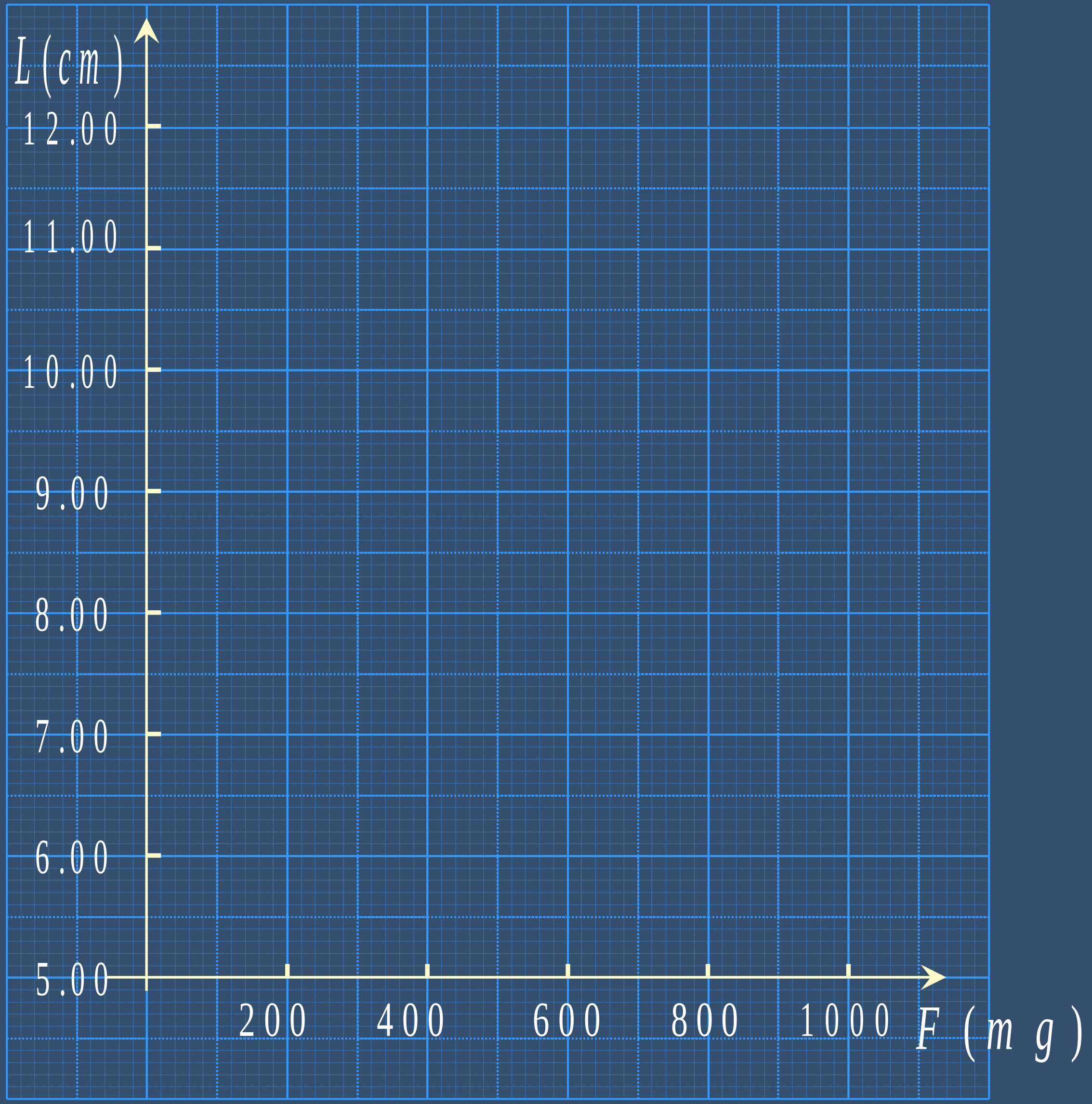
1、Plotting From Data table

2、Using coordinate paper

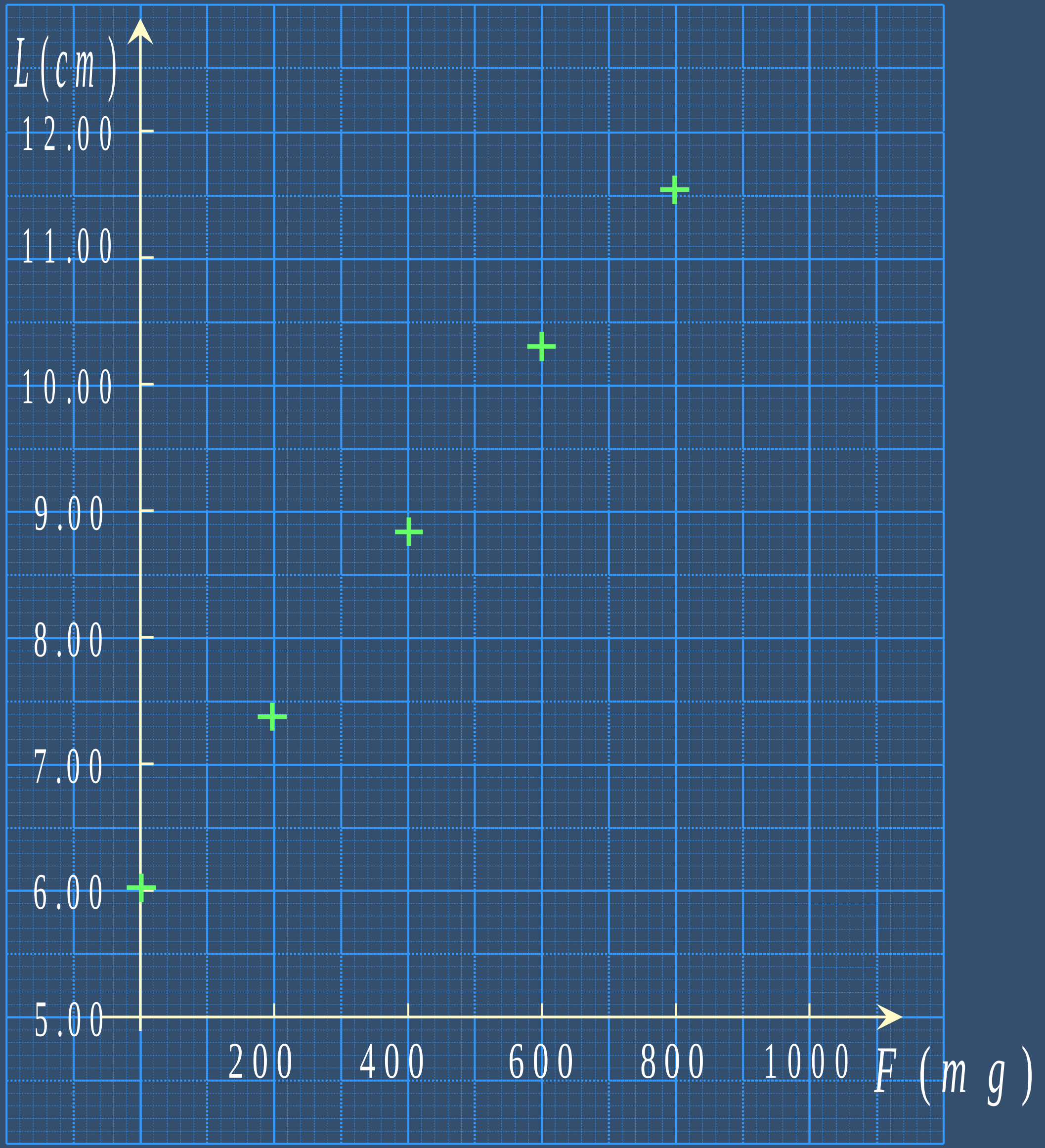
3. Coordinates



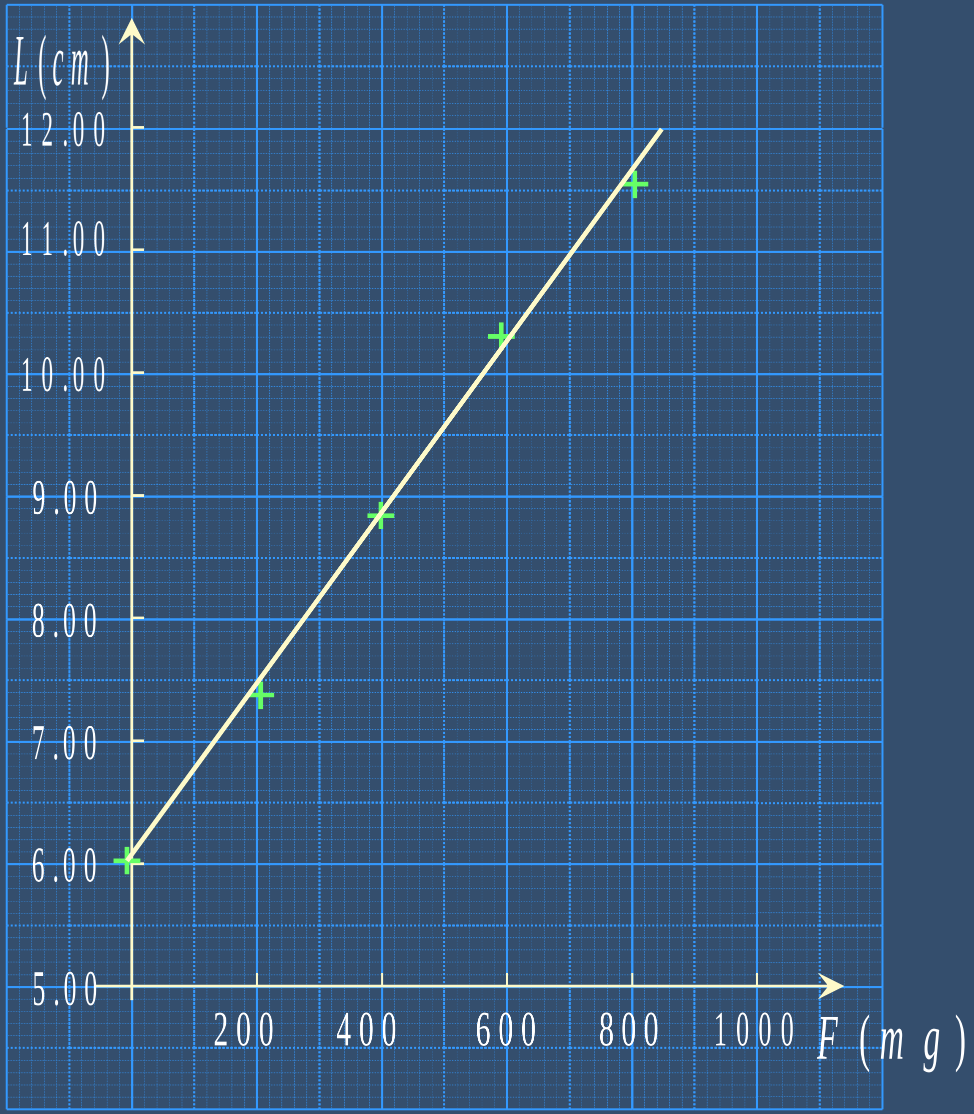
4.Coordinate indexing



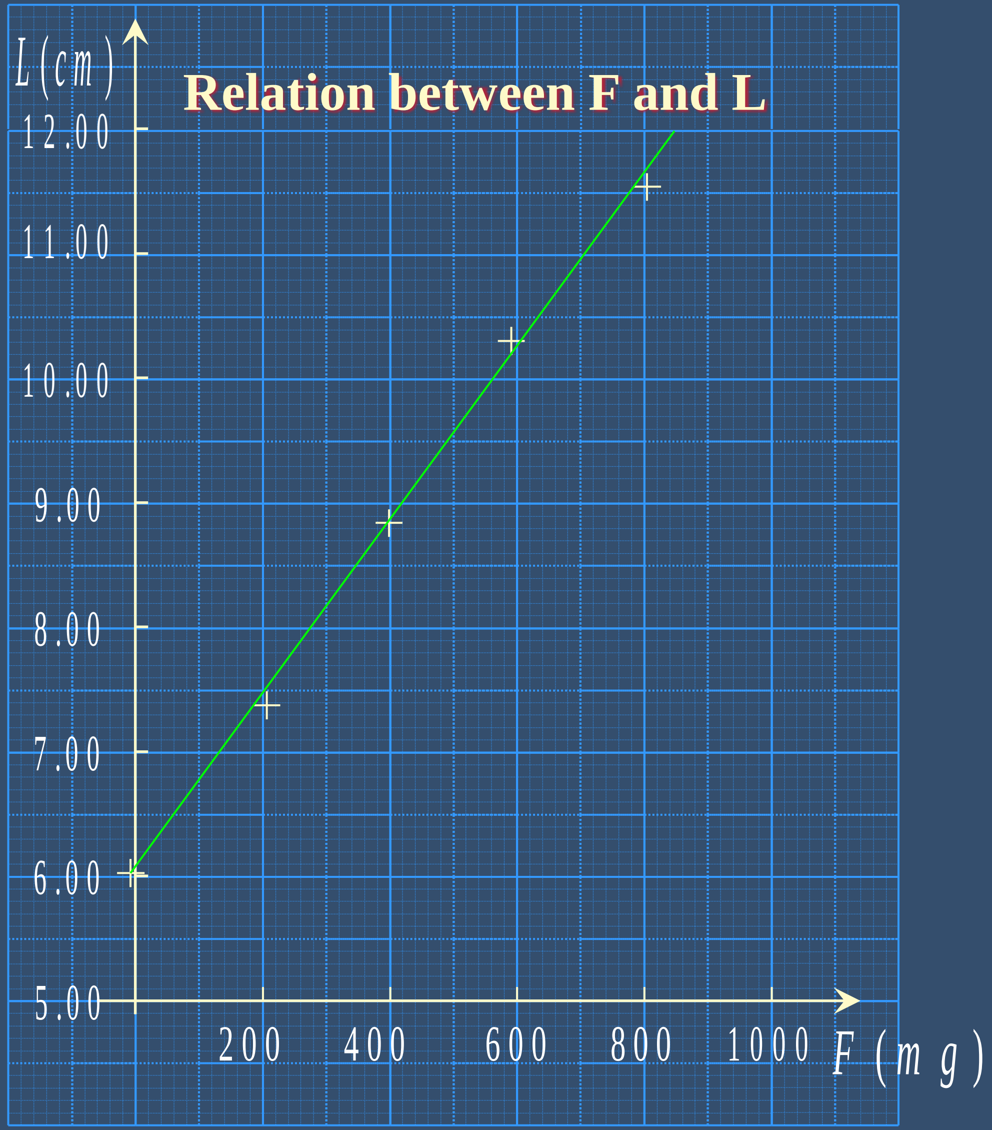
5. Experimental data points



6. Draw curve



7. Introductions



Graphical method

1） Coordinate values

（x_1， y_1）、 （x_2， y_2）。

equation of straight line：

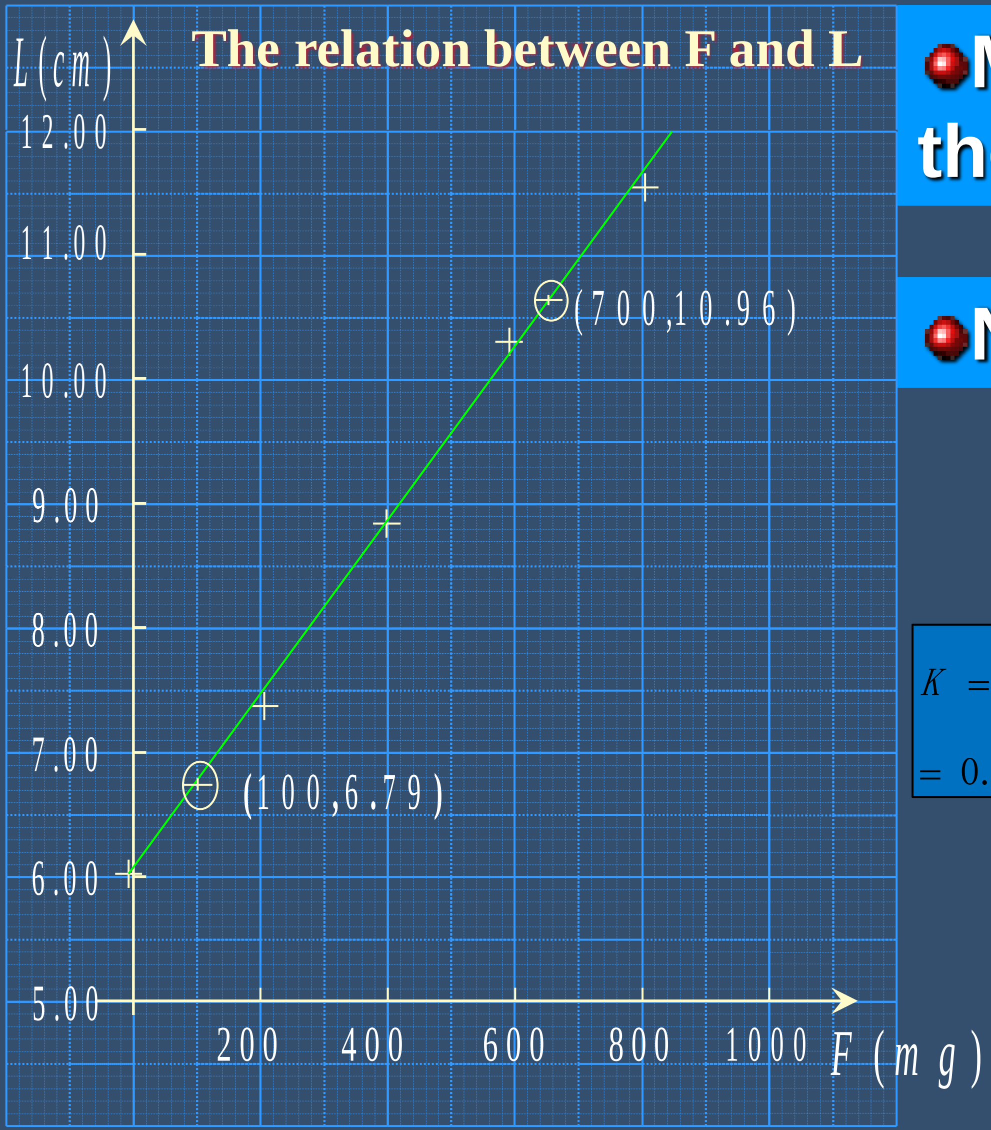
$$y = a + bx$$

2） slope **b**：

$$b = \frac{y_2 - y_1}{x_2 - x_1}$$

3） intercept **a**：

$$a = \frac{x_2 y_1 - x_1 y_2}{x_2 - x_1}$$



- Mark **2** points on the line.

- Note the distance

$$K = \frac{(700-100)\times 9.794\times 10^{-6}}{(10.96-6.79)\times 10^{-2}}$$
$$= 0.141 N/m$$

3. Method of successive minus

- method of successive minus：
  - experimental data->table

    verify law of variation of data.
  - divide into two groups: high,low

    Make full use of data， reduce measurement error。

➢**Verify the *linear relationship of L_i* and*F* 。**

$$\Delta\overline{L} = \tfrac{1}{7}\left[(L_1 - L_0) + (L_2 - L_1) + \cdots + (L_7 - L_6)\right]$$
$$= \tfrac{1}{7}\left[L_7 - L_0\right]$$

Intermediate data ×

beginning and end ○。

If we divide data into（L_7，L_6，L_5，L_4）
and（L_3，L_2，L_1，L_0）。

$$\Delta \overline{L} = \frac{1}{4}[(L_7 - L_3) + (L_6 - L_2) \cdots + (L_4 - L_0)]$$

Make full use of data，Keep all the merits of Multi-times measurement.

Summary

1. Rules of this course;

2. Significant digit， rules for rounding， algorithm， reading

3. Uncertainty calculation， rules for rounding

U_A， U_B， U

Indirect measurement

4. Measurement results：

$$N = N_M \pm u_c \quad \text{(unit)}$$

u_c: *Synthetic uncertainty*， N_M: best estimation of measurement data

5. Data processing methods：

tabulation method， graphical method， method of successive minus

END