Physics : Part 1 : Video 4a : Experimental Enquiry

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Department of Physics

Physics is an Experimental Science first

One must learn by doing the things; for though you think you know it, you have no certainty until you try.

Sophocles (495 – 406 B.C.)

Greek Dramatist

Einstein is a great fan of experimental physics … as you can see, he enjoys a backyard stargazing session even though he can access bigger telescopes anytime.

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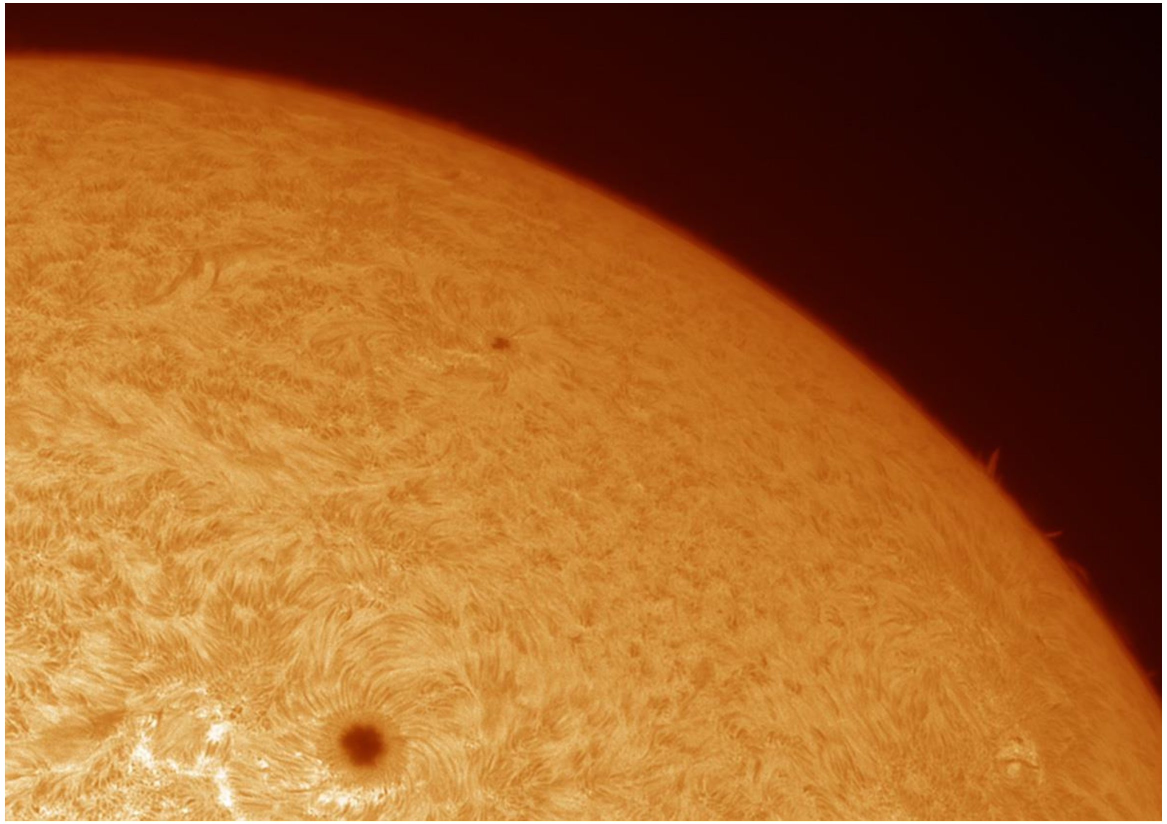
Example : NUS Physics Roof Observatory



Taken by Leong Qixiang (NUS Astro-particle Physics Group)

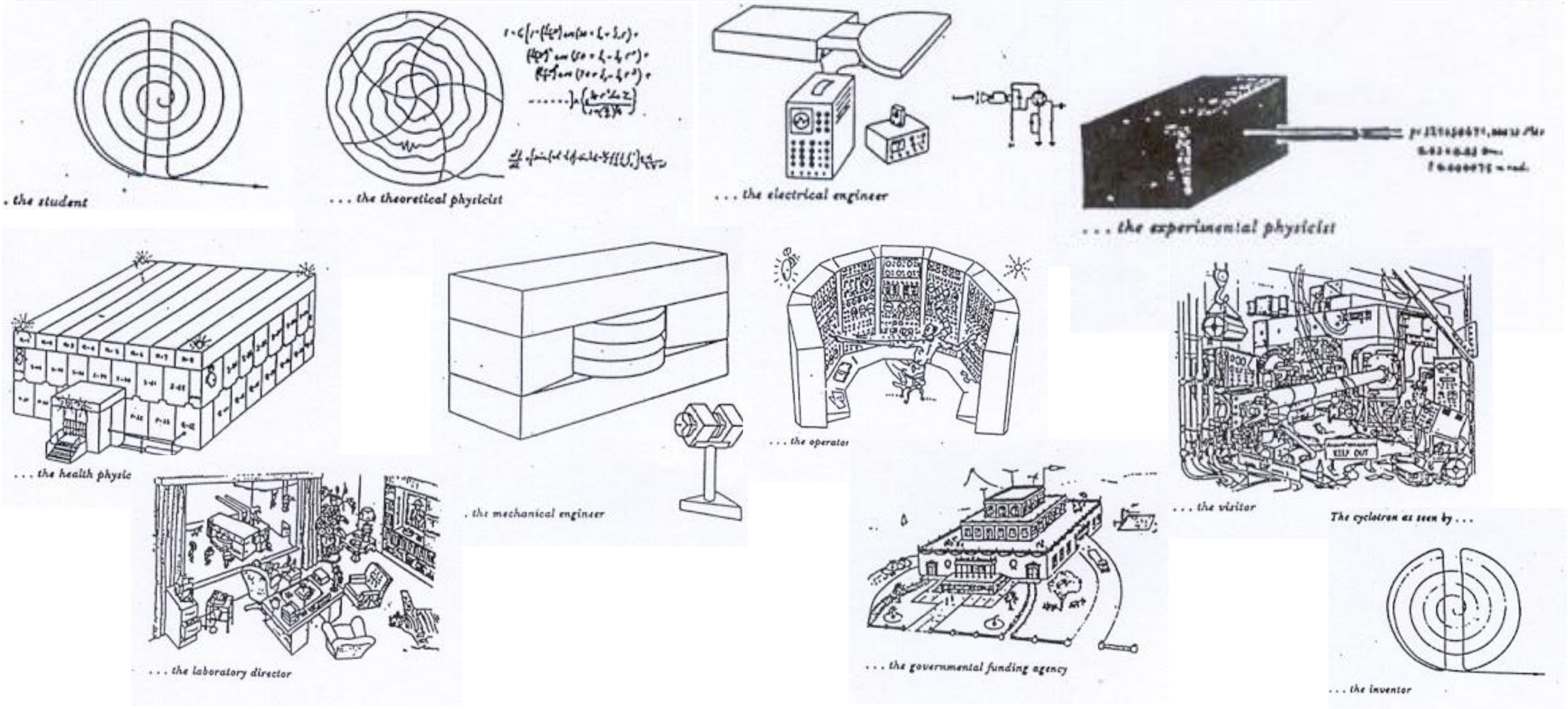
17.5” Plain-Wave CDK (F6.8 Corrected Dall-Kirkham) Astrograph Telescope (Dual carbon-fiber truss design) equipped with a 4” Takahashi (Hydrogen Alpha Solar scope) on the latest computerized Showa 25E German Equatorial Mount.

Example : Big Scientific Collab. CERN

Sometimes
known as
European Center
for Nuclear
Research

Singapore (NUS Physics Department) is a Member (EOI)
of this CERN High Energy Particle Physics Collaboration

Example : Big Scientific Collab. CERN



. the student

. . . the theoretical physicist

. . . the electrical engineer

. . . the experimental physicist

. . . the health physic

. the mechanical engineer

. . . the operator

. . . the visitor

The cyclotron as seen by . . .

. . . the laboratory director

. . . the governmental funding agency

. . . the inventor

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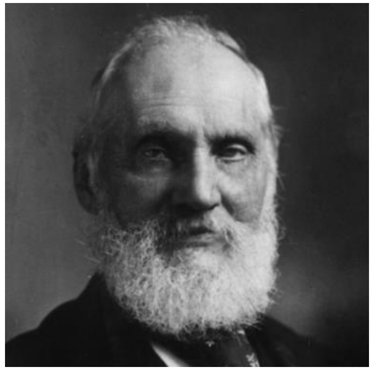
One basic characteristic of Science

When you can measure what you are speaking about, and express it in numbers, you know something about it; when you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind; it may be the beginning of knowledge, but you have scarcely in your thoughts advanced to the stage of science.



To measure is to know !

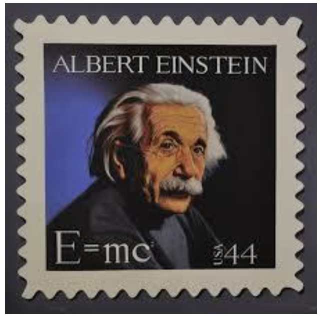
William Thomson, 1st Baron Kelvin

A. Hobson, *Physics, Concepts and Connections*, 2010 Addison-Wesley.

Making a Measurement

Einstein kept a sign in his office that reads :

Not everything that counts can be counted, and not everything that can be counted counts.



A Caveat :

Not everything that matters can be measured.

A. Einstein

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https://www.kellogg.northwestern.edu/news/hits/061101inc.htm

Interpret the Data (through a theory)

… But quantity is less relevant than quality … You must be able to interpret the data and enjoy the process …

Seven of Nine
Star Trek Voyager, S6E09

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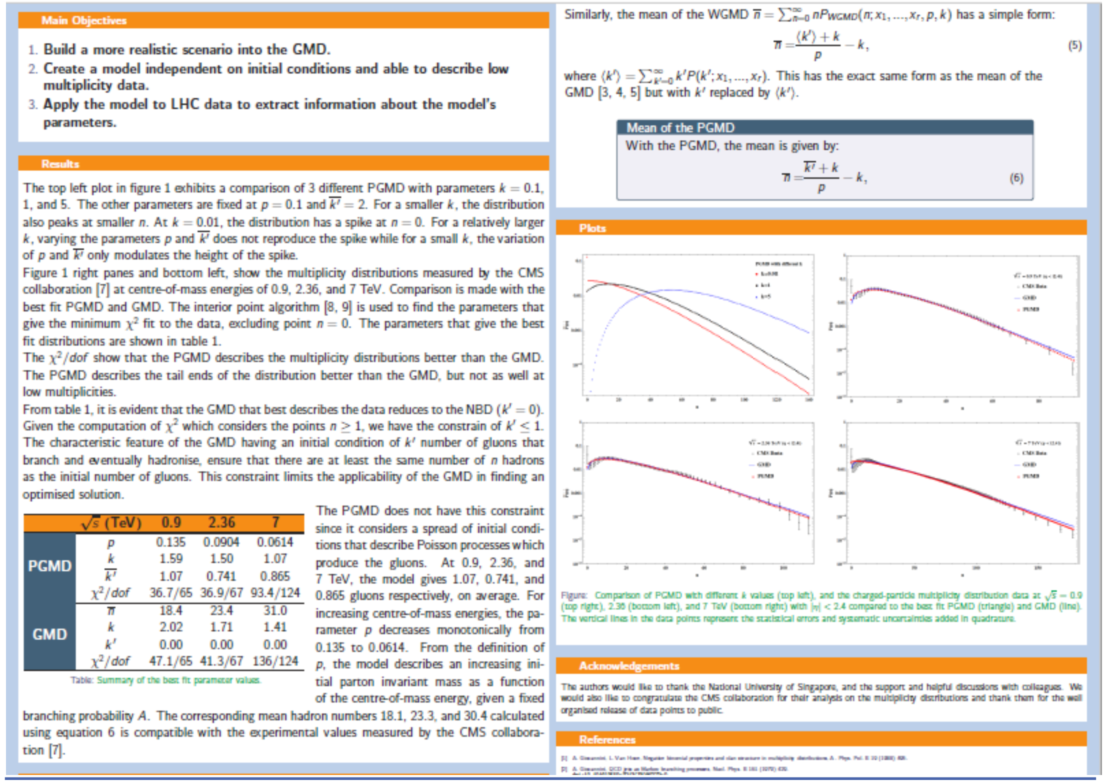
Presentation of data : Graphs & Errors

We normally Examine and Question the Axes, Units and Scales.



Main Objectives

1. **Build a more realistic scenario into the GMD.**
2. **Create a model independent on initial conditions and able to describe low multiplicity data.**
3. **Apply the model to LHC data to extract information about the model's parameters.**

Results

The top left plot in figure 1 exhibits a comparison of 3 different PGMD with parameters $k = 0.1$, 1, and 5. The other parameters are fixed at $p = 0.1$ and $\overline{k'} = 2$. For a smaller k, the distribution also peaks at smaller n. At $k = 0.01$, the distribution has a spike at $n = 0$. For a relatively larger k, varying the parameters p and $\overline{k'}$ does not reproduce the spike while for a small k, the variation of p and $\overline{k'}$ only modulates the height of the spike.

Figure 1 right panes and bottom left, show the multiplicity distributions measured by the CMS collaboration [7] at centre-of-mass energies of 0.9, 2.36, and 7 TeV. Comparison is made with the best fit PGMD and GMD. The interior point algorithm [8, 9] is used to find the parameters that give the minimum χ^2 fit to the data, excluding point $n = 0$. The parameters that give the best fit distributions are shown in table 1.

The χ^2/dof show that the PGMD describes the multiplicity distributions better than the GMD. The PGMD describes the tail ends of the distribution better than the GMD, but not as well at low multiplicities.

From table 1, it is evident that the GMD that best describes the data reduces to the NBD ($k' = 0$). Given the computation of χ^2 which considers the points $n \geq 1$, we have the constrain of $k' \leq 1$. The characteristic feature of the GMD having an initial condition of k' number of gluons that branch and eventually hadronise, ensure that there are at least the same number of n hadrons as the initial number of gluons. This constraint limits the applicability of the GMD in finding an optimised solution.

	$\sqrt{s}$ (TeV)	0.9	2.36	7
PGMD	p	0.135	0.0904	0.0614
	k	1.59	1.50	1.07
	$\overline{k'}$	1.07	0.741	0.865
	χ^2/dof	36.7/65	36.9/67	93.4/124
GMD	$\overline{n}$	18.4	23.4	31.0
	k	2.02	1.71	1.41
	k'	0.00	0.00	0.00
	χ^2/dof	47.1/65	41.3/67	136/124

Table: Summary of the best fit parameter values.

The PGMD does not have this constraint since it considers a spread of initial conditions that describe Poisson processes which produce the gluons. At 0.9, 2.36, and 7 TeV, the model gives 1.07, 0.741, and 0.865 gluons respectively, on average. For increasing centre-of-mass energies, the parameter p decreases monotonically from 0.135 to 0.0614. From the definition of p, the model describes an increasing initial parton invariant mass as a function of the centre-of-mass energy, given a fixed branching probability A. The corresponding mean hadron numbers 18.1, 23.3, and 30.4 calculated using equation 6 is compatible with the experimental values measured by the CMS collaboration [7].

Similarly, the mean of the WGMD $\overline{n} = \sum_{n=0}^{\infty} nP_{WGMD}(n; x_1, ..., x_r, p, k)$ has a simple form:

$$\overline{n} = \frac{\langle k' \rangle + k}{p} - k, \qquad (5)$$

where $\langle k' \rangle = \sum_{k'=0}^{\infty} k' P(k'; x_1, ..., x_r)$. This has the exact same form as the mean of the GMD [3, 4, 5] but with k' replaced by $\langle k' \rangle$.

Mean of the PGMD

With the PGMD, the mean is given by:

$$\overline{n} = \frac{\overline{k'} + k}{p} - k, \qquad (6)$$

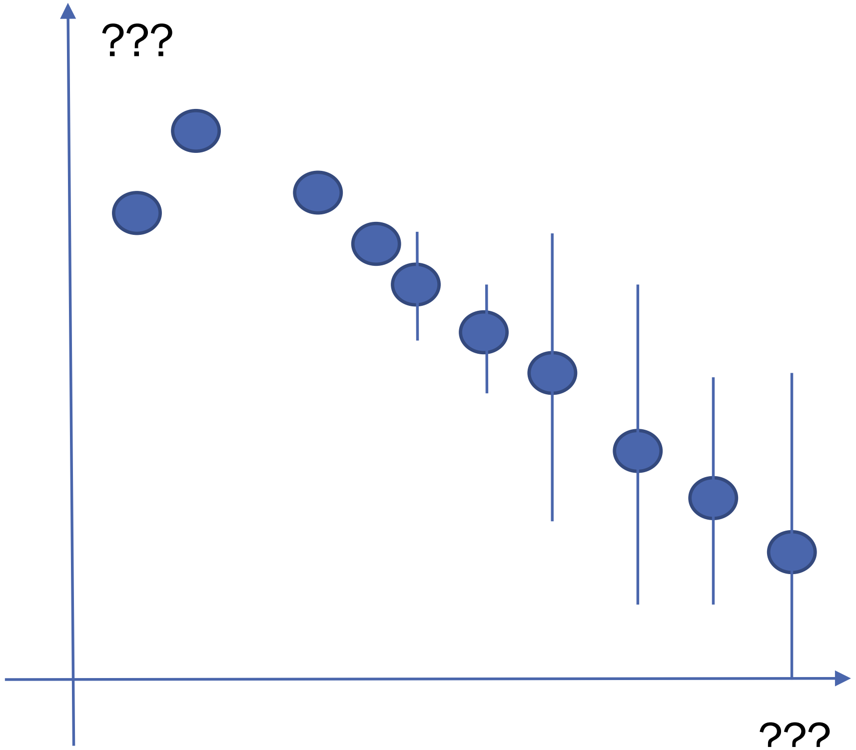
Plots

Figure: Comparison of PGMD with different k values (top left), and the charged-particle multiplicity distribution data at $\sqrt{s} = 0.9$ (top right), 2.36 (bottom left), and 7 TeV (bottom right) with $|\eta| < 2.4$ compared to the best fit PGMD (triangle) and GMD (line). The vertical lines in the data points represent the statistical errors and systematic uncertainties added in quadrature.

Acknowledgements

The authors would like to thank the National University of Singapore, and the support and helpful discussions with colleagues. We would also like to congratulate the CMS collaboration for their analysis on the multiplicity distributions and thank them for the well organised release of data points to public.

References



The above came from a publication done by the NUS High Energy Particle Physics group

Error Analysis is a Big Industry

Here we can only outline the basic ideas and give an appreciation of Error Analysis. We will also make connection on some of the “error” procedures you would have encountered in Junior College and High School physics.

On the up side, mastering Error Analysis will stand a student in good stead for Data Analytics jobs in future.

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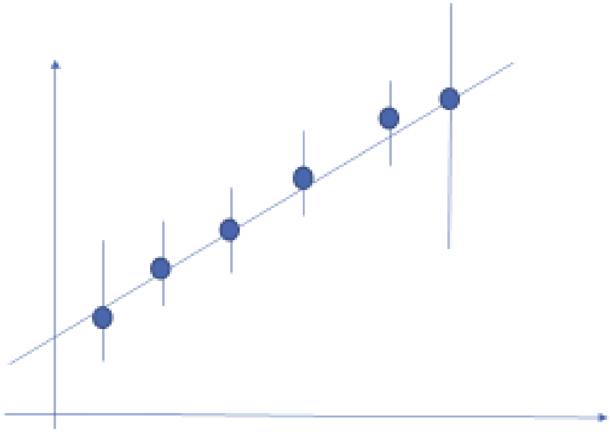
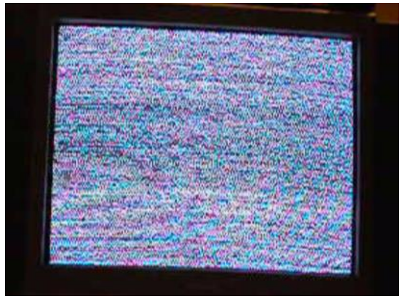
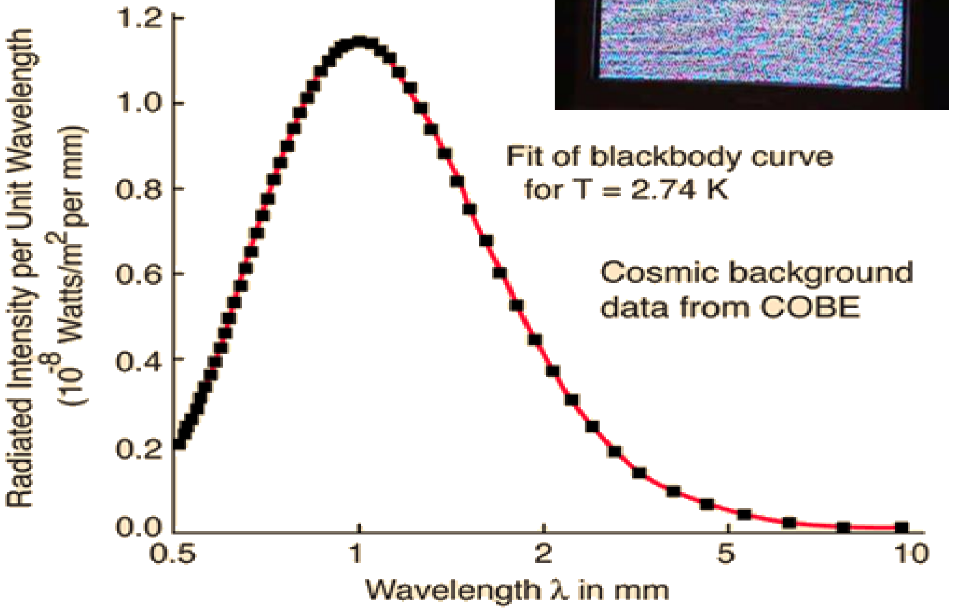
Why are we so interested in Errors ?

The main objective is to put constraints on the Theories.



So any new equation (line graph) that can pass through the error bars is considered a good theory.





Cosmic Background Radiation

What are Errors in an experiment ?

In Physics it is not good enough to quote, the acceleration due to gravity as $g = 9.814\, m/s^2$ but $g = 9.814 \pm 0.003\, m/s^2$

The statement that $g = 9.814 \pm 0.003\, m/s^2$ means that the uncertainty is $\pm\, 0.003$ and that we are 68% sure (i.e. the value g is reliable) that the true value lies between 9.811 and 9.817.

There are 3 types of Errors, *Δ* (called delta):

Random Errors(1), Systematic(Bias) Errors(2), Propagated Errors(3)

Error 1 : Random Errors

When a measurement, x_i is made more than once, the result scatter around the average, or mean value :

$$Mean = \bar{x} = \frac{1}{N}\sum x_i = \frac{x_1 + x_2 + x_3 + x_4 + \ldots}{N}$$

N is the number of measurements.

Example: Data & Statistics

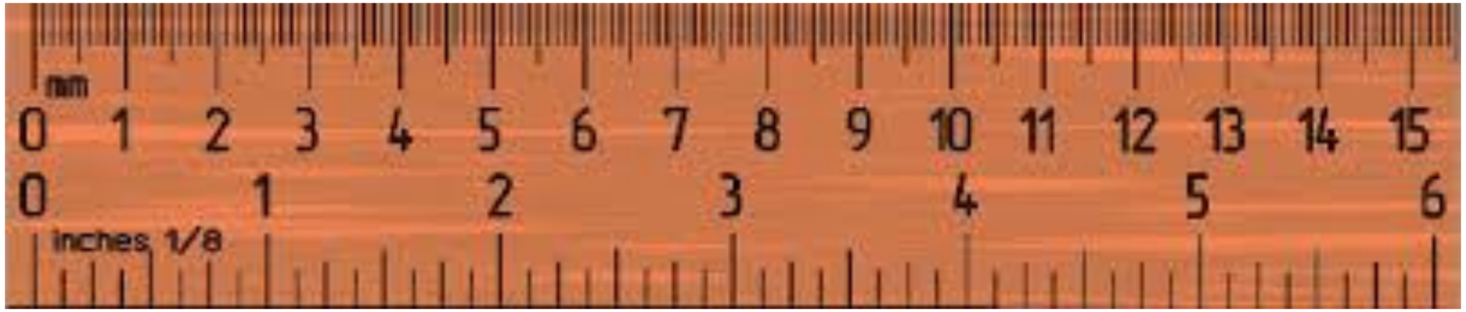
Trial	Mass of Cylinder (gm) M	dev.,	Length of Cylinder (cm) L	dev.	Diameter of Cylinder (cm) d	dev.
1	13.70	.00	9.00	.05	1.22	.01
2	13.85	.15	9.00	.05	1.23	.00
3	13.60	.10	8.90	.05	1.23	.00
4	13.60	.10	8.95	.00	1.23	.00
5	13.75	.05	8.90	.05	1.22	.01
Average	13.70	±.08	8.95	±.04	1.23	±.004

Errors 2 : Systematic Errors (Bias)

Due to such things as uncalibrated instrumentation, human reaction times etc.

These errors do not scatter around a mean (average) value.

Generally, Systemic Errors are related to experimental design.

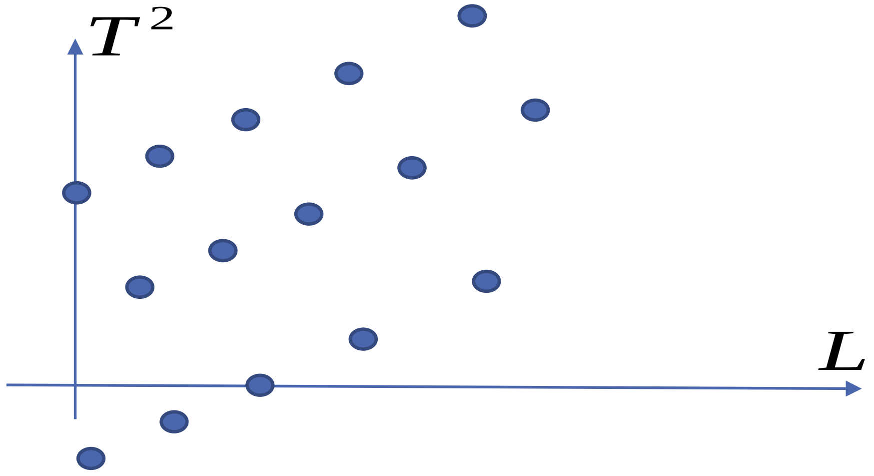


Example : If your data points are linear ?

Consider the graph on the right: Periods (T^2) (also called oscillations) verses Length of the pendulum (L).

The experimenter may have slow reaction time when pressing the stop watch to record the oscillation/period or there may be a dent on the ruler; the experimenter may read the scales on the ruler with a bias.

Sometimes we can eliminate systematic (bias) errors by extracting a piece of physical information from the gradient … you would have done this in Secondary school science.



Random (1) vs Systematic (2) Errors

Caveat :

Random errors may help us determine the reliability of our data, but performing a poorly designed experiment more than once will never help us get to the true value.

Errors 3 : Propagation of Errors

Example : Consider *D*ensity as a function of mass and Volume, in function form, we write $D\,(M, V)$ i.e. function of 2 variables.

Specifically $D = \dfrac{M}{V}$

The Propagated Error in the density D is $dD = \dfrac{\partial D}{\partial M} dM + \dfrac{\partial D}{\partial V} dV$

Simple Chain Rule obtained from Junior College or Secondary school

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J. Barrante, *Applied Mathematics for Physical Chemistry*, 2004 Prentice Hall.

Propagation of Errors

$$dD = \frac{\partial D}{\partial M} dM + \frac{\partial D}{\partial V} dV$$

But scientists like to do this, because we always want Maximum Error incurred.

$$\Delta D = \left|\frac{\partial D}{\partial M}\right| \Delta M + \left|\frac{\partial D}{\partial V}\right| \Delta V$$

The 2 pairs of Chopsticks are mathematical operations that guarantee the contents are always positive. In the language of mathematics, the chopsticks are called “Absolute values”.

J. Barrante, *Applied Mathematics for Physical Chemistry*, 2004 Prentice Hall.

Physics is not Mathematics

Mathematicians are only dealing with structure of reasoning, and they do not really care what they are talking about. They do not even need to know what they are talking about, or as they themselves say, whether what they say is true … In other words, mathematicians prepare abstract reasoning ready to be used if you have a set of axioms about the real world. But the physicist has meaning to all his phrases.

Physics is not mathematics, and mathematics is not physics. One helps the other. But in physics you have to have an understanding of the connection of words with the real world.

R. P. Feynman (on Relation of Mathematics to Physics), *The Character of Physical Law,* 1967, MIT Press.

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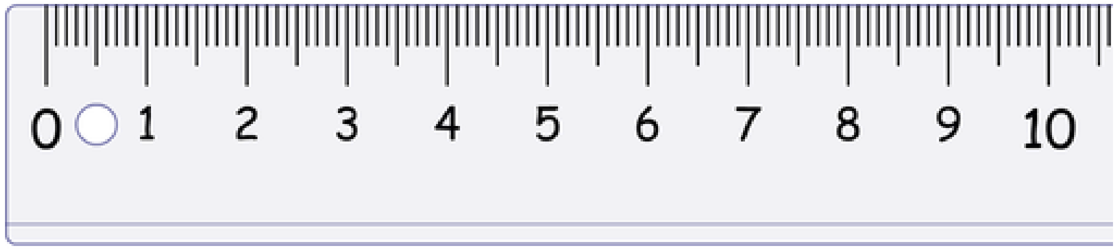


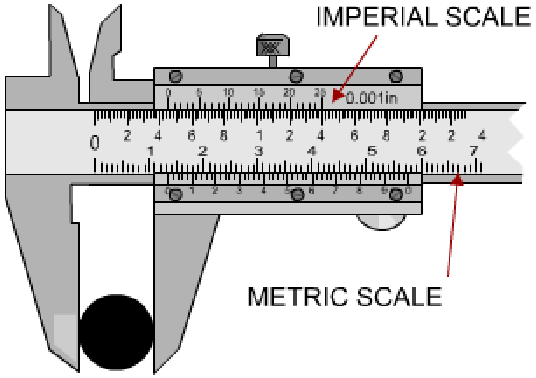
We are interested in finding the *Density* of a round cylinder

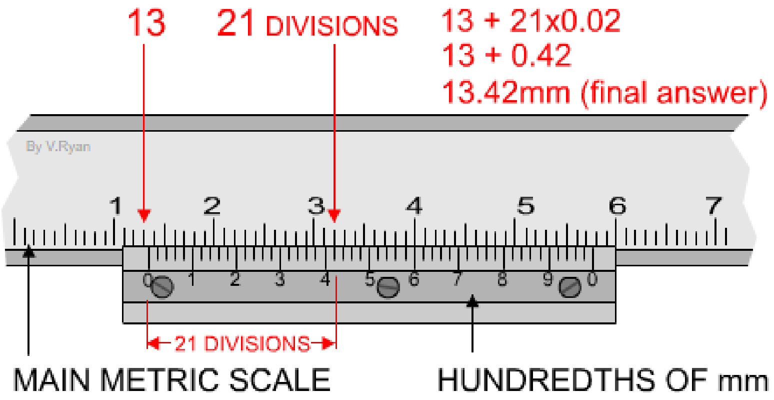
The smallest scale on the mass balance is to 0.1 gm., so we can read more accurately about ½ of this smallest division. i.e. 0.05.

We can read until ½ of smallest division (0.1) on the Ruler, i.e. 0.05

Also we can read until ½ of smallest division (0.01) on the Vernier Caliper, i.e. 0.005.

$$D = \frac{M}{\pi\left(\frac{d}{2}\right)^2 L} = \frac{4M}{\pi d^2 L}$$





Random Error Consideration

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3	13.60	.10	8.90	.05	1.23	.00
4	13.60	.10	8.95	.00	1.23	.00
5	13.75	.05	8.90	.05	1.22	.01
Average	13.70	±.08	8.95	±.04	1.23	±.004

Systematic vs Random Error

Thus M = 13.70 ± 0.08 gm. Here the mean deviation is larger than ½ of the smallest scale division; so the former is used for your error.

Thus L = 8.95 ± 0.05 cm and d = 1.23 ± 0.005 cm. In these 2 cases, the mean deviation is less than ½ of the smallest scale division; so the latter is used for your error.

$$\therefore D = \frac{4(13.70)}{3.14(1.23)^2(8.95)} = 1.288 gm/cm^3$$

Propagation of Error Consideration

In words :

% Error in D = % Error in M + 2 (% Error in d) + % Error in L

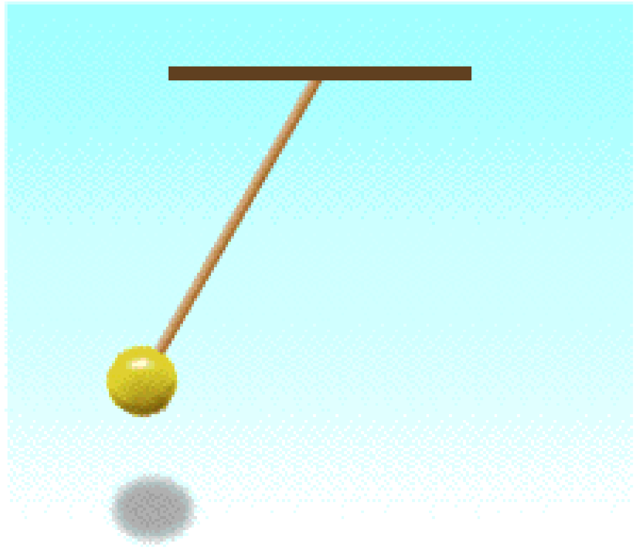
% Error in D = 0.60 + 2 (0.41) + 0.56 = 2.0 %

Final presentation D = $\underline{1.29 \pm 0.03\ \text{gm/cm}^3}$

For the curious: since $D\,(M, d, L)$, we have, $dD = \frac{\partial D}{\partial M} dM + \frac{\partial D}{\partial d} dd + \frac{\partial D}{\partial L} dL$

About your the Pendulum Tutorial

Note : All experimental Errors will be given to you, you need not use calculus to get them.



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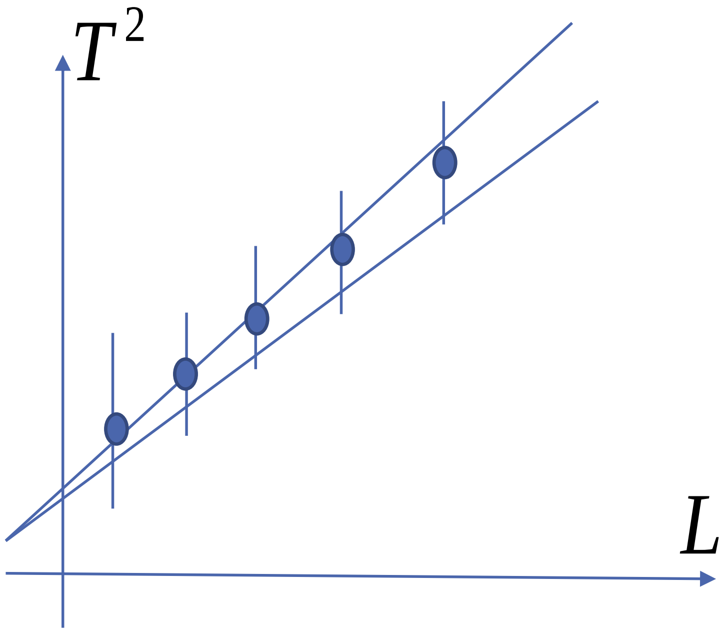
Example :
How to Choose between 2 theories ?

Newton discovered that gravity is an attractive force i.e. a ball will drop to the earth because the earth attracts it.

Suppose another scientist has derived another equation (line graph) from a new theory (say Einstein's Gravity i.e. gravity is not a force but only space-time geometry) about the same pendulum phenomenon shown below.



Choose a Theory : using Occam's Razor

A principle of scientific and philosophical discussion urging the use of the most economical and least complex assumptions, terms and theories. It is usually formulated as "Entities should not be multiplied unnecessarily".

a variant of Ockham's Razor

R. P. Feynman, *The Meaning of It All,* 1998, Basic Books.

Example: using Occam's Razor

Suppose one has 2 competing theories and the theoretical lines (or curves) pass through all the error bars, how would one decide which is a better theory?

Theory 1 : $f\,(\theta, \rho, \omega, \gamma, x)$
Theory 2 : $h\,(\theta, \rho)$,
Applying the Razor, we will choose theory $h\,(\theta, \rho)$

R. P. Feynman, *The Meaning of It All,* 1998, Basic Books.

So why do Error Analysis ?

It is to help us constraint competing good theories … yes, sometimes one has to employ Occam’s Razor.

By good theory, we mean the line graph (curve graph) passes through as many error bars as possible.

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Summary

Physical theory without experiment is empty. Experiment with Theory is blind.

Heinz Pagels

"Error" Enquiry is a huge industry that is not commonly appreciated by science students (including budding physicists); it is this kind of questioning that gives Physical Theories credibility.

Heinz Pagels was a professor of physics at Rockefeller University, the executive director and chief officer of the New York Academy of Sciences, and president of the International League for Human Rights. He is best known to the public for his popular science books *The Cosmic Code* (1982), *Perfect Symmetry* (1985), and *The Dreams of Reason:* (1988).

Appendix : Mathematics is not physics

If we are confident that the various uncertainties are independent and random, we use the following quadrature equation :

For example $D\,(M, V)$:

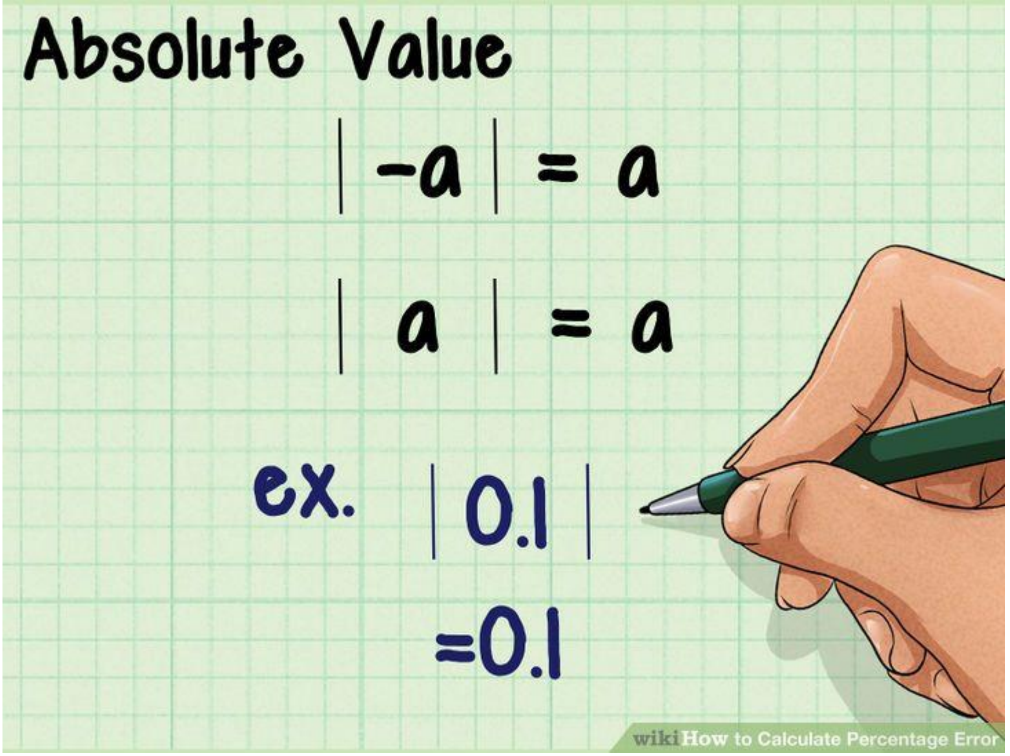
$$dD = \frac{\partial D}{\partial M} dM + \frac{\partial D}{\partial V} dV$$

We square both sides

$$(\Delta D)^2 = \left(\frac{\partial D}{\partial M}\right)^2 (\Delta M)^2 + \left(\frac{\partial D}{\partial V}\right)^2 (\Delta V)^2$$

J. Barrante, *Applied Mathematics for Physical Chemistry*, 2004 Prentice Hall.

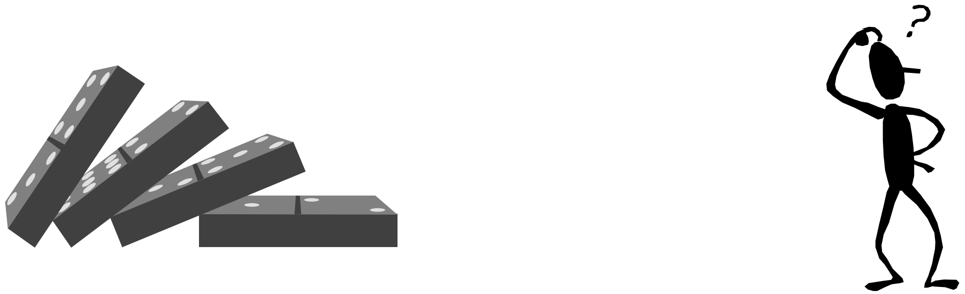
Chopsticks : making contents always positive



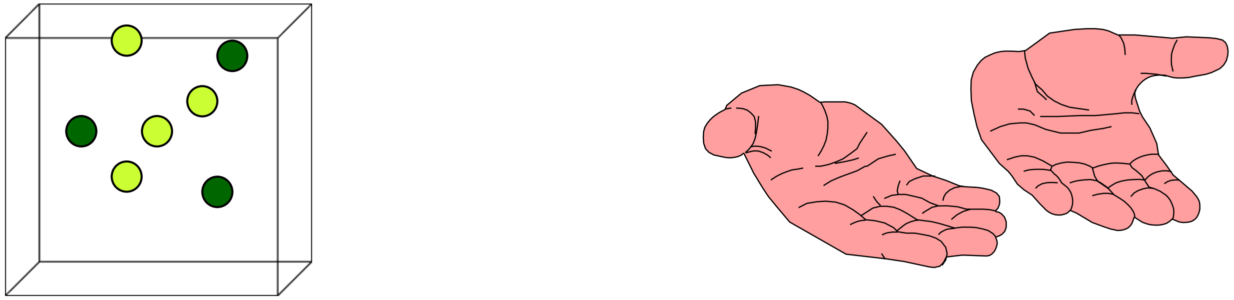
A review of High School Mathematics

J. Taylor, Error Analysis, 1982, University Science Books.

What is the difference between Probability and Statistics ?



In probability, the student already knows the number of black and white balls in the container. He or she is interested to find the probability of drawing a given proportion of black and white balls.



What is the difference between Statistics and Probability ?

In Statistics, we solve the opposite problem. The student observes the proportion of black and white balls drawn from the container and attempts to deduce the number of black and white balls already in the covered container.