Experimental Physics PHYS 2350

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Office hours: ExPhys hrs. or 10am Wed. and Friday

Class Information

Class hours and locations

REGULAR LECTURE TWF 12-12:50PM

LAB M M 8:00-10:50AM and 2:00-2:50PM

LAB R R 8:00 10:50AM and 2:00-2:50PM

Labs will be held in SC3C14

Web site:

www.rpi.edu/dept/phys/Courses/PHYS2350/

Although the stated lab hours total 4 hours per week, you should anticipate that you will need 6 hours per weeks to do the experiments well. You should arrange with your lab partners to meet for the requisite hours.

<u>Required Textbook</u>: *Experimental Physics*, notes by James Napolitano, (It can be downloaded from the web site.

<u>Grading</u>: mostly write-ups; see syllabus

Late assignment policy- always good to finish.

Academic honesty – You are expected to meaningfully participate in all laboratory experiments. If we determine that a student is simply using data from (an)other student(s), we will give you a zero for that lab. You are encouraged to work with your lab partner on analysis, but the actual write-up must be your own.

Experiments for Spring 2001:

A -Voltage divider/filter (E, short)

B – Counting statistics (C, short)
C - Dielectric function (E)
D – Resistivity by inductive decay (E)
E – Temperature coefficient of resistivity (E)
F - Atomic spectroscopy (G)
G - Johnson noise (E)
G - Faraday effect (G)
H - Radioactivity (C)
J- Positron annihilation(C)
K - Compton effect (C)
L - ULI mechanics spring

M- ULI mechanics pendulum

N - ULI rotational inertia

Write-ups

The "mini-lab" write-up

Part 1- the real time logbook

- Statement of goals.
- Statement of planned approach
- Description of equipment (model and serial # if possible, sketch layout)
- Description of logic, what was measured.
- Raw data. Simple plots.
- Observations or ideas.

Part 2 - a separate write-up

brief description of experimental procedure
analysis and discussion,
final plots and graphics,
error analysis,
conclusions.

The "standard" write-up

- Add Title and Abstract
- Rewrite Part 1 above neatly in clear English with complete sentences.

- Part 2, same as for "mini-lab" write up.

Final formal report

- Add a section with introductory ideas and basic theory.

Laboratory Safety

- Review safety issues for each experiment with your partner(s) and the TA or me before you start.
- Do not work alone in the laboratory.
- Think before you do.

- When in doubt, get out. And warn others of risk.

Specific issues for 3C14 lab

Please use the list below as a safety checklist for each experiment as you start it.

Electrical shock (voltage (>20V) can bridge skin resistance or air gaps, current kills)

Watch for: charge on capacitors, current in inductors (magnets)

Keep one hand in your pocket.

TEST VOLTAGES AND THINK.

Explosion/implosion

Gas containers, cryogens, CRT's, light bulbs, vacuum tubes

Asphyxiation from rapid boiling of cryogenic gases

THINK.

Poisoning by ingestion or through skin

(lead bricks, Hg switches, Be windows, dyes and organics, radioactive sources.)

NO FOOD IN THE LAB. WASH YOUR HANDS WHEN YOU LEAVE.

Optical damage (laser beams, Hg discharge lamps)

AVOID LOOKING DOWN ANY BEAM. DON'T EXPOSE OTHERS.

Hot/cold - THINK.

Radioactivity -

REAL-TIME MONITOR (GEIGER).

WEAR EXPOSURE BADGE.

WASH YOUR HANDS WHEN YOU LEAVE THE LAB.

BE FAMILIAR WITH LIMITS OF EXPOSURE.

Radiation safety

Exposure: This is the ionization produced per unit of matter. The standard unit is the Roentgen (R) which is the quantity of X-rays that make one electrostatic unit of ionized charge in 1 cm^3 of air

Absorbed Dose: This is the energy deposited per unit mass. The old unit is the rad defined to be 100 erg/gram. The SI unit is the Gray (Gy) or 1 J/kg=100 rad.

To convert between dose and exposure, you need to know how much energy (in a particular material) produces so much ionization. For air, it takes (on the average for electrons) 33.7 eV of deposited energy to create an ion pair. The conversion factor between exposure (Roentgen) and dose (rad) is about 1.

The rem is a unit of damaging dose to humans, and includes a "quality factor", which is 1 for gamma and x-rays and 10 for alpha particles.

see notes handout for more information

A useful conversion for gamma rays: 1 Curie of gamma source produces ~ 1.3 rem per hour at a distance of 1 meter. So,

$$Dose(rem) \sim 1.3A(Ci)\frac{1}{\left[r(m)\right]^2}t(hr)e^{-\mu d}$$

A=activity in Ci; r= distance in meters, t=time in hours, μ=attenuation coefficient for shielding, d=thickness of shielding.

Good experimental techniques

Use the list below as a checklist as you proceed through each experiment.

Read the book on that experiment before you come to the first lab class.

Write a short list of goals into your notebook.

Think about the logical experimental approach to achieving the goals.

Think about and make a list of safety issues for your experiment. (Estimate radiation dose!)

Familiarize yourself with the equipment. Practice taking data.

Develop a plan.

Take data while testing to see how robust or reproducible the system is. Assess uncertainty in each parameter and how it affects your conclusions. Record data in your notebook in the raw form (e.g.- On an oscilloscope, record the scale settings and then the number of minor divisions.) You may also record calculated parameters at the same time. Assess your reading error while you are making readings.

Think about how you could change the measurement approach or conditions and how you expect that change to influence the measurement or result. Test your ideas.

Uncertainty:

Systematic and Random

- Random uncertainty arises from the fundamentals of a measurement or instrument. The measurement typically scatters about an average value.
- Systematic uncertainty is common to a set of data and depends on experimental method.

Estimation of uncertainty:

a. A sensible fraction of the least significant digit on your measuring device.
b. Analysis of the statistics from a set of measurements.

Common techniques to reduce systematic uncertainty:

Reverse or switch leads.

Switch measurement devices.

Calibrate against a known standard (e.g.- 60 Hz line voltage)

Repeat measurements. Have partner repeat measurements.

Avoid taking data in monotonic increments. (e.g.- Always increasing or always decreasing voltage.)

Measure ratios or differences. (Set up the experiment so it only gives you differences.)

Plot data in your notebook or on your laptop computer as you go to look for anomalies.

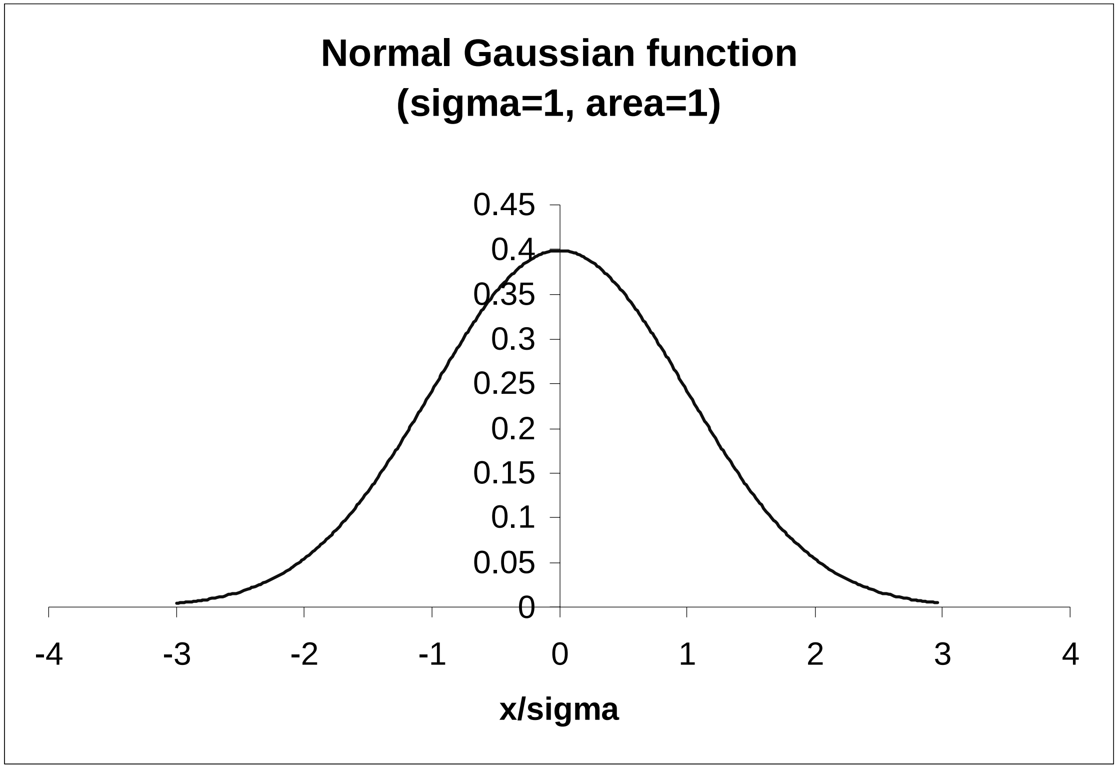
Scale the experiment (i.e.- double length of wire, change area of wire...)

Probability for random errors:

Gaussian or Normal distribution.

Parameters are mean value, width, and total probability.

Width usually given as the standard deviation, σ.


Normal Gaussian function
(sigma=1, area=1)
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
0
-4
-3
-2
-1
0
1
2
3
4
x/sigma

Propagation of Uncertainties:

How does the uncertainty in a particular measurement affect a calculated result?

1) Brute force method: Plug your uncertainty estimate directly into the theoretical prediction and calculate the difference.
2) Expansion approximation: Taylor expand your function about the measured point. Carefully add uncertainties together.

Known function of a single variable (Taylor expansion): $\delta q = \left|\frac{dq}{dx}\right|\delta x$ (for relatively small uncertainties.)

Example: $G = AV^3$ where A=theoretical constant and V=measured quantity.

$$\delta G = \left|\frac{\partial G}{\partial V}\right|_{V=V_0} \delta V = \left|3AV_0^2\right|\delta V = \left|\frac{3AV_0^3}{V_0}\right|\delta V = 3G_0\frac{\delta V}{V_0}$$

$$\frac{\delta G}{G_0} = 3\frac{\delta V}{V_0}$$

Known function of several variables:

$$\delta q_x = \left|\frac{dq}{dx}\right|_{xo} \delta x, \quad \delta q_y = \left|\frac{dq}{dy}\right|_{yo} \delta y$$

Correlated uncertainty (x and y are related)-

carefully add uncertainties.

Uncorrelated uncertainties: add in quadrature. $\delta q^2 = \delta q_x^2 + \delta q_y^2 + \ldots$

Example: What if A in the problem above were also an independently measured quantity?

$$\delta G^2 = \left|\frac{\partial G}{\partial V}\right|^2_{V=V_0} \delta V^2 + \left|\frac{\partial G}{\partial A}\right|^2_{A=A_0} \delta A^2 = \left(\frac{3G_0}{V_0}\right)^2 \delta V^2 + \left(\frac{G_0}{A_0}\right)^2 \delta A^2$$

$$\frac{\delta G^2}{G_0^2} = \left(\frac{3\delta V}{V_0}\right)^2 + \left(\frac{\delta A}{A_0}\right)^2$$

$\frac{\delta G}{G}$ is called the fractional uncertainty.

Statistical Analysis

Computation of uncertainty from several measurements of the same quantity:

Suppose you take n measurements of a quantity x. In previous classes, you used the following definitions.

The mean value of x as: $\bar{x} = \langle x \rangle = \frac{1}{n}\sum_{i=1}^{n} x_i$

The standard deviation of x as:

$$\sigma_x = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2} = \sqrt{\frac{n}{n-1}\left(\left\langle x^2 \right\rangle - \left\langle x \right\rangle^2\right)}$$

Why did you do this, other than that it was a definition?

The logic behind statistical analysis

1. To find the best estimate for a parameter in a fit to a set of measurements.
2. To test whether the function you chose is appropriate (hypothesis testing).

Note: each data point in a set of measurements is usually assumed to be Gaussian distributed. In that case hypothesis testing can be based on the magnitude of χ^2.

<u>The tool</u>: χ^2 (chi-squared)

We define:

$$\chi^2 = \sum_{i=1}^{n} \frac{(y_i - f(x_i))^2}{(\delta y_i^2 + \delta f_i^{\,2})}$$

where x_i and y_i are measured, δy is the uncertainty in a measurement of y, and δf is the uncertainty in f computed from the uncertainty in x.

A reasonable approach to finding best fit parameters is to minimize χ^2 .

Example: Best fit to a constant - the average.

The function for a fit: f(x)=A.

$$\chi^2 = \sum_{i=1}^{n} \frac{(y_i - A)^2}{(\sigma_i^2)}$$

$$\frac{\partial \chi^2}{\partial A} = \sum \frac{2(x_i - A)}{\sigma_i^2} = \sum \frac{2x_i}{\sigma_i^2} - \sum \frac{2A}{\sigma_i^2} = 0$$

solve for A,

$$A = \frac{\sum (x_i / \sigma_i{}^2)}{\sum (1/\sigma_i{}^2)}$$

The quantity $\frac{1}{\sigma_i^2} = w_i$ is called the weight of a measurement.

A then is just the weighted average.

The uncertainty in the weighted average is given by σ_A. For a Gaussian distribution of measurements, σ_A is known as the standard deviation.

For equal uncertainties, $A = \frac{1}{n}\sum_{i=1}^{n} x_i, \quad \sigma_A = \sigma_i / \sqrt{n-1}$

Some useful MATLAB functions:

sum(x), mean(x), std(x) where x is an array of the measured values.

We go through a similar minimization process, solving two simultaneous equations for A and B, to find the slope and intercept of a straight line fit $y=A+Bx$ to the data.

Assuming σ_y is independent of *i* and that σ_x is negligible:

$$A = \frac{(\sum x_i^2)(\sum y_i) - (\sum x_i)(\sum x_i y_i)}{n(\sum x_i^2) - (\sum x_i)^2}$$

$$B = \frac{n(\sum x_i y_i) - (\sum x_i)(\sum y_i)}{n(\sum x_i^2) - (\sum x_i)^2}$$

$$\sigma_A^2 = \frac{\sigma_y^2 \sum x_i^2}{n(\sum x_i^2) - (\sum x_i)^2}$$

$$\sigma_B^2 = \frac{n\sigma_y^2}{n(\sum x_i^2) - (\sum x_i)^2}$$

$$\sigma_y^2 = \frac{1}{n-2}\sum (y_i - A - Bx_i)^2$$

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Assignment: Napolitano Ch. 6, problems 1 and 7, Ch. 9, problem 4. Turn in, on paper, at your first lab.

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Useful MATLAB function:

p=polyfit (x,y,n) where n is the order of the polynomial you want to fit to the data. (Note: This is an "unweighted" or equally-weighted fit.)

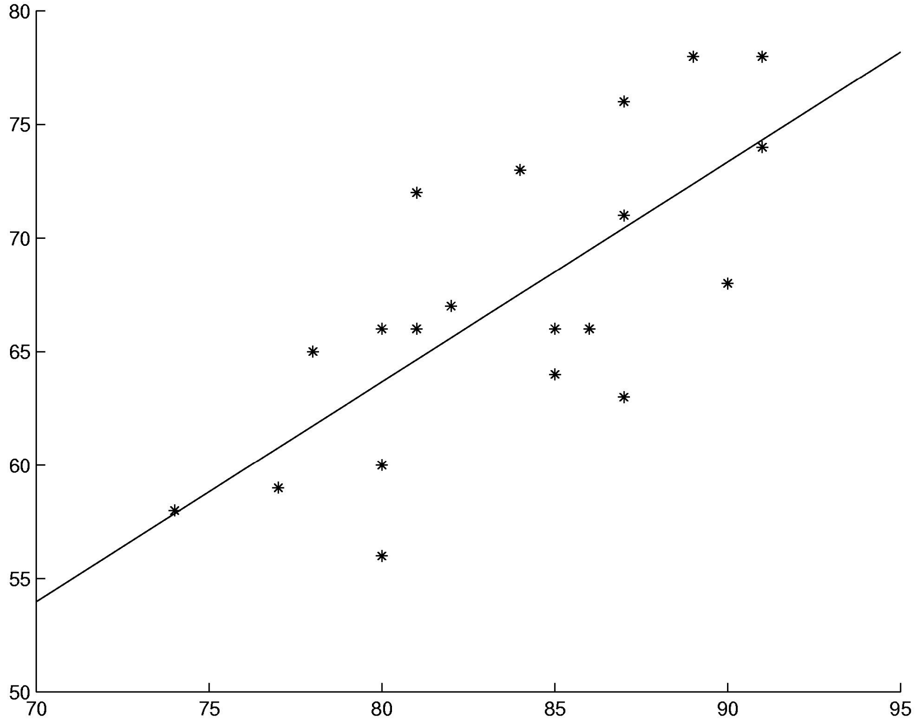
see hw1_92.m in Matlab_examples.

```
% This is a program to demonstrate polynomial
% regression and chi^2 ideas.
clear
x=[78 80 87 84 81 80 82 80 87 91 85 81 85 74 86
77 89 87 91 90];
y=[65 56 71 73 72 60 67 66 63 74 64 66 66 58 66
59 78 76 78 68];
hold on
p=polyfit(x,y,1);
xf=(70:1:95);
yfitp=polyval(p,xf);
```

```
yfit=polyval(p,x);
plot(x,y,'*')
plot(xf,yfitp)
xbar=mean(x)
ybar=mean(y)
covari=cov(x,y)
corrco=corrcoef(x,y)
chisq=sum(((y-yfit).^2)./4.^2)  %(4 is an arbitrary guess for the standard deviation in a single student’s grade on an exam taken many times.)
print -deps covarex.eps
```

```
p =    0.9680  -13.7726
xbar =  83.7500
ybar =   67.3000
covari =
   23.4605   22.7105
   22.7105   41.9053
corrco =
    1.0000    0.7243
    0.7243    1.0000
chisq =  23.6559
```

Note: to test our hypothesis (determine goodness of fit) we can use,
χ^2/degrees_of_freedom = χ^2/(points - parameters)



80
75
70
65
60
55
50
70
75
80
85
90
95

Fits to nonlinear functions of the free parameters

First, don't (try to linearize instead).

Search for best fit parameters

(MATLAB fns: fmins do numerical minimization.
See 'general_fitter.m' for example.)

What does χ^2 mean?

Using χ^2 as a measure of "goodness of fit":

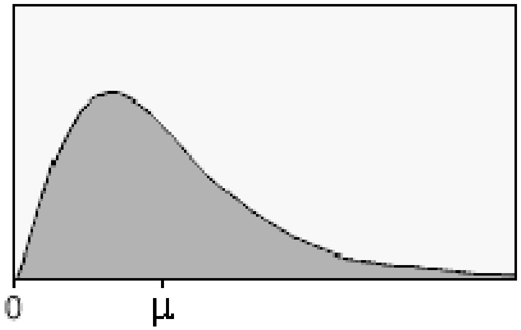
The area under a χ^2 curve, integrated from $\chi^2 = 0$, gives the probability that repeating a measurement will produce a smaller value. χ^2 has an expected (average) value of ν (= DOF), for large number of points. Anything much smaller or larger is improbable. Large χ^2 is an indication that you have chosen the wrong function for your fit. Small χ^2 indicates that you've estimated your error incorrectly.

The χ^2 distribution:

$$P(\chi^2 \le x) = \int_0^x \chi^2(u)du = \frac{1}{2^{\nu/2}\Gamma(\nu/2)}\int_0^x u^{\frac{\nu}{2}-1} e^{-\frac{u}{2}} du$$

$\chi^2(\nu,\delta^2)$ Probability Density Function

Exhibit 1



For large ν(>30), $f = \sqrt{2\chi^2} - \sqrt{2\nu - 1}$ is Gaussian distributed with a mean of zero and variance (σ^2) equal to one.

Note: χ^2 and σ increase with ν.

Practical χ^2 analysis:

1) Make estimates or calculate the standard deviation of your measured quantities
   a. in counting experiments the uncertainty is the square root of the counts ($\sqrt{0} \equiv 1$)
   b. in measurement experiments (e.g. - voltmeter)
      i. repeat measurements and compute standard deviation
      ii. estimate uncertainty from least significant digit

iii. observe variation or drift (similar to repeated measurements)
iv. keep in mind that the method of sampling can skew the data
v. construct a data table

x	dx	y	dy	z	dz
1	0.01	2	0.015	201	14
2	0.01	3	0.017	250	16

2) Decide on a fit function to test.
   a. Note the number of parameters you use in your fit function. (e.g., $z = f(x,y) = a + bx^c + dy$ has 4 parameters and two variables)
   b. Construct chi-squared

$$\chi^2 = \sum_{i=1}^{n} \frac{(z_i - f(x_i, y_i))^2}{(\delta z_i^2 + \left(\frac{\partial f}{\partial x}\right)^2 \delta x_i^2 + \left(\frac{\partial f}{\partial y}\right)^2 \delta y_i^2)}$$

3) Compare chi-squared to the distribution function "chi-squared" for the given number of data

points minus the number of parameters. For larger point numbers, you can compare to a gaussian functional form.

You can then describe the probability that a repetition of the experiment would give you a smaller (or larger) chi-squared value. If p is outside of 0.10 -0.9, then it is likely that something is not right about your data or analysis.

Important Probability Distributions:

These are very important for counting statistics (i.e.- photon counting or radioactivity).

Binomial distribution: If an event has the probability of occurrence *p* for a single measurement, then the probability that it will occur ν times in *n* trials is:

$$b_{n,p}(\nu) = \binom{n}{\nu} p^{\nu} (1-p)^{(n-\nu)}$$

$$\binom{n}{\nu} = \frac{n!}{\nu!(n-\nu)!}$$

mean=μ=np;

variance=$\sigma^2=np(1-p)$

(Note that this is also the expansion for $(x+y)^n$.)

Example: Consider a normal six-sided die. Toss it 20 times. What is the probability that the number 5 will turn up 9 times?

The probability of a 5 on any single throw is p=1/6.

$$b_{20,1/6}(9) = \frac{20!}{9!11!}\left(\frac{1}{6}\right)^{9}\left(\frac{5}{6}\right)^{11} = 0.0048$$

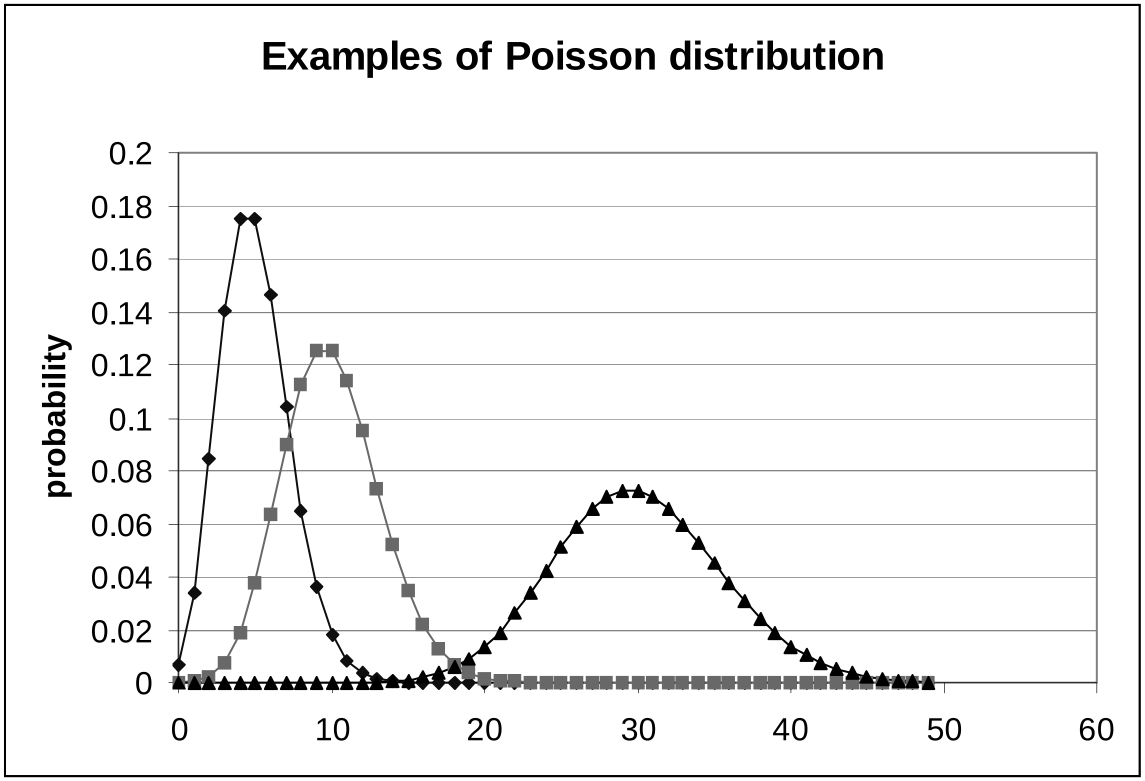
Poisson distribution: Limit of binomial when p becomes small and n becomes large. (such that np= constant=μ)

$$P_\mu(\nu) = \frac{\mu^\nu}{\nu!} e^{-\mu}$$

Variance=σ^2=μ

[All random arrival counting experiments can be recast as Poisson problems. e.g., What is the probability that a count occurs in 10^{-10} sec?]

The Poisson distribution is described by one

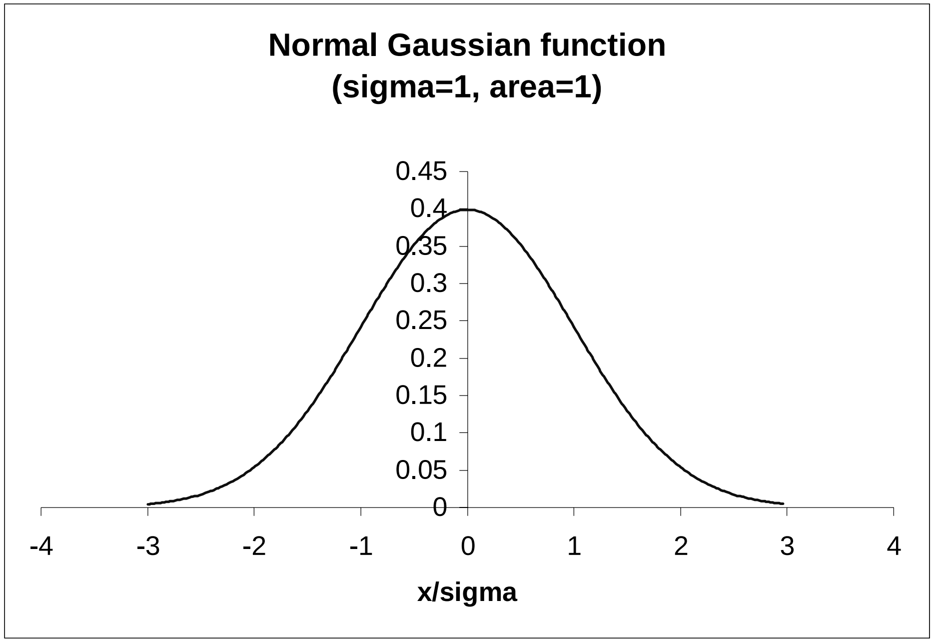


parameter, the average value.

Gaussian distribution:

- Approximation to binomial for large *n*
- and any *p*.
- Good approximation to Poisson for large ($\mu > 10$) average values. (Take $\sigma = \sqrt{\mu}$.)
- Useful for approximating continuous functions.
- "Standard Normal" (Gaussian) function has area =1 $G_{\mu,\sigma}(\nu) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{(\nu-\mu)^2}{2\sigma^2} \right]$

where mean=μ, variance=σ^2.



Some integrals:

$\lvert t\rvert/\sigma$	$P(\lvert x\rvert<t)$
0	0
.5	.38
1	.68

2	.954
3	.997

References:

1) Schaum’s Outlines, Mathematical Handbook
2) Lyons, Statistics for nuclear and particle physicists,
3) Bevington, Data reduction and error analysis for the physical sciences.

Covariance and Correlation

Let's revisit error propagation. Earlier, we said,

$$\delta G^2 = \left|\frac{\partial G}{\partial V}\right|^2_{V=V_0} \delta V^2 + \left|\frac{\partial G}{\partial A}\right|^2_{A=A_0} \delta A^2$$

But, this was only for uncorrelated errors. In general,

$$\sigma_q^2 = \frac{1}{n-1}\sum_{i=1}^{n}(q_i-\overline{q})^2$$

$$\sigma_q^2 = \frac{1}{n-1}\sum_{i=1}^{n}\left[\frac{\partial q}{\partial x}(x_i-\overline{x})+\frac{\partial q}{\partial y}(y_i-\overline{y})\right]^2$$

$$\sigma_q^2 = \left(\frac{\partial q}{\partial x}\right)^2\sigma_x^2+\left(\frac{\partial q}{\partial y}\right)^2\sigma_y^2+2\left(\frac{\partial q}{\partial x}\frac{\partial q}{\partial y}\right)\sigma_{xy}$$

where,

$$\sigma_{xy} = \frac{1}{n-1}\sum_{i=1}^{n}\left[(x_i-\overline{x})(y_i-\overline{y})\right]$$

For uncorrelated errors, σ_{xy} averages to zero.

Are two measurements correlated with one another?
(Should I add uncertainties individually or in quadrature?)

Test for linear correlation:

$$r = \frac{\sum (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum (x_i - \bar{x})^2 \sum (y_i - \bar{y})^2}} = \frac{\sigma_{xy}}{\sigma_x \sigma_y}$$

r is a number between -1 and 1.

$r = \sigma_{xy} = 0$ if x and y are uncorrelated.

σ_{xy} is called the covariance of x and y.

Note: σ_{xy} is easy to measure, but hard to estimate, and hard to interpret.

Probability distribution for *r:*

The probability $P(|r|>r_0)$ that n measurements of two <u>uncorrelated</u> variables x,y would produce a correlation coefficient (in percent) with $|r| > r_0$ is,

r n	0	.1	.2	.3	.4	.5	.6	.7	.8	.9	1
3	100	94	87	81	74	67	59	51	41	29	0
6	100	85	70	56	43	31	21	12	6	1	0
10	100	78	58	40	25	14	7	2	0.5	0.1	0
20	100	67	40	20	8	2	0.5	0.1	0	0	0

50	100	49	16	3	0.4	0.1	0	0	0	0	0

Adding uncertainties for correlated measurements:

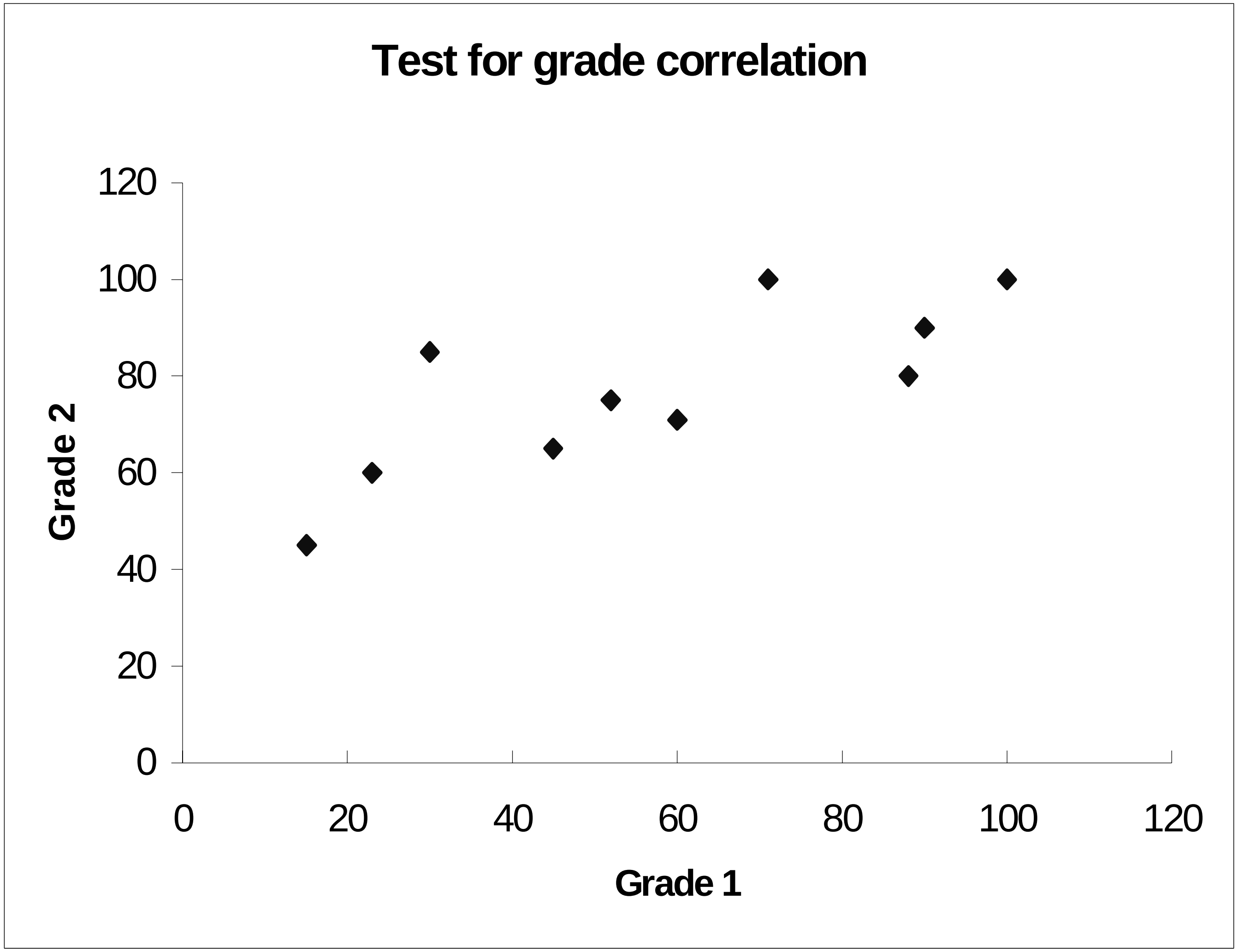
$$\sigma_{xy} = \frac{1}{N} \sum (x_i - \overline{x})(y_i - \overline{y}).$$

$$\sigma_q^2 = \left(\frac{\partial q}{\partial x}\right)^2 \sigma_x^2 + \left(\frac{\partial q}{\partial y}\right)^2 \sigma_y^2 + 2\left(\frac{\partial q}{\partial x}\frac{\partial q}{\partial y}\right)\sigma_{xy}$$

Spreadsheet example:

student	g1	g2	dg1=(g1-g1bar)	dg2=(g2-g2bar)	(dg1*dg2)	dg1*dg1	dg2*dg2
1	90	90	32.6	12.9	420.5	1063	166.4
2	60	71	2.6	-6.1	-15.9	6.76	37.21
3	45	65	-12.4	-12.1	150	153.8	146.4
4	100	100	42.6	22.9	975.5	1815	524.4
5	15	45	-42.4	-32.1	1361	1798	1030
6	23	60	-34.4	-17.1	588.2	1183	292.4
7	52	75	-5.4	-2.1	11.34	29.16	4.41
8	30	85	-27.4	7.9	-216	750.8	62.41
9	71	100	13.6	22.9	311.4	185	524.4
10	88	80	30.6	2.9	88.74	936.4	8.41
sums	574	771			3675	7920	2797
avgs	57.4	77.1					

r= 0.781


Test for grade correlation
Grade 2
120
100
80
60
40
20
0
0
20
40
60
80
100
120
Grade 1

Nonlinear curve fitting example

I have posted an example of a MATLAB program that uses the function ‘fmins’ to fit a Gaussian plus background curve to noisy data.

The “main” program (fitting_routine.m) is used to input the data, input the parameter guesses, call fmins, and plot the result.

fmins is a functional minimization subroutine that minimizes the named function (in our case "chi2ex.m") using the parameters that you pass to it.

We are minimizing chi squared, which is described in the program "chi2ex.m". You can specify any function you please.

"chi2ex.m" in turn calls the function that we are using for the fit. In our case this is named "fnfit.m".

"chi2ex.m" passes the fit parameters back to the main program through fmins. The parameters are contained in the array "pars".

Fundamental Sources of Noise

Brownian motion: KE=kT/2 for each degree of freedom. Translation in gases and liquids, vibrations in solids.

1. Shot noise: due to fluctuations in current due to statistical fluctuations in electron density.

$$\frac{\delta V}{V} = \left[\frac{2e\Delta\nu}{i}\right]^{1/2}$$

2. Johnson noise: due to thermal fluctuations in average electron velocity, resulting in net voltage

across any resistor.

$$\delta V = (4kTR\Delta\nu)^{1/2}$$

3. 1/f noise ? There is no known single fundamental source, but noise with 1/f spectrum is observed in many systems from transistors to thin metal films.

Other Sources of Noise

1. 60 Hz pickup (+ harmonics)
2. Radio and television signals
3. Acoustic pickup
4. Counting statistics
5. ~DC pickup (e.g.- capacitive coupling to your body)

Noise Reduction Techniques

1. THINK about where the noise might come from in your experiment before acting.

a checklist

1. Twist and shield wires.
2. Ground to a single point to avoid current loops.
3. EM Shielding (Faraday cage.)
4. Vibration isolation.
5. Use RLC or op-amp circuits to select desired frequency range, suppress undesirable signals. (Lock-in amplifier.)

6. Average.
7. Optimize experimental method.
8. Design your system to measure differences or ratios directly.
9. Gated detection.
10. “Smooth” your data with a statistical function. Be careful!!!!

Some recommended sources:

Books:

Melissinos, Experimental Physics

Horowitz and Hill, The Art of Electronics

Taylor, An Introduction to Error Analysis

The Student Guide to MATLAB

Squires, Practical Physics

Unusual references:

Applications notes or tutorials in manufacturer's catalogs:

Stanford Research Systems (signal collection, lock-ins, gated counters, boxcar integrator)

Princeton Applied Research (lock-in, boxcar)

Oriel (optics)

Newport (optics, mechanical components)

Melles Griot (optics)

Canberra (counters, timers, ionizing radiation detectors)
Keithley (voltmeters, ammeters, electrometers)

<u>Buyers Guides:</u>
Physics Today
Laser Focus

fitting_routine.m

```
hold off; clear; clf reset
%load data
load ex1.txt
% load data into 1D arrays
channel=ex1(:,1);
intensity=ex1(:,2);
% The fitting function is stored in fnfit.m.
% pars(1)=background, pars(2)=amplitude of Gaussian, pars(3)=center of Gaussian, pars(4)=width of Gaussian.
% Start least squares fitting procedure by guessing starting points for the parameters.
pars=[10 100 80 10]; % (guess)
fitpar=fmins('chi2ex',pars,0,[],channel,intensity)
% minimize the output of the program chi2ex
% using the program fnfit for the function. (fnfit.m is called from chi2ex.m.)
% (fitpar will print on the screen as an array)
%compute the fitted function
ft1=fnfit(channel,fitpar);
% report chi-squared
```

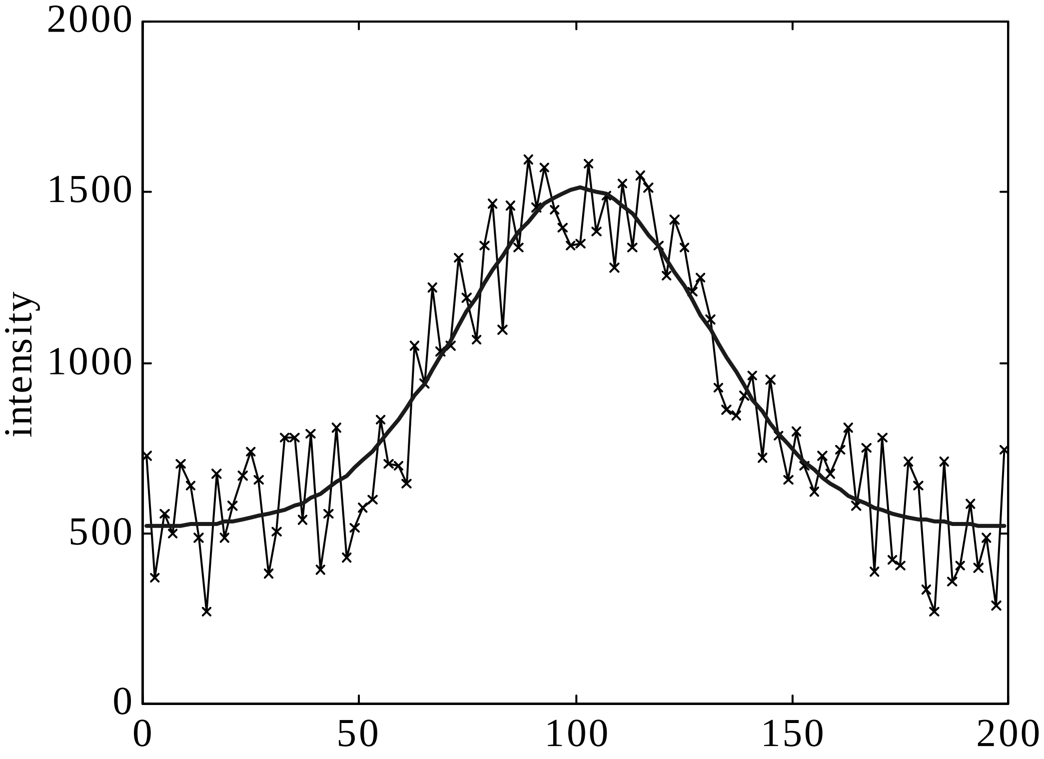
```
chi2=chi2ex(fitpar, channel, intensity)
```

CHI2EX.m

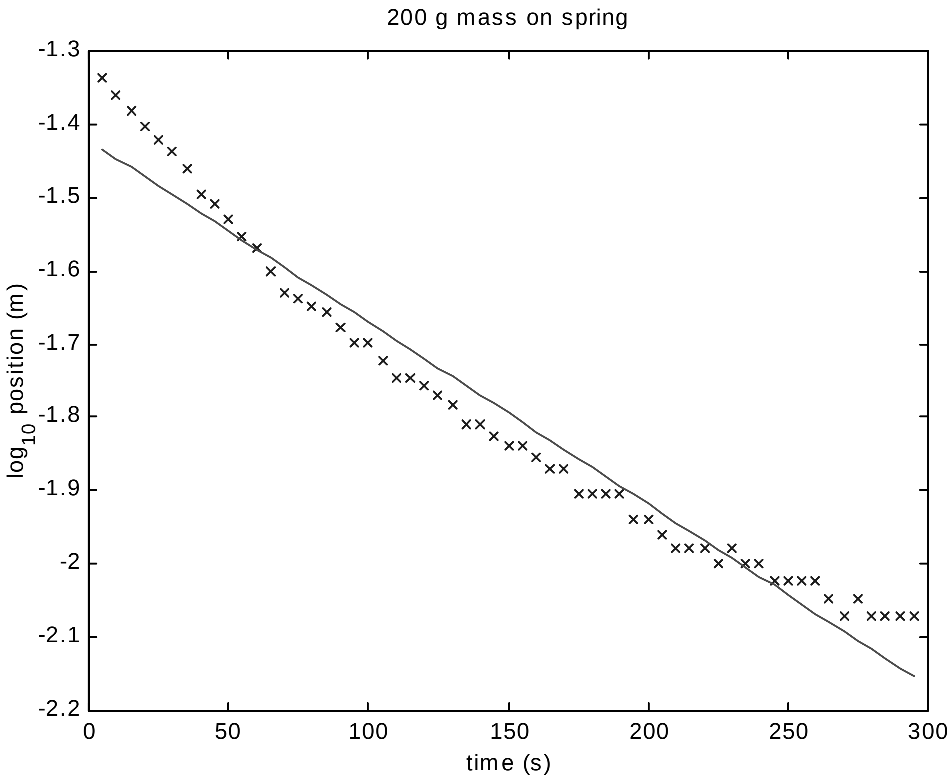
```
function chisqr=chi2ex(pars,channel,intensity)
chisqr=sum(((intensity-fnfit(channel,pars)).^2));
```

FNFIT.m

```
% Gaussian plus polynomial background function
function y=gfit(channel,pars)
y=pars(1)+pars(2).*exp(-((channel-pars(3))./(2.*pars(4))).^2);
```

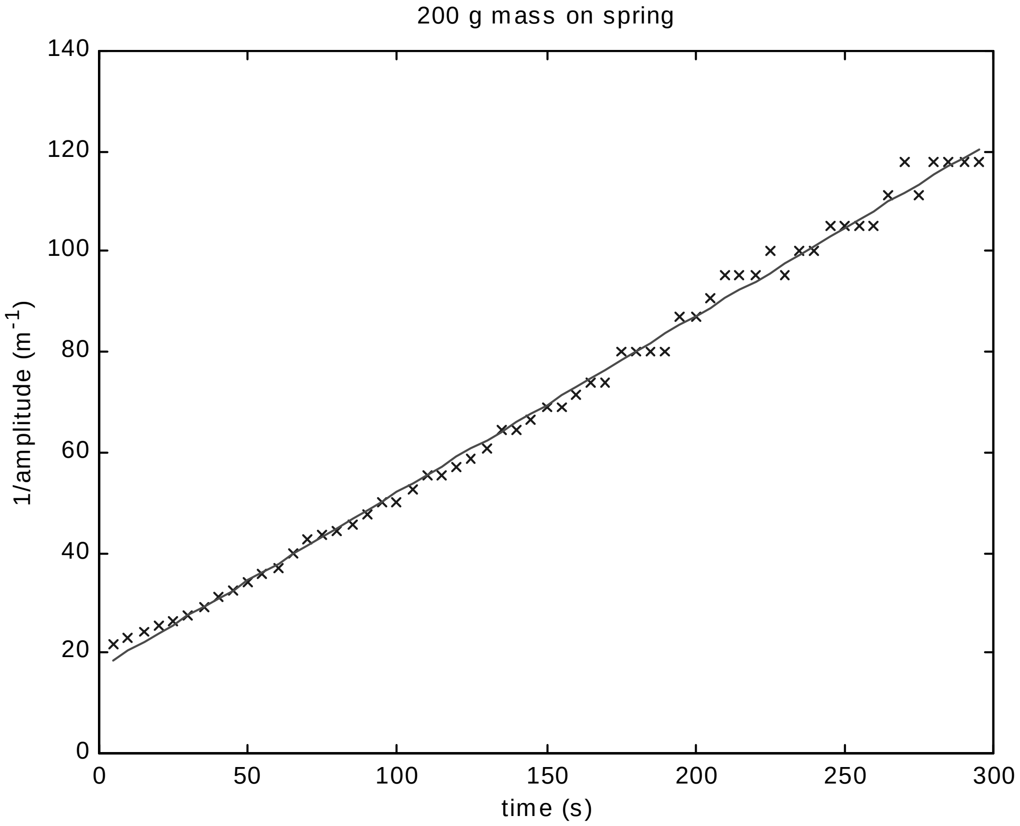


fitpar = 519.7 990.9 101.8 19.9



Example: In Fig. x we show the log of the amplitude extremes of the motion plotted as a function of time. A best-fit straight line is also plotted. Deviations from exponential decay are clearly visible. One way to quantify the deviation is to compute the root mean square deviation

from the fit $\sigma = \sqrt{\frac{1}{n-2}\sum\left(x_i - x_{fit}\right)^2}$. (The n-2 is because we have used two parameters to fit the data.) For the exponential fit the standard deviation is 2.5 mm.



Inverse amplitude from figure 3 plotted against time for comparison with equation 1.9. The best-fit slope is 0.35 s^{-1}m^{-1}. The standard deviation is 1.4 mm, almost a factor of two smaller than the exponential fit.