M & W or T & R 1:00 – 6:00 PM Broida 3223 or 3114

http://hep.ucsb.edu/people/bmonreal/phys128L/

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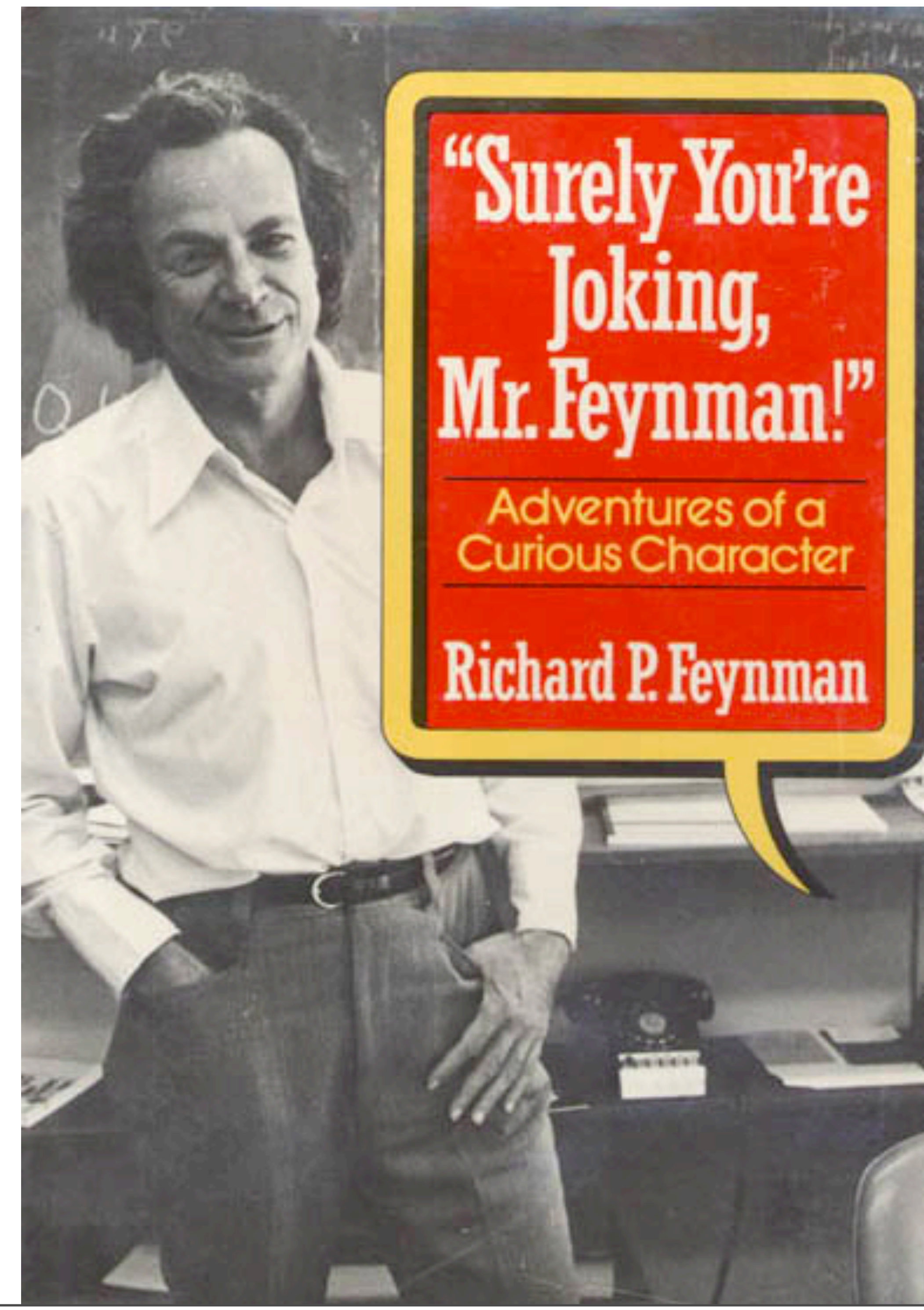
"It doesn't matter how beautiful your theory is; it doesn't matter how smart you are. If it doesn't agree with experiment, it's wrong." -- Richard Feynman



Learning theory and experiment: similarities and differences.

1. Physics sense

- You can tell something is wrong, e.g., limits or units.
- Try a simpler problem, e.g., expand or change vars.
- We'll learn similar experimental intuition and tricks such as measuring correlations, fitting, measuring ratios, that allow you to extract the physics from something messy.

Learning theory and experiment: similarities and differences.

1. Physics sense
2. Tools
   - Math is a theoretical tool.
   - Engineering is an experimental tool.
     (Phys127 and Phys100 are both prep classes.)
   - Both are also fun hobbies.

Learning theory and experiment: similarities and differences.

1. Physics sense
2. Tools
3. Presentation
    - You have to learn how to present your ideas & work.
    - A theorist presents ideas in papers or seminars.
    - An experimentalist does the same, but differently.
    - I hope to teach you how to present results in a talk and in a paper.

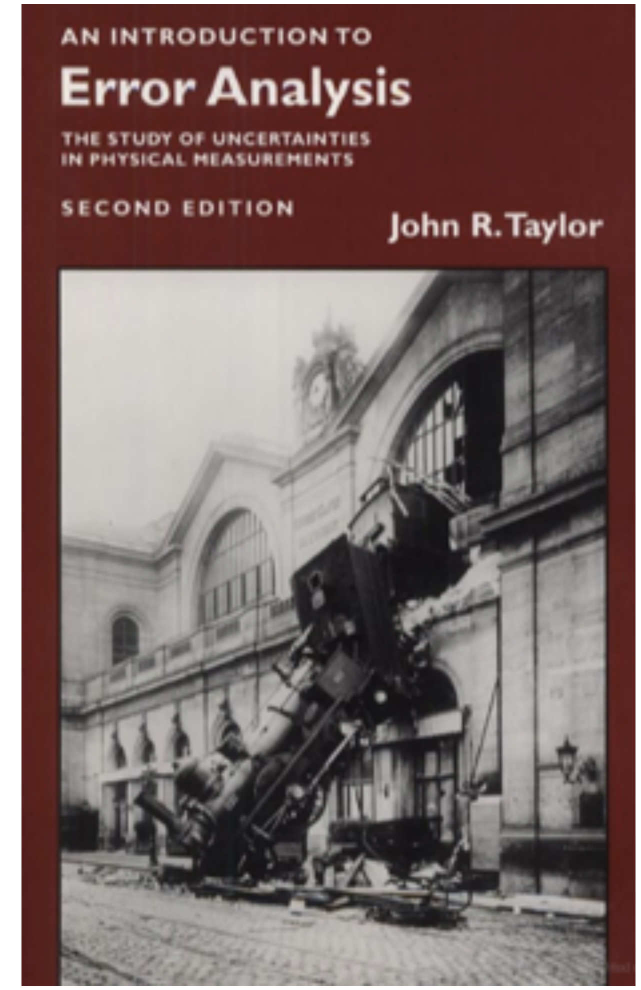
Course Goals

- Learn how to perform careful, organized, documented and systematic measurements.
- Learn proper methods of data analysis.
- Learn how to draw specific and meaningful conclusions.
- Develop a tough-minded and skeptical scrutiny of results.
- Understand issues of precision and uncertainty.
- Become familiar with operation of standard equipment.
- Appreciate the limitations of apparatus.
- Learn to clearly and concisely present your methods, results and conclusions, both verbally and in writing.

Course Grades

- **Do four experiments.**
  3 of ours, 1 of your own design, +1 group warm-up
- **Keep a good logbook record of each experiment.** 75%
  This means "obsessively write down everything you do".
- **Prepare a talk (3 slides) before every experiment.**
  It should cover the theoretical background, experimental 10%
  methods. Turn in slides on Day 1; you may be called to talk at any time.
- **Prepare a scientific style paper about one experiment.** 15%
  The style here is quite different from what you have been taught in English classes. E.g., the length of the paper is an upper, rather than lower limit. The format is prescribed: why, what, how, hence.

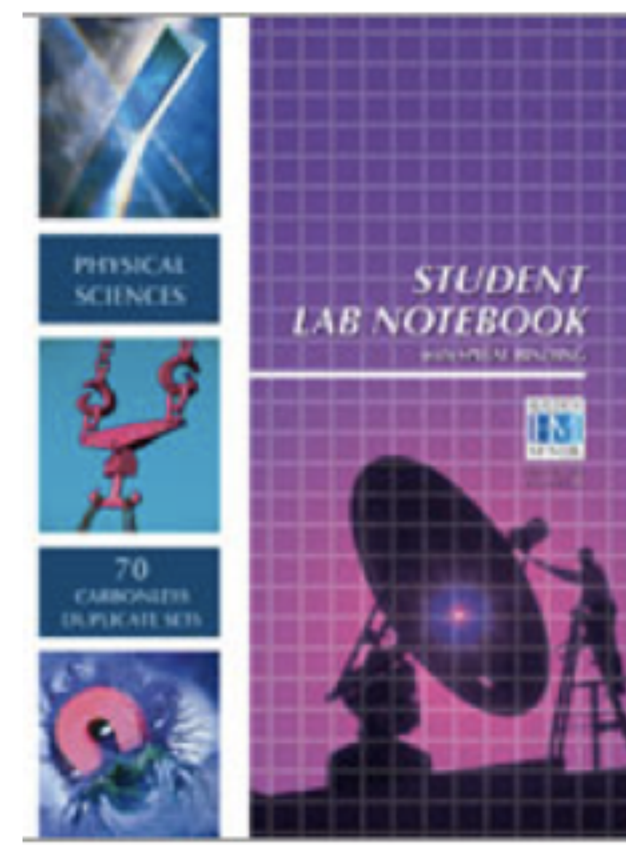
Course Materials



- **Textbook: "An introduction to Error Analysis"**
  I have copies you can borrow.

- **Logbook**:
  You must purchase one. (UCSB Bookstore.)
  Hand in carbon copies.

- **Lab manual**:
  Describes all experiments. (bookstore or web)



- **Software**:
  We will sometimes share data via Google Spreadsheets (spreadsheets.google.com).

  I will analyze data in Mathematica and I recommend that you do too.

Safety is absolutely critical!

You will use hazardous equipment:

High voltage or current, radioactive materials, lasers, extreme temperature or pressure, guns, sticks and stones.

People can get hurt, or die, without proper precautions.

- Read the lab manual before you begin.
- Plan your work with safety issues in mind.
- Write about safety issues in your logbook.
  E.g., Put on goggles before activating laser.
- Talk to your lab partners as you work.

- Never work on equipment alone!
- Never leave activated equipment alone w/o approval.
- Promptly notify us of any problem or accident.

How to do well

1. Plan carefully:

- Read the lab manual beforehand.
- Read background material beforehand, e.g., theory background & equipment manuals.
- Sketch how you are going to do it, including:
  - Safety, i.e., what to avoid.
  - Understand the apparatus.
    - Measure something simple, where you already know what the answer should be.
    - Measure something repeatedly. That gives you an idea how precise the device is.
  - Analyze and conclude as you go, not later!

How to do well

1. **Plan carefully.**
2. **Record everything in your logbook.**
    - Write your own summary of the theory.
    - Describe the goal in your own words.
    - Describe the equipment.
        - Sketch it logically. Paste a diagram & photo.
    - Record everything: time, temperature, equipment settings, humidity, names of people doing measurement…
    - Photos & videos are cheap archives (slo-mo).
    - Paste in plots and photos with captions.

How to do well

1. **Plan carefully.**
2. **Record everything in your logbook.**
    - Write your own summary of the theory.
    - Describe the goal in your own words.
    - Describe the equipment.
        - Sketch it logically. Paste a diagram & photo.
    - Record everything: time, temperature, equipment settings, humidity, names of people

Time is the *great correlator*.

Always record the time of each measurement. You might find an odd effect that you can trace to someone else turning on a pulse generator that causes you to have noise problems.

How to do well

1. **Plan carefully.**
2. **Record everything in your logbook.**
3. **Tabulate data, with comments.**

General description & settings

Time	Var 1	δ Var 1	Var 2	δ Var 2	Ratio	δ Ratio

Write comments here as needed

Write in pen. Don't erase. If you find out something is wrong, cross it out (but still legible) with a comment explaining why it is wrong.

How to do well

1. **Plan carefully.**
2. **Record everything in your logbook.**
3. **Tabulate data, with comments.**
4. **Analyze as you go.**

Calculate differences or ratios (as appropriate) *in the table*.

Plot the data points, and/or ratios, *as you take them*.
This will quickly reveal any problems, which is better than after you have spent hours collecting data.

Take a quick, coarse scan before you do a fine one.

How to do well

1. **Plan carefully.**
2. **Record everything in your logbook.**
3. **Tabulate data, with comments.**
4. **Analyze as you go.**
5. **Make mini-conclusions as you go.**

At the end of each set of measurements, think about, and record, what you have learned.

E.g., "The voltage and current are proportional with a slope of X."

These may be useful later, and they enforce the habit of thinking about what you are doing.

How to do well

1. **Plan carefully.**
2. **Record everything in your logbook.**
3. **Tabulate data, with comments.**
4. **Analyze as you go.**
5. **Make mini-conclusions as you go.**
6. **Write up conclusions, with clean plots, at the end.**

Don't just fill in blanks or answer questions from the manual. Spend time writing what you have learned in your own words. Write about how it could have been done better or new open questions.

Schedule

1. This week we will start with a simple example.

   We'll measure the force constant of a spring. The idea is to do something simple and focus on the experimental *methods*.

2. You will have two weeks to do a measurement of your own invention.

   This can (should) be simple. E.g., you could measure a moment of inertia, dielectric constant, g, speed of sound, whatever. But, you need to do it thoroughly & carefully.

3. Then you will spend two weeks on each of 3 labs of your choice.

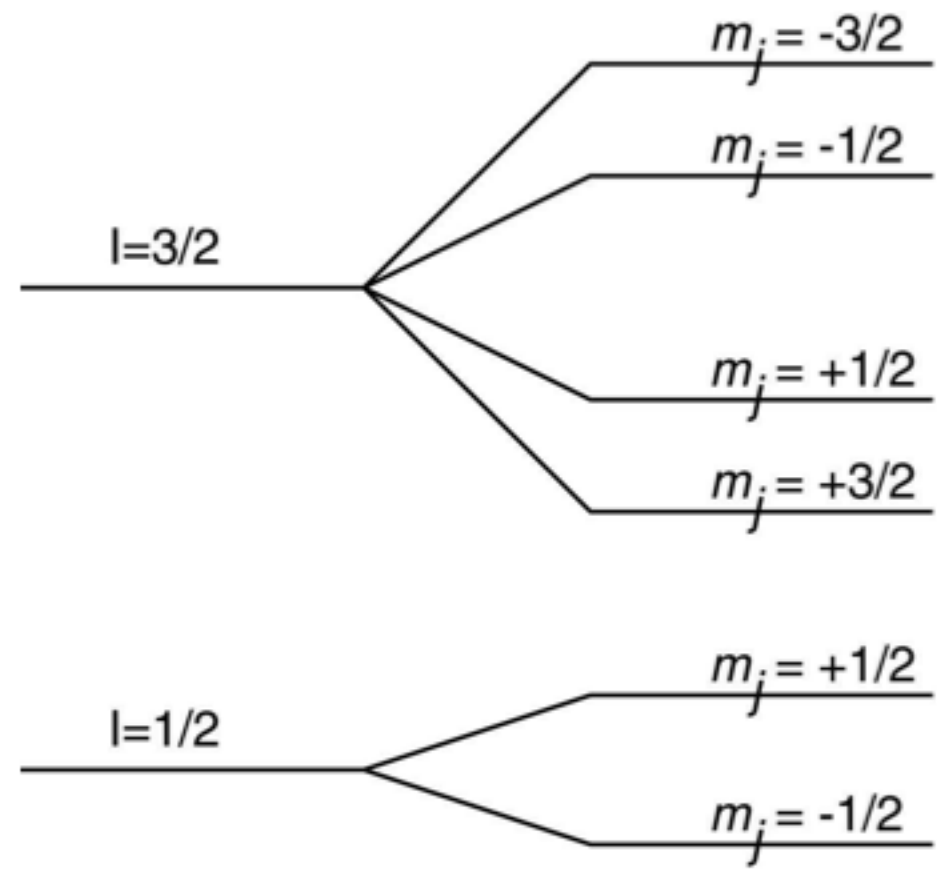
   Done with 1 or 2 partners, possible different grades.

You can choose from the following labs:

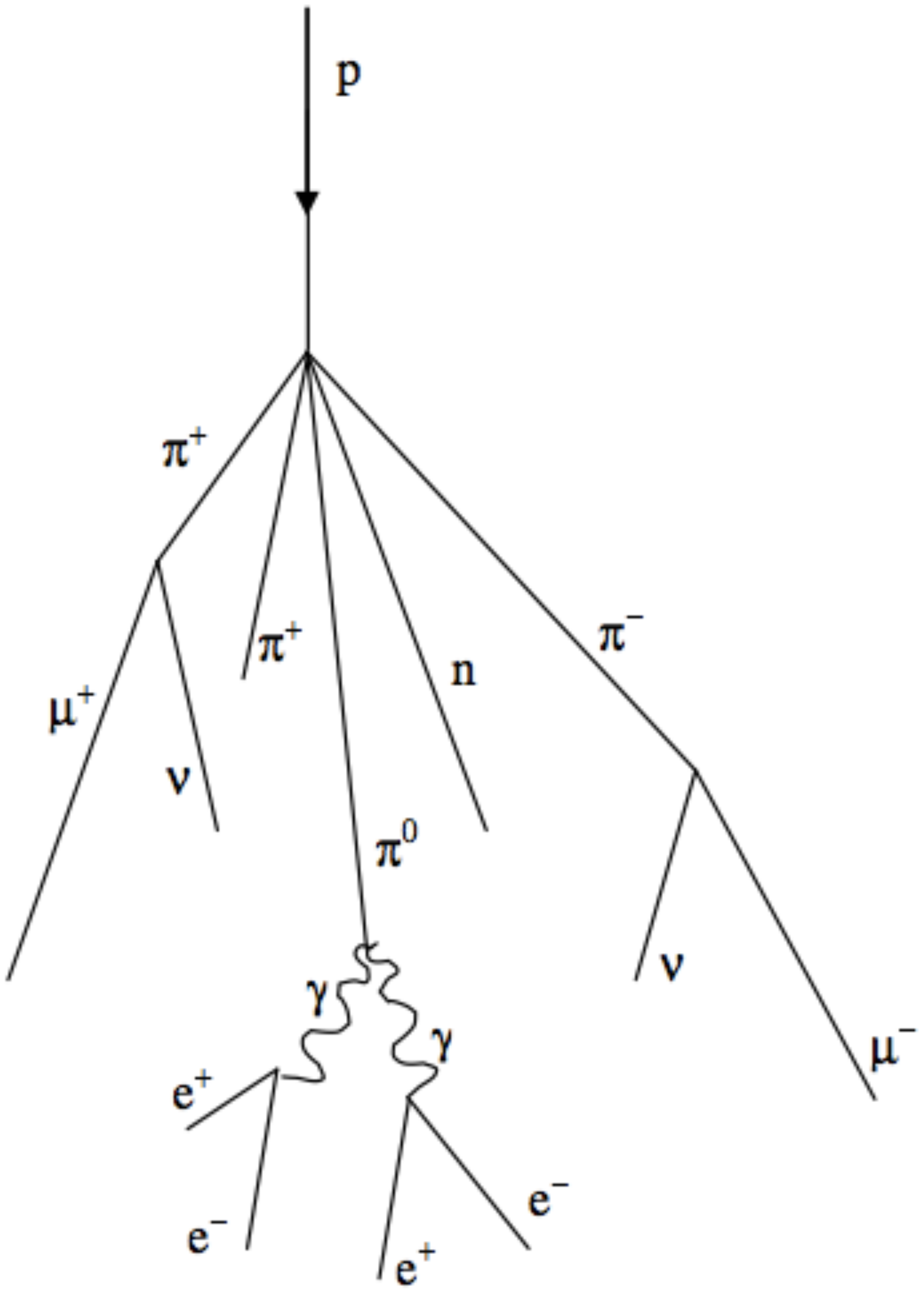
1. Interferometry
2. Holography
3. Pulse Nuclear Magnetic Resonance
4. Laser properties
5. Muon physics
6. Mossbauer Effect
7. HD isotope shift
8. X-ray diffraction
9. Gamma ray spectroscopy
10. e/m and Millikan's oil drop experiment
11. Noise ← Noise is an extra-hard lab. Free 1/3 grade point for trying.
12. Pattern Formation/Bifurcation
13. Vacuum techniques

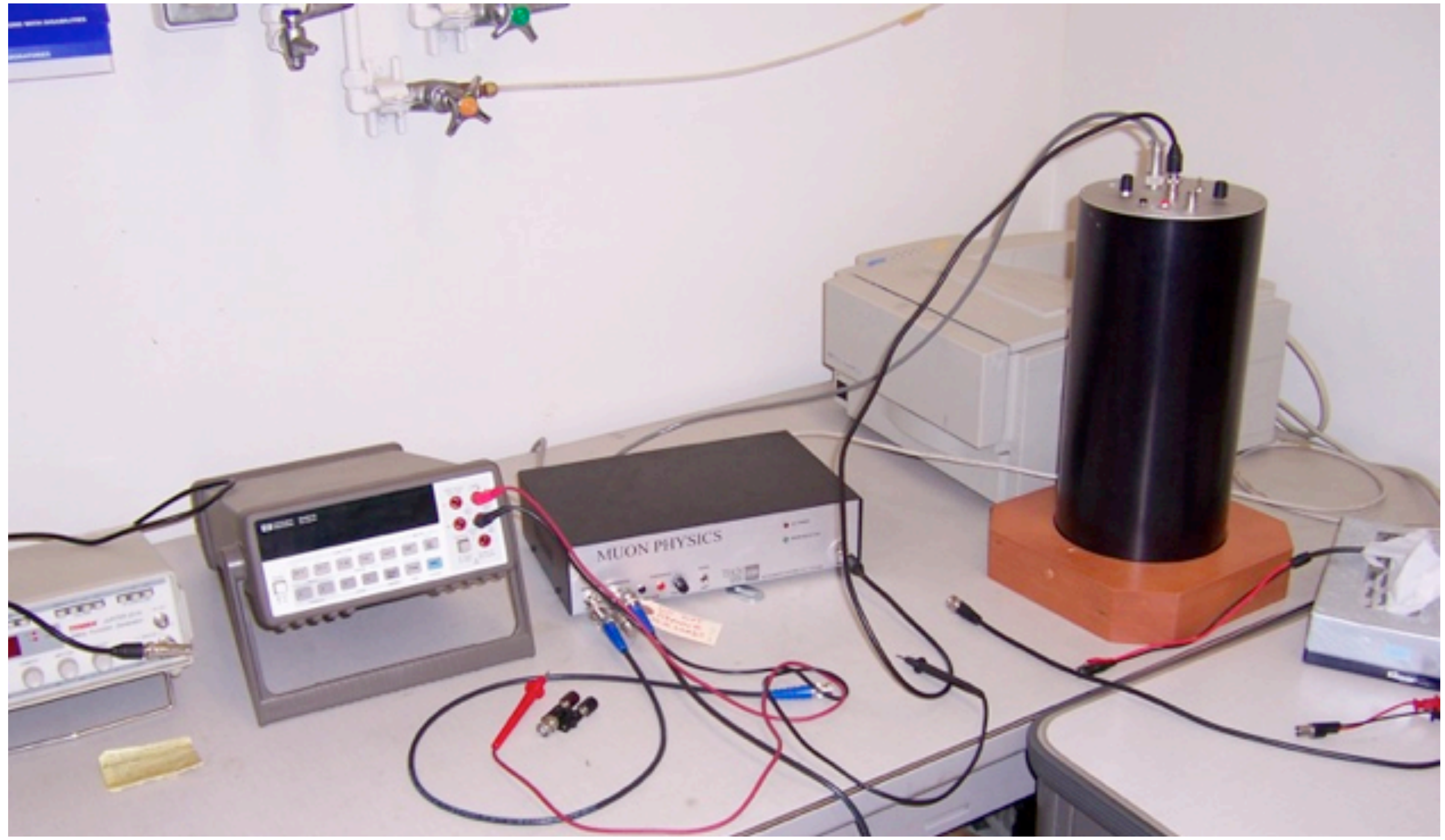
NOT ALL OF THESE WILL BE RUN. We'll choose 7 or 8 based on interest and resources.

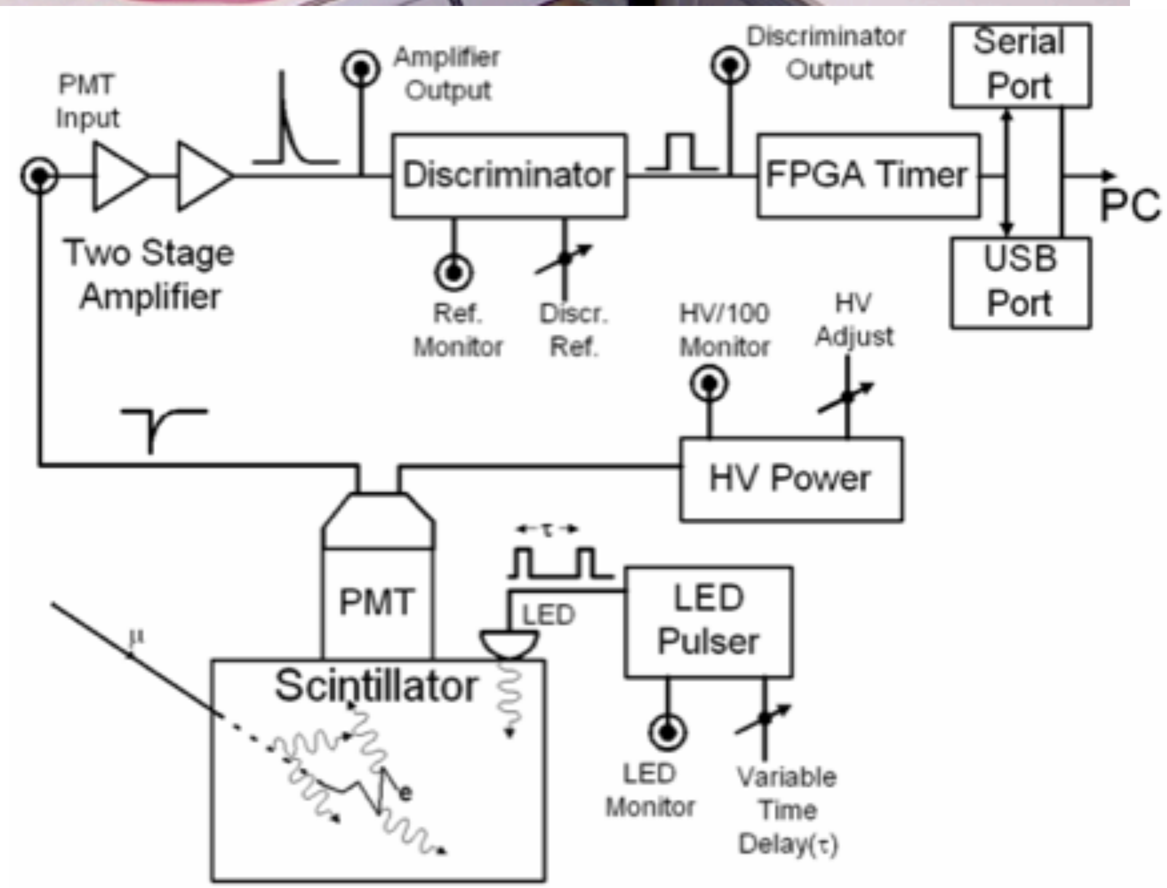
The Mossbauer Effect



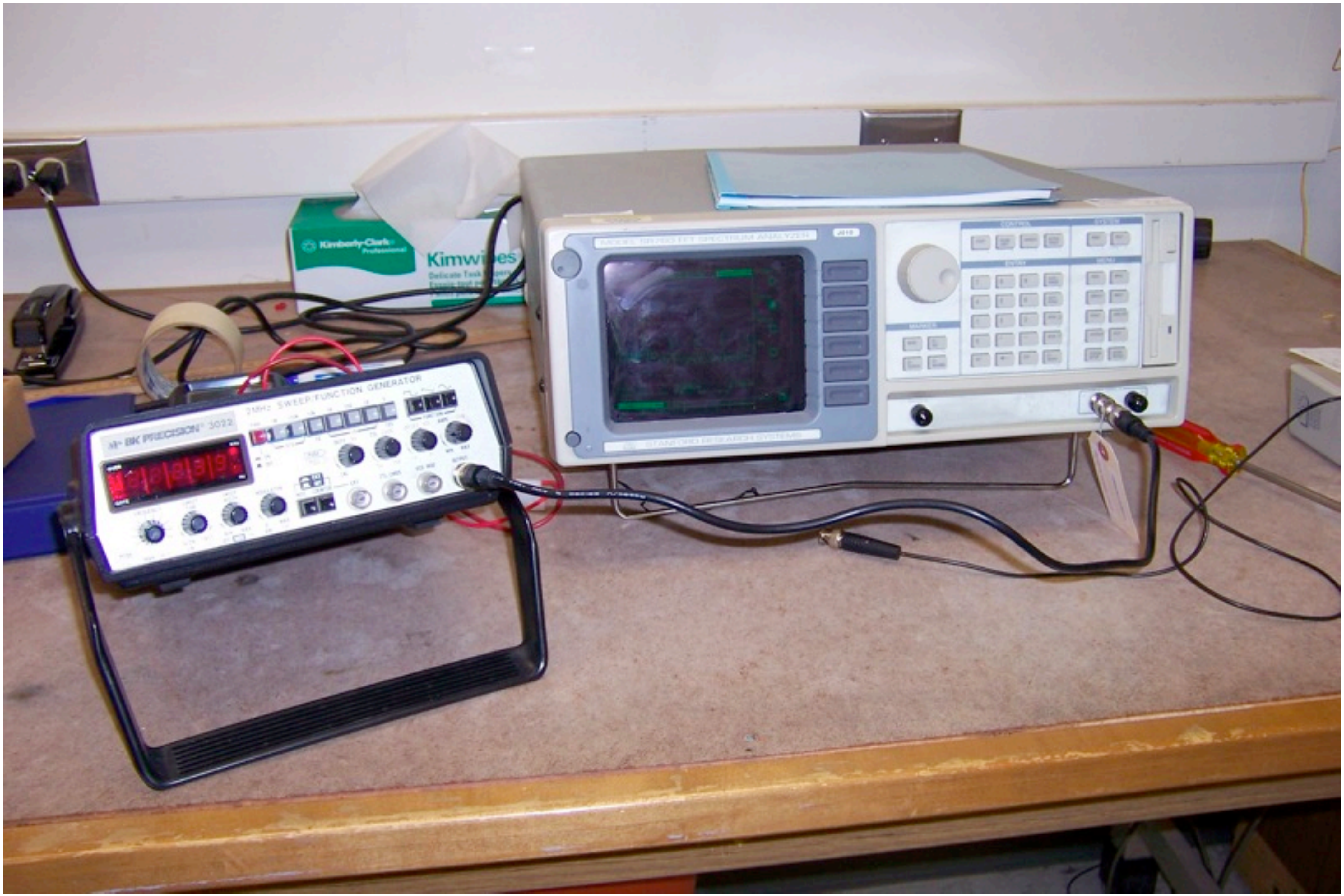
Muon lifetime





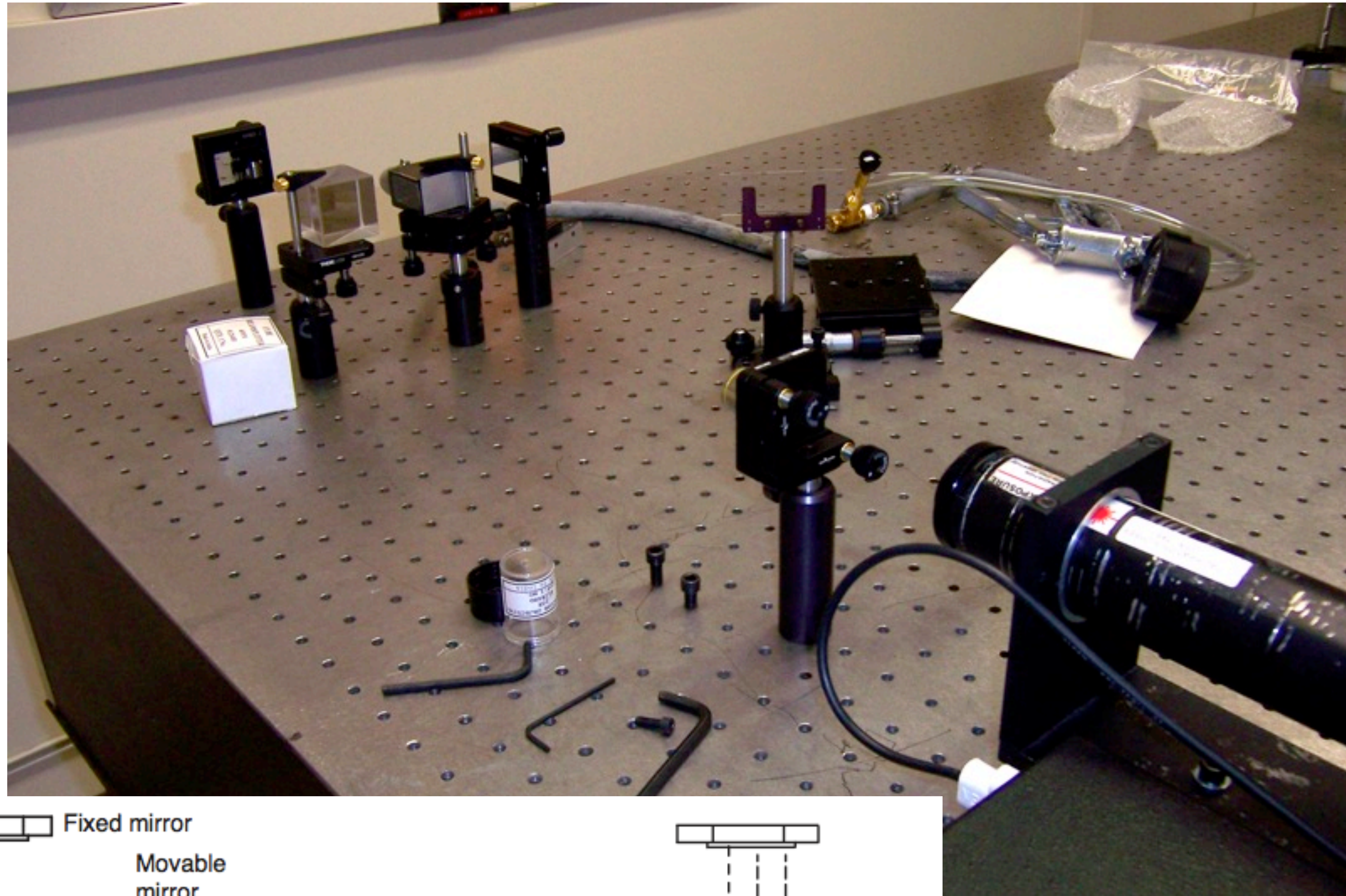


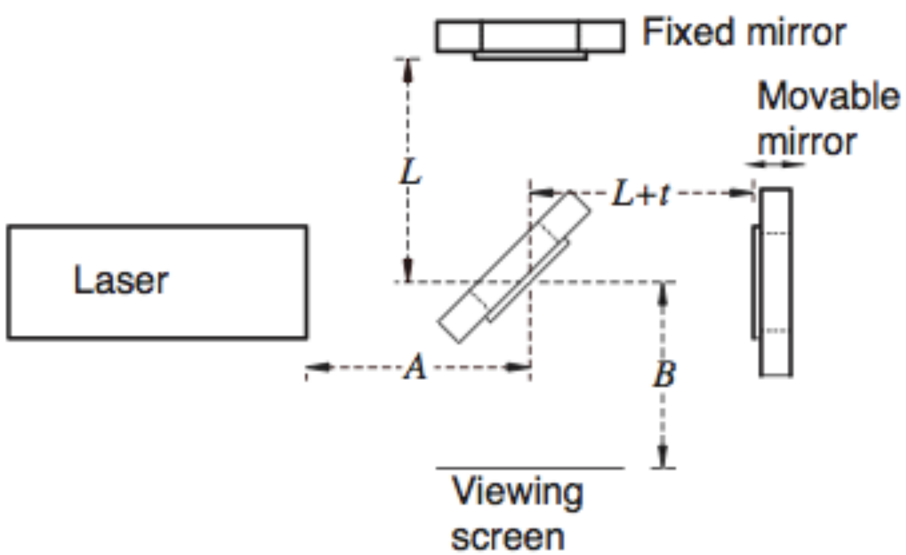
Johnson Noise

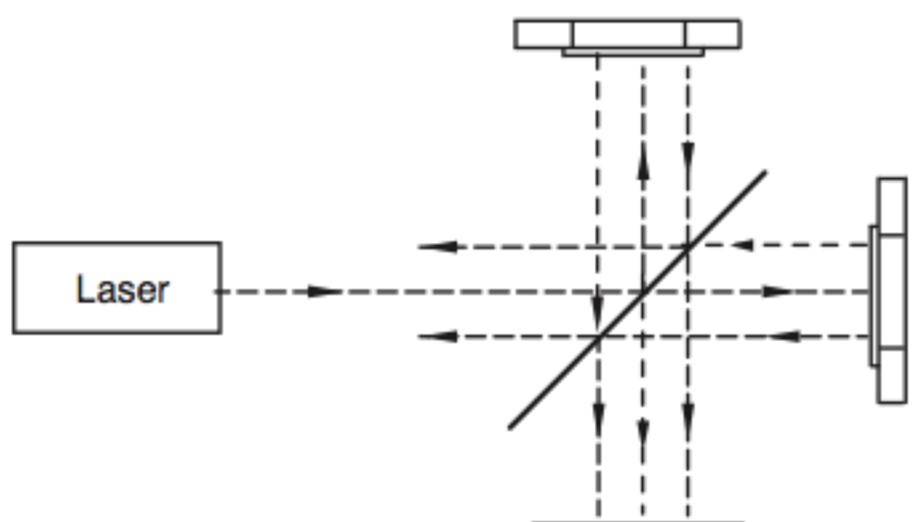


Holography

Interferometry

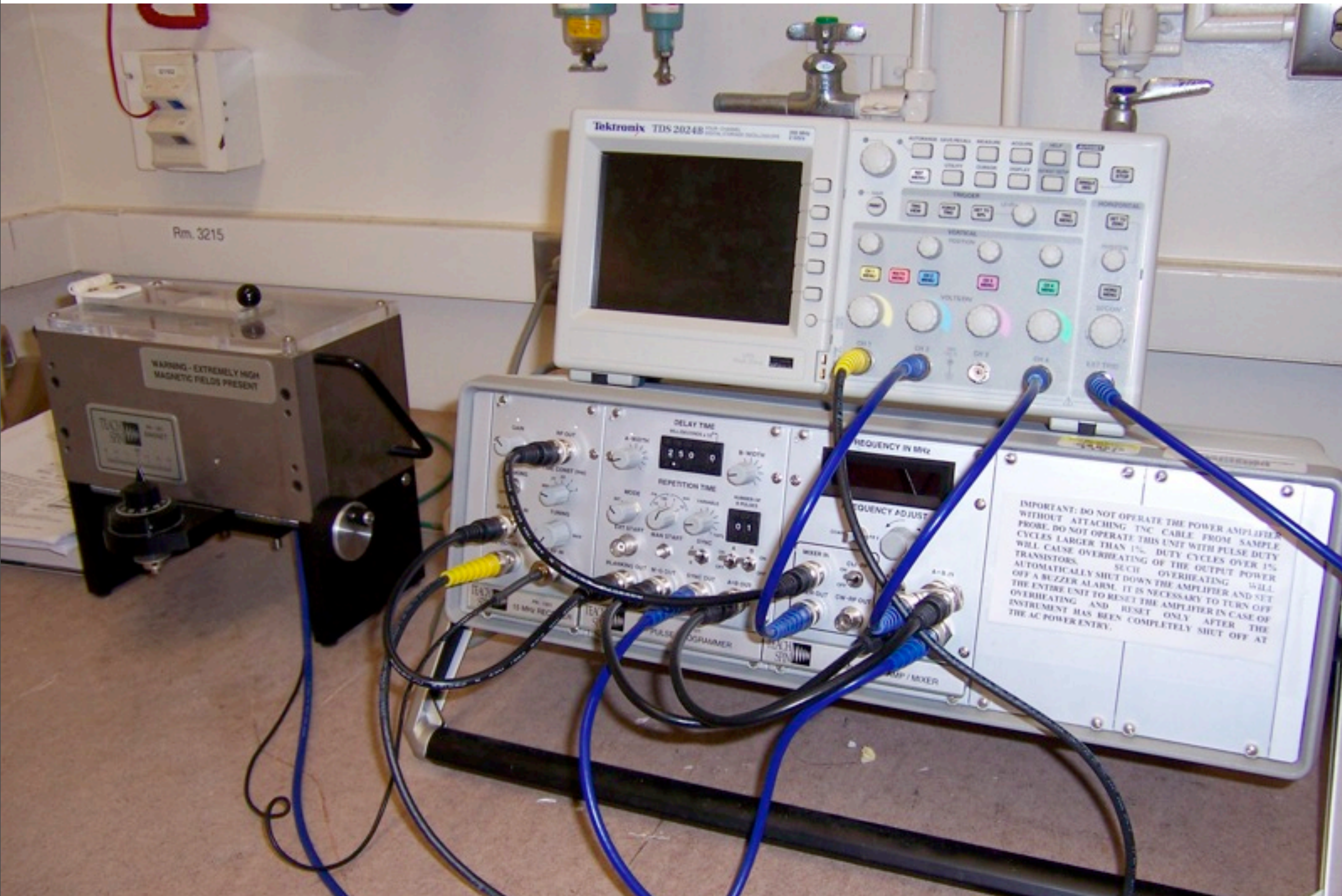






Laser properties

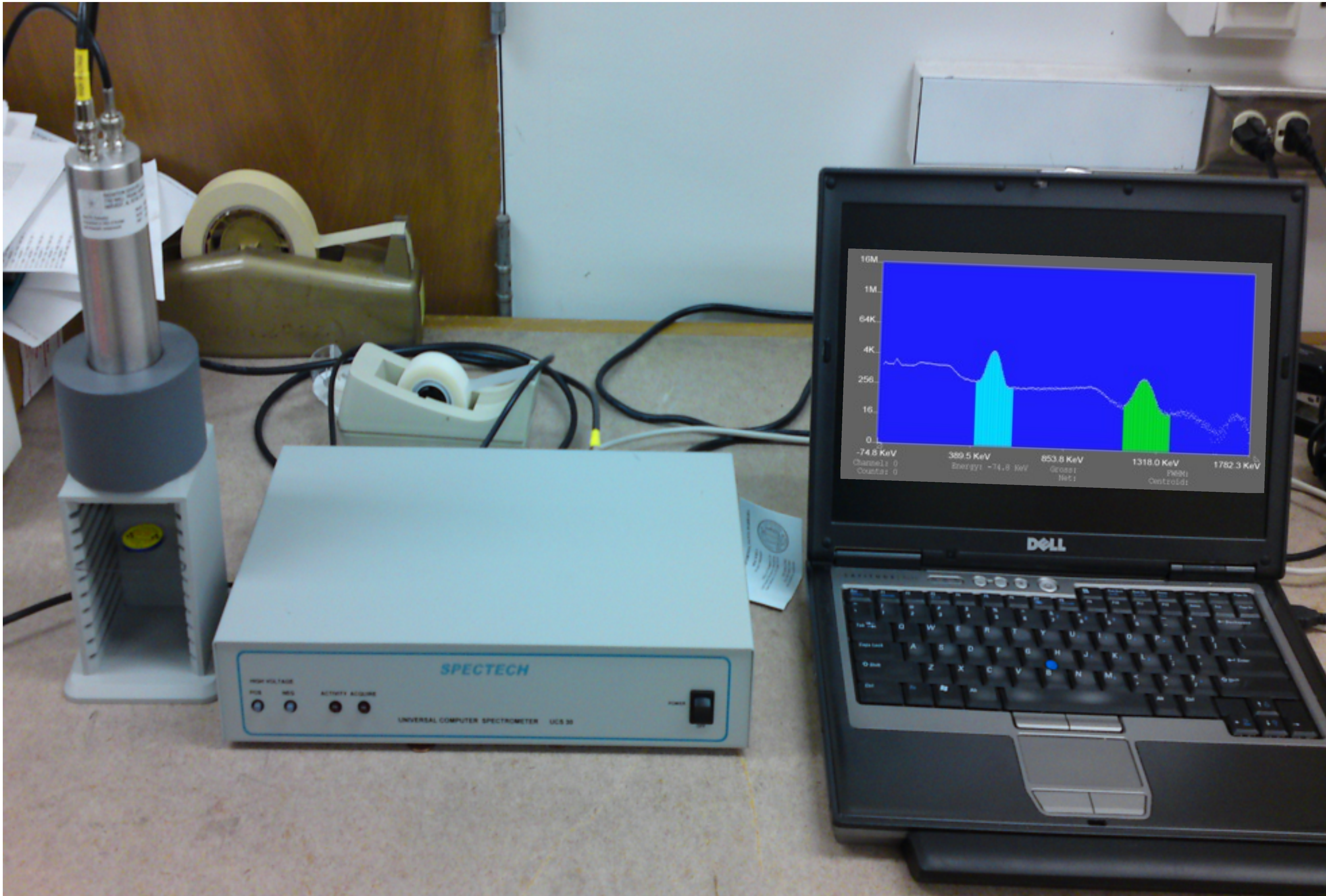
Pulse Nuclear Magnetic Resonance



HD isotope shift

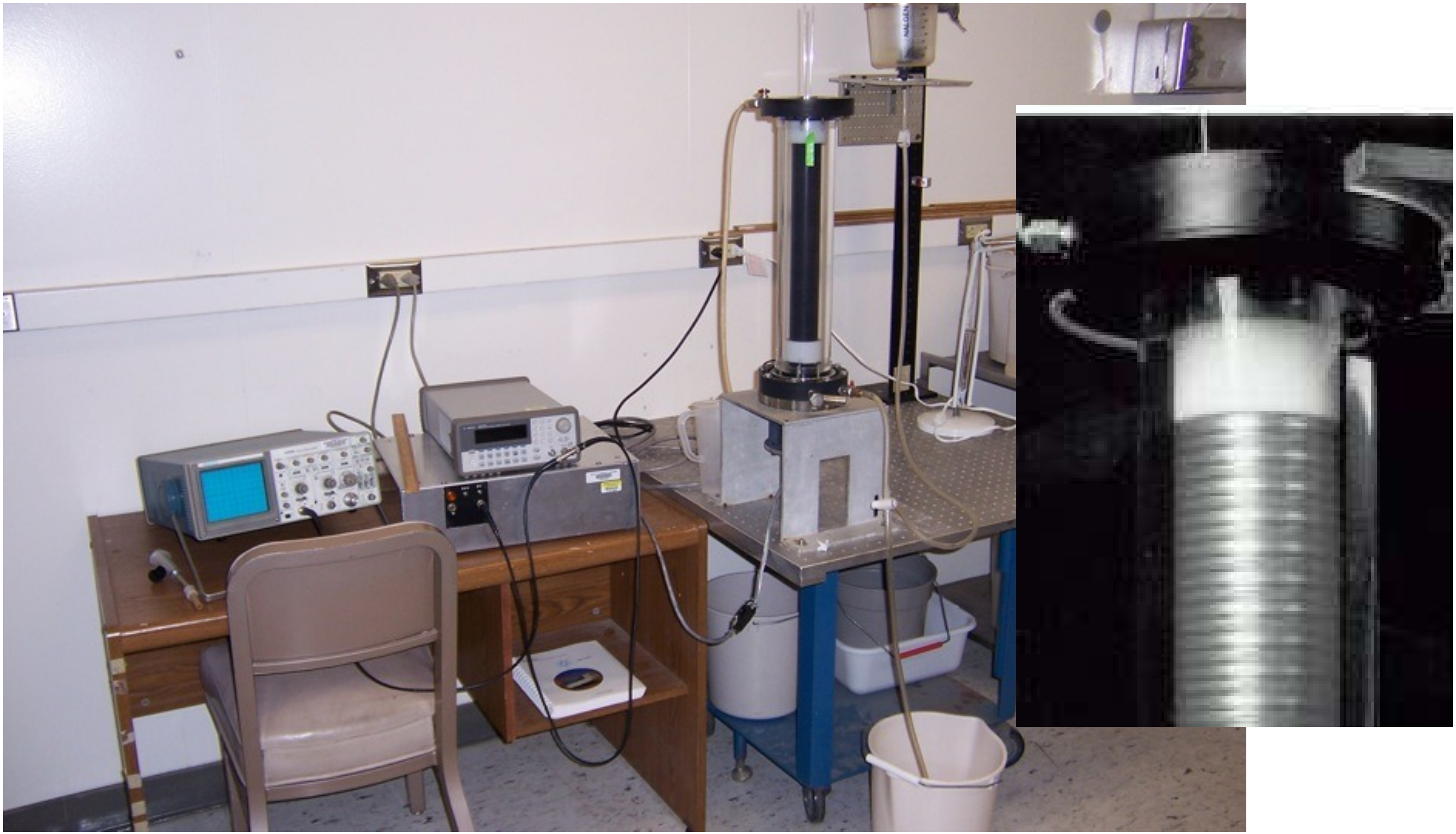
X-ray diffraction

Gamma ray spectroscopy



Vacuum techniques

Pattern formation



Choosing your labs

Please browse the labs and think about what looks interesting to you. I will put up a Web interface for you to enter your preferences. I will choose labs, assign you to them (with partners), taking your preferences into account as much as possible.

It is critical that you come to lab, and be on time, so your lab partner is not left alone.

Every "new lab day" we will begin with everyone meeting in this room. Turn in your transparencies and I'll select people randomly to give talks. (6m talk, 4m questions.) Then you will disperse to your lab setups, where the TAs will give an introduction. **Do not miss these days.**

Lecture #1: Measurements, uncertainties, and real data

Uncertainties

The most important part of your measurement is the uncertainty, i.e., how precise it is.

This is so important that I will spend about 30 minutes reviewing it. And, you should read the first four chapters of Taylor to learn it.

Bear with the repeat if you have seen this before.

Significant figures

From freshman physics. You know that if

$$m = 33\ \text{kg} \quad \text{and} \quad F = 101\ \text{N}$$

then saying that

$$a = 3.060606\overline{06}\ \text{m/s}^2$$

is wrong!

Significant figures

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then saying that

$$a = 3.060606\overline{06}\ \text{m/s}^2$$

is wrong!

Actually,

$$a = 3.1\ \text{m/s}^2$$

Significant figures ≈ uncertainty

This is because the statement that

$$m = 33 \text{ kg}$$

carries an implicit uncertainty about the value of m. It is more than 32 and less than 33 kg.

That statement of the uncertainty is too ambiguous for experimental work. We need to explicitly state how uncertain each number is in order to draw conclusions from a measurement. E.g., we should write:

$$m = 33 \pm 1 \text{ kg}$$

Uncertainties

In your logbook, presentation and paper, all your numbers should include a statement of their uncertainty. This could be an explicit ± value on each number. Or, you could write something like "all voltages have a ± 0.05 V uncertainty in this table".

Your conclusions should also state the uncertainty on the final value that you measured.

This is important.

Uncertainties

What does $m = 33 \pm 1$ kg mean?

In practice, it does not mean that I am confident that the true value of m is between 32 and 34 kg.

Rather, it means that I am 68% confident that the true value lies in that range. So, 32% of the time it could be outside.

That is not high confidence. Why not higher?

1. Using a 100% confidence range would lead to meaninglessly large intervals.
2. It is best to have an unambiguously quantitative statement.
3. You can determine any other confidence range from this.

Mini-experiment #1

"How long will this hourglass run?"

We will get variable answers because BOTH
(a) the hourglass behaves differently every time
(b) measurements are imperfect

Almost everything we do with error analysis is to predict the spread of answers in repeated experiments. (If you can do it, it saves the trouble of actually repeating the experiment.)

Things to notice:

1) The *mean* of the distribution. Unless something is biased, this is your best idea of "the real answer".

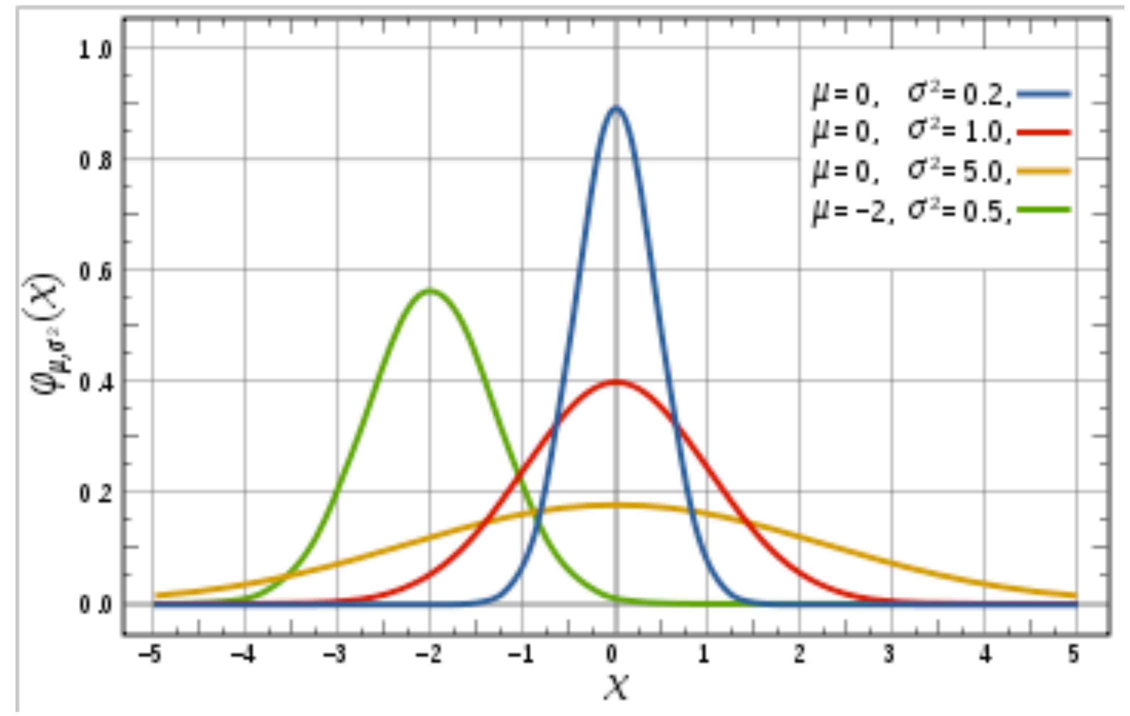
2) The width of the spread. This is the "±". (not "max - min". Find the middle 68%.)

3) How well do you know the mean? Not perfectly. Think about what the mean looked like after the first two measurements.

Uncertainties

Most uncertainties follow a Gaussian distribution (also know as a bell curve or normal distribution).

$$f(x) = \frac{1}{\sqrt{2\pi\sigma^2}}\, e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$



If you specify the mean, μ,
and the standard deviation, σ,
Then the probability for any interval is completely defined.

$$\text{Prob}(a \le x \le b) = \int_a^b f(x)\, dx$$

Uncertainties

For a Gaussian distribution:

$\text{Prob}(\mu-\sigma \leq x \leq \mu+\sigma) = 0.68$

So quoting uncertainty intervals as 68% corresponds to one standard deviation for a Gaussian.

Other probabilities can be obtained with just math:

$\text{Prob}(\mu-2\sigma \leq x \leq \mu+2\sigma) = 0.95$

$\text{Prob}(\mu-3\sigma \leq x \leq \mu+3\sigma) = 0.997$

$\text{Prob}(\mu-4\sigma \leq x \leq \mu+4\sigma) = 1 - 6E\text{-}3$

$\text{Prob}(\mu-5\sigma \leq x \leq \mu+5\sigma) = 1 - 6E\text{-}5$ i.e., possible but very rare.

Uncertainties

Since most random processes, which underlie uncertainties, are Gaussian distributed, this gives a simple way to quantify uncertainties. That is why it is called the *normal* distribution.

Estimators

Of course, we don't know that $\mu = 33$ kg and $\sigma = 1$ kg.
We are just estimating that.

If we measured the mass with a scale and get 33 kg, that is the best estimate that we have for the most probable value μ.

We determine the estimate for σ either by knowing the precision of the device, or by measuring it somehow.

Then, $m = 33 \pm 1$ kg is our estimate of where the true value lies. It is a quantitative approach that allows us to arrive at quantitative conclusions.
But, we need to estimate both μ and σ.
We'll talk about estimating σ later.

Central limit theorem

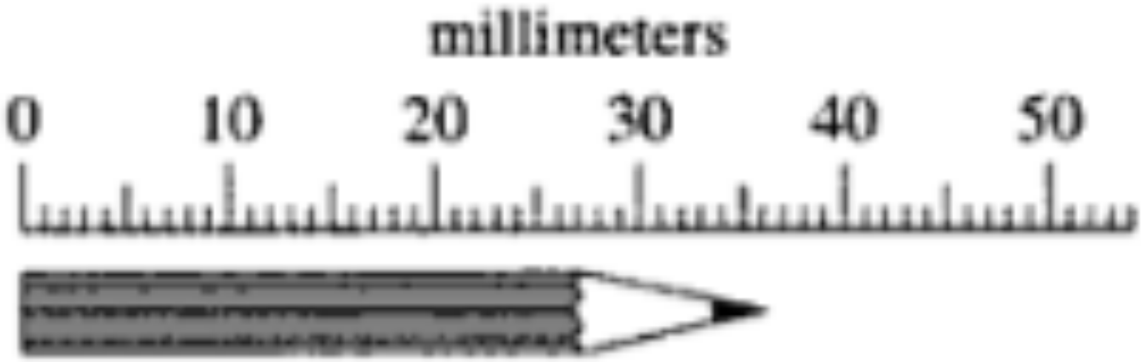
You don't need to worry too much about σ being exactly Gaussian. In fact, it often is not.

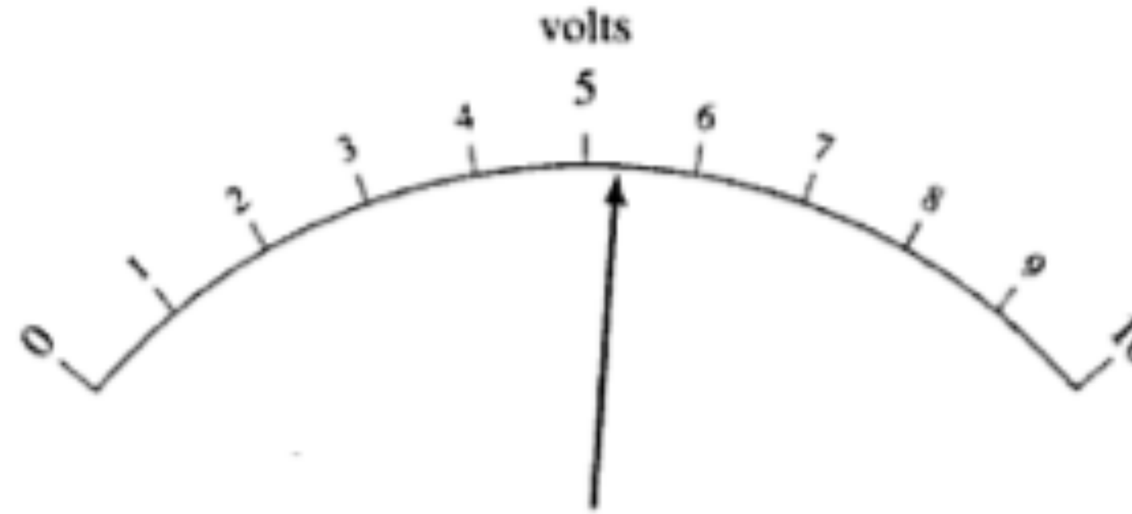
But, the central limit theorem states that the average of many independent random numbers will be normally distributed, even if the numbers themselves are not.

So, you needn't worry much about the probability distribution of any specific measurement being Gaussian. When you combined them all in a set of measurements, the result will be.

But, you do need your σ to correspond to about 68% probability.

MINI-EXPERIMENT #2: measurement scales

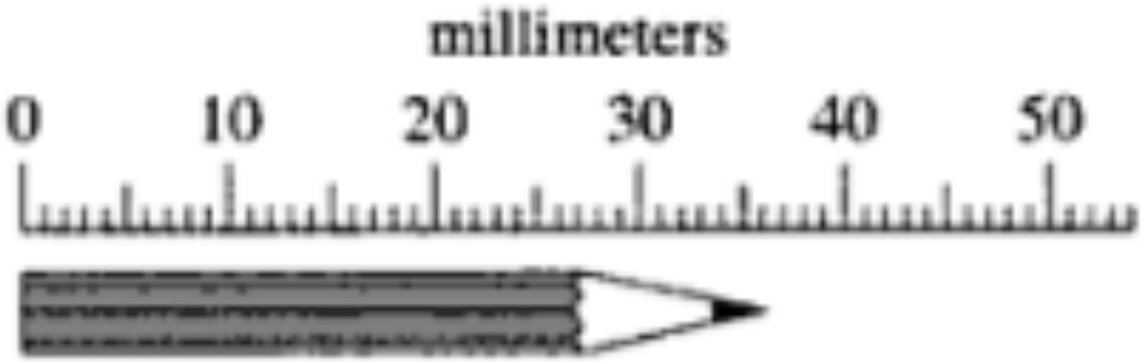


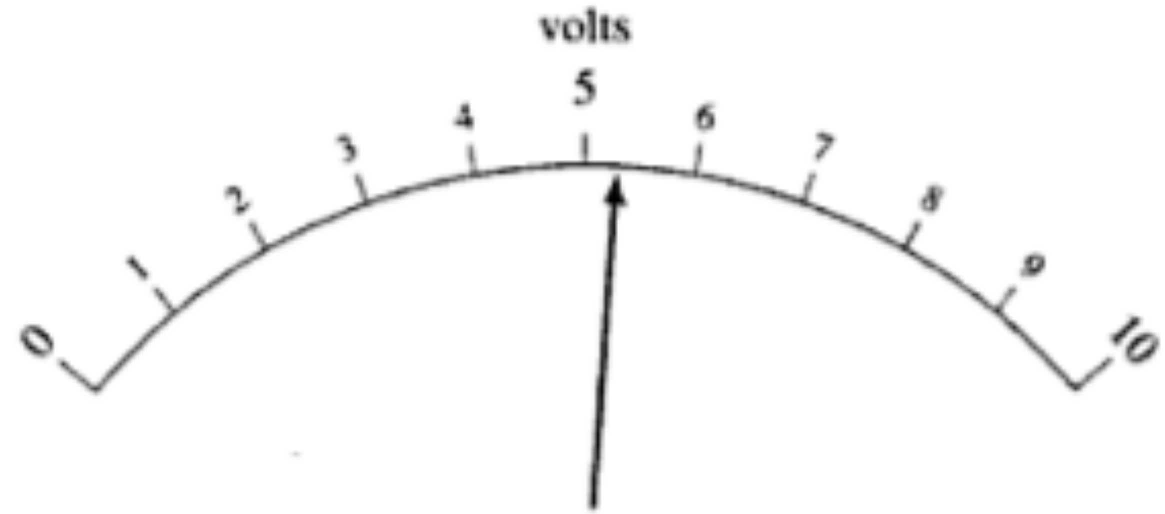


What do you estimate for μ and σ in each case?
Do we all agree?

A variety of different physics processes will alter them, e.g. viewing angle or focus of eye. These ≈ random processes will make our μ values differ, for the same thing. They will also make repeated measurements differ.

Estimating σ





What do we estimate for μ and σ in each case?

Don't try to be "safe" by overestimating σ. Aim for 68%.

A good rule of thumb is to pick the smallest range you are 100% confident in and divide that by sqrt(12).

This is actually rigorously 68% if the probability is flat.

Significant digits on σ

It is usually fine to quote a single significant digit for σ, e.g., $L = 36 \pm 0.2$.

But, in some cases use two significant digits. E.g., there is a meaningful difference between $\sigma=1$ and $\sigma=1.4$, but less between $\sigma=9$ and $\sigma=9.4$.

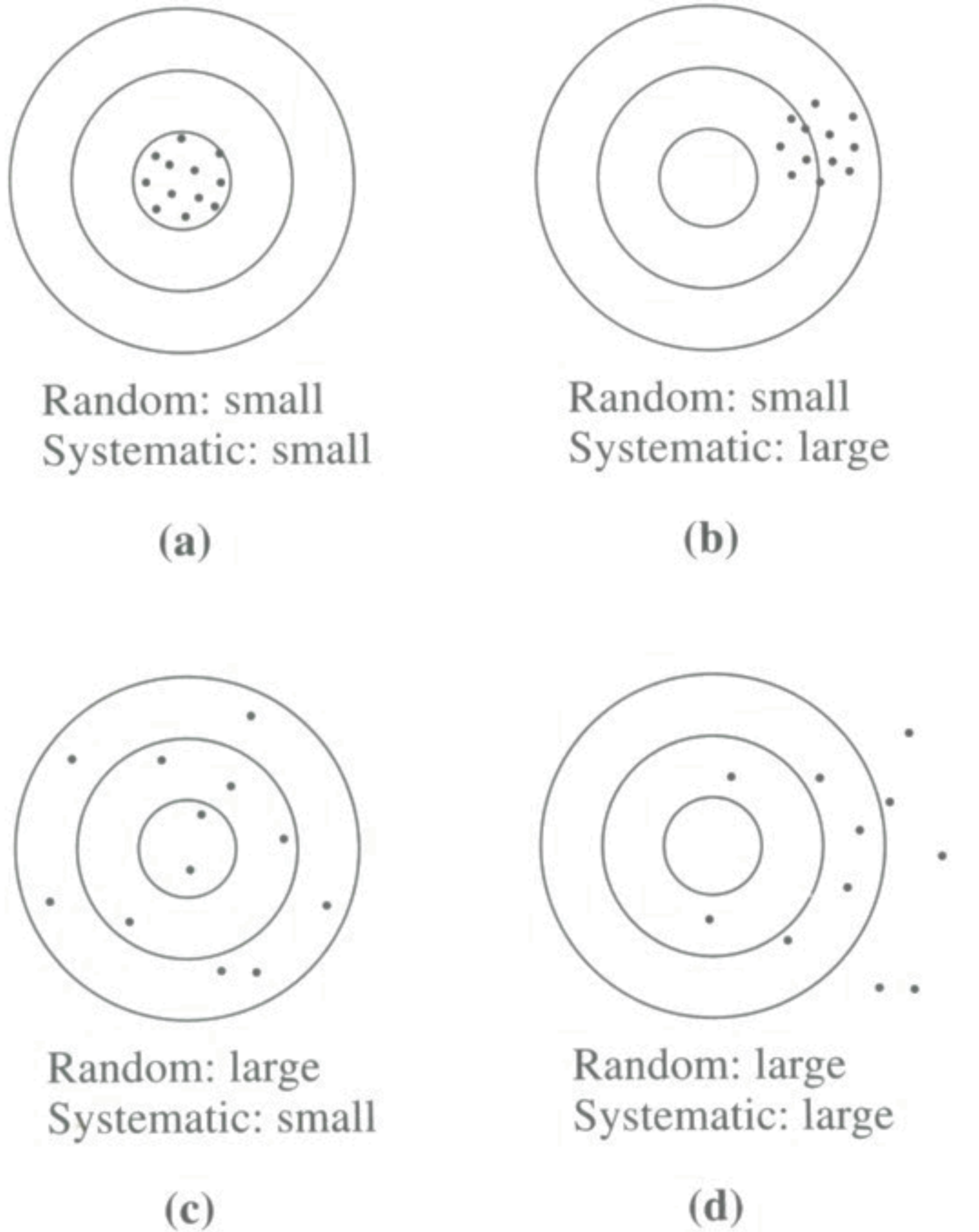
Use your judgement, or just use 1 digit except when that digit is 1, then use 2 digits.

Systematic Uncertainties

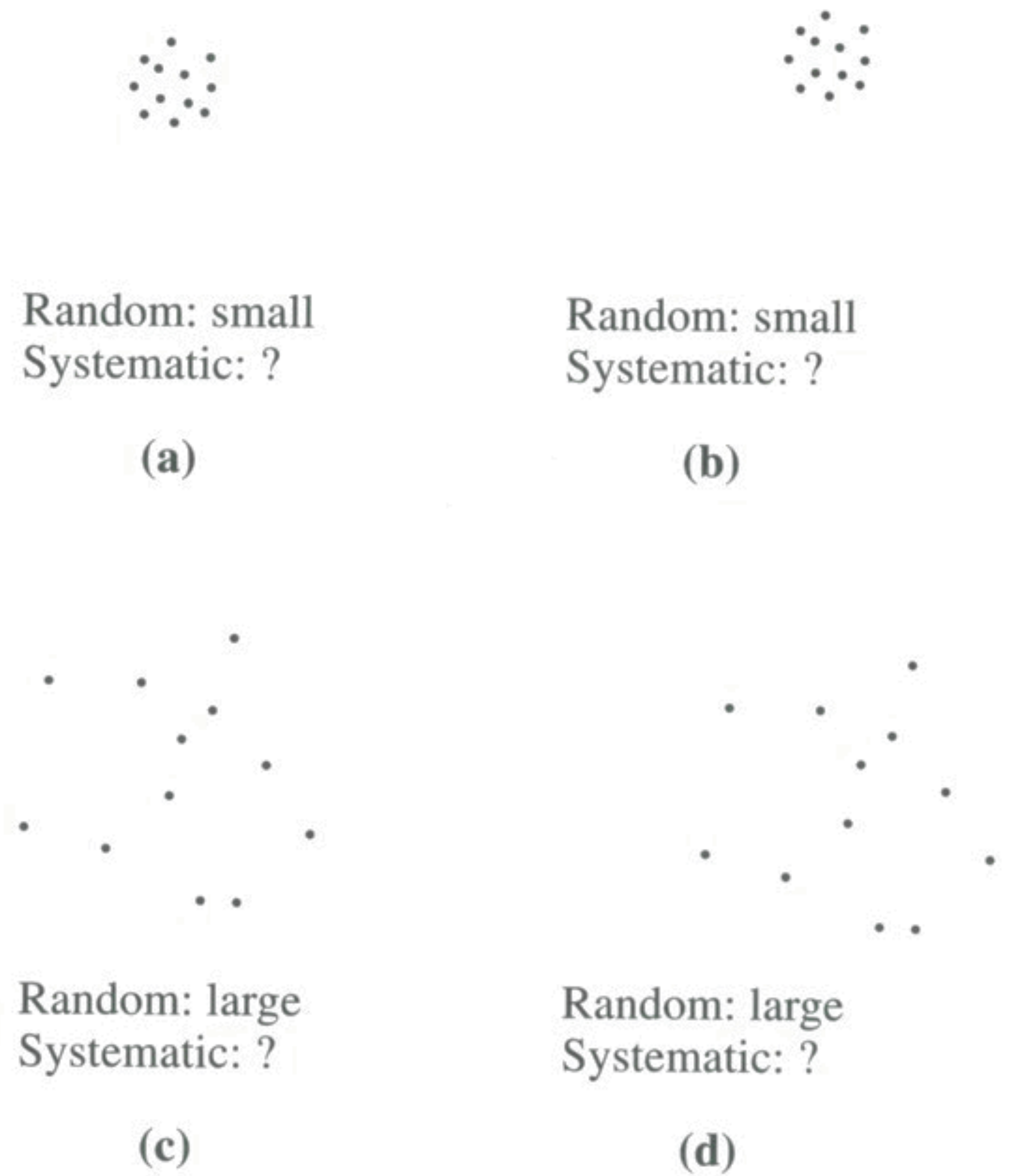
Often there are sources of uncertainty other than just random processes that cause the measurement to vary. There could be something in the system of measurement that biases the value.

The ruler may have expanded due to a temperature change. Or the volt meter may have an offset or a scale error due to a different input impedance than assumed in the calculation.

Systematic Uncertainties



Systematic Uncertainties



Systematic Uncertainties

Often there are sources of uncertainty other than just random processes that cause the measurement to vary. There could be something in the system of measurement that biases the value.

The ruler may have expanded due to a temperature change. Or the volt meter may have an offset or a scale error due to a different input impedance than assumed in the calculation.

These can be hard to estimate, or they can be easy.

Equipment manuals will often tell you.

Otherwise you have to vary things and look for offsets.

Error propagation

In a perfect world, to figure out the uncertainty on any result you would just repeat the experiment 100 times. (Look at spread of results.)

In the real world, if you know the uncertainties on the inputs to a calculation, you can *calculate* the uncertainty on the output. This is *error propagation.*

Error propagation can look like an abstract on-paper exercise; always remember that it boils down to "If I were to repeat the whole experiment 100x ..."

Combining Uncertainties

We often need to combine two sources of uncertainty to get a total uncertainty.

E.g., measuring the length requires subtracting the measurements from the two ends. $L = x_2 - x_1$.

The uncertainty on L is bigger than on x_1 or x_2 because they can both be wrong.

If the two measurements are correlated somehow, like your blindness, then they could add constructively. Then,

$\delta L = \delta x_1 + \delta x_2$ i.e., $L = (x_2 - x_1) \pm (\delta x_1 + \delta x_2)$

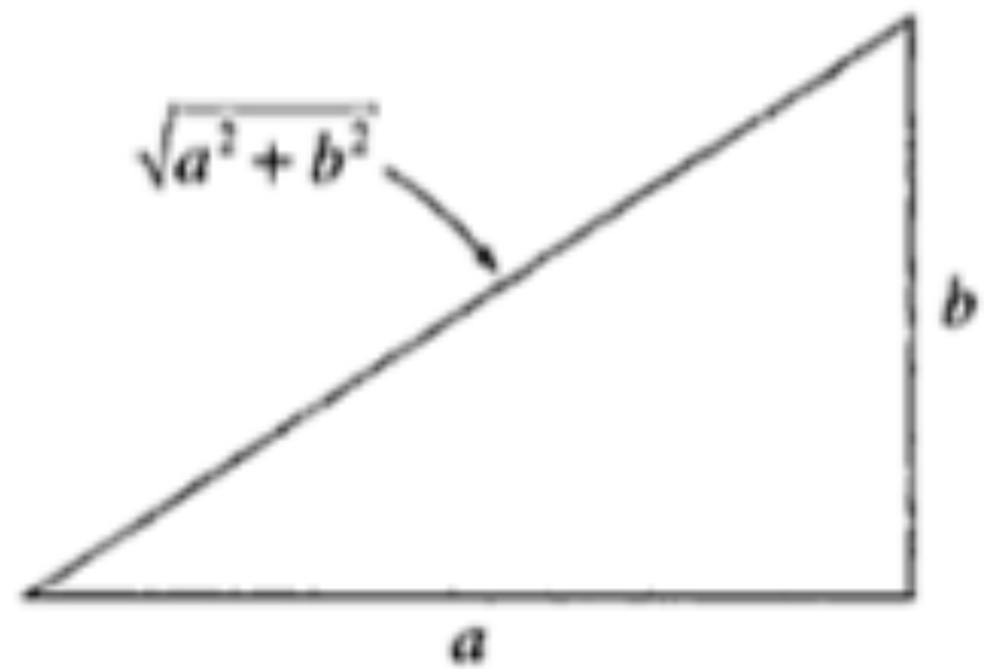
Combining Uncertainties

If they are uncorrelated, i.e., both are random, then

$$\delta L^2 = \delta x_1{}^2 + \delta x_2{}^2$$

This is called adding them in quadruture.

This is because they can randomly add their directions, so think of vectors and Pythagorus.



Combining Uncertainties

Deciding how to combine uncertainties can be tricky because you need to know what is correlated and what is not.

Generally, most measurement uncertainties are uncorrelated—it is due to random effects.

Systematic uncertainties tend to be correlated across all measurements. (E.g., using the same ruler makes all lengths 10% too big).

So, it is best to think about systematic uncertainties separately.

Combining Uncertainties

If you multiply or divide numbers, then you add the *fractional* uncertainties in quadruture.

If

$$C = A * B$$

then

$$(\delta C/C)^2 = (\delta A/A)^2 + (\delta B/B)^2$$

The same is true if $C = A/B$.

Combining Uncertainties: General formula

If you have a general relationship between variables, then use derivatives:

General Formula for Error Propagation: If $q = q(x, \ldots, z)$ is any function of $x, \ldots, z$, then

$$\delta q = \sqrt{\left(\frac{\partial q}{\partial x}\delta x\right)^2 + \cdots + \left(\frac{\partial q}{\partial z}\delta z\right)^2}$$

(provided all errors are independent and random)

and

$$\delta q \leqslant \left|\frac{\partial q}{\partial x}\right|\delta x + \cdots + \left|\frac{\partial q}{\partial z}\right|\delta z$$

(always). [See (3.47) & (3.48)]

MINI EXPERIMENT #3

Measure the length of a spring with four different masses.

Record your data in your logbook.

Plan:

- What to record?
- How to measure? Units? Coordinate system?
- Uncertainty?

How do you plot this data?

Error propagation

This is just a taste; you'll need to learn this properly

You probably measured $\{m, x_1, x_2\}$

Δm: (???)

Δx_1: smallest division of ruler/$\sqrt{12}$

Δx_2: smallest division of ruler/$\sqrt{12}$

$$\Delta x = \sqrt{(\Delta x_1^2 + \Delta x_2^2)}$$

You probably calculated: $mg = kx$, *so* $k = mg/x$

(Are Δm and Δx correlated or uncorrelated?)

$$\Delta k^2 = (\Delta x\ \partial k/\partial x)^2 + (\Delta m\ \partial k/\partial m)^2$$

$$= (\Delta x\ mg/x^2)^2 + (\Delta m\ g/x)^2$$

$$= (\Delta x/x\ k)^2 + (\Delta m/m\ k)^2$$