PHYS 360/460: The DOs and DON'Ts of Scientific Graphs

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Using graphs to display data is common in experimental physics. Good graphs can strengthen physical understanding, convince others, and suggest new ways of looking at data. Bad graphs impede understanding and are a poor reflection on their creators. If care was not taken to present the data, what care was taken in its collection?

Clarity must be the graph-maker's mantra. Specifically, the main points of a graph should be easily grasped by the reader, and the possibility of misinterpretation minimized. All other motivations should be secondary. What follows are specific, concrete directions for the production of clear graphs. When possible these have been illustrated by both good and bad examples from the professional physics literature (on the last pages of this report).

The DOs:

1. **DO:** label each axis of the graph with the physical quantity represented *and* the corresponding units in brackets beside the label. However some quantities are dimensionless and do not require units.

   If the units are arbitary – a situation to be avoided if at all possible – then put "(arb. units)". Avoid "(a.u.)" which can be mis-interpreted as "(atomic units)" (among other things).

   Often a quantity is represented with a mathematical symbol that is also used in equations within the text. In this case it is sometimes helpful – if space permits – to use both the quantitative name and the variable for the axis label. For example "velocity v (m/s)" is better than just "v (m/s)". Sometimes the quantity plotted has no simple qualitative explanation (i.e. the horizontal axis of Fig. 1). In any case, the label should be unambiguous and any necessary information given in the caption.

2. **DO:** use legends to label the different plotted quantities (see Fig. 2). Or, if possible, directly label the data in the plot (see, for example, Fig. 6).

3. **DO:** use sensible scales for axis. For example, if the range of your data is from 6.3 to 9.8, chose your axis to run from 5 to 10. Do not have it start and stop exactly at the extreme values of your data. Choose nice round numbers, and label the axis with round values (in this case: 5,6,7,8,9,10 would be a good choice).

4. **DO:** Assign every graph and diagram in your report a label (e.g. Figure 1, Figure 2, etc ...) so that they may easily be referred to in the text of the report. (A good report will also contain an explicit reference to each figure in its main text.)

5. **DO:** provide an informative caption with each graph, which includes the label that will be used to refer to the graph in the report.

   Both of the preceeding points are illustrated in Fig. 1.

   In elementary reports (perhaps in first year), you may have been encouraged to provide a title for your graphs. This is not normally done in the professional physics literature. Why? These titles are usually somewhat redundant. e.g. The title "x velocity vs time" is redundant since hopefully the axis are labelled with "velocity v_x(m/s)" and "time t (s)". The caption takes the place of the title, in that it allows substantially more information about the the graph to be located near the graph (where it is most useful). Use captions and numbered figures in your reports.

6. **DO:** show error bars for both coordinates if at all possible. Often error bars are very small on the scale of the graph. If so, indicate this in the caption.

   Often when individual data points are graphed, and the error bars are small, the symbol size may be used to represent the error. If so, please note this in the caption.

   Despite the emphasis that error bars are given in laboratory courses, their actual appearance in plotted experimental data in the professional physics literature is less common that one might imagine. Why? Often when there is a lot of data the scatter about a general trend gives a good indication of the random error. Error bars become important when there is little data (often in particle physics) and/or the deviation of the data away from a theory (often shown on the same graph with a line) is particularly important (see Fig. 2).

   If you do not present error bars for plotted data, at the very least justify why. If you do provide error bars their magnitude should be justified.

The DON'Ts:

1. **DON'T:** use colour as the only means to distinguish different plotted quantities. Some people are colour blind!

   Another (more common) problem with using colour is that once photocopied (with a black and white copier) the information contained in the colour is lost. The use of colour is a very common problem with reports written by students for Phys 437 (the fourth year research project). These often contain useful results, and are nice to photocopy to give to future students. Frequently, however, the use of colour limits the usefulness of black and white copies.

   By all means use colour to *help* distinguish between different plotted quantities. Do not, however, make it a necessity for understanding.

2. **DON'T:** plot two physically dissimilar quantities on the same graph with different vertical (common) or horizontal (uncommon) axis. This is frequently done to save space.

   This type of graph is a pain to look at – it's always a hassle to figure out what data corresponds to which axis (see Fig. 5).

3. **DON'T:** use non-standard features, unless there is a compelling reason to do so.

   The problem with non-standard graphs is that when examining them valuable brainpower is wasted on their novelty – when the focus should be on the point the graph is illustrating (see the axis labelling in Fig. 4). Save your originality for scientific ideas!

4. **DON'T:** use "inset" graphs (see Fig. 3). This is unlikely to be an issue in Phys 360/460. However, they frequently appear in the literature and it is worthwhile to point out why.

   These usually employed as a space saving feature in articles with length limitations. However, they present several problems because: 1) they usually reduce the clarity of the main graph, 2) the physical size of the inset graph is often ridiculously small, so as to limit its usefulness, and, 3) they take away white space that a reader can use to make notes in.

   Sometimes an inset makes sense. e.g. to zoom in on a particular detail of a graph that is not readily observable in the main graph (see Fig. 4). Sometimes (but rarely) it makes sense to inset a graph which may need to be frequently consulted as one looks at the main graph.

Software for plotting data in Phys 360/460 Laboratories

Excel is frequently used by students for scientific plotting. Unfortunately, by default, the quality of Excel graphs is quite poor. Much better software for plotting scientific data is available. One program that is commonly used by some research groups in this Department is Igor Pro (www.wavemetrics.com).

The Department of Physics has purchased a course license for Igor Pro. You can download the program from www.wavemetrics.com. Please contact me (`jddmartin@uwaterloo.ca`) to obtain an activation key. I am quite familiar with Igor, so please contact me if you have any questions, or would like a brief tutorial on its use.

You are not required to use Igor Pro. However, you *are* required to produce high quality graphs for your reports. Software alternatives include Matlab and Origin, among others. With sufficient tweaking it is probably possible to produce high quality graphs in Excel.

High quality graphs may even be produced by hand. However a computer can also be used to efficiently analyze your data (data reduction, calibration corrections, least-squares fitting etc...), so hand-plotting of data is rarely done these days. Consequently, it is discouraged here.

Comments and corrections are welcome!

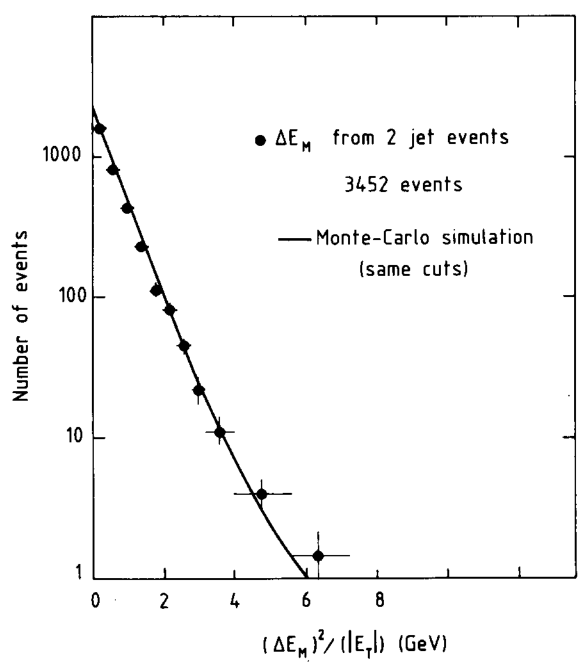

Fig. 1. Distribution of missing energy squared normalized to the total scalar transverse energy observed for a sample of jet triggers. The solid curve is a Monte Carlo simulation.

Figure 1: From Arnison *et al.*, *Phys. Lett. B*, **139** 115 (1984). This is an excellent simple graph. Note the use of error bars (different for the different data points), and comparison with a theory. Note that a qualitative, descriptive label has been used for the vertical axis, but not for the horizontal axis – where a mathematical representation makes more sense. Perhaps the only improvement possible to this graph would be to add “minor” ticks to the axis to allow the values of the data points to be readily estimated.

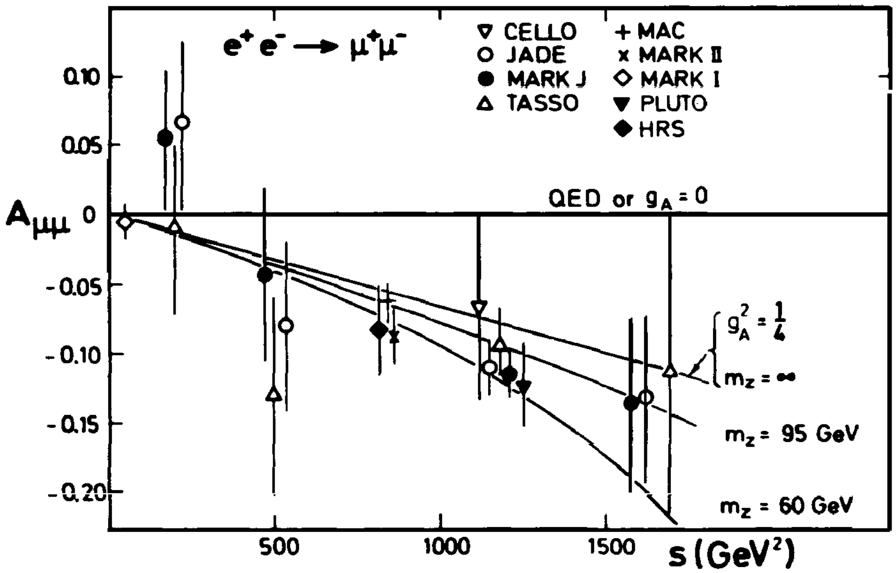

Fig. 23. Experimental evidence for a weak-electromagnetic interference effect in the process $e^+e^- \to \mu^+\mu^-$ at high-energy colliding beams. It can be seen that data are better fitted if the presence of a finite mass m_Z propagator is assumed.

Figure 2: From C. Rubbia's Nobel Lecture (www.nobel.se). This is an excellent example of a graph being used as part of a scientific argument. Note the importance of error bars, and how the different data are distinguished (using a legend on the graph).

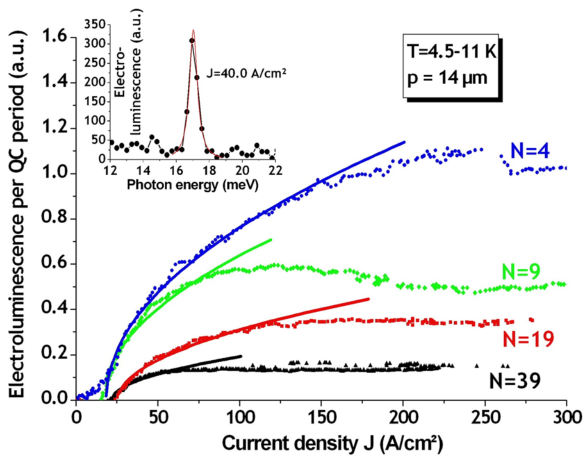

FIG. 2 (color online). Electroluminescence per QC period N as a function of the injected current in devices with a 14 μm period grating, for the four samples. The solid lines are square root fits according to Eq. (3). Inset: experimental spectrum of a $N = 39$ device at $T = 11$ K.

Figure 3: From Todorov *et al.*, *Phys. Rev. Lett.*, **99**, 223603 (2007). This figure uses an "inset", probably due to length restrictions. Avoid this at all costs.

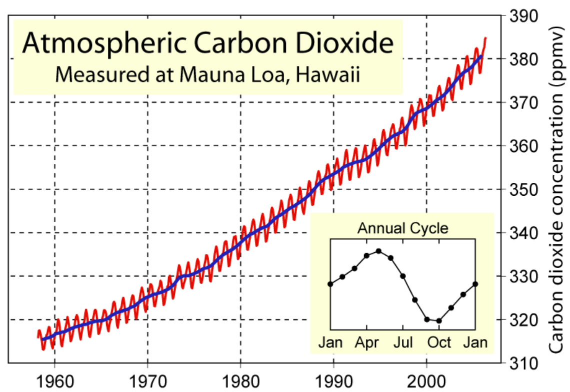

Figure 4: From the "Keeling Curve" article on Wikipedia. There are at least two problems with this graph. One is that the vertical axis is labelled on the right hand side. This is unfamiliar and thus undesirable. The second is that the difference between the two plotted quantities is not clear (i.e. there is no legend). It does however illustrate a reasonable use of an "inset" figure – in this case illustrating that the small undulations occur on a yearly cycle.

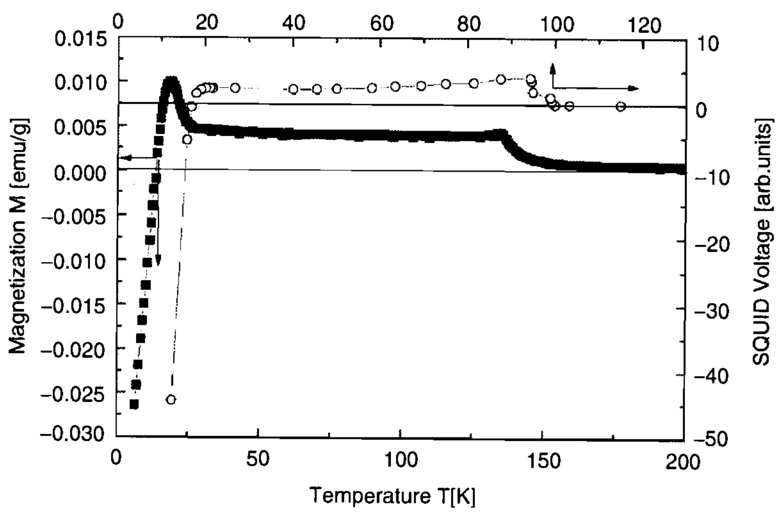

Fig. 3.34. Zero-field cooled DC magnetization measured in a commercial SQUID magnetometer by moving the sample $RuSr_2GdCu_2O_3$ in a field of 0.25 mT through the pick-up coil system of the magnetometer. The magnetization shows an apparent peak at temperatures below $T_c = 30$ K (■). When measuring the output voltage of the SQUID circuit as a function of temperature without moving the sample in the magnetometer no peak like feature is observed (○) [3.155]

Figure 5: From page 89 of "Matter and Methods at Low Temperatures", Pobell, 3rd ed., 2007 (reproduced from an article in the literature). This graph has several problems: 1) it is really two plots combined into one. This is confusing. 2) the "legend" (showing what the different symbols represent) is in the caption instead of directly on the plot. 3) the two horizontal axis are similar but not identical enhancing the chances for mistakes. At least the axis labelling is good (descriptive, with units). Note the absence of error bars.

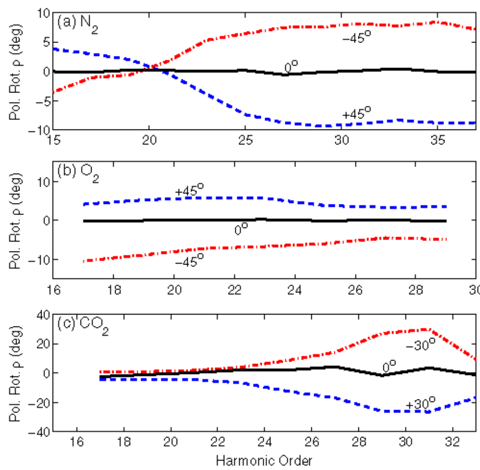

FIG. 3 (color online). Measured values of $\rho(\omega)$, the rotation of the polarization axis from the driving laser's polarization axis, for harmonics generated in (a) N_2 aligned at $0°$ and $\pm 45°$, (b) O_2 aligned at $0°$ and $\pm 45°$, and (c) CO_2 aligned at $0°$ and $\pm 30°$. Here ρ represents the angle between the laser polarization axis and the polarization of the emitted XUV harmonics. Positive ρ means that the XUV polarization has rotated in the direction of the molecular axis. These cuts are taken from the data presented in Fig. 2.

Figure 6: From Levesque *et al.* *Phys. Rev. Lett.*, **99**, 243001 (2007). This graph illustrates how different data may be distinguished by direct labeling (i.e. 45°, 0° etc...). However, it is somewhat surprising that the three horizontal axis were not chosen to cover exactly the same range.