Experimental Errors

Errors: An error is a variation of the “true” value of a measured, or “set”, quantity (Instrumental Error) or of the value of an non-measured (assumed) quantity (Physical Model Error). The variation occurs because of the inability to know exactly, for different reasons, the conditions (the environment) in which the experiment takes place since these conditions affect our measured and unmeasured quantities. If we knew the exact values of all of the variables that make up the condition in which an experiment takes place, then we would have no error in our experiment—our data come out the same way every time we did the experiment.

This kind of reasoning applies to “deterministic” physics and is appropriate for the study of mechanics. (see note 1 at end…). Sometimes we examine very complex phenomena where there are many, many conditions affecting our result and we perceive a random error (see note 2 below).

In order to reduce errors, physicists try to limit the number of conditions that affect experiments (known as trying to do an “idealized” experiment or having a “control” in your experiment—here “control” is used in the sense of controlling all of the conditions in the experiment except for the effect that you are trying to demonstrate).

Experimental Errors: An error associated with your experiment.

Some typical quantities that have an error: A typical measured quantity is a time, a location or a mass. A typical “set” quantity might be a velocity of zero or the slope of a track at different points along the track. A typical assumed quantity is the force of air friction.

A) Instrumental Errors: An instrument is a device that interacts with a sample (or object of interest being studied) that provides some mechanism for determining the result of the interaction. This result is the measurement. Examples are stopwatch, photo-gate timer, ruler, caliper, mass scale, human anticipation of starting times, human anticipation of ending times, protractor, various meters (thermometer, voltmeter, pH meter, pressure gauge, force sensor etc.) that are read by a scale, digital readout or other type of readout. Instrumental errors are errors in measures quantities and there are usually at least three components that exist, simultaneously, for every measurement:

i) Resolution Errors. Typical examples would be reading a scale on the instrument (interpolation), not knowing the next digit of a digital readout. These errors are usually random (sometimes higher and sometimes lower than “true” measurement)

ii) Calibration Errors. Typical examples would be using a balance that is always inaccurate, in one direction or the other according to the manufacturer, or a failure (or inability) to calibrate any instrument. These errors are usually systematic (always either higher or lower than the “true” measurement

iii) Application errors: Errors associated with the way in which an instrument interacts with the sample are called application errors. They will vary based on the nature of the interaction between the instrument and the sample. Typical examples would be parallax error, reaction time of a human to some auditory or visual signal that can’t be anticipated, how a thermometer is thermally connected to a sample, the angle that a caliper makes with flat edges of a rectangular block.

Instruments that are themselves varying in their condition introduce yet another kind of instrumental error that we could call “variable” instrument error—we will not consider this type of error in introductory labs

B) Physical Model Errors: some quantities that affect our experiment either cannot be measured (with the given equipment) or are inconvenient to measure and so they are assumed to be of a
certain value. Errors associated with these values are “physical model” errors. Instruments yield no information about physical model errors since the quantities are not measured or “set”. Typical quantities would be the slope of a track that seems straight at different points along the track, the force of air friction, the shape of an object being cylindrical linear or some other form, the force of friction in a pulley or cart, the direction and strength of gravity, the chemical composition of a material, the temperature and pressure in the room.

Definition Errors: If the quantity being measured or assumed (not measured) is itself not well-defined, then there is an “error of definition” or a definition error. Typical examples would be the height of a door, the length of someone’s hand, the time between when an object is hot and when it is cold; these are vague and will lead to errors of definition. We will not have many errors or definition in our lab classes.

Characteristics (that must be reported) of the different types of experimental errors
1) Quantity and Units
   Every error must be expressed as some physical quantity and therefore has units.
2) Random or systematic
   Every error has both a random and systematic component.
   a) Random errors are errors that are equally likely to be above or below the “average” value.
      Taking many trials reduced random error because of the properties of the standard deviation (S.D.) and the Standard Error (also known as the Standard Error of the mean or SDOM). A low level of random error makes a measurement precise (but not necessarily accurate—see below).
   b) Systematic errors are errors that are always going to be above or always below the “true” value.
      The “true” value here means the value one would get if one could eliminate all of the systematic errors. Systematic errors cannot be eliminated by more trials. Instead a more accurate instrument or more accurate application method must be found. A low level of systematic error means that a measurement will be very accurate (but not necessarily precise).
3) Size (there are several commonly used rules for the size of random instrumental errors [reading scale or digital readout for example] and manufacturers usually state the size of systematic instrumental errors). Determining the size of errors related to application of an instrument or of a non-measured quantity can be challenging. You must state how you determined the size of your errors even if you used a crude estimation; the reader wants to know.

1. “Non-deterministic” physics (e.g. Quantum mechanics) has an inherent probabilistic nature and is encountered in atomic physics; two experiments in the exact same environment can lead to different results in quantum mechanics. Mechanics does not have this problem.
2. Complex phenomena: when many unknown variables affect an experiment, then often the measured quantities will appear to fluctuate, in time, around some average value as if the quantities being measured are random (e.g. number of cars passing under a bridge in one minute at 8:37 am, temperature at a location in a room where billions and billions of molecules are colliding). These fluctuating quantities are referred to as “random variables” but are not actually random in the world of classical (non-quantum) physics; they appear to be random because they are highly complex phenomena. We occasionally will encounter “random” variables in mechanics … which basically means that there are so many unknown quantities (that we either can’t or won’t measure) that are affecting our measured quantities, that the best we can do is attribute the error in our measured quantities to these large number of factors (often these errors appear to be random).
Incomplete definition (may be systematic or random) - One reason that it is impossible to make exact measurements is that the measurement is not always clearly defined. For example, if two different people measure the length of the same rope, they would probably get different results because each person may stretch the rope with a different tension. The best way to minimize definition errors is to carefully consider and specify the conditions that could affect the measurement.

Failure to account for a factor (usually systematic) - The most challenging part of designing an experiment is trying to control or account for all possible factors except the one independent variable that is being analyzed. For instance, you may inadvertently ignore air resistance when measuring free-fall acceleration, or you may fail to account for the effect of the Earth's magnetic field when measuring the field of a small magnet. The best way to account for these sources of error is to brainstorm with your peers about all the factors that could possibly affect your result. This brainstorm should be done before beginning the experiment so that arrangements can be made to account for the confounding factors before taking data. Sometimes a correction can be applied to a result after taking data to account for an error that was not detected.

Environmental factors (systematic or random) - Be aware of errors introduced by your immediate working environment. You may need to take account for or protect your experiment from vibrations, drafts, changes in temperature, electronic noise or other effects from nearby apparatus.

Instrument resolution (random) - All instruments have finite precision that limits the ability to resolve small measurement differences. For instance, a meter stick cannot distinguish distances to a precision much better than about half of its smallest scale division (0.5 mm in this case). One of the best ways to obtain more precise measurements is to use a null difference method instead of measuring a quantity directly. Null or balance methods involve using instrumentation to measure the difference between two similar quantities, one of which is known very accurately and is adjustable. The adjustable reference quantity is varied until the difference is reduced to zero. The two quantities are then balanced and the magnitude of the unknown quantity can be found by comparison with the reference sample. With this method, problems of source instability are eliminated, and the measuring instrument can be very sensitive and does not even need a scale.

Failure to calibrate or check zero of instrument (systematic) - Whenever possible, the calibration of an instrument should be checked before taking data. If a calibration standard is not available, the accuracy of the instrument should be checked by comparing with another instrument that is at least as precise, or by consulting the technical data provided by the manufacturer. When making a measurement with a micrometer, electronic balance, or an electrical meter, always check the zero reading first. Re-zero the instrument if possible, or measure the displacement of the zero reading from the true zero and correct any measurements accordingly. It is a good idea to check the zero reading throughout the experiment.

Physical variations (random) - It is always wise to obtain multiple measurements over the entire range being investigated. Doing so often reveals variations that might otherwise go undetected. These variations may call for closer examination, or they may be combined to find an average value.

Parallax (systematic or random) - This error can occur whenever there is some distance between the measuring scale and the indicator used to obtain a measurement. If the observer's eye is not squarely aligned with the pointer and scale, the reading may be too high or low (some analog meters have mirrors to help with this alignment).

Instrument drift (systematic) - Most electronic instruments have readings that drift over time. The amount of drift is generally not a concern, but occasionally this source of error can be significant and should be considered.

Lag time and hysteresis (systematic) - Some measuring devices require time to reach equilibrium, and taking a measurement before the instrument is stable will result in a measurement that is generally too low. The most common example is taking temperature readings with a thermometer that has not reached thermal equilibrium with its environment. A similar effect is hysteresis where the instrument readings lag behind and appear to have a "memory" effect as data are taken sequentially moving up or down through a range of values. Hysteresis is most commonly associated with materials that become magnetized when a changing magnetic field is applied.

Personal errors come from carelessness, poor technique, or bias on the part of the experimenter. The experimenter may measure incorrectly, or may use poor technique in taking a measurement, or may introduce a bias into measurements by expecting (and inadvertently forcing) the results to agree with the expected outcome.

Gross personal errors, sometimes called mistakes or blunders, should be avoided and corrected if discovered. As a rule, gross personal errors are excluded from the error analysis discussion because it is generally assumed that the experimental result was obtained by following correct procedures. The term human error should also be avoided in error analysis discussions because it is too general to be useful.