Type A and Type B Elemental Uncertainties

2

This chapter discusses elemental uncertainties and their origin. There is no mathematics in this chapter. The next chapter deals with the mathematics.

Elemental uncertainties are those associated with a particular measurement. As such, they are related to the accuracy of measured quantities, rather than the accuracy of calculated quantities. Elemental uncertainties are inherent in every transducer, with better quality transducers usually having less uncertainty (i.e., they are more accurate) than lower quality transducers. Elemental uncertainties may also be due to variability in the measurand. For example, if you are measuring the diameter of a shaft using calipers, the calipers have a certain 'accuracy.' Also the shaft diameter will vary slightly from place to place due to size variations. These are both examples of elemental uncertainties. For calibrated transducers the calibration certificate will include the effect of all elemental uncertainties associated with the transducer itself. While it can be educational to look into the cause for the transducer uncertainty, the transducer uncertainty will not need to be calculated since the calibration certificate gives everything that is need. However, there will still be additional uncertainty in the measurand that needs to be included in the uncertainty analysis.

There are fundamentally two types of elemental uncertainty: those that are repeatable and those that vary. The variable uncertainties were previously called random uncertainties; they vary from measurement to measurement; from time to time; and from place to place. Conversely, the common wisdom is that repeatable uncertainties do not vary. We will soon see that this is not actually the case!

Random Uncertainty

If it is possible to identify which statistical distribution (for example, normal distribution, uniform distribution, U-distribution) best models the random uncertainties it may be possible to identify the properties of the distribution, such as mean, standard deviation, skewness and kurtosis. Using these properties we can predict a range in

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which the next random event is likely to occur, but we are not able to predict the actual value of that event—this is the very nature of randomness.

Calibration can estimate (quantify) the amount of transducer random elemental uncertainty, but the calibration cannot reduce it.

One way of reducing the effect of randomness is to take a large number of readings and calculate the average. Statistically, this is reducing the standard deviation of the mean by increasing the sample size. As an example, random uncertainties are those that cause a bathroom scale to show a slightly different reading each time you step off and back on again; averaging several readings will help reduce this variability.

If you can only take a single measurement, typically the only way to reduce transducer elemental uncertainty due to randomness is to have a better quality transducer. Randomness in the measurand is usually reduced by, for example, higher quality manufacturing of the item being measured. Sometimes environmental issues can introduce randomness. For example, ground vibration may affect the accuracy with which a theodolite can be aimed at a target, and electrical interference will affect electronic apparatus. The amount of random uncertainty can be reduced by isolating the transducer (physically or electronically) from the environment. None of these approaches can completely eliminate random elemental uncertainty.

Repeatable, or Systematic, Uncertainty

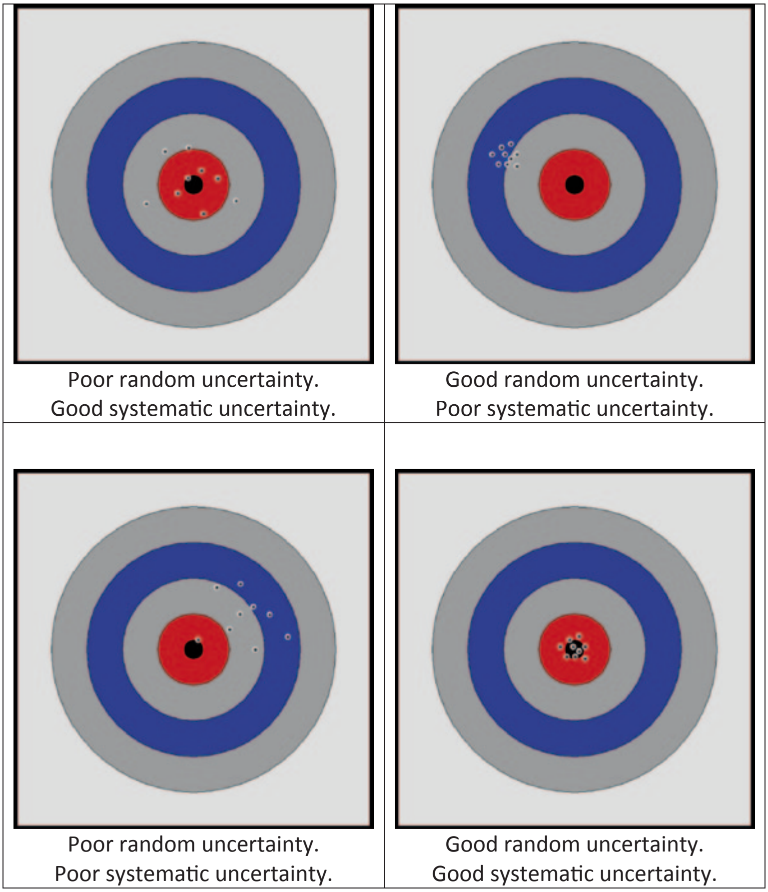
As was mentioned previously, the common wisdom is that systematic uncertainties are repeatable and do not vary. However this is not true. Systematic uncertainties can vary significantly from measurement to measurement. The systematic uncertainty will be the same if all measurement conditions are identical, but for different measured values or under different measuring conditions, the uncertainty can be different.

Improving the quality of equipment can reduce systematic uncertainty. Calibration can also reduce the elemental uncertainty, but only (at best) to the uncertainty of the calibration process. Systematic uncertainty can never be totally eliminated.

Averaging repeated measurements will not change the systematic uncertainty. Indeed, since systematic uncertainties are repeatable their effect is not easy to see, and one can easily be lead to the false conclusion that taking the average of several measurements will give a number that is close to the true value. *Just because you can get an experiment to give repeatable results does not mean it is accurate*!

Systematic uncertainty can be reduced by improved calibration and better quality equipment, but it can never be eliminated totally. Thus, for a given type of transducer, elemental uncertainty can only be reduced by using a more sensitive and accurate transducer. This can be expensive. An uncertainty budget can help determine which transducers in a measurement scenario need to be improved. The topic of uncertainty budgets is discussed later in this monograph.

Systematic and random uncertainties are demonstrated in the following figure:



Poor random uncertainty.
Good systematic uncertainty.

Good random uncertainty.
Poor systematic uncertainty.

Poor random uncertainty.
Poor systematic uncertainty.

Good random uncertainty.
Good systematic uncertainty.

Type A and Type B Elemental Uncertainty

As mentioned previously, the GUM—the Guide to Uncertainty in Measurement—was first published in 1992 by ISO/BIPM. It has seen several revisions and is now accepted in industry as the recognized method for determining uncertainty in all measurements. The GUM classifies elemental uncertainties in two categories: Type A and Type B. The GUM requires that uncertainties that can be evaluated by statistical methods be treated as Type A uncertainties, and those evaluated by any other means be treated as Type B uncertainties.

As described in the GUM, the uncertainty analysis is based on the concept that there is no inherent difference between an uncertainty component arising from a random effect and one arising from a correction for a systematic effect. As a consequence, and as stated in the GUM, it is unnecessary to classify components as "random" or "systematic" because all components of uncertainty are treated in the same way. Often, though, it can be educational to separate the two types of uncertainty, and that is the method adopted in both the GUM and this monograph.

Most uncertainties that were formerly called random uncertainties will be treated as Type A uncertainties. This is because we use the underlying statistical model to estimate them. Most uncertainties formerly called systematic uncertainties will be treated as Type B uncertainties. This is because a systematic 'error' does not have any variability, and thus it cannot be analyzed with statistics.

Returning to your bathroom, imagine your bathroom scale has a zero offset so that it shows 5 lb too light, and the individual readings vary by about 1 lb. When you use your scale you will measure your weight about 5 lb too light *every time*. The zero offset is systematic and is therefore a Type B uncertainty. The variability from reading to reading of about 1 lb is a Type A uncertainty.

If an uncertainty is based on a statistical analysis, it is to be treated as a Type A uncertainty. Most random uncertainties are Type A uncertainties.

They vary each time a measurement is made. The uncertainty can be reduced by averaging lots of measurements, but it can never be totally eliminated.

Any uncertainty not based on a statistical analysis is to be treated as a Type B uncertainty.

Most systematic uncertainties are Type B uncertainties.

Both Type A and Type B elemental uncertainties can be reduced by having a better quality transducer.

Calibration can quantify Type A elemental uncertainty, but not reduce it.

Calibration can reduce the level of Type B elemental uncertainty but there will always be a residual amount that cannot be determined.

The one exception to the above rule of classifying uncertainties as Type A or B based on statistics is the treatment of the uncertainty introduced by *scale resolution*. There are some good arguments as to why it should be treated as a Type A uncertainty, for example a statistical uniform random distribution is used to assess this uncertainty. There are also some good arguments as to why it should be treated as a Type B uncertainty. For this specific case the GUM states that *scale resolution is to be treated as a Type B uncertainty*.

Sources of Elemental Uncertainty

Let's look at some of the more common sources of elemental uncertainty.

Repeatability Repeatability is the ability of a transducer to give the same output when it is used several times to measure the same thing.

Repeatability is considered as randomly distributed with a normal distribution. It is a Type A uncertainty.

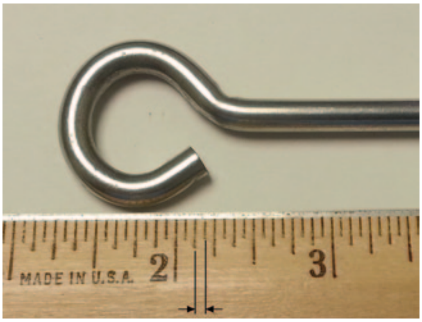
Thermal Stability Many systems, both mechanical and electrical, can be sensitive to temperature. For example, the output from a strain gage depends on the resistance of the metal foil wires that make the gage. The wires' resistance depends on temperature, and if a gage is used in a changing temperature environment the output caused by the temperature change can wrongly be attributed to a changing strain. While the effect of large temperature changes can be mollified by techniques such as temperature compensation, there will be some residual non-compensated effect.

Thermal stability is often treated as a random Type A uncertainty with a normal distribution.

Noise By "noise" we do not (normally) mean acoustic noise, although there are some measurements that are sensitive to acoustic noise. Rather, we usually mean the effect on a signal due to electrical interference from surrounding electrical and magnetic fields.

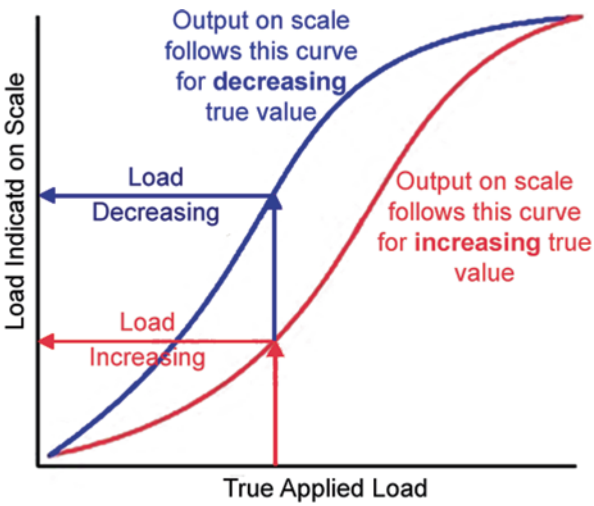
Noise is usually treated as a random Type A uncertainty.

Resolution, Scale Size and Quantization Most devices do not give continuous output; rather, the output is in the form of a series of steps. For example, when you use a simple tape measure to measure a length, you might quote the length to the nearest 1/8 in. Wire-wound potentiometers are limited to the change in resistance caused by the pick-up moving over a discrete coil. Many digital systems include analog-to-digital conversion, which automatically introduces the "stepped" output, and digital displays are limited to the resolution of the least significant digit.



Resolution is treated as a Type B uncertainty.

Hysteresis Hysteresis causes a reading to be different depending on whether the device is being "loaded" or "unloaded" when the measurement is taken. As an example, the hysteresis in a spring balance is caused by mechanical problems such as friction and bearing misalignment in the device. Thus, hysteresis will cause a mechanical scale to consistently measure the applied weight too low (for increasing load) or consistently too high (for decreasing load). Other types of device also demonstrate hysteresis although the hysteresis in electrical devices is usually very small. There are some systems (such as spectrum analyzers) that have user-selectable variable hysteresis.



Hysteresis cannot be analyzed by statistics and it is classified as a Type B uncertainty.

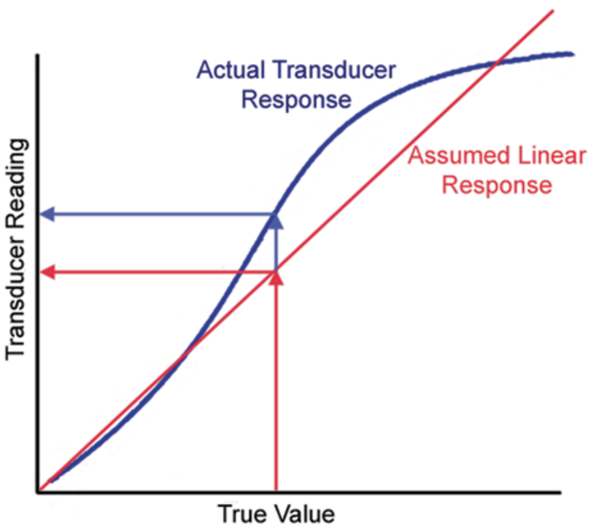
Common Mode Voltage When different voltages are applied to two input terminals of an amplifier, the amplifier will produce an output. Ideally, if the *same* voltage (relative to ground) is applied to the terminals the amplifier will produce zero output. Common mode voltage uncertainty is the uncertainty caused by the amplifier actually producing some output under these conditions.

Common mode voltage is treated as a Type B uncertainty.

Installation A pitot tube can be used to measure air speed, for example in aircraft. An example of installation uncertainty is when a pitot tube is removed and replaced. Because of the boundary layer effect, if the pitot tube is not put back in *exactly* the same place the reading will be slightly different for the same true value of air speed. Another example is using calipers to measure the diameter of a sphere. Slight misplacing of the calipers from the true diameter can result in a measurement that is slightly too small.

Installation is treated as a Type B uncertainty.

Nonlinearity (or Linearity) This is a common problem for calibration. It is often assumed that doubling the input to a transducer will double its output. For many transducers this assumption may be adequate, however, actual nonlinearity of the transducer will cause the measurement to have a systematic uncertainty. One extreme example of nonlinearity is the thermocouple, where the voltage output is not a linear function of the temperature. In an attempt to take into account the inherent nonlinearity of the thermocouple, systems designed to measure temperature with thermocouples incorporate polynomials in the conversion from voltage to temperature. Since the polynomials do not *exactly* resolve the issue there is still some residual systematic uncertainty.



Nonlinearity is treated as a Type B uncertainty.

Spatial Variation We have already hinted at uncertainty due to spatial variation when, in the introduction to this monograph, we said that the temperature in a room would vary from place to place. If we were measuring near a "hot spot", the thermometer would *always* read too high. Spatial variation is typically associated with the measurand (rather than the transducer). As an example, if a shaft has a nominal diameter of 2 in its actual diameter will vary slightly from place to place, and this variability is systematic—repeatedly measuring the shaft at the same place will determine the same diameter.

Spatial variation is a Type B uncertainty.

Loading Imagine putting a cold mercury-in-glass thermometer into a beaker of hot water—that is, if you can still find a mercury thermometer and your safety department will let you use it! Otherwise, try the experiment with an alcohol-in-glass thermometer! Some of the heat will go from the water into the thermometer. As a result, the final temperature of the hot water will be too low because the water has cooled down a bit. This is an example of a loading issue. Many transducers cause loading uncertainty. As another example, imagine that during quality control you have to use a micrometer to measure the thickness of corrugated cardboard. The micrometer squeezes the cardboard and the thickness you measure depends upon how firmly you grasp the cardboard. The ratchet in the micrometer is to enable a more consistent jaw pressure, but there is still some variability from measurement to measurement.

Loading uncertainties are treated as Type B.

Zero Offset This is often caused if a device is not "zeroed" properly. That is, when the device does not give a zero reading when the quantity being measured is zero. Calibration and setting the zero point both aim to minimize this uncertainty, but they never totally remove it.

Zero offset is a Type B uncertainty.

Sensitivity This is the measure of how much the output of a transducer varies as the input (the measured quantity) varies. For example, the quoted sensitivity of an accelerometer may be 98.1 mV/g. This indicates that the device will generate a 98.1 mV signal if the input is 1 × (acceleration due to gravity). While calibration aims to give the best sensitivity for a transducer, there will still be some residual error.

Unknown errors in sensitivity cause systematic uncertainty, and they are treated as Type B uncertainties.

> Uncertainties that are random in nature can usually be analyzed with statistics, and are treated as Type A uncertainties.
>
> Systematic uncertainties are repeatable and cannot be analyzed with statistics. Consequently they are normally treated as Type B uncertainties.

Accuracy—Pandora's Box?

Accuracy is defined as how close the measurement is to the true value. Although we use the term *accuracy*, it is really the *inaccuracy* that is specified. Different manufacturers have different interpretations of their meaning of the term *accuracy*, and in a real-world application you should be careful to ensure you are using the appropriate definition. However, when accuracy is quoted, it normally includes all the residual Type A and Type B uncertainties in the measuring system. Accuracy is often quoted as the percentage of full scale. Thus for a balance that can weigh up to 250 lb with the accuracy quoted as 1 % of full scale, the uncertainty is ±2.5 lb regardless of the reading or divisions on the scale.

Despite the fact that some companies quote a transducer's accuracy, NIST (Technical Note 1297, 1994 edition) states, "Because 'accuracy' is a qualitative concept, one should not use it quantitatively, that is, associate numbers with it."

Final reminder

Remember that there are many more sources of elemental uncertainty. If you need to classify them, apply the logic that if the analysis of the uncertainty can be done with statistics it is a Type A uncertainty. If statistics cannot be used (for example, if the uncertainty is systematic and repeatable) then it is to be treated as a Type B uncertainty.

If you wrongly classify a Type A elemental uncertainty as Type B, or vice versa, the consequences may not be significant. While the mistake will change the attribution of uncertainty to different components of the uncertainty analysis, the final estimated uncertainty will be the same, irrespective of wrong Type A/B classification!

Wrongly classifying Type A and Type B uncertainties will lead to different intermediate numbers.

But the final uncertainty will be the same!

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