DO STUDENT CHEMICAL ENGINEERS UNDERSTAND EXPERIMENTAL ERROR?

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DO PROFESSORS PAY lip service to teaching mathematical statistics but leave the philosophy of the "scientific method" unlearned? We provide our students with example after example of "sanitized" models in the form of mathematical correlations obtained from "dirty" data after a liberal application of scientific hygienics. Such filtering of information requires a mature understanding of error analysis, even though we treat the variability of our data as if it should be suppressed.

Most chemical engineers have used empirical equations like the Sieder-Tate relationship and, after checking that the variables are in the permissible range, they tend to ignore the accuracy of the predicted values. If pressed, most would admit that some level of uncertainty is present that is hopefully tolerable. However, if asked about $E = mC^2$, many would say, "That's not an empirical equation: it represents physical reality," and they might be reluctant to agree that there is any uncertainty in it.

Engineers, however, must work in the real world with measured quantities. We, as engineers, are also forced to recognize that no communication exists between the real and the mathematical worlds except through some sort of measurement (see Figure 1). Although we can make all sorts of flights of fancy about $E = mC^2$, they have no meaning in the world of things that we touch and manipulate except through the single bridge provided by measurements. Furthermore, measurements (except in trivial cases) are always contaminated by error. For example, if we set out to check how closely $E = mC^2$ corresponds to reality, we find insurmountable difficulties in defining the symbols so they can be perfectly verified in the real world. One of these concerns the concept of mass. How can it be determined except by comparison and how can that comparison be made on an indefinitely fine scale?

To step from this into the real world of chemical

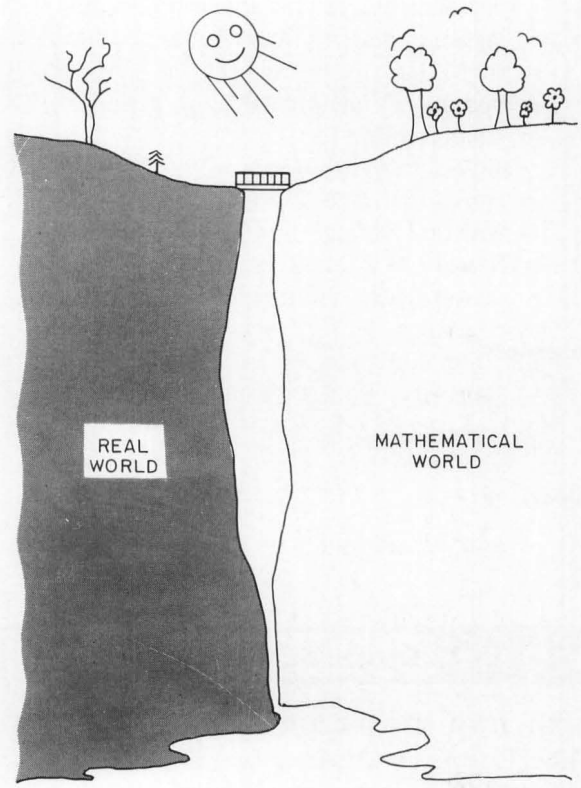
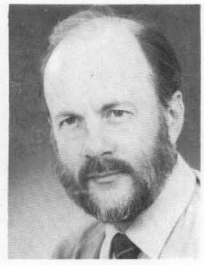


FIGURE 1. Measurement—the Precarious Bridge



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experiments is to meet error head-on. Students in an undergraduate laboratory have spent most of their scientific lives on the abstract side of the measurement bridge. They tend to think that there are only two options if the results do not agree nicely with the theory: 1) there is something wrong with the equipment or its value in elucidating the theory, or 2) the real and the mathematical worlds cannot be bridged, so theory is of little value in the real world.

A critical examination of undergraduate laboratories reveals that most of the experiments are contrived to illustrate one or more points of physical or chemical theory. Statistical design and analysis are usually considered nuisances at best. "Error analysis," when it is carried out, consists most often of an examination of what the maximum error might be, without regard to any evaluation of what typical errors could have occurred.

In this vein, the most powerful method of assessing what errors are likely to occur is that of replication of experimental trials. In the atmosphere of the laboratory, students regard this as a waste of time.

We believe that it is possible to design undergraduate experiments in such a way that the true relationship between theory and practice can be respected, the presence of error can be accounted for in a rational manner, and at the same time the physical or chemical point can be made. Above all, we believe that each experiment can be a learning experience in experimentation as such, so that the students gain some skill and knowledge which will help them in any future experiments.

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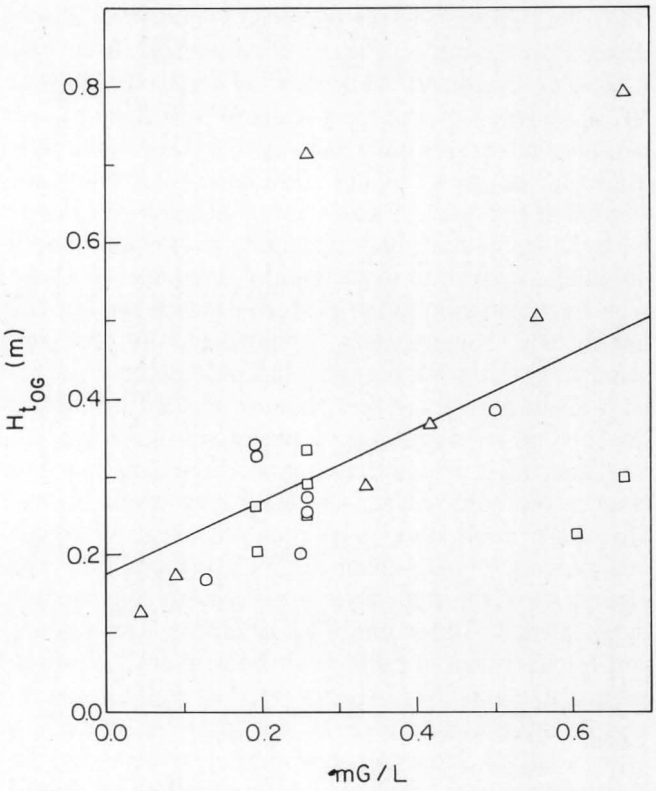

FIGURE 2. Height of a transfer unit (based on overall gas) vs. mG/L for acetone absorption from air into water. Three different symbols represent three different sessions of data collection. Least-squares line is shown for all points.

GAS ABSORPTION: AN EXPERIMENT WITH MEASUREMENT ERROR

As an example of an experiment with considerable scatter in the measurements, let us examine a gas absorption experiment, specifically the one used in the undergraduate curriculum in the Department of Chemical Engineering, University of Waterloo. In this experiment, air picks up a predetermined quantity of acetone vapour and enters the bottom of a packed tower of Raschig rings where it meets fresh water entering from above. The water leaving the gas absorber is sampled and analyzed chromatographically for acetone. The results are worked up (see Figure 2) into a plot of the height of an overall gas transfer unit *vs.* the mG/L quotient, in which m is the Henry's Law coefficient for acetone in water, G is the air flow in moles/time, and L is the water flow in moles/time. The final data sets of three different blocks of seven experiments each are plotted in Figure 2. Ordinarily, a student group will obtain only about six points in a day's work. These usually represent the sole basis the group has for an entire report on gas absorption.

Scattered data like those in Figure 2 are usually subjected to a scathing sort of error analysis by student groups. Verdict: "bad data" or "defective experiment" or "waste of time." Recommendations: "replace the gas chromatograph" or "check the pumps" or "put controllers on all the flows." The word about the gas absorption experiment soon reaches incoming classes, with the result that students new to the laboratory have to be coaxed or coerced into selecting gas absorption as an optional experiment. After all, who cares about error analysis in the face of what is known *via* the grapevine? Replicate shmeplicate—the experiment's a dud. Everyone knows that!

In their defense, our students have a point. The

$H_{t,OG}$ values in the centre of Figure 2 scatter over nearly a three-fold range. Also, students take only about six points in a single lab period, often giving the appearance of incoherence to their already sparse data. However, they almost always fail to notice that the data they have taken are not much, if any, worse than what appears in the chemical engineering literature. For example, Figure 3, sketched from the *Chemical Engineers' Handbook* (Perry and Chilton, 1973), shows that the mass transfer coefficient (*i.e.*, height of a transfer unit) has a two- to three-fold variation at a given liquid flowrate (*i.e.*, constant Reynolds number). Except for a little inexperience with the equipment, undergraduate students probably do almost as well in experimental technique as those who have contributed to posterity's data pool in the handbooks. Nevertheless, somewhere in our consciousness the myth persists that data points must lie on a clean line of the sort that we plotted in physics lab the day we measured current against voltage.

Thus, we conclude that student engineers who find themselves confronting scattered measurements really don't understand experimental error. Changes are needed to help them appreciate more fully the structure of the data they are encountering in such experiments. Unfortunately, laboratory experience can fortify those durable prejudices about "good experiments" and "bad experiments" as well as encourage an informed interpretation based on statistical error analysis. Much depends on the experimental design and the way students are encouraged to regard their results.

Specific ways to encourage clear thinking about error analysis are:

1) **Design into the undergraduate labs some opportunities to view "real" rather than "contrived" phenomena in chemical engineering experiments.**
2) **Design out the features that shield students from confronting the large variability which is common in complex chemical engineering systems. Instead, promote replication and other statistical devices which help deal with variability as it exists.**
3) **Require students to become familiar with the chemical engineering literature that shows the kind of variability that is common to various systems.**
4) **Teach students to resist the temptation to try to explain "everything" about complex engineering systems.**

MAKING LAB EXPERIMENTS MORE INSTRUCTIVE

In view of the above statements, it is clear that the gas absorption experiment referred to previously needs redesigning. The various items in such a redesign are numbered in keeping with the above four points.

1) The gas absorption experiment already offers students a chance to see something real. For example, acetone is a material that has a high affinity for water, so water is a logical medium for use in removing acetone vapours from the air. Also, a glass column is used to display the intermingling of the gas and liquid flows over the packing. This provides a sense of reality to the experiment. The only contrived aspect of this experiment is its scale, which is kept small for reasons of convenience.

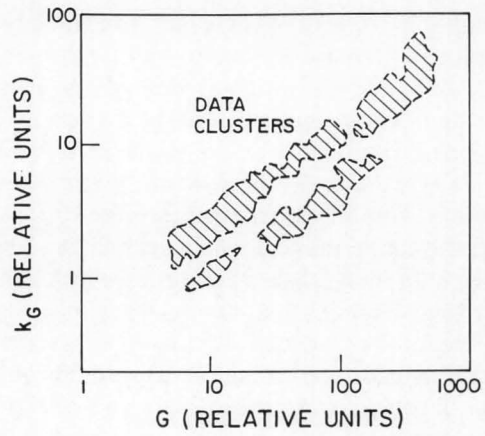

FIGURE 3. Mass transfer coefficient k_G vs. gas flow rate G for gas absorption (after Perry and Chilton, 1973).

2) The major block to students' perception that scatter is the rule in complex chemical engineering systems is probably the fact that in most of our teaching we tend to use deterministic models without mentioning the associated error. Therefore, the student who discovers a lot of scatter in an experiment may conclude that experiments are less trustworthy than models.

The misunderstanding of scatter is aggravated by the fact that students are able to obtain relatively little data on the gas absorber during a single laboratory session. Often, if only two of, say, six runs are done under replicate conditions, and the two observations are quite different, students will view the equipment as behaving capriciously.

A further difficulty occurs in the gas absorption experiment because of the fact that a G/L ratio tends to compress the range of the data. For example, if both G and L are doubled, the mG/L ratio thus remains constant. This tends to reduce the experimental data base.

One helpful idea in redesigning this undergraduate experiment is to reduce the number of variables by one; for example, by maintaining G constant and varying L. This will eliminate the compression of the data base by the use of the G/L ratio as well as reduce

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the complexity of the experiment by one dimension.

Next, it is evident that because of the variability in the gas absorption experiments, a single laboratory session generates too few data for a meaningful error analysis. One way out of this difficulty is to pool the data obtained in several sessions before allowing the various student groups to analyze it. Also, they should attempt to get the largest range of L possible with the equipment and concentrate on replication. At each session, a student group will carry out duplicate experiments, for example, at just three values of L: highest, lowest, and at the mid-point to permit a test of the linearity of the correlation. After three or four groups have completed their experiments, the data can be pooled and analyzed. Students who have taken statistics courses that teach experimental design might wish to plan a single factorial experiment to include several student groups. In any event, the between-group variation can be analyzed to see if this is a contributing factor to the error.

3) Students should be encouraged to go directly to the original literature data and examine the actual measurements without citing a correlation for the least-squares fit of the data or some other deterministic model. They should be asked to note the scatter in the data through a variance or coefficient of variation or some other measure of variability.

4) Because our educational system pays high rewards for explaining phenomena, there is a great temptation for students to try to explain "everything." Without the restraint learned from error analysis, some students will try to explain random error, given the opportunity, and of course, the opportunity seems very tempting when the data are so few that the scatter is not obvious. Thus, the notion of caution and even of reluctance to explain can be one of the important by-products of error analysis.

CONCLUSIONS

While we do pay lip service to teaching mathematical statistics, its use in experimental design is often neglected. Therefore, student engineers, faced with experiments with large variability in the measurements, do not understand experimental error. They tend either to despair or to explain too much. Statistical analysis of error plus good experimental design can help students account for error and become informed about the relationship between theory and practice.

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