You may do a class project where you actually do an experiment instead of the final. The experiment should be a 2^k with $k \geq 3$ or a split plot experiment or a repeated measures experiment or a fractional factorial experiment with at least 8 runs.

If you get the class project into me by December 5, I can tell you whether you made any massive errors. If so then you can take the final and drop the class project.

Box, Hunter and Hunter p. 215-219 describe a project done by a student. The paper helicopter experiment on p. 490-503 is also reasonable but I will not allow a duplication of this experiment.

The paper below also describes projects done by students.

Some Ideas About Teaching Design of Experiments, with 2^5 Examples of Experiments Conducted by Students

W. G. HUNTER*

ABSTRACT

Some experiences with the use of student projects in experimental design courses at Wisconsin are described. Each student is given the opportunity of selecting a problem of direct interest to him/her, designing and performing an experiment, collecting and analyzing the data. Some ideas with regard to pedagogy and the use of simulated data are also discussed.

Key Words

Teaching
Design of Experiments
Student Projects
Pedagogy

I want to share some ideas about teaching design of experiments. They are related to something I have often wondered about: Is it possible to let students experience first-hand all the steps involved in an experimental investigation—thinking of the problem, deciding what experiments might shed light on the problem, planning the runs to be made, carrying them out, analyzing the results, and writing a report summarizing the work. In most courses on experimental design students get no practice *designing* experiments although, from homework assignments, they do get practice *analyzing* data. Clearly, however, because of limitations of time and money, if students are to design experiments and actually carry them out, they cannot be involved with elaborate investigations. Therefore the key question is this: Is it feasible for students to devise their own simple experiments and

* Dept. of Statistics, Univ. of Wisconsin, Madison, WI 53706.

carry them through to completion and, if so, is it of any educational value to have them do so? I believe the answer to both parts of the question is yes, and the main purpose of this paper is to explain why.

Background

The particular one-semester course I have taught most often includes these standard statistical techniques: t-tests (paired and unpaired), analysis of variance (primarily for one-way and two-way layouts), factorial and fractional factorial designs (emphasis given to two-level designs), the method of least squares (for linear and nonlinear models), and response surface methodology. The value of randomization and blocking is stressed. Special attention is given to these questions: What are the assumptions being made? What if they are violated? What common pitfalls are encountered in practice? What precautions can be taken to avoid these pitfalls? In analyzing data how can one determine whether the model is adequate? Homework problems provide ample opportunity for carefully examining residuals, especially by plotting them. The material for this course is discussed in the context of the iterative nature of experimental investigations.

Most of those who have taken this course have been graduate students, principally in engineering (chemical, civil, mechanical, industrial, agricultural) but also in a variety of other fields including statistics, food science, forestry, chemistry, and biology.

Simulated Data

One possibility that permits students to gain experience in designing experiments is to use simulated data. The scope here is wide, especially with the availability of computers. At times I have given assignments of this kind, especially response surface problems. Each student receives sets of data *based upon the designs he or she chooses*.

The problem might be set up as one involving a chemist who wishes to find the best settings of five variables—temperature, concentration, pH, stirring rate, and amount of catalyst—and to determine the local geography of the response surface(s) near the optimum. To define the region of operability, ranges are specified for each of these variables. Perhaps more than one response can be measured, for instance, yield and cost. The student is given a certain budget, either in terms of runs or money, the latter being appropriate if there is an option provided for different types of experiments which have different costs. The student can ask for data in, say, three stages. Between these stages the accumulated data can be analyzed so that future experiments can be planned on the basis of all available information.

In generating the data, which contain experimental error, there are many possibilities. Different models can be used for each student, the models not necessarily being the usual simple first-order or second-order linear models. Not all variables need to be important, that is, some may be inert or dummy variables (different ones for different students). Time trends and other abnormalities can be deliberately introduced into the data provided to the students.

The student prepares a report (1) including a summary of the most important facts discovered and (2) perhaps containing a contour map of the response surface(s) for the two most important variables (if three of the five variables are inert, this map should correspond to the true surface from which the data were generated). It is instructive then to compare each student's findings with the corresponding true situation.

Students enjoy games of this type and learn a considerable amount from them. For many it is the first time they realize just how frustrating the presence of an appreciable amount of experimental error can be. For example, one student wrote, "I gained my first *real* understanding of the meaning of noisey data from the simulated experiment". Prearranged undergraduate laboratory experiments in physics and chemistry, of course, usually have all important known sources of experimental error removed (typically the data are supposed to fall on a straight line—exactly—or else).

If the teacher uses simulated data creatively, students can learn many important aspects of design and analysis in a most effective way. I believe the untapped potential here is enormous. While not meaning to detract from the value of such an approach, I will emphasize in this paper the use of real data.

Real Data

A few years ago I asked each student to perform an experiment of his or her own devising. The students were given three weeks to complete this assignment and hand in a detailed report describing what they had done and what they had learned. The students obviously enjoyed the project and derived quite a bit from it. In particular, they seemed to get a much better appreciation of the efficiency and beauty of experimental designs. Moreover, the experience was fun. Consequently I have repeated the assignment every semester I have taught the course since then.

One's first reaction might be that there are not enough possibilities for experiments of this kind. But this is incorrect, as is illustrated by Table 1, which lists some of the approximately 200 experiments that have been reported by students. Experiments number 1–21 are of the home type and experiments number 22–32 are of the laboratory type. Note the variety of studies done. To save space, for most variables the levels used are not given. Most of these experiments were 2^3 factorial designs. Let us look briefly at the first two home experiments and the first two laboratory experiments.

Table 1.
List of some studies done by students in an experimental design course.

	variables	responses
1.	seat height (26, 30 inches), generator (off, on), tire pressure (40, 55 psi)	time to complete fixed course on bicycle and pulse rate at finish
2.	brand of popcorn (ordinary, gourmet), size of batch (⅓, ⅔ cup), popcorn to oil ratio (low, high)	yield of popcorn
3.	amount of yeast, amount of sugar, liquid (milk, water), rise temperature, rise time	quality of bread, especially the total rise
4.	hours of illumination, water temperature, specific gravity of water	growth rate of algae in salt water aquarium
5.	blending speed, amount of water, temperature of water, soaking time before blending	blending time for soy beans
6.	asprin buffered? (no, yes), dose, water temperature	hours of relief from migraine headache
7.	width to height ratio of sheet of balsa wood, slant angle, dihedral angle, weight added, thickness of wood	length of flight of model airplane
8.	type of drink (beer, rum), number of drinks, rate of drinking, hours after last meal	time to get steel ball through a maze
9.	stamp (first class, air mail), zip code (used, not used), time of day when letter mailed	number of days required for letter to be delivered to another city
10.	distance to target, guns (A, B), powders (C, D)	number of shot that penetrated a one foot diameter circle on the target
11.	viscosity of oil, type of pick-up shoes, number of teeth in gear	speed of H. O. scale slot racers
12.	amounts of cooking wine, oyster sauce, sesame oil	taste of stewed chicken
13.	ambient temperature, choke setting, number of charges	number of kicks necessary to start motorcycle
14.	amounts of flour, eggs, milk	taste of pancakes, consensus of group of four living together
15.	brand of tape deck used for playing music, bass level, treble level, synthesizer? (no, yes)	clearness and quality of sound, and absence of noise
16.	child's weight (13, 22 pounds), spring tension (4, 8 cranks), swing orientation (level, tilted)	number of swings and duration of these swings obtained from an automatic infant swing
17.	orientation of football, kick (ordinary, soccer style), steps taken before kick, shoe (soft, hard)	distance football was kicked
18.	weight of bowling ball, spin, bowling line (A, B)	bowling pins knocked down
19.	amount of detergent (¼, ½ cup), bleach (none, 1 cup), fabric softener (not used, used)	ability to remove oil and grape juice stains
20.	appearance (with and without a crutch), location, time	time to get a ride hitchhiking and number of cars that passed before getting a ride
21.	frequency of watering plants, use of plant food (no, yes) temperature of water	growth rate of house plants
22.	plunger A up (slow, fast), plunger A down (slow, fast), plunger B up (slow, fast), plunger B down (slow, fast)	reproducibility of automatic dilutor, optical density readings made with spectrophotometer
23.	temperature of gas chromatograph column, tube type (U, J), voltage	size of unwanted droplet
24.	concentration of lactose crystal, crystal size, rate of agitation	spreadability of caramel candy
25.	proportional band, manual reset, regulator pressure	sensitivity of a pneumatic valve control system for a heat exchanger
26.	temperature, nitrate concentration, amount of preservative added	measured nitrate concentration in sewage, comparison of three different methods
27.	solar radiation collector size, ratio of storage capacity to collector size, extent of short-term intermittency of radiation, average daily radiation on three successive days	efficiency of solar space-heating system, a computer simulation
28.	pH, dissolved oxygen content of water, temperature	extent of corrosion of iron
29.	amperage, contact tube height, travel speed, edge preparation	quality of weld made by submerged arc welding process
30.	longitudinal feed rate, transverse feed rate, depth of cut	longitudinal and thrust forces for surface grinding operation
31.	amounts of nickel, manganese, carbon	impact strength of steel alloy
32.	temperature difference between surface and bottom waters, thickness of surface layer, jet distance to thermocline, velocity of jet, temperature difference between jet and bottom waters	mixing time for an initially thermally stratified tank of water

NOTE: A more complete list of 101 examples, from which these 32 were selected, is available from the author.

Bicycle Experiment

In experiment number 1, Norman Miller, using a 2^3 factorial design with all points replicated, studied the effects of three variables—seat height (26, 30 inches), light generator (on or off), and tire pressure (40, 55 psi)—on two responses, the time required to ride his bicycle over a particular course and his pulse rate at the finish of each run (pulse rate at the start was virtually constant). To him the most surprising result was how much he was slowed down by having the generator on. The average time for each run was approximately 50 seconds. He discovered that raising the seat reduced the time by about 10 seconds, having the generator on increased it by about one-third that amount and inflating the tires to 55 psi reduced the time by about the same amount that the generator increased it. He planned further experiments.

Popcorn Experiment

In experiment number 2, Karen Vlasek, using a 2^3 factorial design with four replicated center points, determined the effects of three variables on the amount of popcorn produced. She found, for example, that although double the yield was obtained with the gourmet popcorn, it cost three times as much as the regular popcorn. By using this experimental design she discovered approximately what combination of variables gave her best results. She noted that it differed from that recommended by the manufacturer of her popcorn popper and both suppliers of popcorn.

Dilution Experiment

In experiment number 22, Dean Hafeman studied a routine laboratory procedure (a dilution) that was performed many times each day where he worked—almost on a mass production basis. The manufacturer of the equipment used for this work emphasized that the key operations, the raising and lowering of two plungers, had to be done *slowly* for good results. The student wondered what difference it would make if these operations were done *quickly*. He set up a 2^4 factorial design in which the variables were the raising and lowering of plunger A and the raising and lowering of plunger B. The two levels of each variable were slow and fast. To his surprise, he found that none of the variables had any measurable effect on the readings. This conclusion had important practical implications in his laboratory because it meant that good results could be obtained even if the plungers were moved quickly; consequently a considerable amount of time could be saved in doing this routine work.

Trouble-Shooting Experiment

In experiment number 23, Rodger Melton solved a trouble-shooting problem that he encountered in his research work. In one piece of apparatus an extremely small quantity of a certain chemical was separated, to be collected in a second piece of apparatus. Unfortunately, some of this material condensed prematurely in the line between these two pieces of apparatus. By using a 2^3 factorial design the problem was solved, it being discovered that by suitably adjusting the voltage and using a *J*-tube none of the material condensed prematurely. The column temperature, which was discovered to be minor consequence as far as premature condensation was concerned (a surprise), could be set to maximize throughput.

Most Popular Experiments

The most popular home experiments have concerned cooking, since recipes lend themselves so readily to variations. What to use for the response has sometimes created a problem. Usually a quality characteristic such as taste has been recorded on a 1–5 or 1–10 scale. Growing seeds has also been an easy and popular experiment. In the laboratory experiments, sensitivity or robustness tests have been the most common (the dilution experiment, number 22, discussed above is of this type). Typically the experimenter varies the conditions for a standard analytical procedure to see how much the measured value is affected. The variations are chosen to be of the size that might be encountered in practice. That is, if the standard procedure calls for the addition of 20 ml. of a particular chemical, 18 ml. and 22 ml. might be tried. Such tests are useful whether it is discovered that the procedure is sensitive to such variations or not.

Structuring the Assignment

I have always made these assignments completely open, saying that they could study anything that interested them. I have tended to favor home rather than laboratory experiments. I have suggested they choose something they care about, preferably something they've wondered about. Such projects seem to turn out better than those picked for no particularly good reason. Here is how a few of the reports began: "Ever since we came to Madison my family has experienced difficulty in making bread that will rise properly." "Since moving to Madison, my green thumb has turned black. Every plant I have tried to grow has died." (Nothing works in Madison?) "This experiment deals with how best to prepare pancakes to satisfy the group of four of us living together." "I rent an efficiency on the second floor of an apartment building which has cooking facilities on the first floor only. When I cook rice, my staple food, I have to make one to three visits to the kitchen to make sure it is ready to be served and not burned. Because of this inconvenience I wanted to study the effects of certain variables on the cooking time of rice." "My wife and I were wondering if our oldest daughter had a favorite toy." "For the home brewer, a small kitchen blender does a good job of grinding malt, provided the right levels of speed, batch size and time are used. This is the basis of the experimental design." "During my career as a beer drinker, various questions have arisen." "I do much of the maintenance and repair work around my home, and some of the repairs require the use of epoxy glue. I was curious about some of the factors affecting its performance." "My wife and I are interested in indoor plants, and often we like to give them as gifts. We usually select a cutting from one of our fifty or so plants, put it in a glass of water until it develops roots, and then pot it.

We have observed that sometimes the cutting roots quickly and sometimes it roots slowly, so we decided to experiment with several factors that we thought might be important in this process." "I chose to find out how my shotguns were firing. I reload my own shells with powders that were recommended to me, one for short range shooting and one for long range shooting. I had my doubts if the recommendations were valid."

What Did the Students Learn?

The conclusion reached in this last experiment was: "As it looks now, I should use my Gun A with powder C for close range shooting, such as for grouse and woodcock. I should use gun B and powder D for longer range shooting as for ducks and geese." As is illustrated by this example and the first four discussed above, the students sometimes learned things that were directly useful to them. Some other examples: "Spending $70 extra to buy tape deck 2 is not justified as the quality of sound is better with the other, or probably there is no difference. The synthesizer appears not to affect the quality of the sound." "In operating my calculator I can anticipate increasing operation time by an additional 15 minutes and 23 seconds on the average by charging 60 minutes instead of 30 minutes." "In conclusion, the Chinese dumplings turned out very pretty and very delicious, especially the ones with thin skins. I think this was a successful experiment."

Naturally, not all experiments were successful. Many reports have contained remarks such as: "A better way to have run the experiment would have been to . . ." Various troubles arose. "The reason that there is only one observation for the eighth row is that one of the cups was knocked over by a curious cat." "One observation made during the experiment was that the child's posture may have affected the duration of the ride. Mark (13 pounds) leaned back, thus distributing his weight more evenly. On the other hand, Mike (22 pounds) preferred to sit forward, which may have made the restoring action of the spring more difficult." (The trouble here was that the variable the student wanted to study was weight, not posture.) Another student, who was varying certain factors to determine how they affected the rate at which snow melted on sidewalks, had some of his data destroyed because the sun came out brightly (and unexpectedly) one day near the end of his experiment and melted all the snow.

Because of such troubles, these simple experiments have served as a useful vehicle for discussing important practical points that arise in more serious scientific investigations. Excellent questions for this purpose have arisen from these studies. "Do I really need to use a completely randomized experiment? It will take *much* longer to do that way." There have been good examples illustrating the sequential nature of experimentation. "This must have been the main reason why the first experiment completely failed. I decided to try another factorial design. Synchronization of the flash unit and camera still bothered me. I therefore decided to experiment with [some different factors]." In this experiment the student finally concluded: "The factorial design proved to be efficient in solving the problem. I did get off on the wrong track initially but the information learned concerning synchronization is quite valuable." Another student: "It is interesting to see how a few experiments can give so much information."

There is another point, and it is not the least important. Most of the students had fun with these projects. And I did too. Just looking through Table 1 suggests why this is so, I think. Some students have reported that this was the best part of the course.

There is a tendency sometimes for experimenters to discount what they have learned, this being true not only for students in this class but also for experimenters in general. That is, they learn more than they realize. Hindsight is the culprit. On pondering a certain conclusion, one is prone to say "Oh yes, that makes sense. Yes, that's the way it should be. That's what I expected." While this reaction is often correct, one is sometimes just fooling oneself. So that students could more accurately gauge what they learned from their simple experiments, I tried the following and it seemed to work: after having decided on the experimental runs to perform, the students were asked to guess what the major conclusions would be and write them down. Upon completion of the assignment these guesses were checked against the actual results, which immediately provided a clear picture of what was learned (the surprises) and what was confirmed (the non-surprises). Incidentally, the way our educational system works, students rarely have the opportunity to be surprised. But yet isn't that an important part of learning?

I don't claim originality for the idea of having students perform experiments as part of a course in statistics. I know that the following persons have done this: Thomas Boardman (Colorado State), Richard Freund and J. Edward Jackson (Kodak), Brian Joiner and Peter Nemenyi* (Wisconsin), Fred Leone (American Statistical Association), Ronald Snee (DuPont), Donald Watts (Queen's), and Grant Wernimont (formerly with Kodak, now a private consultant). There are undoubtedly many more.

Pedagogy

To provide motivation, I now tend to spend much more time introducing each new topic than I used to. I have found that it is generally better to use concrete

* See, for example, Chapter 3, Section 5, of *Statistics from Scratch* by Peter Nemenyi, Sylvia K. Dixon, and Nathaniel B. White, Jr., Holden-Day Publishing Company, San Francisco, 1976.

examples followed by the general theory rather than the reverse. I try to describe a particular problem in some detail, preferably a real one with which I am familiar, and then pose the question: What would *you* do? I find it helpful to resist the temptation to move on too quickly to the prepared lecture so that there is ample time for students to consider this question seriously, to discuss it, to ask questions of clarification, to express ideas they have, and ultimately (and this really the object of the exercise) to realize that a genuine problem exists and they do not know how to solve it. They are then ready to learn. And after we have finished with that particular topic they *know* they have learned something of value. (I realize as I write this that I have been strongly influenced by George Barnard, who conducted a seminar in this manner at Imperial College, London, in 1964–65, which I was fortunate to have attended.)

Current examples are well-received, especially controversies (for example, weather modification experiments). Some useful sources are court cases, advertisements, TV and radio commercials, *Consumer Reports, Science*, and other journals. An older controversy still of considerable interest from a pedagogical point of view is the AD-X2 battery additive case. Gosset's comments on the Lanarkshire Milk Experiment are still illuminating. Sometimes trying to get the data that support a particular TV commercial or the facts from both parties of a dispute has made an interesting side project to carry along through a semester.

Summary

The purpose of this paper has been to share some ideas about the teaching of design of experiments. While it has included a few words about pedagogy, the emphasis has been on the idea that it has proved worthwhile to encourage students to exercise initiative in thinking up experiments and carrying them through to completion. Using games involving simulated data has served a similar purpose. I have incorporated such projects into courses I have taught, and I urge others to do the same, for three reasons. First of all, it's fun for the students. Secondly, the students have obtained a deepening of understanding that comes from having been through a study from start to finish. Thirdly, I have found it particularly worthwhile to discuss with them in class some of the practical questions that naturally emerge from these studies.

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A Framework for the Development of Measurement Instruments for Evaluating the Introductory Statistics Course

NORMAN L. CHERVANY, RAYMOND O. COLLIER, JR., STEPHEN E. FIENBERG, PAUL E. JOHNSON AND JOHN NETER*

ABSTRACT

This paper proposes a framework for the development of instruments to measure content learning and problem-solving skills for the introductory statistics course. This framework is based upon a model of the problem-solving process central to statistical reasoning. The framework defines and interrelates six measurement tasks: (1) subjective reports; (2) reports concerning truth, falsity, or equivalence; (3) supply the appropriate missing information in a message; (4) answer a question based upon a specific message; (5) reproduce a message; and (6) carry out a procedure.

Key Words

Measurement Instruments
Evaluation of Introductory Statistics
Statistical Reasoning Process
Statistical Problem Solving Process

* Chervany is with the Dept. of Mgmt. Sciences, Collier and Johnson with Psychological Foundations, all at the Univ. of Minnesota, Minneapolis, MN 55455. Fienberg is at the Dept. of Applied Statistics, Univ. of Minnesota, St. Paul, MN 55108. Neter is at the Dept. of Risk Mgmt. and Insurance, Univ. of Georgia, Athens, GA 30602.

New teaching methods and tools, including most recently the use of electronic computers, have been increasingly utilized in the introductory statistics course. At the same time, little effort has been made to evaluate properly these teaching techniques. Much of the evaluation that has been done in the past has been limited in that it has focused principally on either student satisfaction/reaction or content learning, and has tended to omit assessment of problem-solving skills. This paper presents a framework for the development of instruments to measure content learning and problem-solving skills for an introductory statistics course. The proposed structure is based upon a model of the problem-solving process central to statistical reasoning.

Background

The introductory statistics course, usually taught without a calculus prerequisite, is generally a one-

Helicopters

Bill Hunter and I believed that it was important to learn by doing. We wanted the class to experience how process improvement could be achieved using statistical design. In many of our demonstrations, we used a paper helicopter (Figure 1) because it was easy to make, modify, and test. Our basic helicopter design is shown in the figure. The heavy lines show where to make cuts in the paper and the dotted lines show where to make folds. If you release the helicopter, it will rotate and fall slowly to the ground. The problem is to modify the design so that the helicopter will stay in the air for the longest possible time.

For simplicity we illustrate with possible designs – all combinations of long and short wing, long and short body width, and long and short body length arranged in a 2^3 experiment. Over these comparatively short flight times, the effects are roughly linear and can be represented by parallel contours plotted on a cube. The arrow (Figure 2) indicates that a helicopter with shorter body (*W*) width and longer wing (*S*) length will fly longer, but a change in body length doesn't make much difference. Of course an experiment such as this may be run with more than three factors.

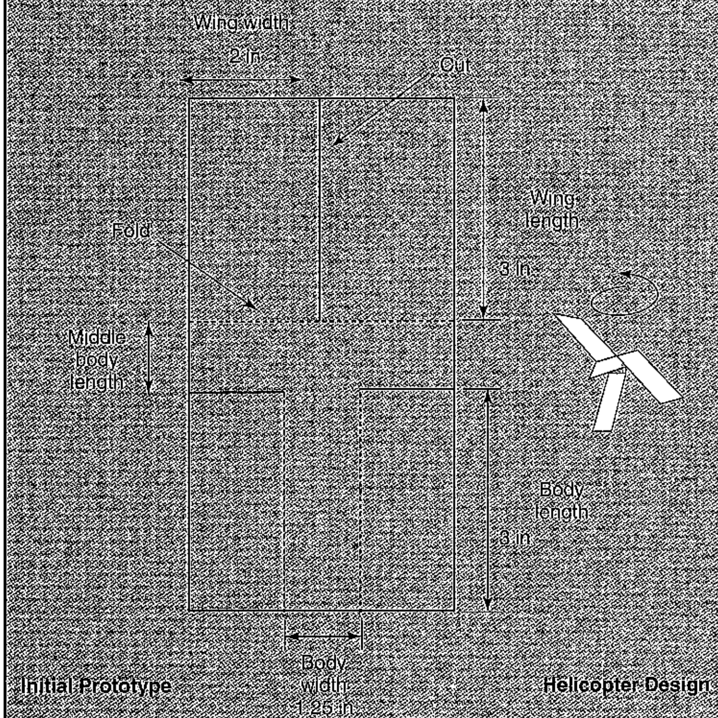

Figure 1.

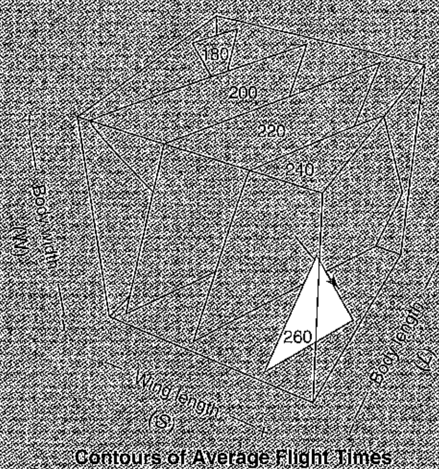

Figure 2.

Also, there was a single lounge where they might discuss problems over coffee. Unfortunately, time proved our plan a miserable failure: Statisticians and computer scientists were not interested in talking to each other.

Initially Madison had a department that was like no other, with a proper balance between theory and practice. What I thought statistics was about was solving "real-life" problems in engineering, chemistry, biology, agriculture, etc. Unfortunately, later on the influence of theoreticians outvoted all attempts to keep the department on its original intended path.

It wasn't long after the new department was started that I became afraid that the teaching of the students might be overly theoretical. This prompted me to begin the "Monday Night Beer Session," which met every Monday evening in the basement of my house. It was not a formal university course; you got no grades or credits, and you just came when you felt like it. It could be attended by students and faculty from any department. People came, piled their coats on the ping pong table or on [my son] Harry's train set, and we talked. We sat on an odd array of chairs and on an old sofa that had seen better days. There was a cupboard door that we painted black, and it became a substitute blackboard. Not a lot of beer was consumed, but it was always available. I tried to simulate the experience I had gained in industry by letting students experience the catalysis to discovery that occurred from discussions using statistics. The meetings were a great success. A number of discoveries and more than one publication with multiple authors came about as a result. These meetings went on pretty much until my retirement. Much later, my daughter Helen presented me with a beer-making kit. When we tried it out, somehow there was an unexpected explosion that left us both covered in beer and reduced to helpless giggles. Later, after I had mastered the bottling stage, I served the homemade brew at the Monday Night Sessions. Unfortunately my students didn't like my homemade brew and I decided that beer making was not my best talent.

It became a tradition that the students presented a [Christmas] skit and the faculty presented a skit. These were high-class performances on which a good deal of effort was expended. The competition was intense, and often the students were ahead. This pleased me because I believed that if you could write a first-class skit, you could also write a first-class thesis. Originality and wit are very close.

I tell my students that it's best if you try to try to think of problems from first principles. If you come to Madison, you will be impressed by the number of beautiful trees in the city. Each autumn the collection and disposal of millions of leaves requires a major effort. The city had been divided up into a number of approximately equal areas with a team allotted for leaf collection in each area. But by making a survey, [it was] found that some of these areas had many trees and others had hardly any, so that some of the teams had almost nothing to do and others were rushed off their feet. Redistributing the areas produced a much more efficient system. You may say that the solution was obvious. That is true, but frequently nothing is less obvious than the obvious. If this were not true, my reputation as a valued consultant would greatly suffer.

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