Gertrude M. Cox and Statistical Design

Figure 1. Gertrude Cox in office.

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Introduction

On December 2, 1959, Gertrude Cox (Figure 1), Director of the Institute of Statistics at the consolidated University of North Carolina, responded to a query from a young woman named Pat Barber about career opportunities in

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statistics for women. Cox replied that the "field of statistics is certainly wide open to women" and described some of her own experiences as a statistician:

> In this area of experimental statistics, we cooperate with the research workers in other science areas with the planning and then with the evaluation and interpretation of their research results. I could give a list of a variety of interesting areas in which I have cooperated such as, the best methods of raising flowers in a greenhouse, development and selection of new varieties of corn, the nutritional problems among the Indian children in Guatemala, how to sample

gold in South Africa, variations in ways to make instant frosting for cakes, how to evaluate the effectiveness of fly sprays, and many others [17].

Cox's letter reflected her view of the statistician as a partner in science, a view that, in part because of her influence, is now standard in the discipline. Her pioneering contributions and example widened opportunities in statistics around the world. To list just a few of her accomplishments, Cox:

- Founded one of the world's first statistics departments (1941) at North Carolina State College.
- Became the first woman elected to membership in the International Statistical Institute (1949) and one of the first statisticians elected to the National Academy of Sciences (1975).
- Received the O. Max Gardner Award (1959) from the University of North Carolina for "contribution to the welfare of the human race."
- Served as president of the American Statistical Association (1956) and the International Biometric Society (1968), and was founding editor of the journal *Biometrics* (1947–1955).
- Co-authored one of the most influential statistics books ever written, *Experimental Designs*, first published in 1950 and still in print.
- Championed the use of electronic computers for statistical work.

Her collaborator William G. Cochran wrote, "I doubt if anyone contributed more than Gertrude Cox to building up the profession of statistics as we know it today" [11].

Early Career

Few would have predicted in 1924 that Gertrude Mary Cox would become one of the most influential statisticians of the twentieth century. She was then a 24-year-old housemother for 16 boys at a Montana orphanage, having previously taught in a one-room schoolhouse in Iowa and studied at the Iowa National Bible Training School [21].

Cox enrolled in Iowa State College to obtain the training and credentials needed for her planned career as an orphanage superintendent. She explained in a 1975 interview how she became a statistician: she took courses in math because she liked it and it was "the easiest subject," giving her time to also take the classes in psychology and crafts she would need in her chosen career. She became interested in statistics after her calculus professor, George Snedecor, invited her to work as a computer in the Mathematical Statistical Service Center. She reminisced, "As soon as I could learn to use that math knowledge with people and their orientation, it became life" [19].

Through the 1950s, a "computer" referred to a person—usually a woman—who performed calculations on a hand-operated machine such as the one seen on the table by the radiator in Figure 1. Women were hired for this work because they were thought to be more patient with the tedious calculations than men—and, incidentally, could also be paid much less [19, 20, 30].

Many of the statistical computations involved finding correlation or regression coefficients—calculations for a regression model with a large number of independent variables could take weeks [25]. The main result in Cox's first publication [13] was a table of correlations between scores on the Iowa State College Aptitude Test, high school subjects, and college courses.

Cox received her bachelor's degree in mathematics in 1929. She stayed on at Iowa State to earn the first master's degree awarded in statistics from the Department of Mathematics in 1931, with Snedecor as advisor.

In 1933, while she was midway through a doctoral program in psychology at University of California, Berkeley, Snedecor invited her to return to Iowa State, writing, "I … am rapidly being drawn into statistical responsibilities for a large part of the College. Would you like to be a part of this? I think the opportunity is great. Are you interested? Immediately you would have charge of the girls, 140 calculating machines, and all the *stray* jobs that I can rustle for you" [18].

As one of three initial faculty members in the Iowa State Statistical Laboratory, Cox supervised the computers performing data analyses. She visited laboratories and fields to see how the data were collected, which led to collaborations with researchers to develop experimental designs and analyses that would best answer the scientific questions. Her classes in experimental design attracted students from across the campus, and she soon became known as an expert in the field. Initially hired as an assistant to Snedecor, Cox was appointed Research Assistant Professor in 1939.

In 1941 Cox became the first female full professor and the first female department head at North Carolina State College, charged with developing a department that would provide statistical expertise to researchers. Her colleague Richard Anderson related how the appointment was made:

> In 1940 Snedecor was asked to recommend candidates to head the new Department of Experimental Statistics in the School of Agriculture at North Carolina State College. "Why didn't you put my name on list?" Gertrude asked when he showed her his all-male list of candidates, and her name was added to the accompanying letter in the following postscript: "If you would consider a woman for this position, I would recommend Gertrude Cox of my staff." This terse note was to have far-reaching consequences for statistics, for not only was Gertrude considered, she was selected [10].

Historian Margaret Rossiter described how unusual it was for a woman to be considered for a position as department head in the 1940s: "As for department chairmanships,

the lowest level of academic administration, women scientists still so rarely held these positions at coeducational institutions in the forties, fifties, and mid-sixties that one can almost count these exceptions on two hands." Rossiter singled out Cox as the most successful of this handful, noting that she, unlike many other university women of the time, ended up getting credit for her accomplishments in building her department and scientific discipline: "She not only managed to ride the wave of Big Science in the 1950s and 1960s but to be enough ahead of it to shape the form it took and the impact it had on her university, field, and region" [29].

Designing Experiments

Cox began her new position in North Carolina with the same energy she had shown in her work at Iowa State. She immediately started establishing training programs, hiring faculty members, collaborating with scientists, promoting statistics in the university and nationally, and teaching classes on experimental design. She expanded her mimeographed notes from the design classes into the book *Experimental Designs* [12], published with collaborator William G. Cochran in 1950.

Experimental Designs emphasized three principles:

1. Statisticians need to be involved in the research from the planning stages: the first steps, setting out the objectives of the experiment and planning the analysis, are crucial. Often, one of the statistician's most valuable contributions arises "by getting the investigator to explain clearly why he is doing the experiment, to justify the experimental treatments whose effects he proposes to compare, and to defend his claim that the completed experiment will enable its objectives to be realized." When a statistician is consulted only after the data are collected and discovers that the poorly planned experiment cannot answer the research questions, "[i]n these unhappy circumstances, about all that can be done is to indicate, if possible, how to avoid this outcome in future experiments" [12, pp. 9, 10].

2. Randomize everything that can be randomized. "Randomization is somewhat analogous to insurance, in that it is a precaution against disturbances that may or may not occur and that may or may not be serious if they do occur. It is generally advisable to take the trouble to randomize even when it is not expected that there will be any serious bias from failure to randomize. The experimenter is thus protected against unusual events that upset his expectations" [12, p. 8].

3. Use blocking whenever possible to reduce the effects of variability. Blocks are homogeneous groups of experimental units: for example, identical twins, neighboring agricultural plots, batches of raw material, cancer patients with similar demographics and disease stage, schools in the same city, or experimental runs done on the same day. When treatments are randomly assigned to

experimental units within blocks—one twin is randomly chosen to receive treatment A, and the other treatment B—the block-to-block variability is removed from the treatment comparison. If blocks represent a range of experimental conditions, results from the blocked experiment have wider applicability as well as increased precision for estimating treatment effects.

The 1950 book and its second edition in 1957 set out detailed plans for Latin square, factorial, fractional factorial, split plot, lattice, balanced incomplete block, and other designs. Each design description started with examples, followed by a discussion of when the design was suitable and detailed instructions for how to perform randomization. Then came one or more detailed case studies, showing why that design had been chosen for each experiment and how it had been randomized, and taking the reader step-by-step through the calculations needed to construct the analysis of variance table and estimate the standard errors for differences of treatment means. The authors also discussed how to estimate the efficiency of the design relative to a completely randomized design and how to do the calculations for the unbalanced structure that resulted when one or more experimental runs had missing data.

The chapters on the complex designs contained tables of designs for different block sizes and numbers of treatments. Today, statistical software quickly calculates optimal designs for almost any experimental structure, but in 1950 printed design tables were needed, particularly when there was more than one blocking variable or when the number of treatments (t) exceeded the number of experimental units in a block (k).

For the latter situation, a balanced incomplete block design was recommended, where each pair of treatments occurs together in the same number of blocks. Of course such a design can always be constructed by using all combinations of the t treatments taken k at a time, but *Experimental Designs* laid out the designs that met the constraint with the smallest numbers of experimental units. For example, the smallest balanced incomplete block design with seven treatments and blocks of size four required only seven blocks and twenty-eight experimental units—one-fifth the size of the fully combinatorial design.

Cox's experience as a consulting statistician can be seen on every page of the book. Her background as a computer is also apparent: each set of instructions for calculating an analysis of variance table came with practical tips and quality checks for ensuring the calculations are accurate. Indeed, the first experiment described in *Experimental Designs* compared the speed of two calculating machines, A and B, using a cross-over design, where the same person computed the sum of squares of 10 sets (blocks) of 27 numbers on each machine; machine B turned out to be significantly faster, taking only 2 minutes 13.6 seconds, on average, to calculate the sum of squares for 27 numbers.

When Cox began her career, randomization was seldom used to protect against systematic errors or to promote valid inferences from experiments; some thought that randomization conflicted with attempts to control variation [25]. She viewed randomization as the distinguishing feature of modern statistical experimental design, and the feature that allowed proper inferences to be drawn from the results.

Cox emphasized the importance of randomization for each case study in the book. In the calculating machine experiment, for example, randomizing the machine order was essential. If the sums of squares for each block of numbers were computed first on machine A and then on machine B, and machine B turned out to be faster, one could not attribute the difference to the machines; it could have occurred because the operator became familiar with the numbers after entering them on the first machine and was able to enter them more quickly on the second. By randomly assigning machine A to be first for five of the blocks and machine B to be first for the other five, Cox could separate out the order effect and conclude that the speed difference was indeed due to the machines [12].

Cox advised the statistician to "use the simplest design that meets the needs of the experiment" [14]. In many of the experiments she consulted on, the simplest design meeting cost constraints needed blocking or other types of restricted randomization, and she and her staff tailored and developed designs for each experiment. From 1942 to 1948, all but 59 of the 6,317 experiments performed at the North Carolina Agricultural Experiment Station involved some form of blocking; 62 percent were randomized complete block designs [14]. She strove to develop ways of conducting experiments "so that the greatest amount of information can be obtained with the least expenditure of time and money" [6].

Experimental Designs is still widely used by persons designing experiments. The many experimental researchers who have recently relied on the book for guidance include Wood and Porter [33], who adopted a Latin square design to study the effects of presenting factual information to persons with strong political views, and Reeves et al. [28], who used a balanced incomplete block design to compare community and hospital eye care for persons with macular degeneration.

Designing the Statistical Profession

Of equal importance to Cox's contributions in designing experiments were her contributions in shaping the discipline of statistics.

Statistical Training

One of her earliest activities in North Carolina was establishing a summer training program in statistics. In the first six-week program, during June and July of 1941, Cox taught beginning and advanced courses on design of experiments, Snedecor taught two courses on applied statistics, and Harold Hotelling taught mathematical statistics; Ronald Fisher

had been scheduled to teach, but wartime authorities in London withheld authorization for his travel. During the program, all faculty and staff members were available for individual consultations with students about statistical problems [5, 3, 21]. These courses and three affiliated one-week conferences drew 243 registrants from around the country, including many who were, or were to become, leaders of the statistics profession.

Instruction was not limited to future statisticians. The department taught multiple courses to help state government workers and other persons in the community. Cox, in addition to her administrative and other teaching duties, offered an introductory course on experimental statistics intended for tabulating clerks and computers.

In 1943, Cox intensified the department's efforts to provide trained statisticians to meet wartime and postwar needs. The summer session in 1943 offered "[f]our intensive courses in applied statistics, designed to appeal to young women who are college graduates or advanced undergraduates," including training in sampling methods. Cox said, "This training is offered because of the extreme importance of having efficient workers to help with rush work. There are numerous sampling investigations now in progress, such as those for locating sources and requirements of farm labor as well as those for studying food production and distribution problems. Training in machine problems and statistical and sampling methods is of immediate value in prosecution of the war with limited manpower" [2].

By 1946, statistics in North Carolina had grown under Cox's leadership to include the Department of Experimental Statistics at North Carolina State College and the Department of Mathematical Statistics at the University of North Carolina. Both departments were incorporated in the Institute of Statistics, which Cox directed [27]. After retiring from the university in 1960, Cox led the statistical research division at the newly formed Research Triangle Institute. She continued promoting statistics after her second "retirement" in 1965, traveling around the world to provide statistical advice and help establish statistical programs. Between travels, she served on advisory boards for the US Census Bureau, the Department of Agriculture, the National Science Foundation, and many other organizations.

When Cox established the Department of Experimental Statistics at North Carolina State in 1941, there were only a handful of statistics departments in the world: the first, Karl Pearson's Department of Applied Statistics at University College London, had been established in 1911. In general, mathematical statistics classes were taught in mathematics departments; applied statistics classes were taught in a department of agriculture, psychology, biology, or another discipline. In each, statistics was viewed as a subfield of the discipline where it was taught. Harold Hotelling, who later joined Cox's Institute of Statistics, wrote in 1940 that a great deal of the current knowledge in statistics was still in the

form of oral tradition and "the seeker after truth regarding statistical theory must make his way through or around an enormous amount of trash and downright error. The great accumulation of published writings on statistical theory and methods by authors who have not sufficiently studied the subject is even more dangerous than the classroom teaching by the same people" [23].

Cox insisted that students receive a thorough grounding in mathematical theory and applications of statistics, and that they gain experience in collaborating with scientists. The universities and organizations that consulted her about establishing statistics programs inherited this philosophy, and most statistics departments today are organized around the principles she advocated for training students.

The American Statistical Association's recent guidelines for graduate and undergraduate programs in statistics [8, 9], urging that "graduates should have a solid foundation in statistical theory and methods" as well as experience with collaborating on real problems and designing studies, repeat many of the principles for statistical education that Cox outlined in 1953:

> It is the statistician's duty to keep informed of the rapidly expanding knowledge of statistics and to make such information available to the users of statistics. This combination of a thorough knowledge of statistical theory and method along with adequate competence in the field of application requires that the consultant statistician be a person of substantial ability…. A close integration between theory and applications constitutes the best foundation for important advances in the science of statistics [15].

Statistics as a Collaborative Discipline

Cox held that statistics is by its nature collaborative. Although statisticians engage in a wide range of theoretical and applied investigations, those investigations need to be directed toward "solving problems concerned with decision making" [16]. "The cooperation involved when the statistician consults and works with researchers in other fields is an advantage to all. Also, the consulting or applied statistician in his daily use of statistics encounters new problems which call for help from the theoretical statistician. The theoretical statistician requires the stimulus of practical needs which lead him into useful developments of new techniques" [18].

Equally important was the presentation of results, and a good experimental design leads to clear findings: "close cooperation between the research worker and the statistician before the experiment is started—planning the experiment so that the statistics collected will be easily interpreted by the average reasonably intelligent person" [1].

Cox practiced what she preached. Less than a week after her arrival at North Carolina State College in 1940, "she was out trooping over a soybean field near Raleigh, helping an Experiment Station agronomist work out the best set-up for an experiment. She has also visited several of the test farms for the same purpose" [1]. Throughout her career, she tirelessly promoted statistics around the world, providing expertise and helping develop programs in statistics. Her travels included consultations in Egypt, Thailand, South Africa, Guatemala, Japan, Hong Kong, Lebanon, Malaysia, Brazil, and Honduras.

Cox encouraged collaboration and sound statistical practice in her many presentations at US and international statistical conferences. She also viewed the community as a partner in statistical activity and regularly spoke about statistics and her travels to civic organizations and women's clubs in Raleigh. The *Raleigh News and Observer* reported on many of Cox's local talks. In 1954, for example, they wrote: "A talk by Gertrude Cox, director of Statistics at the University of North Carolina, was a highlight of last night's meeting of the Lewis school PTA." Her talk was followed by a presentation of a minuet from Mrs. Hicks's fourth grade class [4].

Cox provided statistical expertise locally, as well as internationally, throughout her years in Raleigh. In 1975, for example, she was asked to evaluate a controversial statistical investigation on the effectiveness of kindergarten in North Carolina. The investigators had selected 18 schools for the assessment but had omitted one school—whose results would have changed the conclusions—from the analysis. Cox's primary recommendation was that analysts should not be selective in choosing data to be analyzed unless there is justification, and she argued that the small sample size and possible selection biases made it difficult to draw clear conclusions from the study. She concluded that the investigators "could use a great deal more help from qualified statisticians" [7]—a gentle way of saying that the controversy could have been avoided if the investigators had consulted a statistician before conducting the study.

Computation and Statistics

Cox, well aware of the importance of computation to the field of statistics, established a computing laboratory soon after moving to North Carolina. The laboratory performed computations for statistical analyses as well as for other units on campus. During World War II, the department offered classes to train women as computers for the war effort.

Perhaps because of her work as a human computer, Cox was one of the first persons in statistics to embrace the ability of "electronic computing machines" to contribute to the discipline. She immediately saw their use for regression problems and computing standard errors for complex sampling designs, and she forecast that they would soon allow statisticians to "open up even wider frontiers" in statistics [16].

Not surprisingly, Cox's department was one of the first in the country to acquire one of the new IBM-650 electronic computing machines, in 1956 [27]. Computations for large regression models could now be done in less than

20 minutes rather than taking weeks. Some of the earliest computer programs for regression and analysis of variance were written at North Carolina State College [22].

Cox's interest in computational issues continued well after her retirement from the university. In the early 1970s, she provided expertise to the Department of Health, Education, and Welfare on statistical, computational, and privacy issues relating to the proposed use of the Social Security number as a universal personal identifier and, more generally, to the large amounts of personal data that were being collected in computer-based record-keeping systems. The 1973 report of the Advisory Committee on Automated Personal Data Systems set forth principles—the Code of Fair Information Practices—that became the foundation of subsequent US privacy legislation [32, 31]. The report's recommendations reflected Cox's strong views that an individual has a right to know how his or her data are being used.

Statistical Frontiers

Cox summarized her vision for statistics in her 1956 address as President of the American Statistical Association, titled "Statistical Frontiers." She invited the audience to tour the three major continents of the statistical universe: "(1) descriptive statistics, (2) design of experiments and investigations, and (3) analysis and theory" [16]. As she visited each continent, she briefly described some of the "well developed countries" where statisticians have developed many techniques for design and analysis, and she then gave examples of frontiers needing more exploration.

The descriptive statistics continent, although having the longest history of exploration, nevertheless had multiple frontiers. Cox noted that although statistical tabulations were common, too few persons described the variability of a population or the uncertainty of an estimate. She also emphasized the statistician's contributions to the presentation of results country, where "you will be asked to swear allegiance to logical organization, preciseness, and ease of comprehension" [16, p. 3].

The longest sojourn of the tour, not surprisingly, was in the design of experiments and investigations (sampling) continent. Cox foresaw the survey sampling research problems that would arise in future decades, such as the need for statistical methods to assess and control nonsampling errors, and she anticipated the development of computer-intensive methods for estimating variances [24].

While visiting the analysis and theory continent, Cox mentioned some of the frontiers of the late 1950s such as variance component models and nonparametric methods. She also discerned the fundamental problems of inference facing future statisticians in these general frontiers. The methods of statistical inference that work for data from a designed experiment or carefully collected probability sample do not necessarily apply to data that happen to be conveniently at hand. She wrote, "How far are we justified in using statistical methods based on probability theory for the analysis of nonexperimental data? Much of the data used in the descriptive methods continent are observational or nonexperimental records" [16].

Cox's comments are relevant to many of today's frontiers in statistics. One frontier in 2019 concerns making inferences from large observational data sets such as credit card transactions, electronic medical records, sensor data, or internet activity. Statistics from "big data" are often presented without any measures of uncertainty.

Participants in the 2017 National Academies of Sciences workshop on "Refining the Concept of Scientific Inference When Working with Big Data" echoed Cox's views on the need for statistical collaboration, carefully designed experiments, and appropriate statistical inference. In their report they wrote:

- "[T]oo often statisticians become involved in scientific research projects only after experiments have been designed and data collected. Inadequate involvement of statisticians in such 'upstream' activities can negatively impact 'downstream' inference, owing to suboptimal collection of information necessary for reliable inference" [26, p. 5].

- "[B]igger data does not necessarily lead to better inferences," in part "because a lot of big data is collected opportunistically instead of through randomized experiments or probability samples designed specifically for the inference task at hand" [26, p. 14].

- "Without careful consideration of the suitability of both available data and the statistical models applied, analysis of big data may result in misleading correlations and false discoveries, which can potentially undermine confidence in scientific research if the results are not reproducible" [26, p. 1].

Most of Cox's views on statistics do not seem revolutionary to a statistician in 2019. That is because Cox helped define the profession of statistics from her entrance in the 1920s until her death in 1978. Her vision of the statistician as a partner in science—who collaborates on designing and analyzing studies, and who can develop new statistical theory as needed—characterizes the discipline today. She promoted sound statistical practice in the department and institutes she founded, in the community, and around the world.

As she said in 1940, "There is fascination about experimental work. In searching the unknown for new truths, there is mystery, and there is adventure, and there is the thrill of discovery" [1].

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