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Author(s): Joan Fisher Box
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Guinness, Gosset, Fisher, and Small Samples

Joan Fisher Box

Abstract. The environment in which W. S. Gosset (Student) worked as a brewer at Guinness' Brewery at the turn of the century is described fully enough to show how it forced him to confront problems of small sample statistics, using the techniques he picked up from Karl Pearson. R. A. Fisher's interest in human genetics prompted biometrical applications of his mathematical training even as an undergraduate. As soon as he considered Student's work, he perceived its importance and began to extend its applications. Consequently, when he started work at Rothamsted Experimental Station in 1919, he was ready to respond to the experimental problems by developing statistical theory along with appropriate methods of experimental analysis and design.

Key words and phrases: Gosset, Student's t, Fisher, small samples, analysis of variance, correlation.

The two men I want to write about are W. S. Gosset, better known as Student, who invented Student's t test, and R. A. Fisher, who took up Gosset's work and extended and generalized it so greatly. I am interested in the circumstances that forced them to break new ground where they did. Gosset was a brewer, Fisher a mathematics student when he started. Why should they have invented statistical methods for experimenters? How did they pinpoint the problem area where human thought was dammed back and baffled? Sometimes the most important step in creative work is simply to ask the right question. The question nobody thinks to ask—that may seem too trivial, or too difficult—but which, once asked, must be answered. Gosset asked the first question and found the answer, despite his lack of mathematics. Fisher made it elegant and went on from there. Why did they persist while experts in the field ignored or belittled their work? Mathematicians only slowly realized that an intellectual revolution was taking place through the new inductive uses of mathematics. Even now, people often think statistics can be reduced to deduction—that once you have learned the theory you understand statistics. Gosset and Fisher believed otherwise. They believed that understanding of inductive reasoning is acquired through learning to deal with real data inductively, knowing that practical action will be taken on the basis of your conclusions. Knowing the theory is not the answer, but it can help you find the answer to statistical problems.

One of the first things you learn in statistics is to distinguish between the true parameter value of the standard deviation σ and the sample standard deviation s. But at the turn of the century statisticians did not. They called both σ and s the standard deviation. They always used such large samples that their estimate really did approximate the parameter value, so it did not make much difference to their results. But their methods would not do for experimental work. You cannot get samples of thousands of experimental points. Any experiment large enough would spread so far in time or space that extraneous variation would drown out any effects of treatment you might be looking for.

My story begins with Gosset, for he came first in time. Born in 1876, the oldest of five children of a Colonel in the Royal Engineers, Gosset entered the Royal Military Academy, Woolwich, to become a Royal Engineer himself before being rejected on account of his poor eyesight. He was very bright, with high ideals, and an impish sense of humor. A most appealing character—quiet, unaffectedly friendly, helpful, patient, loyal—everybody liked and trusted him. In the very quarrelsome world of statistics, he managed to be on friendly terms with everyone. He was never employed as a statistician. After school at Winchester and New College, Oxford, where he won a first class degree in chemistry in 1899, he took a job

Joan Fisher Box is the author of "R. A. Fisher, the Life of a Scientist" (Wiley, New York, 1978) and lives at 230 North Hillside Terrace, Madison, Wisconsin 53705.

W. S. Gosset, 1899

as brewer at Guinness' Brewery in Dublin. He was Head Brewer when he died in 1937. It was the environment at Guinness' that made him a statistician. That is what we look at next.

One hundred years ago, in 1886, there was eager buying on the London Stock Exchange when Guinness' was incorporated as Arthur Guinness Son and Company, Ltd. and sold to the public for six million pounds. Until then, it had been a family firm, run almost exclusively by Guinness and one other family. The first Arthur Guinness and son had started brewing at St. James' Gate on the southwest of Dublin in 1759. Forty years later they were getting a foothold in the London market, selling the brown beer called "porter" because of its popularity with London porters. Later, Guinness offered what they called "a stouter porter" or stout. As this gained in popularity, it came to be known simply as Guinness. All through the century Guinness kept extending its market and building and extending the brewery to deal with growing trade. By the end of the century, it was the largest brewery in the world, producing over 1.5 million bulk barrels a year for distribution in England and Ireland and for export to the ends of the earth.

Ireland is a small island and, all through the barley-growing districts of the south and east, Guinness commissioned maltsters to buy local barley and malt it exclusively for the St. James' Gate brewery. Their commission maltsters were prosperous citizens of influence in their own areas.

After incorporation, Cecil Guinness, head of the firm, became Chairman of the Board and Christopher Digges La Touche (one of two brewers taken in from outside the family in the 1870s) was made Managing Director. Although Guinness himself was apparently removed from the running of the brewery, it was he, with La Touche's advice, who made all the important decisions. In particular, Guinness, by then the first Lord Iveagh, and La Touche together brought about a quiet revolution around the turn of the century. They had decided to make the brewing scientific. Up to that time the brewers had learned as apprentices to know every process and to follow meticulously the traditional practices—all the black magic of brewing, as it were. Now, Guinness espoused a new approach and invested a lot in it.

First, they began to hire a series of the brightest young men they could find—all of them newly graduated from Oxford or Cambridge University with first class degrees in chemistry—and to appoint them brewers. Other breweries employed the occasional chemist in research laboratories, but Guinness brought in these chemists as their top management, in positions previously occupied by the Guinness family. As soon as each new brewer completed 2 years as a junior, learning his duties under senior brewers in every department, he was put in charge of a section of the brewery and research work. Guinness brewers were awfully grand. Stella Cunliffe (1976) recalls how, on arrival at St. James' Gate as a newly-hired statistician in 1947, she was instructed how to dress and how to behave in her new work. If she was lucky enough to meet a brewer in the corridor, she was told, she was on no account to recognize him but to lower her eyes until he had passed.

So, the new brewers were appointed: 1893, Thomas Case; 1895, Alan McMullen; 1897, Arthur Jackson; 1899, E. G. Peake; October 1899, W. S. Gosset; January 1900, Geoffrey Phillpotts; and so on. Until they married, they lived together at the Guinness house for unmarried brewers at St. James' Gate. At work, they ate together in the brewers' dining room. Off duty, they seem to have been very active outdoors; they skied, fished, sailed, golfed, cycled, and walked in the Wicklow Hills, and visited and read and talked together. In some ways, their life was like an extension of college.

As they got involved in research, of course, they needed new facilities. Case and McMullen started with

chemical analyses to try to identify and quantify what it was that gave hops and barley their brewing quality. Until then the criteria were qualitative, e.g., the "rub" of hops or the "texture" of barley, which might be "milky" or "steely." So, in addition to the brewers' and chemists' laboratories, a new Guinness Research Laboratory was opened in 1900, headed by the most distinguished brewing chemist alive, Horace Brown.

The next questions concerned the raw materials, barley and hops. Where could they be got best and cheapest? What varieties of barley and hops, what cultivation and manuring, what conditions of drying and storing gave the best malting value of barley and the best brewing value of malt and hops? So, in 1899, Guinness started a program of barley plot experiments through Henry Bennett, their Commission Maltster at Ballinacurra, County Cork. He selected the farms and supervised the experiments to compare different varieties and cultivations and fertilizers. The variety trials seemed most promising and these experiments were extended, with cooperation from other maltsters and farmers in every barley-growing district in Ireland. The new Ministry of Agriculture in Ireland was officially in charge and in 1904 appointed a barley expert, Herbert Hunter, who made his headquarters with Henry Bennett. Together they toured the barley experiments several times during the growing season. The Grand Tour was shortly before harvest—Grand because brewers from Dublin as well as Bennett and Hunter attended this tour which lasted 2 weeks; they spent long days in the barley fields with the farmers and local maltsters (and were entertained in style by the maltsters afterward), while they saw for themselves the condition of experimental plots and of the barley that would soon be harvested and sent to St. James' Gate.

In 1901, an experimental malthouse was built at St. James' Gate, of a suitable size for malting each experimental batch of barley separately. In 1903, an experimental brewery was opened there. Now, barley grown on experimental plots could be followed from seedcorn to harvest, through malting and brewing to the final beer in a unique and comprehensive series of observations (McMullen, 1908).

At the same time, enquiries were going forward regarding varieties and cultivation of hops, and how best to dry and store them. Many years later, Rupert Guinness, the second Lord Iveagh, recalled 1902 when he had gone on a cycle tour of Kent hop gardens with Case and McMullen to see what they could discover about hop culture. They had dropped in at the new Wye Agricultural College and introduced themselves to the Director, A. D. Hall. Following up this visit in 1904, the first Lord Iveagh and La Touche visited Hall and arranged to rent two hop farms nearby, putting one of Hall's graduates in as manager. Later, these farms were bought and gradually added to, until Guinness was one of the largest hop growers in England. But it all started for the young research brewers to do research on what hops to grow, and how, to get the best flavor and the longest life for their beer, and to find out how much it cost (Brown, 1980).

R. A. Fisher, 1912

The life of the beer was important because Guinness is a naturally conditioned beer—it has no additives or preservatives nor, of course, is it pasteurized—and it has to remain potable while it is exported to Africa or the Far East, or stored in the barrel at varying temperatures before reaching the consumer.

Now, can you imagine half a dozen energetic and bright researchers given a free hand to explore the whole subject of brewing from a condition of almost total ignorance? And given the experimental laboratories, barley fields, hop gardens, malthouse, and brewery for their experiments. What happens next? Well, of course, they studied available literature, and found some of it useful. Case read about a new analysis of hops for soft resin content and tried it. He found the quantity of soft resin in the hops paralleled Guinness' qualitative assessment of hop "condition." The

condition of hops stored at ambient temperatures deteriorated and their soft resin content fell as soft resin was converted to hard resin. If the hops were cooled in storage, both hop condition and soft resin content fell less. Thus, soft resins looked like a good predictor of hop condition, and the brewers began routine analysis of hop soft resin content. Guinness found this measure very valuable for assessing hops before purchase. In particular, American hops were cheaper than European and it turned out they had a naturally high soft resin content.

Similarly, in 1902, studies were published in which malting quality of barley was shown to depend on nitrogen content. The brewers began routine analyses of barley for nitrogen, in addition to their records of yield, moisture, size of barleycorns, and the old qualitative assessments for mellowness and texture.

Reading led to analysis, experiments, and measurements. They began to accumulate data and, at once, they ran into difficulties because their measurements varied. The effects they were looking for were not usually clearcut or consistent, as they had expected, and they had no way of judging whether the differences they found were effects of treatment or accident. Two difficulties were confounded: the variation was high and the observations were few. As a result, for example, when Case reported his hop-cooling experiments in 1898, he pointed out "the weak link between examination or analysis and the brewing value," that is, between treatment and effect, and said "most of the results . . . require substantiation by irreproachable figures," which his obviously were not. He concluded, "The comparative value in terms of life between the cooled and uncooled hops may be regarded provisionally as of the order of about 10%" (Brown, 1980). He was not sticking out his neck, although a 10% difference is quite a lot.

Other brewers, on starting their experiments, found the same difficulty. They had no way of taking account of the variation in interpreting their data. After trying to correlate fertilizer treatments with barley plot yields, E. G. Peake ended up recommending that each farmer should find out the manurial needs of his own land, because "the results were most irregular and varied with every farm." Peake tried to correlate spring rainfall with yield of barley from Rothamsted data that A. D. Hall also had analyzed. By taking a slightly different period than Hall had for the rainfall, Peake managed to discern correlations in the opposite direction to those found by Hall, and had to give up, concluding that "the whole subject of the effect of weather . . . deserves further careful investigation" (McMullen, 1908).

In the case of the barley plots, the variation was excessive. First, it was obvious that alien barley was intermixed in the seed, for perhaps 10% of plants in a plot of a short, late-maturing variety would grow tall and mature early, and so on. Next, plants even from seed genuinely of one variety showed many smaller variations. Old Irish was the most heterogeneous variety. Unlike the others which had been selected originally from a single plant or small stand of plants, Old Irish was an indigenous Irish variety that had never been selected. It retained the variability accumulated throughout its ancestry, and made an extremely uneven and unsatisfactory crop.

This cause of variation, at least, could be eliminated. Barley is usually self-fertilized. In 1904, therefore, Bennett and Hunter began propagation of each variety of interest in pure lines from single grains of barley. In 1907 they had enough pure-line seed to sow all the experimental plots, and on the Grand Tour everyone marvelled at the wonderfully even growth of the fields. But genetic variability was a special case. One could not eliminate variations of rainfall, bird damage, soil chemistry, temperature (which affected brewing beer as well as growing crops), or any of the unrecognized variables affecting their data. They needed some way to decide which differences to ignore and which to take seriously.

The young research brewers worked well together—some were very close friends. Each seemed to fit into his own role in brewery affairs. And to them it seemed natural to take their numerical problems to Gosset. He had done some mathematics at Oxford and seemed less scared of mathematics than they were. (In a report on the theory of error, he observed, "It may seem strange that reasoning of this nature had not been more widely made use of, but this is due, first, to the popular dread of mathematics.") He was always ready to listen to them, and very quick to grasp their concerns. He would always do his best to come up with an answer, going back to first principles and arguing through to a solution (McMullen, 1938), and he was not satisfied until he reached it. So, statistical problems came to him. He got hold of Airy's textbook on the theory of errors, and studied and annotated his copy in the margins. In 1903 he could calculate standard errors. In 1904 he wrote a report on the subject for the brewery. This report led directly to his being sent to consult Karl Pearson about his difficulties, Professor Pearson being the great name in biometrics in those days. In 1905, Gosset was using a homemade measure of correlation, based on examination of the difference between $\sum (A + B)^2$ and $\sum (A - B)^2$, at the time he visited Pearson and learned about the product-moment correlation coefficient (Pearson, 1938).

One great difficulty in interpreting their experimental data was that the samples were always small. For instance, the barley experiments started with four farms each growing one plot of each variety. The estimate m of the mean based on a sample of four is

obviously not exact, and the error in the estimate s of the standard deviation cannot be ignored. This Gosset recognized. For him, the main question was exactly how much wider should the error limits be to make allowance for the error introduced by using the estimates m and s instead of the parameters μ and σ. Pearson could not answer that question for Gosset in 1905, nor the one that followed, which was: what level of probability should be called significant?

The meeting took place in July 1905 during Gosset's summer holiday in England when he cycled about 20 miles from his parents' home to Pearson's summer home, and they had a long talk, which Gosset found very helpful. Later, he recalled that Pearson "was able in about half an hour to put me in the way of learning the practice of nearly all the methods then in use." He went back to Guinness and practiced those methods for the next year as acting Brewer-in-Charge of the Experimental Brewery, where analysis of the collected data became a major concern. The meeting was so successful, in fact, that Guinness arranged for Gosset to spend a year in Pearson's department at University College, London, "to take up the study of the law of error, the working of which we have found of great service in the brewery." Gosset had found his vocation.

During the academic year 1906–1907 at Pearson's laboratory, Gosset worked out the exact answer to his question about the probable error of the mean and tabulated the probability values of his criterion $z = (m - \mu)/s$ for samples of $N = 2, 3, \ldots, 10$. He tried also to calculate the distribution of the correlation coefficient by the same method but managed to get the answer only for the case when the true correlation is zero. It is almost a miracle that he got so far, for his mathematics had to be helped out by inspired guesses.

Gosset quietly returned to Guinness in 1907, to become Brewer-in-Charge of the Experimental Brewery for the following 7 years.

He was just in time to provide the answer to McMullen's prayers. The first series of barley experiments was coming to a close. The results of 7 years of work were to be analyzed and reported to Guinness. McMullen prepared the text, with assistance from Jackson on the taxonomy and identification of barleys, from Peake on matters of soil and weather, from Hunter on genetics and barley breeding, while Gosset took over the entire statistical analysis: there were barley yields, measurements and assessments for different varieties, different farms and districts, and different seasons; there were malting assessments and brewing results for the same barley lots. Gosset finally analyzed barley yield and quality together in terms of value per acre, and at every opportunity he quoted the odds (from his newly calculated t table)—it was the natural way for him to express probabilities, especially in the native land of horse racing! (McMullen, 1908).

And Guinness were delighted. Now, they knew that Archer was the best barley for Ireland and they wanted to grow it all over the island. They discovered 1,000 barrels of pure-line Danish Archer seed was available to buy. They bought it all. Then, through their Commission Maltsters, they distributed it as seed to chosen farmers together with 300 barrels of Danish Archer seed they had grown in Ireland, guaranteeing a minimum yield, all of it to be bought back at harvest. The next year they had some 10,000 barrels to distribute as seed, which was grown and bought back as before. After that, they had enough to distribute to any farmer who wanted to grow it in the ordinary way. For many years thereafter, most barley seed in Ireland was selected by brewers at the Grand Tour reserving the cleanest fields for seed, to be harvested and stored apart and distributed by their maltsters. Maltsters continued as seedsmen after World War I when Archer gave way to a new variety, the hybrid Spratt-Archer, which Hunter, at his first attempt at making a hybrid cross, had created in 1908. Between the wars, 90% of the barley grown in Ireland was Spratt-Archer, as was most of what was grown in England too (Hoctor, 1971; Hunter, 1882–1959).

In his spare time in 1908, Gosset prepared his papers on the probable error of the mean and of the correlation coefficient for publication (Student, 1908a and 1908b). Guinness had earlier agreed to permit publication. As the Board minutes recorded, "It was decided by La Touche that such publication might be made without the brewers' names appearing. They would be merely designated "Pupil" or "Student." So Gosset took the pseudonym Student. He continued statistical researches in his spare time, because they were not strictly brewery business. And, in his spare time also, he made himself the trusted friend of E. S. Beaven. Beaven was a self-made man and a rugged individualist who had no patience at all with statistics and statisticians. But Gosset showed himself so genuinely interested in Beaven's work that soon he had Beaven eating out of his hand so far as statistics went (Beaven papers).

Beaven was a maltster at Warminster, Wilts, celebrated for barley breeding, which was his passion. In 1904, when Guinness became interested in the subject, Beaven had become a Commission Maltster for Guinness and, in 1919, he became Guinness' buyer of all imported barley, but he always regarded the barley breeding as his private affair. At that time, he had already selected and bred pure lines of several varieties and, with his friends from the new Cambridge University Agriculture Department, Rowland Biffin and T. B. Wood, he had started to make crosses between varieties in the hope of creating new and better

barleys. They had become keen geneticists and breeders since the rediscovery in 1900 of Mendel's paper on hybridization. In 1904, Guinness sought their advice on the best direction for the barley research in Ireland. In 1907, Gosset came into Beaven's life just in time to help him develop the nursery experiments needed to test several of Beaven's hybrids against each other and against standard varieties. In 1912 and 1913, Gosset even managed to run cooperative experiments with Hunter and Bennett at Ballinacurra, Biffin at Cambridge, and Beaven at Warminster, all testing their own against the others' selected seed. He did the analyses himself and, analyzing always in terms of differences between pairs of neighboring plots, managed to evolve a test of significance for these experiments—an extension of Student's test, producing much the same numerical results as an F test (Beaven papers).

So we arrive at Cambridge in 1912 when R. A. Fisher was introduced to Gosset. Fisher was an undergraduate at Gonville and Caius College, Cambridge, and his tutor was F. J. M. Stratton, the astronomer. Biffin was a Fellow of the same College and had interested Stratton in analyzing a field experiment for T. B. Wood. Gosset had met him in their company. In April 1912, Fisher's first paper was published, "On an Absolute Criterion for Fitting Frequency Curves," in which he introduced the idea of the likelihood function and the method of maximum likelihood but, without the word "likelihood," his presentation was rather confusing. Gosset read it and thought it "A neat but as far as I could understand it, quite unpractical and unserviceable way of looking at things." In June, Fisher sat his final examinations for the mathematics degree. He must then have talked to Stratton about a discrepancy he had found between the formula for standard deviation in his own paper and in Student's. Maximum likelihood gave a denominator n instead of $n - 1$ in this equation. Stratton told him to write to Gosset about it. He wrote to introduce Fisher, and Fisher sent his proof. The rest of the story is given as Gosset wrote of it to Pearson on 12 September 1912 (Pearson, 1968):

> This [proof], Stratton, the tutor, made him send me and with some exertion I mastered it, spotted the fallacy (as I believe) and wrote him a letter showing, I hope, an intelligent interest in the matter and incidentally making a blunder. To this he replied with two foolscap pages covered with mathematics of the deepest dye in which he proved, by using n-dimensions that the formula was, after all, $\sqrt{\sum (x - m)^2/(n - 1)}$ and, of course, exposing my mistake. I couldn't understand his stuff and wrote and said I was going to study it when I had time. I actually took it up to the lakes with me—and lost it! Now he sends this to me [the mathematical proof of Student's distribution]. It seemed to me that if it's all right perhaps you might like to put the proof in a note. It's so nice and mathematical that it might appeal to some people.

And he said, "Would you mind looking at it for me. I don't feel at home in more than three dimensions even if I could understand it otherwise."

That's Gosset for you—his humorous account of a chapter of accidents, his frank inability to deal with stiff mathematics, and his generous appreciation nevertheless of the "nice and mathematical" proof that deserved publication if it was "all right." In contrast, Pearson, who might have understood it, did not choose to publish the note. (Pearson did publish it, however, in 1915, when Fisher included it in his paper on the sampling distribution of the correlation coefficient, again derived by representing the sample in n-dimensional space.)

Let us turn now to Fisher and ask why he should be involved with applied mathematics when it was despised by pure mathematicians. After all, as Stratton wrote on Fisher's behalf when he was looking for a job in 1919, Fisher "could have been a first class mathematician had he stuck to the ropes, but he would not." Why?

Fisher was the seventh child of a fine arts auctioneer in the West End of London. Always brilliant at mathematics, he had won a scholarship in mathematics to Harrow and later to Gonville and Caius College, Cambridge, where he won a first class honors degree in mathematics. Unlike Gosset, he had no contact with experiments or experimenters up to that time. Instead, he had a consuming desire to make himself useful, to serve his country and humankind in a significant, practical way. Pure mathematics, although it may be a source of the greatest intellectual gratification to its professor, is not a subject of immediate practical utility.

Fisher had nearly decided to take biology instead of mathematics at Cambridge, because he could see its importance, and he was seriously interested in evolution and genetics. He was especially interested in human genetics and that brought him at once to statistical considerations because few human characters are dichotomous, being controlled by a single pair of genes like the characters Mendel investigated in garden peas—for example, tall or short plants, green or yellow peas. Variables such as human height, skin color, and intelligence have continuous distributions and must therefore be controlled by multiple pairs of genes. To deal with the populations of genes in human heredity, one must deal with probabilities. One can state what happens only in statistical terms.

It seems that as soon as he felt he could choose, Fisher veered to biological applications of mathematics. Having succeeded in forming the Cambridge

University Eugenics Society during his second undergraduate year, he was chairman of the undergraduate committee in 1911–1912. At the November 1911 meeting he was the speaker on the subject of Mendelism (i.e., genetics) and Biometry (i.e., Pearson's statistical methods of dealing with continuous variables), which he explained, saying both were necessary for human genetic research. He mentioned Maxwell's theory of gases to illustrate the necessity of speaking of gene populations in terms of probabilities. We have noticed that his first paper was on fitting frequency curves. We have seen how quick he was not only to prove Gosset's distribution in 1912 but to realize the importance of determining the sampling distributions of other statistics in common use and to go on to find the sampling distribution of the correlation coefficient in 1915 and a series of other distributions thereafter. As a graduate student at Cambridge in 1912–1913, he chose to study the theory of errors with Stratton and quantum theory with the astronomer, James Jeans.

A very important early paper of Fisher took up a question that had been fought over for a decade: whether, in fact, human inheritance was compatable with Mendelian principles. Biometricians were divided: Pearson said not, and rejected genetics; G. Udny Yule thought it might be compatable but could not prove it; geneticists just *assumed* all inheritance was Mendelian. Fisher brought his mathematical genius to bear on the problem and proved that the inheritance of continuous variables was entirely consistent with Mendelian principles—in fact, that Mendelian principles must result in precisely the numerical relationships that existed. The way he proved it was as important as the result because, in order to deal with intractable sample correlations, he formulated the problem in a different way and introduced the concept of analysis of variance (Fisher, 1918).

Although Fisher's biological interests stimulated him to do these important mathematical researches even while he was a school teacher during World War I, it was after he became the statistician at Rothamsted Experimental Station in 1919 that he really, as he put it, found his feet in research. Papers poured from his hand, many of them containing fundamental new work. Between 1921 and 1926 the number of his publications rose from 13 to 55 papers, and he wrote *Statistical Methods for Research Workers* (1925). Rothamsted is the oldest agricultural research institution in Great Britain. Fisher was presented with data—lots of data from long-term experiments with wheat and roots and grass plots and farm rotations. His first job was to analyze the manurial experiment with wheat on Broadbalk field where the same fertilizers had been applied to the same plots for 67 years. He was asked, could anything more be done with the data than A. D. Hall had done some years before? Besides, there were about a dozen staff when Fisher went there, all busy with research projects.

The activities at Rothamsted, the interests and problems of the staff, the discussions over a cup of tea, the data, all were a great stimulus to Fisher's ingenuity and inventiveness. His papers were all a mix of new developments of statistical theory and practice. There was one big paper "On the Mathematical Foundations of Theoretical Statistics" (1922) but even in that he inserted the first nonlinear experimental design, which he had created for one of his colleagues at Rothamsted. The series of studies in crop variation were ostensibly applied papers. "Studies in Crop Variation I" was "An examination of the yield of dressed grain on Broadbalk" (1921). That contains orthogonal polynomials and the analysis of variance procedure and one or two other statistical innovations. "Studies in Crop Variation II: The manurial response of different potato varieties" (1923) introduces the analysis of variance table with the new z test and its validity is stated to be conditional on randomization of the plot treatments. These ideas are all just slipped in without fanfare. A paper on "The influence of rainfall on the yield of wheat at Rothamsted" (1924) includes a short essay on problems of analysis of meteorological data and the derivation of the null distribution of the multiple correlation coefficient in addition to its advertised content, not to mention the use of what would today be called transfer functions in the analysis. This was conceived as "Studies in Crop Variation III" but the prefix was dropped when the paper became unsuitable for publication in an agricultural journal merely.

When Fisher brought together all this new material in the book *Statistical Methods for Research Workers* (1925), it was not as a development of theory but in terms of methods that experimenters could use in their work, whose principles they could understand, even if the mathematical workings were beyond them. Fisher set forth his philosophy in the preface:

> For several years the author has been working in somewhat intimate cooperation with a number of biological research departments; the present book is in every sense the product of this circumstance. Daily contact with the statistical problems which present themselves to the laboratory worker has stimulated the purely mathematical researches upon which are based the methods here presented. Little experience is sufficient to show that the traditional machinery of statistical processes is wholly unsuited to the needs of practical research. Not only does it take a cannon to shoot a sparrow, but it misses the sparrow! The elaborate mechanism built on the theory of infinitely large samples is not accurate enough for simple laboratory data. Only by

systematically tackling small sample problems on their own merits does it seem possible to apply accurate tests to practical data. Such at least has been the aim of this book.

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