evaluated at $\theta_1 = 0$, $\theta_j = \hat{\theta}_j$ $(j > 1)$, where $\hat{\theta}_j$ are maximum likelihood estimates (more generally, estimates with what Neyman termed 'local root-*n* consistency'), and β_j are the regression coefficients of $\partial L/\partial \theta_1$ on the $\partial L/\partial \theta_j$, as estimated from the second-order derivatives. Neyman's procedures were, however, subsequently examined by P. A. P. Moran [**R17**], who showed that they were asymptotically equivalent to the use of the likelihood ratio test and to tests using maximum likelihood estimators, and noted that they had also previously been discussed by myself [**R2**]. Moran also noted the generalization to the case where the null hypothesis involved more than one parameter e.g. $\theta_1 = \theta_2 = \ldots = \theta_r = 0$ $(1 < r < k)$.

Neyman's wide-ranging contributions to applied fields are referred to elsewhere in this memoir; but within the framework of the general theory of statistical inference it might be added that his avowedly behaviouristic approach to inductive problems [e.g. **I132**] did not inhibit his emphasis on the need for specific stochastic models applicable to the particular problem under investigation. As his interest in applications developed, model-building became an even more important aspect of his researches. At the end of his own review of his illustrious and influential research career he notes [**I160**, p. 162]:

> 'particularly in the more recent decades, the delight I experience in trying to fathom the chance mechanisms of phenomena in the empirical world'.

III. Neyman as astronomer
by Thornton L. Page

I'd like to contribute as much as possible to the Royal Society Memoir on Jerry Neyman. He was a true friend, as well as my statistical mentor. As you may remember, he put me up in his house on Amherst Avenue; then, after I suffered a serious auto accident, arranged for me to spend a quarter doing research and editing several books at Berkeley. I have strong memories of his humour and devotion to work. One evening he joined us for supper in our Berkeley apartment, and I served herring snacks on crackers with 6 o'clock drinks. Jerry said, 'Oh, I like dead fish', and herring snacks have been 'dead fish' to us ever since. When we were working on the statistics of double galaxies, he would often terminate supper with 'It's time to get to *work*', which he pronounced to rhyme with York.

Jerry was intensely Polish. I first got to know him after the I.A.U. Congress in Moscow when we (together with 16 other western astronomers) toured southern Russia, visiting several Soviet observatories. At one point we were taken to a Soviet resort on the Black Sea for swimming and boating. I was swimming while Jerry and several others drank coffee in a small seaside restaurant. When I joined them, in my bathing suit, the Soviet police moved in and arrested me. It seems that there is a strict Soviet law against entering a public restaurant in a bathing suit. Jerry persuaded them that I was just a dumb American, but told me that I must change my clothes then and there under police escort. I was embarrassed as I did this in full view of several lady astronomers, but it satisfied the police.

On another occasion, Neyman showed his understanding of Russians and their language. At each observatory we were given a ceremonial luncheon highlighted by toasts in wine by the hosts 'to our guests from overseas', and by one of us 'to our hospitable hosts'. We took turns making the responses, and in Burakan, Soviet

Armenia, it was the turn of a Canadian astronomer, who ended, 'to our friends, the Russians'. When this was translated, there was a dead silence. Jerry, knowing that the Armenians dislike the northern Russians, jumped up and said 'She means the Armenians'; which led to clapping and laughter.

On statistical problems, Neyman was a perfectionist. Near the end of his life, I crossed swords with him on the question of weather modification by cloud seeding, which I think has been proved by tests in Israel and off the coast of Florida. Jerry insisted that, because the Israelis shifted their time intervals of rain-gauge readings, their results were statistically meaningless. He had earlier shown that western U.S. tests of cloud seeding proved nothing. He doubted the NOAA Florida tests, but did not live long enough to see them completed.

My major scientific association with Jerzy Neyman was in the study of binary galaxies. He and Elizabeth Scott had reviewed counts of galaxies by Shane and Wirtanen showing the clustering of galaxies. My main idea was to measure the average mass of galaxies by their motions in pairs. Because the orbit of one galaxy around another takes millions of years, the only significant data are the measured differences in radial velocity (from Doppler shifts in the spectra) of galaxies in pairs. In 1932, the Swedish astronomer, Erik Holmberg, had proposed that, statistically, such measurements could be used to estimate the combined mass of two galaxies in a pair. I measured radial velocities of 35 pairs of galaxies, and sought Jerzy Neyman's help in analysing them in 1958.

Despite several simplifying assumptions (circular orbits, linear separations of known distribution, random orientation of orbits, negligible error in angular separations, etc.), the statistical problems turned out to be complex. Neyman soon recognised that my measured *differences* in radial velocity, DV, between the two galaxies in a pair had the largest errors, and assumed that DV is a normal random variable. He then helped me through the mathematics, involving integration over two projection angles, to derive a regression between the observed $(DV)^2$, the angular separation, S, and the mean radial velocity, V, allowing for a weighting factor to credit the better observations over less accurate ones. The mean mass obtained from this regression turned out to be different for spiral and elliptical galaxies. These results were presented and discussed at the 4th Berkeley Symposium on Mathematical Statistics and Probability **[III10]**.

Neyman himself greatly enjoyed organising symposia, and was very good at it. He seemed to know personally all the statisticians in the world, and kept in touch with them through the International Statistical Institute. He was quick to recognise new applications of statistics in fields as different as astronomy and meteorology. He strongly encouraged scientists to get more data so as to improve their statistical conclusions. By using radial velocities published by others, I was able to increase my 35 to 66 pairs of galaxies, and my average masses and mass/luminosity ratios were accepted for almost 20 years. Recently, Turner collected data on 156 galaxy pairs, carefully avoiding selection effects, and used different statistics to analyse the data, trying to show that galaxies have large, dark, massive haloes. He has been challenged by Peterson and Rood, using radio as well as optical data. It is fair to say that the statistics of double galaxies are unsettled in 1982!

In 1961, Neyman, Scott, and I organised a Conference on the Instability of Systems of Galaxies, at Santa Barbara, California, just before the I.A.U. meeting in Berkeley. As might have been expected, Jerry exercised his organisational expertise, rounding up 17 prominent astronomers from Russia, Sweden, Germany, Holland, Belgium, the U.S., and Canada to discuss motions in groups of galaxies ranging from

2 to over 1000 members. In preparing a Summary of the Conference (published [1123], along with the 18 separate papers) he used excellent judgement in selecting the major contributions and pointing out the statistical puzzles, many of which remain today. The Summary closes with the admission that "more questions have been raised than settled". That well describes Jerzy Neyman: he raised questions.

BIBLIOGRAPHY

I. *Research papers*

[0] 'Integral of Lebesgue'. (Russian thesis at the University of Kharkov, 1916, not published.)

[2] 'Sur une théorème métrique', *Fundam. Math.*, 5 (1923), 328–330.

[11] 'On the correlation of the mean and the variance', *Biometrika*, 18 (1926), 401–413.

[14] (With E. S. PEARSON) 'On the use and interpretation of certain test criteria for purposes of statistical inference', *Biometrika*, 20-A (1928), 175–240; 263–294.

[33] (With E. S. PEARSON) 'On the problem of the most efficient tests of statistical hypotheses', *Phil. Trans. R. Soc. Lond.* A, 231 (1933), 289–337.

[34] (With E. S. PEARSON) 'The testing of statistical hypotheses in relation to probabilities *a priori*', *Proc. Camb. phil. Soc. math. phys. Sci.*, 29 (1933), 492–510.

[35] 'On the two different aspects of the representative method', *Jl. R. statist. Soc.*, 97 (1934), 558–625. (Spanish version of this paper appeared in *Estadistica, J. Inter-Amer Stat. Inst.*, 17 (1959), 587–651.)

[43] (With K. IWASZKIEWICZ & S. KOŁODZIEJCZYK) 'Statistical problems in agricultural experimentation', *Jl. R. statist. Soc. Suppl.*, 2 (1935), 107–180.

[51] (With E. S. PEARSON) 'Contributions to the theory of testing statistical hypotheses (1) Unbiased critical regions of Type A and Type A_1', *Statist. Res. Mem. Univ. Coll. Lond.*, 1 (1936), 1–37.

[56] 'Outline of a theory of statistical estimation based on the classical theory of probability', *Phil. Trans. R. Soc. Lond.* A, 236 (1937), 333–380.

[69] 'Fiducial argument and the theory of confidence intervals', *Biometrika*, 32 (1941), 128–150.

[76] 'Contribution to the theory of the chi-square test', *Proc. Berkeley Symp. math. Statist. Probab. of 1945* (ed. J. Neyman, Berkeley: University of California Press, 1949), pp. 239–273.

[90] 'Sur une famille de tests asymptotiques des hypothèses statistiques composées', *Trab. Estadistica*, V (1954), 161–168.

[106] 'Optimal asymptotic tests of composite statistical hypotheses', *Probability and statistics* (The Harald Cramér Volume), (ed. U. Grenander, Uppsala, Sweden: Almquist & Wiksells, 1959), pp. 213–234.

[116] 'Silver Jubilee of my dispute with Fisher', *J. Ops. Res. Soc. Japan*, 3 (1961), 145–154.

[123] 'Conference on the instability of systems of galaxies', *Astr. J.N.Y.*, 66 (1961), 533–534; 633–636.

[132] 'Behavioristic points of view on mathematical statistics', *On political economy and econometrics: Essays in Honor of Oskar Lange* (Warsaw: Polish Scientific Publications, 1966), pp. 445–462.

[143] 'R. A. Fisher (1890–1962): An Appreciation', *Science N.Y.*, 156 (1967), 1456–1460.

[160] 'A glance at some of my personal experiences in the process of research', *Scientists at Work* (ed. T. Dalenius, G. Karlsson & S. Malmquist, Uppsala, Sweden: Almquist & Wiksells, 1970), pp. 148–164.

III. *Books and monographs*†

[1] *An Introduction to the theory of Probability* (Polish: Warsaw, 1930).

[5] *First course in probability and statistics*, ix + 350 pages (New York: Henry Holt and Co., 1950).

[6] *Lectures and Conferences on mathematical statistics and probability* (2nd ed.) vii + 274 pages (Washington, D.C.: Graduate School, U.S. Dept. of Agriculture, 1952).

[7] *Proceedings of the Berkeley Symposium on Mathematical Statistics and Probability* (ed. J. Neyman, Berkeley, California: University of California Press, 1949).

[10] *Proceedings of the Fourth Berkeley Symposium on Mathematical Statistics and Probability*, (ed. J. Neyman, Berkeley, California: University of California Press, 1961).
Vol. I *Theory of statistics*, 767 pages.
Vol. II *Probability theory*, 633 pages.
Vol. III *Astronomy, meteorology and physics*, 335 pages.
Vol. IV *Biology and problems of health*, 413 pages.

† Part II is omitted entirely; it will be found in the original version.

[14] *A Selection of Early Statistical Papers of J. Neyman*, 429 pages (Berkeley & Los Angeles: University of California Press, 1967).

[15] *Joint Statistical Papers of J. Neyman and E. S. Pearson*, 299 pages (Cambridge University Press, 1967).

[20] *Heritage of Copernicus: theories "pleasing to the mind"* (ed. J. Neyman, Cambridge MIT Press, 1974), 542 pages.

IV. *Miscellaneous short articles*

[20] Egon S. Pearson (August 11, 1895–June 12, 1980). An Appreciation. *Ann. Statist.*, 9 (1981), 1–2.

REFERENCES

[R1] M. S. BARTLETT, 'The information available in small samples', *Proc. Camb. phil Soc.*, 32 (1936), 560–566.

[R2] M. S. BARTLETT, 'Approximate confidence intervals, II: more than one unknown parameter', *Biometrika*, 40 (1953), 306–317.

[R3] M. S. BARTLETT, 'Egon Sharpe Pearson: 1895–1980', *Biogr. Mem. Fell. R. Soc. Lond.*, 27 (1981), 425–443.

[R4] R. BARTOSZYŃSKI, E. FIDELIS & W. KLONECKI (eds.), 1977 *Proceedings of the Symposium to Honour Jerzy Neyman* (Warsaw: PWN).

[R5] A. S. BESICOVITCH, 'On diagonal values of probability vectors of infinitely many components', *Proc. Camb. phil. Soc.*, 57 (1961), 759–766.

[R6] F. N. DAVID (ed.), *Research papers in statistics: Festschrift for J. Neyman* (New York: John Wiley & Sons, 1966).

[R7] R. A. FISHER, 'On the mathematical foundations of theoretical statistics', *Phil. Trans. R. Soc. Lond.*, A222 (1922), 309–368.

[R8] R. A. FISHER, 'Theory of statistical estimation', *Proc. Camb. phil. Soc.*, 22 (1925), 700–725.

[R9] R. A. FISHER, 'Inverse probability', *Proc. Camb. phil. Soc.*, 26 (1930), 528–535.

[R10] M. GUMOWSKI, *Handbuch der Polnischen Heraldik* (Graz, 1969).

[R11] I. HACKING, *Logic of statistical inference* (Cambridge University Press, 1965).

[R12] H. JEFFREYS, *Scientific inference* (Cambridge University Press, 1931).

[R13] H. JEFFREYS, 'Note on the Behrens–Fisher formula', *Ann. Eugen.*, 10 (1940), 48–51.

[R14] A. N. KOLMOGOROV, *Grundbegriffe der Wahrscheinlichkeitrsrechnung*, Ergebn. Math. II, 3 (Berlin: Springer, 1933).

[R15] L. LE CAM & E. L. LEHMANN, 'J. Neyman, on the occasion of his 80th birthday', *Ann. Statist.* 2, pt. 3 (1974), iv–xiii.

[R16] L. LE CAM, 'Jerzy Neyman', *Intern. Encycl. Social Sci.* (Biogr. Suppl.), 18 (1979), 587–590.

[R17] P. A. P. MORAN, 'On asymptotically optimal tests of composite hypotheses', *Biometrika*, 57 (1970), 47–55.

[R18] J. OSTROWSKI, *Księga Herbowa Rodów polskich* (Warsaw, 1897–1906).

[R19] C. REID, *Neyman–from life* (Berlin: Springer, 1982).

[R20] J. B. RIETSTAP, *Armorial Général* (2nd ed., Gouda, 1884–7).

[R21] H. STUPNICKI, *Herbarz Polski* (Lwow, 1855; this is a lithographic reproduction of an earlier work by Niesiecki).

[R22] The serial publication entitled: *Rocznik Towarzystwa Heraldycznego we Lwowie* (1910–1932).