THE CONTRIBUTIONS OF CHARLES S. PEIRCE TO METROLOGY

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I

METROLOGY is the science of weights and measures: of units of measurement, of standards that embody fundamental units, and of the reduction of quantitative measures. The United States Office of Weights and Measures was a department of the Coast and Geodetic Survey, initially authorized by Congress in 1807 for the Survey of the Coast of the United States, until the Office provided the nucleus of the National Bureau of Standards in 1901. Significant contributions to the progress of Metrology were made by Charles S. Peirce, initially an aid, then Assistant from July 1, 1867, to December 31, 1891, in the Survey.

Charles Sanders Peirce (1839–1914) is best known as a philosopher who founded Pragmatism, and as a logician who contributed to the development of mathematical logic. His *Collected Papers,* principally on philosophy and logic, has been published by the Harvard University Press (1931–1958). But he also contributed to linear algebra, to the mathematical theory of map projections, and to several fields of physical science. He observed solar eclipses with the spectroscope or polariscope, discovered and measured spectral lines of the aurora borealis, investigated photometrically the light from the stars and made a pioneer determination of surfaces of equal star-density, determined the intensity of gravity with a pendulum and developed the theory of this instrument, calculated the ellipticity of the earth from variations of gravity, and contributed to spectroscopy while employing it in the service of metrology. Peirce's principal contributions to Metrology were:

(1) The acquisition for the Coast Survey of a line-meter from the German Imperial Standards Office, to serve as a standard of length for his determinations of gravity with a reversible pendulum.

(2) The comparison of the Low Moor Iron Yard No. 57 with the British Imperial Yards Nos. 1 and 58, in 1883, at the Standards Office, London.

(3) Comparison of the yard and meter from the length of the second's pendulum at Kew Observatory, as determined by Captain Heaviside in inches and by Peirce in meters. Observations on the periods of oscillation, at high and low temperatures, of Peirce Yard and Meter Invariable, Reversible Pendulums, for the comparison of the Yard and Meter.

(4) A pioneer determination of the meter in terms of a wavelength of light, 1877–1879.

(5) Membership in the American Metrological Society, service on its committees, and initiation of a resolution at a meeting, December 30, 1884, that a committee of the society be appointed to address the Secretary of the Treasury, and to memorialize Congress, upon the need to establish an efficient bureau of weights, measures, and physical units.

(6) Direction of the Office of Weights and Measures, from October 1, 1884, to February 22, 1885.

(7) Testimony to the Allison Commission of Congress, January 24, 1885, on behalf of a strengthened office of weights and measures, one empowered to grant certificates for standards that would be valid in courts.

(8) Membership on the Committee on Weights, Measures and Coinage of the National Academy of Sciences.

(9) Appointment by the President of the United States, in 1888, to the Assay Commission for United States Coinage.

(10) Authorship of definitions of terms for weights and measures for the *Century Dictionary.* Authorship of revision of section on units in Mach's *Science of Mechanics,* a translation from the German.

II

The significance of Peirce's work in Metrology can be understood best against a background of

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the history of standards of weights and measures in Europe and America during the nineteenth century.

Colonial America under British rule used weights and measures principally of English origin. The standards employed in the colonies were more or less authentic copies of English standards and had been brought over from England at various times.

On February 10, 1807, President Thomas Jefferson approved an act of the Ninth Congress, Second Session, that authorized and requested the President to cause a survey to be taken of the coasts of the United States.[1] Albert Gallatin, Secretary of the Treasury, on March 25, 1807, addressed a circular letter to scientific men, asking for plans to carry the survey into effect. Ferdinand Rudolph Hassler replied on April 3, 1807. A commission, sitting in Philadelphia, recommended Hassler's plan, and by direction of Jefferson he was so notified under date of July 21, 1807, by Robert Patterson, Director of the Mint in Philadelphia.[2] Execution of the survey was suspended on account of political disturbances in Europe and America, and actually began in 1816.

Hassler was a native of Switzerland who had come to the United States in 1805.[3] In his native land, he had been a student of Johann Georg Tralles, a German from Hamburg, who had been elected Professor of Mathematics, Physics and Chemistry at the Academy in Bern. Tralles and Hassler in 1791 measured a base-line for geodetic purposes in the neighborhood of Aarsburg, a town near Bern. Subsequently, Tralles participated in the establishment of the metric system in France.

In 1790 *L'Assemblée Constituante* of France, upon the initiative of Talleyrand, acted to create a new and uniform system of weights and measures.[4] The deliberations and operations of various committees and commissions led to the decision to create a metric system, and in September, 1798, an international commission was assembled in Paris, to take cognizance of the work done and to fix authentically the standards of the new system. Tralles was the deputy of the Helvetic Republic on this International Commission which in 1799 completed the creation of the Metric System. A platinum bar, constructed so that the distance between the end faces was one ten-millionth of the distance from the North Pole to the Equator, became the metric standard of length and was called the *Mètre des Archives*. A similar platinum bar became the *Mètre du Conservatoire*. When Hassler came to the United States in 1805, he brought with him a copy of the *Mètre des Archives,* a bar of iron that became known in the United States as the "Committee Meter." Hassler described this standard in a memoir published in the *Transactions of the American Philosophical Society:*

> An iron metre standarded at Paris, in 1799, by the Committee of Weights and Measures, composed of members of the National Institute and of deputies from other countries.[5] Its breadth is 1.13 inches, its thickness 0.36 inches, English measure. My friend, Mr. J. G. Tralles, now member of the Academy of Sciences of Berlin, was at that time the deputy of the Helvetic Republic for this purpose; and as may be seen in the account of the operations of this committee, he was the foreign member directing the construction and comparison of the measures of length. He had one metre constructed for himself and one for me, at the same time with all the others, and subjected in all respects to the same processes and comparisons.

Hassler also brought to America a standard kilogram, also a gift from Tralles, and three toises. The toise, slightly less than two meters in length, had been a standard in France and, indeed, furnished a rival to the meter until the last quarter of the nineteenth century.[6] Hassler in 1806 or 1807 sold the standard meter, kilogram, and the three toises to John Vaughan, who on February 20, 1807, read before the American Philosophical Society Hassler's description of these standards, and it was recorded "that he considers the above standards as in the offer of the Society at any future day at the price at which he paid for them." [7] The instruments were loaned to Hassler for comparisons and application in his work as Superintendent of Weights and Measures

[1] *Annals of the Congress of the United States, Ninth Congress,* Second Session (Washington, 1852), p. 1255.

[2] F. R. Hassler, "Papers on Various Subjects connected with the Survey of the Coast of the United States." Communicated 3d March, 1820. *Trans. Amer. Philos. Soc.,* n.s., **2,** 12 (1825) : pp. 232–420.

[3] Florian Cajori, *The Chequered Career of Ferdinand Rudolph Hassler* (Boston, 1929).

[4] G. Bigourdan, *La Système Métrique des Poids et Mesures* (Paris, 1901), p. 4.

[5] *Supra,* note 2 (n. 2), p. 253.

[6] C. S. Peirce defined the word toise in the *Century Dictionary* as follows: "toise. An old measure of length in France, containing 6 French feet, or 1.949 meters, equivalent to 6.395 English feet."

[7] "Early Proceedings of the American Philosophical Society, 1744 to 1838," *Proc. Amer. Philos. Soc.* **22** (1884) : p. 393.

and of the Coast Survey. Indeed, the Committee Meter served as the standard of length for the Coast and Geodetic Survey until 1890.

In preparation for the survey of the coast, Hassler was sent to Europe in 1811 to secure the necessary instruments.[8] A principal instrument maker in London, Edward Troughton, undertook to make many of the required instruments. We shall take notice only of the Troughton scale, a scale of 82 inches subdivided to tenths of inches on a silver inlay in a brass bar about 86 inches long. In 1815 Hassler returned to the United States with the Troughton scale and other instruments for the Survey. On August 3, 1815, he was formally notified by letter from Secretary of the Treasury Dallas of his appointment by President James Madison as Superintendent of the Survey of the Coast. Hassler then began operations to establish baselines, but in 1818 he was relieved as Superintendent after an act of Congress, approved on April 18 of that year, repealed so much of the Act of 1807 as authorized the employment of other persons in the execution of said act, than the persons belonging to the army and navy.

A resolution of the United States Senate, May 29, 1830, directed the Secretary of the Treasury to cause a comparison to be made of the standards of weight and measure used in the several customhouses in the United States. On November 2, 1830, President Andrew Jackson appointed Hassler Superintendent of Weights and Measures. The Secretary of the Treasury, S. D. Ingham, on March 3, 1831, reported to the President of the Senate that the comparison required by the resolution of May 29, 1830, commenced under the immediate superintendence of Hassler, and the Secretary mentioned the Troughton scale as one of the authentic units adopted for the comparison. Hassler's reports were dated January 27, 1832, and June 29, 1832, and are recorded in House of Representatives, 22nd Congress, 1st Session, Document No. 299, "Comparison of Weights and Measures of Length and Capacity reported to the Senate of the United States by the Treasury Department in 1832 and made by Ferd. Rod. Hassler."[9] On August 9, 1832, Hassler was reappointed Superintendent of the Coast Survey by President Jackson.

The interest and competence of Hassler in the subject of weights and measures, and the creation of a joint superintendency of the Coast Survey and of Weights and Measures, impressed a concern for standards upon the Coast Survey throughout its history. In 1817 Hassler compared the Committee Meter, which represented the French standard, with the Troughton scale, which represented the English standard, at various temperatures. In 1831 he again compared these standards. His final result,[10] the average of results obtained in 1817 and 1831, was stated in the form that the Committee Meter was 39.38091714 inches of the Troughton scale, with meter and scale at 32° F.

An Act of Congress, approved June 14, 1836, directed the Secretary of the Treasury to cause a complete set of all the weights and measures adopted as standards, for the use of customhouses, to be delivered to the Governor of each State, "to the end that a uniform standard of weights and measures may be established throughout the United States."[11] L. A. Fischer states in his historical account of United States standards,

> It is evident from the reports of Mr. Hassler that he regarded the English Yard as the real standard of length of the United States and the Troughton scale merely as a copy whose length should be corrected if it was subsequently found to differ from the English Yard, and this view was taken by those who subsequently had charge of our standards.[12]

In fact, the brass scale of 82 inches had been copied from Troughton's own scale without verification by comparison with the English standard.

The Troughton scale was held to be identical with Bird's Standard Yard of 1760, which had been tested and deemed identical with the British Parliamentary Standard of 1758, by Sir George Shuckburgh in 1798; and by Captain Kater in 1821, on the occasion of a determination of weights and measures in England which had been ordered by Parliament in 1814. The new standards were executed in 1825 and were called the Imperial Standards. On October 16, 1834, the Houses of Parliament burned and the British standards were destroyed. New imperial standards were made

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[8] *Supra,* n. 2.

[9] In *Executive Documents* **6**. Printed by Order of the House of Representatives at the First Session of the Twenty-Second Congress. Begun and Held at the City of Washington December 7, 1831 (Washington, 1832), Document No. 299, pp. iv + 122, 4 plates. Also *supra* n. 3.

[10] *Ibid.,* p. 72.

[11] 24th Congress, 1st Session, *Register of Debates in Congress* **12,** 4 (Washington, 1836), Appendix, p. xix.

[12] L. A. Fischer, "History of the Standard Weights and Measures of the United States," *Bulletin of the Bureau of Standards,* **1** 3, (Washington, 1905) : p. 370.

to replace the destroyed ones, and in 1856 two copies of the Imperial Yard were presented to the United States through G. B. Airy, Astronomer Royal. In a letter of transmittal, dated December 21, 1855, Airy described the presented standards as Bronze Yard No. 11, specified as standard at 61.79° F; and Low Moor Iron Yard No. 57, standard at 62.58° F, and similar to No. 58 in the collection of standard yards at the Board of Trade in London.[13]

III

Charles S. Peirce became concerned with standards of length when he undertook to determine the absolute intensity of gravity with a reversible pendulum. Peirce was put in charge of determinations of gravity for the Coast Survey on November 30, 1872.[14] He first conducted observations in 1873 at Massachusetts stations on the times of swing of an invariable pendulum for the determination of relative values of gravity. He received authorization, however, to order from the firm of A. Repsold and Sons, Hamburg, an apparatus with a Bessel reversible pendulum, for the determination of absolute values. Now the determination of absolute values of gravity with a reversible pendulum requires the measurement of periods of oscillation about each of two knife-edges and also the measurement of lengths, such as the distance between the knife-edges. Since a high order of accuracy was sought, the measurement of lengths pertaining to a pendulum required authentic standards of length. The Committee Meter of the Coast Survey was an end-measure; Peirce brought to the United States from Berlin a line-meter for which he claimed high accuracy.[15]

[13] J. E. Hilgard, "Comparison of American and British Standard Yards," *Report of the Superintendent of the United States Coast Survey for the fiscal year ending June 30, 1877* (Washington, 1880), Appendix No. 12, p. 154. Further references to Reports of the Superintendent will be written *Report of the Superintendent, 1877.* Yard No. 11 and Yard No. 57, along with the Troughton scale and the Committee Meter, are exhibited in the Vault at the National Bureau of Standards, Washington, D. C. A photograph of the exhibit is reproduced on a plate in "Weights and Measures Standards of the United States," by Lewis V. Judson, *National Bureau of Standards, Miscellaneous Publication No. 247,* issued October, 1963.

[14] Carolyn Eisele, "Charles S. Peirce, Nineteenth Century Man of Science," *Scripta Mathematica* **24** (1959): pp. 305–324; specific reference, p. 308.

[15] Carolyn Eisele, "The Charles S. Peirce-Simon Newcomb Correspondence," *Proc. Amer. Philos. Soc.* **101** 5 (1957): p. 429.

Peirce was sent to Europe in April, 1875, by the United States Coast Survey, to acquire the Repsold pendulum apparatus, to learn its application, and to determine the intensity of gravity at initial stations in Europe.[16] From the German Imperial Normaleichungsamt (Standards Office), Berlin, of which Professor Förster was the Director, Peirce obtained, and brought to America in August, 1876, a brass normal meter No. 49, for use in his research on gravity. In 1876 the United States Lake Survey acquired from the Repsolds a steel meter scale, the Repsold 1876 Meter, as its standard.[17] Like Meter No. 49, the Repsold 1876 Meter was a line-meter, that is, the standard of length was the distance between two lines engraved on a bar. In Bulletin No. 17 of the Coast and Geodetic Survey, dated October 11, 1889, "The Relation between the Metric Standards of Length of the United States Coast Survey and the United States Lake Survey," C. A. Schott and O. H. Tittmann state,

> It is well known that all results of the Coast and Geodetic Survey relating to lengths are expressed in terms of the Committee Meter, and that certain metric lengths given by the Lake Survey are expressed in terms of the Repsold meter of 1876; also that special use has been made by the Coast and Geodetic Survey of the Berlin Meter No. 49 in observations for the intensity of gravity at various places at home and abroad.[18]

A description of Meter No. 49 was given by Professor Förster in a letter to Peirce, dated March 29, 1878. As translated from the German, he stated,

> No. 49 is a brass bar with a shoulder at each end. The surfaces of these shoulders are in a horizontal plane passing through the axis of the bar. Let into

[16] C. S. Peirce, "Measurements of Gravity at Initial Stations in America and Europe," *Report of the Superintendent,* **1876** (Washington, 1879), Appendix No. 15, pp. 202–337, 410–416.

[17] Lieut. Col. C. B. Comstock, Brevet Brigidier-General, U. S. A., "Report upon the Primary Triangulation of the United States Lake Survey," *Professional Papers of the Corps of Engineers U. S. Army* No. 24 (Washington, 1882), Appendix I, "Additional Data Relative to Metre R 1876," pp. 835–862; Appendix V (February 28, 1885), "Value of Metre R 1876," pp. 923–925, by C. B. Comstock.

[18] C. A. Schott and O. H. Tittmann, "The Relation between the Metric Standards of Length of the United States Coast Survey and the United States Lake Survey," *Coast and Geodetic Survey Bulletin* No. 17 (Washington, 1890), pp. 165–173, specifically p. 165.

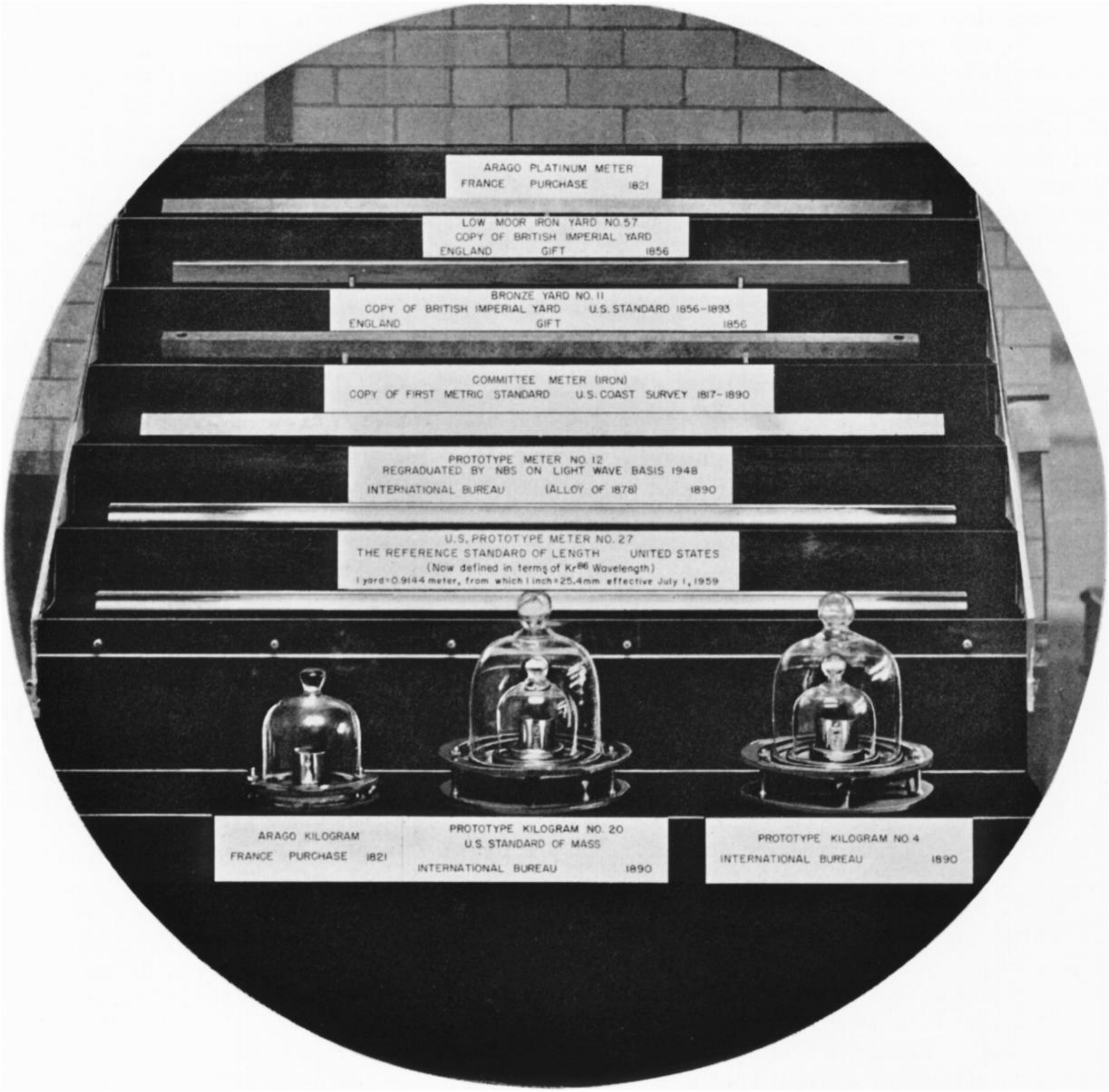

FIG. 1. The Standards Vault at the National Bureau of Standards, Washington, D. C. The case in the illustration contains the historic Committee Meter, Bronze Yard No. 11, and Iron Yard No. 57. The Troughton scale is in a case on the right. Courtesy of the National Bureau of Standards.

the surface of each shoulder is a silver plate having three lines ruled on it.[19]

[19] *Supra,* n. 16, pp. 302–305. Professor Förster wrote four letters to Peirce concerning this meter, letters dated: November 15, 1877, March 29, 1878, June 24, 1878, and November 15, 1880. These letters are in *U. S. Bureau of Weights and Measures* **13** (1840–1889) Length, Weight. National Archives. The discovery of this meter among the many standards preserved at the National Bureau of Standards, Washington, D. C., was made by Mr. Walter W. Weinstein, Records Officer, with the aid of a report from Mr. Larry Chisholm of a record at the Office of Weights and Measures.

Standard No. 49 was carefully compared at different temperatures with standard meter No. 1605 belonging to the German Standards Commission. No. 1605 had been compared repeatedly with a platinum meter belonging to the Commission. The length of the platinum meter was derived from comparisons made in 1860 between it and the Mètre des Archives and the Mètre du Conservatoire. Both these latter meters, constituted of platinum, had been standardized during operations for the establishment of the Metric System. The direct comparisons between the platinum meter and meter No. 1605 were not as accurate as the direct comparisons between the platinum meter and No. 49. Accordingly, Professor Förster gave the results of the comparisons between No. 1605 and No. 49 for future reference, but determined the length of No. 49 from that of the platinum meter. He stated that the length of the platinum meter was not known with sufficient accuracy, in view of the difference in values obtained from comparisons of the platinum meter with the Mètre des Archives and the Mètre du Conservatoire. Since the direct comparison of the platinum meter with the Mètre des Archives was less complete than its indirect comparison through the Mètre du Conservatoire, Professor Förster gave as the length of No. 49 the value derived from the indirect comparison, namely, in millimeters,

$$\text{No. } 49 = 999.9948 + 0.01869\, t,$$

where t is the temperature in degrees Centigrade, a value for No. 49 subject to a much greater uncertainty than is indicated by the probable error of the comparisons utilized, on account of the imperfections of the Paris results.

The Repsold pendulum apparatus included a meter for measuring the distance between the knife-edges. In 1875 and 1877 Peirce made comparisons in Berlin between the United States pendulum meter and the German pendulum meter. The mean of these results showed that the reading of the U. S. pendulum meter exceeded that of the German pendulum meter by 131.6 μ.[20]

One of the problems in the comparison of lengths was the determination of coefficients of expansion, since data were obtained for different temperatures. Peirce, therefore, had to determine the coefficients of expansion of the pendulum and of the meter scales. The pendulum-meter, which was assumed to have the same coefficient as the pendulum, was compared at different temperatures with Meter No. 49. Peirce also had made a meter marked U. S. C. S.-C. S. P.-1878-A, for the purpose of determining the coefficient of expansion of No. 49. Comparisons between Meter No. 49 and Meter A were made at temperatures between 3° and 18° C. The coefficient of No. 49 was checked by comparison at various temperatures with the platinum meter of the German Imperial Normaleichungsamt. The value of the coefficient of No. 49 was given by Peirce as 18.83 μ for 1° C, between 3° and 18° C.[21] It may be noted that Schott and Tittmann, in the previously cited report of 1889, obtained for the coefficient of expansion of No. 49 the value 18.795×10^{-6}, with probable error 0.031×10^{-6}, a value with which Peirce's value was declared to be in "good accord."

The comparison of bars which served as standards of length was carried out on a comparator. A concise description of this instrument, of the form during the period of Peirce's work, may be given by quoting from the definition of the term written by Peirce for the *Century Dictionary*. A comparator is

> an instrument for comparing the lengths of nearly equal bars, either from end to end or between lines engraved on them. The usual optical comparator has two microscopes, firmly attached to a bar or something of the sort, with their focal planes coincident and furnished with filar micrometers, whose screws lie virtually in one right line. There is also a carriage moving at right angles to the screws so as to bring first one bar and then another under the microscope.

The microscopes are focused upon the rulings at the ends of the standard bar, with the cross-hairs in the eyepieces accurately set upon the lines. The small difference is measured by noting the revolutions of the micrometer screws necessary to bring the cross-hairs over the lines. To compare an end measure with a line measure, such as No. 49, contact cylinders were used and considered part of the line measure.

Since the microscopes of comparators were set with screw-micrometers, the evaluation of a revolution of a micrometer was an essential operation. For this purpose, glass scales were used which had been ruled by a ruling machine, in Peirce's time the ruling machine of L. M. Rutherfurd. A fundamental scale was the United States glass decimeter scale of centimeters which was upon a piece of glass 0.29 cm. thick and roughly cut into rectangular shape of 14.3 cm. by 5.3 cm. This scale had been made by J. E. Hilgard, and the different centimeters of the scale were compared together in 1872 by C. A. Schott.[22]

Peirce's historically significant memoir, "Measurements of Gravity at Initial Stations in America and Europe," Appendix No. 15 to the *Report of the Superintendent of the Coast Survey for 1875–76*, contains the records of many measurements

[20] *Supra,* n. 16, p. 305.

[21] *Supra,* n. 16, p. 272. The author is indebted to Mr. Weinstein for the discovery of the Peirce Meters A and B.

[22] *Supra,* n. 16, p. 282.

with comparators. In order to illustrate the meticulous experimental work required to compare bars with respect to length, we shall describe some of the operations.[23] For the measurements in the just cited report, Peirce used glass centimeter No. 1, which had been ruled upon the best ruling-machine of Rutherfurd. This centimeter was on a piece of glass 0.20 cm. thick, 3.5 cm. broad, and 3.6 cm. long. Though used January 16, 1878, it was marked "January 18, 1878, No. 1, 18 329/360 $\frac{1}{2}$ rev." The lines upon the scale were about 2 cm. long and one micron broad. They were filled with black lead and varnished over. The limiting lines of the centimeter were each midway between two bundles of 10 lines each, distant from one another 5/360 rev. of the micrometer screw. The limiting lines were distant 45/360 rev. from the nearest lines of the bundles. The extremities of the limiting lines were marked by crosses roughly cut by hand. The measures were made over a longitudinal line, which was marked by crosses at the two ends.

Peirce compared this glass centimeter No. 1 with the United States glass decimeter scale of centimeters. On January 16, 1878, he superposed the glass centimeter face to face on centimeter 5 to 6 on the upper glass decimeter scale of centimeters. The difference was measured upon a Rutherfurd screw micrometer. Centimeter No. 1 was also compared with the U. S. centimeter 3 to 4. On January 17, measures were made on the same Rutherfurd screw micrometer, using revolutions 55$\frac{1}{2}$ to 150$\frac{1}{2}$, of the U. S. 5 centimeters from 0 to 5, the 5 centimeters from 5 to 10; and there were also made 5 measures of centimeter No. 1, so as to cover the same part of the screw. The conclusion of this meticulous study of the centimeter scale yielded the value 1.0001 cm. for the length of the centimeter. Peirce stated that this centimeter was equal to 6,809$\frac{1}{2}$ teeth of Rutherfurd's machine, and as it was 1/10,000 too long, he concluded that 6,809 teeth made a centimeter at ordinary temperatures, say about 18° C. Peirce stated that from another investigation it had been ascertained that the accidental error of position of a line ruled upon Rutherfurd's machine was only ±0.01 micron; the periodic error differed greatly on different plates, but never amounted nearly to 0.1 micron. He adopted the following values:

1 mm. of 681 teeth	=	1.0002 mm.
1/10 mm. of 68 teeth	=	99.87 micron.
1/100 mm. of 7 teeth	=	10.28 micron.

The U. S. Coast Survey pendulum meter was similar to the German pendulum meter. At one end, the meter began with three lines ruled at distances of tenths of millimeters. At the other end, there was a scale of similar lines. In February, 1878, Peirce compared a part of this scale with a millimeter scale of tenths (No. 3) ruled on Rutherfurd's machine. He found the mean value of the divisions of the glass scale to be 0.995 *r* (revolutions), whence he assumed 1/10 millimeter to be equal to 0.996 *r*. From this result he found values of the spaces between the lines on the brass scale of the pendulum meter. He also made a study January 21, 1878, of the value of the screw revolutions of the upper microscope of the Repsold vertical comparator with which he compared the length of the pendulum (distance between the knife-edges) with his pendulum meter which was suspended alongside the pendulum. The value for one revolution between 1 *r* and 3 *r* was found to be 0.1005 mm. For the lower microscope he obtained the value 0.1004 mm. for one revolution of the micrometer screw.

Peirce's Meter No. 49 was the object of comparison by other metrologists. Professor William A. Rogers, while a member of the staff of the Harvard College Observatory, undertook a critical study of certain standards of length, which had been compared either directly or indirectly with the original standards, i.e., the Imperial Yard at London and the Mètre des Archives at the International Bureau of Weights and Measures.[24] One of the instruments with which he worked was the Tresca Meter, a bar of copper with narrow strips of platinum inserted at each end. The defining lines were traced on the platinum surfaces at 2 A.M., February 6, 1880, by direct comparison with a meter designated No. 19 at the Conservatoire des Arts et Métiers, Paris, by G. Tresca, the son of Professor Tresca of the Conservatoire. Rogers also had a bronze Yard and Meter, made of

[23] The operations are described in the cited memoir (*supra,* n. 16) on pages 286–298. The instrument employed was a filar micrometer.

[24] William A. Rogers: (1) "Communication to F. A. P. Barnard, December 26, 1883," *Proc. Amer. Metrological Soc.* **4** (New York, 1884): pp. 109–116. (2) *Ibid.* **5** (New York, 1885): pp. 33–48. (3) "Studies in Metrology," *Proc. Amer. Acad. Arts and Sciences* **18** (1882–1883): pp. 287–398. (4) "Report to the Pratt and Whitney Co.," *Standards of Length and their Practical Application,* edited by George M. Bond, M. E. (Hartford, Conn., 1887), pp. 1–48.

Baily's metal, of which the Imperial Yard was composed. This standard formed the basis of the units which he undertook to obtain for the gauges of Pratt and Whitney, Hartford, Connecticut. The defining lines of the Yard were obtained indirectly from the Imperial Yard through comparison with Bronze Yard No. 11 of the Coast and Geodetic Survey, January and February, 1881. But during this period Rogers also made comparisons between the Tresca Meter and Meter No. 49. He found that

$$\text{No. } 49 + 11.1\ \mu = \text{Mètre des Archives.}$$

This result was compared with the values of No. 49 given by Professor Förster. We have previously quoted Förster's value for No. 49 obtained through comparison of the platinum meter with the Mètre du Conservatoire. The relation between No. 49 and the Mètre des Archives obtained by this indirect method may be stated by

$$\text{No. } 49 + 5.2\ \mu = \text{Mètre des Archives.}$$

Rogers, however, also used the relation obtained from the less complete comparison of the platinum meter directly with the Mètre des Archives, namely,

$$\text{No. } 49 + 21.4\ \mu = \text{Mètre des Archives.}$$

In stating the above relations the temperature was taken as zero. The average value for the relation between No. 49 and the Mètre des Archives then was

$$\text{No. } 49 + 13.3\ \mu = \text{Mètre des Archives,}$$

a result that did not differ markedly from the value obtained by Rogers from comparison with the Tresca Meter, namely,

$$\text{No. } 49 + 11.1\ \mu = \text{Mètre des Archives.}$$

Schott and Tittmann, in a previously cited publication, also reported a new value for Meter No. 49. The principal purpose of their investigation was to compare the Repsold 1876 Meter, the standard for the Lake Survey, under General C. B. Comstock as Superintendent, with the Committee Meter, the standard for the Coast and Geodetic Survey, in order that the results of the Lake Survey could be tied to the transcontinental survey for the connection of the surveys on the Atlantic and Pacific Coasts. They found the Repsold 1876 Meter to be 98.19 microns longer than the Committee Meter, both at 0° C, with a probable error in length ±0.70 microns. Since Meter No. 49 of Peirce was a secondary standard, they compared it with the Committee Meter and found that

$$\text{No. } 49 = \text{Committee Meter} - 14.18 \pm 0.77 \text{ microns.}$$

The Repsold 1876 Meter had been sent to Paris and in January, 1883, compared with the standard at the International Bureau of Weights and Measures. The result was that the Repsold 1876 Meter was equal to the provisional meter + 97.81 microns, at the temperature of melting ice. In consequence, the Committee Meter was determined to be

$$1 \text{ Meter (provisional)} - 0.38 \pm 0.70 \text{ micron.}$$[25]

In a footnote, written after the National Prototype Meter No. 27 had been brought from France in 1889, to serve as the United States standard of length, Schott and Tittmann state that the value assumed for the provisional metre, $I_2 = 1 + 6\ \mu$, had been confirmed. In view of the assignment of a new value to No. 49, different from the value given preference by Förster, Schott reported in 1895 to F. R. Helmert, Director of the Royal Prussian Geodetic Institute, Potsdam, and Director of the Centralbureau for the International Geodetic Association, that lengths of the second's pendulum, as determined by Peirce with measurements based upon No. 49, had been changed by −9.4 microns.[26] It would appear from this result that Peirce would have been advised to have used the average of the two values for No. 49 given by Förster, instead of the preferred value based on an indirect comparison, through the Mètre du Conservatoire, of the German platinum meter with the Mètre des Archives. Nevertheless on comparing No. 49 with the Repsold 1876 Meter, Peirce's claim that he brought the first accurate line-meter to the United States appears to be justified.

Peirce also made a contribution to the creation of a standard of measurement for micrometry.[27]

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[25] *Supra,* n. 18, p. 173; also *supra,* n. 17, Appendices I and V.

[26] *Verhandlungen der vom 25 September bis 12 October 1895 in Berlin abgehaltenen Elften Allgemeinen Conferenz der Internationale Erdmessung* (Berlin, 1896), Beilage A. I., p. 167.

[27] The documents for this topic are in *Proc. Amer. Soc. Microscopists,* Sixth Annual Meeting, August 7–10, 1883, (Chicago, Illinois) **5**: pp. 178–200. Courtesy of Max H. Fisch.

In 1879 a National Committee on Micrometry was formed under the chairmanship of F. A. P. Barnard. The secretary of the committee, R. H. Ward, reported on "The Standard Micrometer, Scale A, 1882," to the American Society of Microscopists at the annual meeting, August, 1883, in Chicago, Illinois. He reported that the committee had recognized the need to select or prepare a standard micrometer, and

> after much conference and correspondence, it was decided to procure, from a source capable of giving it originally an official character, a new scale as nearly indestructible as possible and of carefully determined value. The U. S. Bureau of Weights and Measures, through the kindness of Prof. J. E. Hilgard, undertook to prepare and authenticate such a standard, . . . and a scale excellently ruled on a platiniridium bar and verified with great care by Prof. C. S. Peirce was placed at the disposal of the committee in August, 1882. A subcommittee on testing this micrometer was appointed on whose behalf Professor William A. Rogers subjected the plate to a prolonged and elaborate study which was not completed until August, 1883.

Professor Hilgard's report stated that the scale was divided into ten millimeters, each division being marked by three lines distant from one another ten microns, and the measurement was to be made from the mean positions of one triplet of lines to that of another. The first millimeter again was divided in the same manner into tenths of millimeters. The first tenth of a millimeter was subdivided into ten spaces of ten microns each. There were thirteen of these lines at the beginning of the centimeter, the first tenth of a millimeter being measured from the mean of the first three to the mean of the eleventh, twelfth, and thirteenth. Professor Hilgard gave the corrections to the different divisions of the Scale A, 1882, at 70 degrees F.

In his study of Centimeter A, Professor Rogers used as the original unit the Tresca Meter and a bronze bar to which the Tresca Meter had been transferred. He also used the data concerning Peirce's Meter No. 49 and compared the bronze meter with No. 49. Professor Rogers concluded that Centimeter A, defined by the middle lines of the terminal bands, required no sensible correction at 62.0° F, and that the second millimeter was exactly one tenth part of the standard unit and required no correction.

The National Committee on Micrometry accepted the plate and unanimously tendered it to the American Society of Microscopists at the Chicago meeting of August, 1883. The Society announced rules for the control of the standard micrometer.

IV

As we have seen, Peirce's first studies in Metrology were of Meter No. 49 and its relation to the fundamental metric standard. He also participated, however, in the investigation of British standards. In order to place his contribution in its historical setting, we shall provide further background.

We have noted earlier that the Troughton scale, the Bronze Yard No. 11, and the Low Moor Iron Yard No. 57 represented the English standard of length in the Office of Weights and Measures of the United States Coast Survey. Since the discussion now will refer to the yard, it will be of interest to mention some steps in the creation of the British Imperial Yard. For this purpose, it is instructive to quote from the definition of the word yard written by Peirce about 1890 for the *Century Dictionary*.

> Yard. The fundamental unit of English long measure. The prototype of the British imperial yard (to which the United States Office of Weights and Measures conforms, though without express authority) was legalized in 1855. It is a bar made of a kind of bronze or gunmetal known as *Baily's metal*. It has a square section of 1 inch on the sides and is 38 inches long. But at 1 inch from each end a well is drilled into one of its surfaces so that the bottom is in the central plane of the bar, and into the bottom of the well is sunk a gold plug, upon whose mat surface is engraved one of the two defining lines. The yard is defined as the distance between these lines at 62° F., with the understanding that the bar is to be supported in a particular manner, and that the thermometers are to be constructed according to certain rules. The lines are designed to be looked at with the microscopes of a comparator; but they are not so free from blur that their middles can be determined more nearly than to a millionth part of the distance between them. This standard was made after the practical destruction of the previous legal prototype, that of 1760, in the burning of the Houses of Parliament, October 16th, 1834, and was legalized as a new prototype because its length agreed with what had been recognized in 1819 by the Standards Commission as the scientific standard yard—namely, with a certain scale, or rather with Captain Kater's measures of that scale, known as Shuckburgh's scale, having been made in 1794 by Troughton for Sir George Shuckburgh, who in his comparisons of it first introduced the comparator with micrometer microscopes. This scale was a copy of another which had been made for the Royal Society in 1742, from which the standard of 1760 was copied. This was a bar having upon one side two gold studs, each with a dot pricked upon it;

and it was used by bringing the points of a beam-compass into these dots, which had thus become badly worn. Older standards still extant are those of Queen Elizabeth and of Henry VII. The latter is shorter than the present yard by one thousandth part of its length, or about 1/27 of an inch. It is said that the yard was made to be the length of Henry I's arm—doubtless a fable, even if believed by that monarch himself.

Peirce's critical account of the yard was based upon first-hand observation, as we shall have occasion to learn presently.

Hassler, who brought the Committee Meter and the Troughton scale to the United States, also determined the length of the Committee Meter in terms of the Troughton scale and therefore in terms of the Yard. He found that the Committee Meter was 39.38091714 inches of the Troughton scale, with meter and scale at 32° Fahrenheit. Alexander Dallas Bache, Superintendent of the Coast Survey from 1843 to 1867, using Hassler's coefficient of expansion as determined from a brass wire, inferred from Hassler's result that the Committee Meter was 39.368505 inches of the Troughton scale at 62° F, and the value 39.3685 inches was used in the Coast Survey from 1851 to 1868. The Committee Meter, as we have already noted, was the standard of length for the Survey from 1817 to 1890; this Meter was sent to France by the United States Government for comparison with the standard platinum meter of the Conservatoire Imperial des Arts et Métiers. A report, dated March 5, 1864, had stated that the Mètre du Conservatoire was 0.00329 millimeter longer than the Mètre des Archives. A comparison of the United States Committee Meter and the Mètre du Conservatoire, on August 24, 1867, by the American physicist F. A. P. Barnard and H. Tresca, yielded the result that the Committee Meter was longer than that of the Conservatoire by 0.00007 mm. The result of the comparison was that the United States Committee Meter was 1.000 00336 meters at the temperature of melting ice, for which comparison the Mètre des Archives was the basic standard.[28]

The metric system was made legal for the United States by approval of an Act of Congress, July 28, 1866. The meter was declared to be 39.37 inches and the kilogram 2.2046 pounds. The iron Committee Meter, and the platinum Arago Kilogram obtained in 1821 by Albert Gallatin, then U. S. Minister to France, were available as standards.

Since the British Imperial Yard as a standard of length for the United States was represented by the Troughton scale and Yards Nos. 11 and 57, it was desirable to make intercomparisons between them. This work of comparison was done by Assistant J. E. Hilgard, with the assistance of J. Homer Lane, H. W. Blair, and O. H. Tittmann of the Coast and Geodetic Survey, between 1876 and 1879. Hilgard was at the time in charge of the Office of Weights and Measures, and had been a United States delegate to the meetings of the international committee which drafted the Metric Convention, signed on May 20, 1875, providing for the establishment of an International Bureau of Weights and Measures in France. In the course of the intercomparisons, Yard No. 11 was sent to Ottawa, Ontario, in May, 1877, for comparison with the copies of the British standards there. Then, in July, 1878, Hilgard took Yard No. 11 to England, and with the help of Mr. H. J. Chaney, Warden of Standards, Board of Trade, London, compared No. 11 with the British Imperial Standards, Yards No. 1 and No. 6. Hilgard's reports, dated July 8, 1879 and July 10, 1880, were published as appendices to the Reports of the Superintendent of the Coast and Geodetic Survey for 1876 and 1877, respectively.[29] Hilgard found that Yard No. 11, initially longer than the British Imperial Standard by 0.000072 inch in 1853, had become shorter by 0.000088 inch, that is, No. 11 had shortened 0.000160 inch, with respect to the British standard, from 1853 to 1878. No. 11 was now equal to the British standard at 62.25° F. Based upon comparison of the Troughton scale with No. 11, Hilgard inferred that at 62° F the Troughton scale was too long by 0.00083 inch and standard at 59.62° F. Hilgard also inferred that No. 11 had become shorter than No. 57 by 0.00025 inch in the twenty-five years.

It has been noted that Bache had derived from Hassler's value of the Committee Meter that it

[28] F. A. P. Barnard and H. Tresca, "Report upon the Comparison of an Iron Meter forwarded to France by the Government of the United States of America," *Report of the Superintendent,* **1867** (Washington, 1869), Appendix No. 7, pp. 134–137.

[29] J. E. Hilgard, "Relation of Lawful standards of Measure of the United States to those of Great Britain and France," *Report of the Superintendent,* **1876** (Washington, 1879), Appendix No. 22, pp. 402–406. J. E. Hilgard, "Comparison of American and British Standard Yards," *Report of the Superintendent,* **1877** (Washington, 1880), Appendix No. 12, pp. 148–181.

was 39.368505 inches of the Troughton scale at 62° F. On the basis of comparisons of the British Imperial Standards with several well-accredited copies of the meter in England, and with the aid of well-determined coefficients of expansion, Lieutenant A. R. Clarke at the Office of the British Ordnance Survey determined the meter to be 39.370432 inches, and after 1868 the value of 39.3704 inches was used by the Coast Survey. Hilgard pointed out that, if one applied to Bache's value of the Committee Meter the corrected Troughton scale, and also used the coefficient of expansion of bronze alloys of which the imperial standards were made, the Committee Meter would be 39.37054 inches, a result that differed little from Clarke's value. If one used for the coefficient of expansion of bronze the value determined by Fizeau, one would obtain the value of 39.37023 inches for the meter.

The difficulties in determining the relation between the meter and the yard were set forth by Peirce in a report to the Superintendent in 1884.[30] The main difficulties were four:

1. To obtain a length known to be equal to a meter.
2. To compare quantities practically incommensurable.
3. To compare two bars, one of which is standard at the freezing point while the other is standard at 62° F.
4. To compare a line-measure with an end-measure. The imperial yards were line-measures, the Mèter des Archives was an end-measure.

As we have seen, Hilgard found that Yard No. 11, original fellow of British Imperial Yards No. 1 and No. 6, had shortened with reference to them in twenty-five years by the amount 0.000160 inch. Comparison of No. 11 with No. 57 showed an even greater shortening of No. 11 with respect to No. 57, so that Iron Yard No. 57 was inferred to have become longer, relative to British Imperial Yard No. 1, by 0.000108 inch, although it was stated that this might have been covered by errors of observation. Hilgard, however, expressed the opinion that the excess of No. 57 might be real. The bronze of the imperial standards, and also of No. 11, was Baily's metal, consisting of 16 parts of copper, 2½ parts of tin, and 1 part of zinc; the British Yards No. 1 and No. 6 might have been shortened by molecular changes in the alloy. Bronze Yard No. 11, however, was the United States Standard for the Yard from 1856 to 1893; Iron Yard No. 57 was a secondary standard.

Hilgard in his report of 1880 stated that Iron Yard No. 57 had been sent to England for direct comparison with the British imperial standards, and especially with its fellow of Low Moor iron, Yard No. 58. On the occasion of a trip to Europe in 1883, Charles S. Peirce carried out such comparisons with the assistance of Mr. H. J. Chaney. The *Report of the Superintendent* for the year ending June 30, 1884, states concerning Peirce:

> In June and July, 1883, he carefully compared the Coast and Geodetic Survey Standard Yard No. 57 with the Imperial Yard No. 1, and also with the Iron Yard No. 58 at the British Standards Office, London.[31]

On July 6, 1883, Peirce reported to Hilgard, now Superintendent of the Coast and Geodetic Survey, that he and Mr. Chaney had made 24 comparisons each of Yard No. 57 with the Imperial Standard No. 1, with temperatures first below 62° F, and then above 62° F. Such comparisons were finished on July 3, but then micrometers were compared, especially the values of the screw revolutions. Comparisons were also made between Yard No. 57 and its fellow No. 58, from July 6 to July 12, 1883. There were twelve sets by Peirce and six by Chaney. The bars were transposed and the temperatures were between 66° F and 68° F. Peirce's results were concordant, but differed markedly from those of Chaney, owing to the peculiarity in ruling of one line. In his report to Hilgard, Peirce stated that his comparisons of No. 57 and No. 58

> are very concordant and make No. 57 almost four divisions of the micrometer shorter. This accords with the comparisons of 1853. But the bisection of one of the lines of No. 57 is a matter of possible doubt, and in my opinion, the yard in the United States ought not to rest upon comparisons of this bar. Either the bar No. 11 should be taken, or better, a new yard should be compared with No. 1 after the completion of the new comparator.[32]

The results of the comparisons of Yard No. 57 with Imperial Yard No. 1, after Peirce had reduced the observations, were reported to the House of Commons by the Board of Trade, Au-

[30] *Report of the Superintendent,* **1884** (Washington, 1885), p. 81.

[31] *Ibid.,* p. 40.

[32] *Assistants' Reports,* U. S. Coast and Geodetic Survey, National Archives (Washington, D. C.).

gust 9, 1883, over the signature of T. H. Farrer.[33] The report stated:

During the past year the Standards Department has had the opportunity of assisting the United States Government in a comparison of their standard of length Yard No. 57 with the Standards of this office. Professor C. S. Peirce, of the United States Coast and Geodetic Survey, came to London for this purpose in June last, on behalf of Professor J. E. Hilgard, who has charge of the Bureau of Weights and Measures at Washington. A large number of comparisons of these measures was made with all possible care, and it was found that at 62° Fahr., Yard No. 57 was 0.000022 inch longer than the Yard No. 1 deposited at this office. The results of these comparisons as calculated by Professor Peirce, will be referred to in a printed memorandum which will be separately drawn up.

It may be added that Professor William A. Rogers in his critical study of standards of length, previously mentioned, reported that Peirce found Yard No. 11 to be 0.000022 inch shorter than the Imperial Yard No. 1, whereas Hilgard had obtained the value 0.000088 inch.[34] Rogers then used the average of the two results, namely, 0.000055 inch, for his own determinations. The result officially reported for Peirce applies, however, to Yard No. 57, and we have not been able to find evidence for Roger's conclusions with respect to Yard No. 11.

Prior to Peirce's comparisons of standards in 1883, the reports of Hilgard had raised questions concerning the permanence of length of the various standards of length in the United States and England. Possible molecular changes in alloys and the effect of variations of temperature had raised doubts of the invariability of length of standards. As we shall see later, Peirce made a pioneer contribution to this problem with the aid of spectroscopic methods.

V

During the years 1881–1882 there were constructed at the Office of the Coast and Geodetic Survey four invariable, reversible pendulums after the original design of Peirce.[35] These pendulums were designated Peirce Nos. 1, 2, 3, 4, and were cylindrical in form with hemispherical ends. The reversibility of a pendulum required that one end be heavier than the other, and in order to attain this asymmetry with respect to weight with the cylindrical form, the compensating weights were placed within the cylinder. The Peirce pendulums were the first pendulums thus constructed, although credit for this innovation has been given to Defforges whose work succeeded that of Peirce. The function of the Peirce pendulums was to carry on research into the intensity of gravity. It was intended that the invariability of length of the pendulum would make possible relative determinations of gravity from times of swing. The reversibility of the pendulum would serve to check occasionally on the invariable property. Experimentation with pendulums served Peirce for other investigations also. The cylindrical form of the Peirce pendulums enabled him to test Stokes' theory of motion of a cylinder in a viscous medium from the rate of decrease of the amplitude of oscillation of a pendulum. In the present discussion, the important fact about the four Peirce pendulums was that Nos. 1, 2, and 4 were meter pendulums, that is, the distance between the knife-edges was one meter, whereas No. 3 was a yard pendulum.

Peirce's views on the use of pendulums for metrological purposes were set forth in the *Report of the Superintendent* for the year ending June 30, 1884. Peirce is quoted as follows:

The ratio of the meter to the yard is still a matter of considerable uncertainty. Kater's value of the meter, 39.3707 inches, is universally regarded as too long. Clarke's 39.3704 inches, though undoubtedly more nearly correct, is not founded upon an examination of sufficiently good meters. The value given by Professor W. A. Rogers, 39.37027 inches, is probably the most correct, but may be in error by one or two thousands of an inch. . . . As the amount in doubt is large as compared with the best measures of the length of the second's pendulum, we may obtain a value of the meter not unworthy of consideration by comparing the value of the second's pendulum at Kew as determined by Captain Heavyside in inches with the same value as determined in terms of the meter by myself. This gives for the meter 39.3700 inches. In order to obtain a better comparison, two reversible pendulums, made on the same pattern, one measuring a yard and the other a meter between the knife-edges, were swung simultaneously, each near its standard temperature at the Coast Survey Office. The pendulums were also interchanged so as to determine at the same time their coefficients of expansion.[36]

[33] *British Sessional Papers,* House of Commons, 27 (1883), p. 854.

[34] *Supra,* n. 24, No. 4, p. 40.

[35] *Report of the Superintendent,* 1882 (Washington, 1883), p. 32.

[36] *Report of the Superintendent,* 1884 (Washington, 1885), p. 81. Letter *y* used in Heaviside's name is incorrect according to the *Great Trigonometrical Survey of India* 5 (Calcutta, 1879).

The records of the Coast Survey show that Peirce swung No. 2, a meter pendulum, and No. 3, the yard pendulum, at high and low temperatures, for the purpose of comparing the meter with the yard, a method of comparison of which he claimed to be the originator. Such experiments were reported by the Superintendent in the annual *Report*,[37] but no results were published.

The final outcome of decades of experimentation with meters and yards was the manufacture and intercomparison of new prototype meters by the International Bureau of Weights and Measures. In 1889, Assistant George Davidson, of the Coast and Geodetic Survey, brought from France National Prototype Meter No. 27 and National Prototype Kilogram No. 20. The seals of the packages were broken and the standards exhibited at Executive Mansion, January 2, 1890, in the presence of President Benjamin Harrison, the Secretary of State, the Secretary of the Treasury, Superintendent Mendenhall, and some invited guests.[38] Meter No. 21 and Kilogramme No. 4 were received from the International Bureau of Weights and Measures in July, 1890.

Superintendent Mendenhall, in Bulletin 17 of the Coast and Geodetic Survey, dated April 5, 1893, stated that "the Office of Weights and Measures, with the approval of the Secretary of the Treasury, will in the future, regard the International Prototype Metre and Kilogramme as fundamental standards, and the customary units, the yard and pound, will be derived therefrom in accordance with the Act of July 28, 1866."

The National Bureau of Standards initially continued the ruling of 1893. In an addendum to Circular No. 572, "Calibration of the Line Standards of Length and Measuring Tapes at the National Bureau of Standards," issued June 4, 1956, it is stated that

> a redefinition of the yard became effective July 1, 1959. The new definition of the yard is
>
> 1 yard = 0.914 4 meter exactly.

In the United States there is an exception at the request of the United States Coast and Geodetic Survey:

> Any data expressed in feet derived from and published as a result of geodetic surveys within the United States will continue to bear the following relationship as defined in 1893: 1 foot = 1200/3937 meter.

The U. S. Survey Foot will be used until geodetic survey networks are readjusted.

The Eleventh General (International) Conference on Weights and Measures adopted a new definition of the meter by the convention that the meter = 1 650 763.73 wave lengths of the orange-red line which results from the $2P_{10}$ $5d_5$ transition of krypton 86. The International Committee of Weights and Measures, has also approved as secondary standards 4 additional transitions in krypton 86, 4 in mercury 198, and 4 in cadmium 114.[39]

VI

We have seen that intercomparisons of standard yards indicated that some, if not all, standards of length had changed with time. The problem was of concern to the European Geodetic Association (Europäische Gradmessung), as well as to scientists in England and America. Peirce's work with standards or scales of length led him to attempt to detect secular changes of metallic bars used as standards. His method was announced to the European Geodetic Association at the third meeting, October 1, 1877, of the Permanent Commission at Stuttgart. As translated from the Proceedings of the Commission, the following is recorded:

> To Mr. Peirce a very suitable means of determining the invariability of lengths appears to consist in referring the unit of length to the length of the light wave. To measure the relation between these intervals and the length of the light wave will be easy, since the lengths of the former or their relations to the millimeter can be obtained in making gratings that in fineness and accuracy leave nothing to be desired.[40]

Peirce's work on the spectrum-meter, although historically important, is represented only by fragmentary publications, and therefore it is useful to quote his statement in a letter to Simon Newcomb, dated June 10, 1899. He said,

> My work of comparing the length of a bar with the mean ruling of a gitter-plate, with a view of obtaining a check on secular changes in the length of bars, has many merits. My measurements of the direction of the ray were more accurate perhaps than any measurements of a large angle ever made. The

[37] *Ibid.*, p. 40.

[38] *Report of the Superintendent,* **1890** (Washington, 1891), Appendix No. 18, pp. 735–758, specifically pp. 750–751.

[39] *National Bureau of Standards Technical News Bulletin* **44** (1960): p. 199; *Physics Today* **17** (1964): p. 101.

[40] *Verhandlungen der vom 26 September bis 3 October 1877 in Stuttgart Vereinigten Permanenten Commission der Europäischen Gradmessung* (Berlin, 1878), p. 40.

peculiar comparator I invented and used enabled me to build up from a double centimeter with a probable error of less than a millionth part, which was quite a feat. True Rowland found a break in my gitter which vitiated my value of the wave length of light. But that does not, I believe, affect my main purpose, as long as the plate can be used again.[41]

The references to Rutherfurd's ruling machine in the present and preceding sections make it appropriate to interpolate a description of this machine which was an important contribution to exact science in America and even in Europe. The ruling machine of L. M. Rutherfurd, of New York, constituted a notable advance over that of the German Nobert, who preserved secrecy regarding his own machine. A brief description of Rutherfurd's machine, as illustrated in the article "Spectrum," by Professor A. M. Mayer, in the American Cyclopedia, second edition (1876), is as follows: The plate of glass or metal to be ruled by the machine was carried on a frame which was made to advance in short successive steps in a direction parallel to the axis of a screw with 48 threads to the inch. The head of this screw was formed by a circular plate the rim of which was notched by 360 equally-spaced teeth. An oscillating lever pressed a pawl against one of the notches of the circular plate and rotated the wheel a definite fraction of its circumference, then lifted the pawl and retracted it for another forward motion on the circular plate. While the screw was advancing the plate carrying the glass or metal to be ruled, the diamond pointed tool was raised and carried forward above the surface of the glass or speculum plate. After the screw ceased its rotation, the diamond point gently fell upon the glass or metal and then retracted and cut a line. The reciprocating action of the tool was caused by the action of the vertical arm of a lever which was attached to the same shaft which carried the lever. The machine was operated by the reciprocating action of a rod on the lever through a crank-pin of a driving wheel revolved by a small turbine.

Rutherfurd ruled gratings on glass and on speculum metal. For the gratings on glass, it was noticed that the right and left spectra of the same order were of different brightness. Peirce, who worked with Rutherfurd, reported in a paper read to the National Academy of Sciences, April, 1879,[42] that examination showed that this characteristic was due to a difference in the sides of the grooves ruled in glass. The diamond ploughing through the surface raised a burr on the side of the furrow, and hence made the two sides of the cut of unequal length. To correct this, the groove was filled with black-lead, the burr polished off, and the black-lead removed. Plates were thereby obtained which gave spectra of the utmost brillance with no difference in brightness.

The speculum metal, on which Rutherfurd also ruled gratings, consisted of 70 per cent copper and 30 per cent tin. The advantage of this material was that it was softer, so that the diamond did not dig into it as much and did not have the same disposition to jump. This made it possible to carry out much finer divisions than otherwise would have been possible. The gratings could be used only in reflection, but as Kayser has pointed out, this was no disadvantage in photography of the ultraviolet, since absorption of radiation by the grating material was thereby avoided.[43] According to determinations by Kurlbaum, most of the Rutherfurd gratings were 43.36148 mm. wide and held 29,521 furrows, that is, 680 per mm.

Peirce published a brief progress report in the *American Journal of Science* in 1879 and stated that the deviation of a spectral line (Van der Willigen's No. 16) had been measured in 1877 and 1879 using a certain grating (340½ lines to the mm.).[44] In a short article in *Nature,* 1881, Peirce gave for the closest-ruled diffraction plates of Rurtherfurd, the mean width of ruling as 68,078 to 68,082 lines to the decimeter at 70° F.[45] He stated that there was a solar line well suited to precise observation and gave the wave length as 5624825, subject to corrections, and proposed it as a standard. Rowland in 1882 invented a ruling engine by which improved gratings were made. He also invented the concave grating and with it determined relative wave lengths of lines in the solar spectrum. On February 14, 1884, Rowland was awarded the Rumford medal by the American Academy of Arts and Sciences. In his response to the address of presentation, Rowland stated, "My map of wave lengths is based upon Professor Charles S. Peirce's measurement of a

[41] *Supra,* n. 15, p. 429.

[42] Reported in *Nature* **20** (1879): p. 99.

[43] H. Kayser, *Handbuch der Spectroscopie* **1** (Leipzig, 1900): p. 403.

[44] C. S. Peirce, "Note on the Progress of Experiments for Comparing a Wave-Length with a Meter," *Amer. Jour. Science,* ser. 3, **18** (July, 1879): p. 51.

[45] C. S. Peirce, "Width of Mr. Rutherfurd's Rulings," *Nature* **24** (1881): p. 262.

line in the green portion of the spectrum."[46] Rowland reported subsequently that the wave length of the solar line adopted by Peirce as standard, and given by Peirce as 5624.825, was corrected by Rowland to be 5624.86, and finally corected by Rowland and Bell for error of ruling and standard of length to 5624.66. The unit in which Rowland stated the foregoing results was the Angstrom unit, equal to 10^{-10} or 1/10,000,000,000 meter.

Records of the Coast and Geodetic Survey indicate that Peirce prepared a report on the spectrum-meter, which was reviewed and praised by Professor Benjamin Peirce, Consulting Geometer to the Survey,[47] but which was not published on account of lack of space. Peirce's method has been described by Michelson and Morley as follows:

> The method involved two distinct measurements, first that of the angular displacement of the image of a slit by a diffraction-grating, and second, that of the distance between the lines of a grating.[48]

Peirce gave his gratings and decimeter scales for use in Rowland's laboratory in Johns Hopkins University. Louis Bell, Fellow in Physics, stated in his paper, "The Absolute Wave-Length of Light," concerning Peirce,

> No full report of his work has as yet been published, though it is evidently very careful, and has already consumed several years. Certain results were communicated to Professor Rowland of this University to serve as a standard of reference for his great map of the solar spectrum now nearly completed; and it was to serve as a check on these results and to furnish a value of the absolute wave-length as nearly as possible commensurate in accuracy with the micrometrical observations, that the experiments detailed in the present paper were undertaken.[49]

Bell stated that grating "H" with which a large part of Peirce's work was done, showed as was suspected, a local error, equivalent to a correction of one part in 55,000. Bell also stated that Peirce used glass decimeters III and IV, standards of length tested on indirect comparison with Meter No. 49, a standard of which the exact length was in doubt. In another article in the *American Journal of Science,* Bell stated:

> At all events it is quite sure that of the wave-length determinations made up to 1880, those of Peirce, and of Angstrom corrected by Thalén, are by all odds the best. Of the two, Peirce's is probably the better by reason of better gratings.[50]

Rowland stated: "The determination of Mr. C. S. Peirce of the U. S. Coast Survey is certainly a very accurate one."[51] Rowland gave the wave length of the D_1 line of sodium, as derived from Peirce's standard, as 5896.27. Correcting for the error in the ruling −.07 gave the result 5896.20 Angstrom units, a result that agreed with the value obtained by Bell. The Rowland Primary Standard for the Solar Spectrum was the D_1 line of sodium, based upon the work of five investigators, including Peirce.[52] The individual values, with weights assigned by Rowland, were as follows:

Investigators	Wave Length	Weight
Angstrom, corrected by Thalén	5895.81	1
Müller and Kempf	5896.25	2
Kurlbaum	5895.90	2
Peirce	5896.20	5
Bell	5896.20	10

The mean was 5896.156 Angstrom units in air at 20° C and 760 mm. pressure. Thus the wave length of the D_1 line of sodium, as derived from the corrected wave length of a spectral line measured by Peirce, was incorporated in Rowland's standard which was accepted for several decades. Michelson and Morley acknowledged Peirce's pioneer efforts by the statement, "The first actual attempt to make the wave length of sodium light a standard was made by Peirce."[53]

A by-product of Peirce's work on the spectrum-meter, and an important contribution for the use of diffraction gratings for purposes of metrology, was his first theoretical explanation of "ghosts" in a spectrum. These ghosts, or false lines, which are repetitions of the principal spectrum, had been pointed out by Quincke in 1872. For the spectrum-meter it was essential to know the influence of these ghosts upon the positions of the true spectral lines. Peirce developed a theory that the ghosts are caused by irregularities in the grating

[46] *Proc. Amer. Acad. of Arts and Sciences* **19** (1884): pp. 482–483.

[47] Benjamin Peirce is quoted in *supra,* n. 14, p. 316.

[48] A. A. Michelson and E. W. Morley, "On a Method of Making the Wave-Length of Sodium Light the Actual and Practical Standard of Length," *Philosophical Magazine,* ser. 5, **24** (1887): p. 463.

[49] Louis Bell, "The Absolute Wave-Length of Light," *Amer. Jour. Science,* ser. 3, **33** (1887): p. 167.

[50] Louis Bell, "The Absolute Wave-Length of Light," *Amer. Jour. Science,* ser. 3, **35** (1888): p. 270.

[51] H. A. Rowland, "On a Table of Standard Wave Lengths of the Spectral Lines," *Mem. Amer. Acad. Arts and Sciences* **12** (Cambridge, 1902): p. 107.

[52] H. A. Rowland, "A New Table of Standard Wave-Lengths," *Astronomy and Astrophysics,* new ser., **12** (1893): pp. 321–347. Reference to Peirce on pp. 321, 340.

[53] *Supra,* n. 48.

and confirmed it by measurements on Rutherfurd gratings. His memoir, "On the Ghosts in Rutherfurd's Diffraction-Spectra," appeared in the *American Journal of Mathematics*.[54] In the previously cited *Handbuch,* Kayser states, "the first theoretical investigation was undertaken by Peirce, who tested and confirmed his theory for a grating of Rutherfurd." [55]

In a paper, "On Concave Gratings for Optical Purposes," Rowland refers to Peirce's theory of ghosts as follows,

> Having recently completed a very successful machine for ruling gratings, my attention was naturally called to the effect of irregularity in the form and position of the lines and the form of the surfaces on the definition of the grating. Mr. C. S. Peirce has recently shown, the *American Journal of Mathematics,* that a periodic error in the ruling produces what have been called ghosts in the spectrum.[56]

Further, Rowland states,

> Professor Peirce has measured some of Mr. Rutherfurd's gratings and found that the space increased in passing along the grating and he also found that the foci of symmetrical spectra were different.

The conjunction of these two results is set forth in Rowland's paper. In his article "Screw" in the ninth edition of the *Encyclopedia Britannica,* Rowland says,

> In making gratings for optical purposes the periodic error must be perfectly eliminated, since the periodic displacement of the lines only one millionth of an inch from their mean position will produce "ghosts" in the spectrum. Indeed, this is the most sensitive method of detecting the existence of this error, and it is practically impossible to mount the most perfect of screws without introducing it.

In his paper, "Gratings in Theory and Practice," Rowland presents a table which shows how a primary line weakens and the ghosts strengthen as the periodic error (in the grating) increases. "Thus one may obtain an estimate of the error from the appearance of the ghost." [57] It would appear that Peirce's theory of ghosts was a factor in the development of improved gratings by Rowland.

VII

Charles Peirce's activity in Metrology is also demonstrated by his activity in the American Metrological Society, which was organized on December 30, 1873, and which published proceedings until 1888 in five volumes. Among the committees of the Society was one on units of force, and the Proceedings for May 19, 1875 record that on February 11, 1875, Charles S. Peirce had been added to the Committee on Units of Force by the President, F. A. P. Barnard.[58] The record of the meeting of the Society, December 29, 1877, at Columbia College, states, "Prof. C. S. Peirce referring to the action previously taken relative to Units of Force, stated what he considered to be the proper form and character of such units." "The Committee on Units of Force and Energy reported progress; and Prof. C. L. Peirce was added to that committee." [59]

Peirce also served on the Society's Committee on Standard Time. At a meeting, May 20, 1879, at Columbia College, the Committee, consisting of Cleveland Abbe, Chairman, E. B. Elliott, H. A. Newton and C. S. Peirce, submitted a report on Standard Time. Under Section V, International Standard of Time, the Committee expressed the opinion that the meridian 180 degrees distant from Greenwich offered a convenient and practical common point of union among the nations. The relations of the meridian to all parts of the world were shown (Appendix V) at a glance by reference to an accompanying chart of the world on the Quincuncial Projections of C. S. Peirce. The proceedings of the meeting state, "A qualified assent to this report is given by Messrs. H. A. Newton and Chas. S. Peirce." [60]

Peirce was especially active at the meeting of the Society on December 30, 1884, at Columbia College. He gave

> a very interesting and detailed description of the pendulum experiments now being carried out by him, to determine the force of gravity at different points in the United States and elsewhere. . . . In answer to Mr. Elliott, Mr. Peirce said that he thought both Clarke's and Roger's meters were too long. . . . By re-

[54] 2 (1879) : pp. 330–347.

[55] *Supra,* n. 43, p. 447.

[56] H. A. Rowland, "On Concave Gratings for Optical Purposes," *Amer. Jour. Science,* ser. 3, **26** (1883) : pp. 87–98. Through the courtesy of Dr. Robert P. Multhauf, Head of the Department of Science and Technology, Smithsonian Institution, the writer has had the opportunity to consult a valuable paper on the present subject, prepared for the Department, by Mr. Michael Aronson: "C. S. Peirce and H. A. Rowland—Two Contributors to the Art of Ruling Diffraction Gratings."

[57] H. A. Rowland, "Gratings in Theory and Practice," *Astronomy and Astrophysics,* n.s., **12** (1893) : p. 144.

[58] *Proc. Amer. Metrological Soc.* **1** (1880) : p. 36. This reference through the courtesy of Professor M. H. Fisch.

[59] *Ibid.,* p. 78.

[60] *Ibid.,* 2 (1880) : p. 29.

quest of the President, Mr. Peirce gave an account of his measures on old Newport Mill or Tower. He said his measures pointed to the use of the old Norse foot. . . . Prof. Peirce inquired of Mr. Burchard (Director of the Mint) whether or not any allowance was made for the different buoyancy of brass (relative to gold) at the mints in Carson and Denver, and those nearer the sea-level. Mr. Burchard said they used the weights furnished by the Office of Weights and Measures without correction.[61]

At the time of this meeting at Columbia College, Peirce was in charge of the Office of Weights and Measures of the Coast and Geodetic Survey. In this capacity he gave to the members of the Society an account of the uncertainties in the Troy and avoirdupois pounds, derived from England, as used in the United States. With respect to the Troy pound of the Mint, Peirce said that the Troy pound of the Philadelphia Mint was hollow, and its specific gravity and consequently its exact mass were unknown. What was certain was that the Troy weights issued by the Office of Weights and Measures did not bear the exact relation to the avoirdupois weights which was legal in England. Peirce said that such a state of confusion was sufficient of itself to prevent the use of the English system in scientific work.[62] At the meeting of December 30, 1884, the following resolution was adopted,

Resolved, that a Committee be appointed to address the Secretary of the Treasury, and to memorialize Congress, upon the need of establishing an efficient bureau of weights, measures and physical units.[63]

The *Proceedings* of the meeting on May 20, 1885, state,

the Secretary called the attention of the Committee to Memorialize Congress to the resolution passed at the last meeting on the suggestion of Prof. C. S. Peirce, of the Coast Survey.[64]

VIII

Peirce was in charge of the Office of Weights and Measures from October 1, 1884, to February 22, 1885, after which time he declined to serve. One of his activities while in charge of the Office was reported by the Superintendent in the *Report* for the fiscal year ending June 30, 1885.

During the winter, under instructions from the Superintendent, Mr. Peirce proceeded to Boston, Providence, Hartford, New York and Philadelphia, and conferred with the manufacturers of gauges and machinery, and also with electricians and others with reference to the resolutions passed by the United States Electrical Conference concerning weights and measures and the best ways of meeting the wants of the country.[65]

During his tenure in charge of the Office of Weights and Measures, Peirce gave testimony to a Joint Commission of Congress, appointed under the chairmanship of Senator William B. Allison, "To Consider the Present Organization of the Signal Service, Geological Survey, Coast and Geodetic Survey, and the Hydrographic Office of the Navy Department. . . ." The hearings were authorized by the Sundry Civil Act, approved July 7, 1884, and continued by the Sundry Civil Act, approved March 3, 1885. Peirce testified before the Commission on January 24, 1885.[66] In conformity with the resolution of the American Metrological Society of December 30, 1884, Peirce spoke in favor of strengthening the Office of Weights and Measures. To that end, he proposed that the Office should be empowered to grant certificates for weights and measures that would be valid in the courts. As an illustration of the uncertain state of weights and measures in the United States, he said of the Troy pound of the Mint, the standard of United States Coinage, and made by Captain Kater, which was obtained in 1827 when Gallatin was Minister to Great Britain, "it is a weight which now would be deemed badly made, because their buoyancy cannot be accurately ascertained. The Mint pound was not weighed in vacuo by Captain Kater and it never has ben weighed since." Peirce stated that the British pound was one made in 1855 and that there was no doubt about the relations of our pound to the pound in England. But we did not know the Troy pound in relation to the British pound. Peirce also discussed the relative advantages of the metric and English systems of weights and measures. He said that the yard was the distance between two lines at 62° F, whereas the meter was the distance between the ends of a bar at the freezing point of water, and thus comparison was rendered more difficult in the case of the meter.

Peirce's proposal for a National Bureau of Standards, as expressed by the resolution of the American Metrological Society, and as implied by his testimony to the Allison Commission, had to

[61] *Ibid.*, **5** (1885): p. 46.
[62] *Ibid.*, p. 47.
[63] *Ibid.*, p. 48.
[64] *Ibid.*, p. 83.

[65] *Report of the Superintendent,* **1885** (Washington, 1886), p. 38.

wait many years for its realization. In Germany there was established in 1887 a Physikalische-Technische Reichsanstalt, and in England there was founded in 1899 the National Physical Laboratory. Finally, on April 18, 1900, Lyman J. Gage, Secretary of the Treasury, proposed to Congress the establishment of a National Standardizing Bureau, in order to free the United States from dependence upon European nations for standardizing work. The Hearings before the Senate Committee on Commerce during the second session of the 56th Congress, December 28, 1900, brought forth many resolutions of support from Scientific men, Universities, and Professional Societies.[67] The supporting documents of earliest date were two; a resolution of the Electrical Conference at Philadelphia, September 11, 1884, and the resolution of the American Metrological Society of December 30, 1884, which had been suggested by Charles S. Peirce.

In view of his experience in Metrology, Peirce was appointed to the Committee on Weights, Measures, and Coinage of the National Academy of Sciences, upon his election to the Academy during the meeting of April 17–20, 1877.[68]

Further evidence of his standing in the field was his appointment by President Grover Cleveland, January 9, 1888, to the Assay Commission for United States Coinage. An Assay Commission was appointed every year to examine and test the fineness and weight of coins reserved by the several mints during the previous year. As required by law, the Commission for the year 1888 met the second Wednesday of February, 1888, the eighth, at the Mint in Philadelphia, and in the presence of the Director of that Mint proceded to test the fineness and weight of gold and silver coins reserved during the calendar year 1887 at the mints in Philadelphia, San Francisco, and New Orleans.[69]

Additional recognition came to Peirce by his selection to write the definitions of terms for weights and measures for the *Century Dictionary*, first copyright 1889. For the English translation of the book by Ernst Mach, *Die Mechanik in ihrer Entwickelung* (1883), Peirce rewrote the section on units and measures so that it would be suited to English speaking readers of the *Science of Mechanics* (1893).

IX

In the present paper we have set forth the development of weights and measures in the United States during the nineteenth century, as background for an account of the contributions of Charles S. Peirce. He played his role as a member of the United States Coast and Geodetic Survey, which during that century included the Office of Weights and Measures. When Peirce joined the Coast Survey in 1861, it was perhaps the principal institution in the United States for research in the physical sciences. Peirce's role can be understood only in relation to that of his coworkers in the Survey, men such as Hassler, Bache, Hilgard, and others. The painstaking efforts on the part of these pioneer scientists to create authentic standards of measure laid the foundations for the quantitative development of American science.

66 Testimony before the Allison Commission appointed, "To Consider the Present Organization of the Signal Service, . . ." Senate Miscellaneous Documents, No. 82, Forty-Ninth Congress, First Session (Washington, 1886), pp. 370–378.

67 Hearing before the Subcommitte of the Committee on Commerce. U. S. Senate, Fifty-Sixth Congress, Second Session, December 28, 1900. Senate Document No. 70, pp. 1–57; specifically p. 37.

68 *Proc. National Acad. of Sciences,* Part 2, 1 (1877): p. 125.

69 *Report of the Director of the Mint, for the Fiscal Year ended June 30, 1888* (Washington, 1888), pp. 53–54.