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The Divided Bridge, Due Tension, and Rational Striking Point in Early English Grand Pianos

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Introduction

A DECISIVE EVENT IN THE HISTORY OF THE PIANO occurred in England about 1790. Previously, piano bridges, like the 8′ bridges of harpsichords, formed a smooth curve, continuous from bass to treble (see fig. 1, showing an instrument by Robert Stodart, the principal British maker of grand pianos from the late 1770s to the late 1780s). After that time the builders of English grand pianos divided their bridges into separate bass and treble sections, usually between G♯ and A in the bass octave, such that the vibrating string length of G♯, though sounding a lower note, was shorter than that of A (see fig. 2).[1] The division of the

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1. The divided bridge was first devised by John Broadwood, with whom Robert Stodart had worked during the early 1770s. It was soon adopted by other British piano makers, such as Matthew and William Stodart (Robert's nephews and his business successors after about 1792), makers of the instrument shown in fig. 2.

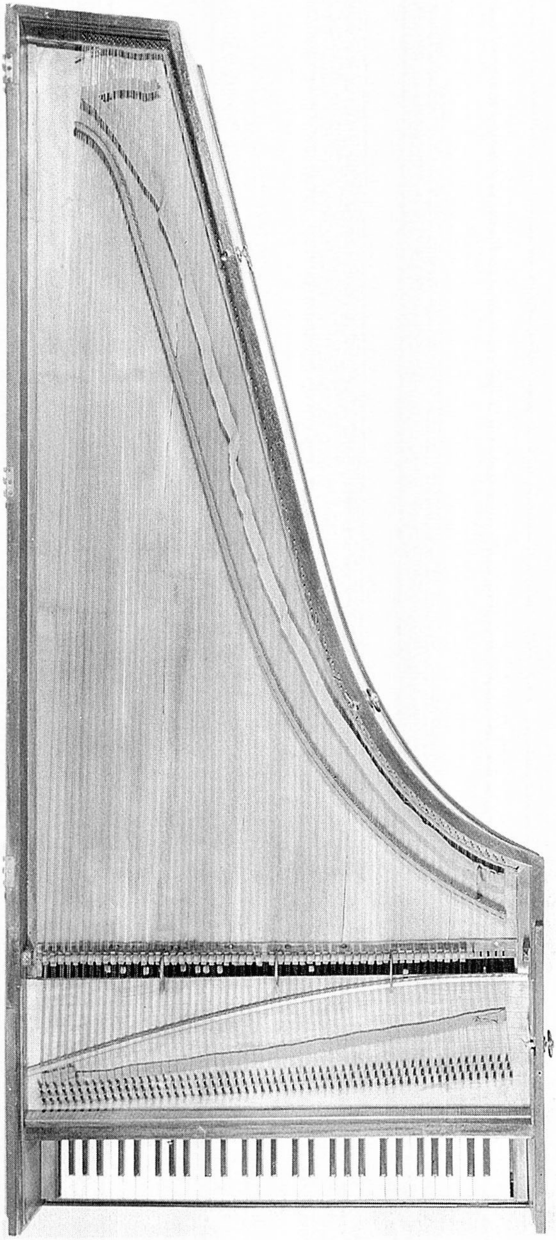

FIGURE 1. Grand piano by Robert Stodart & Co., London, 1790. Smithsonian Institution, Washington, D.C. (cat. no. 303,526).

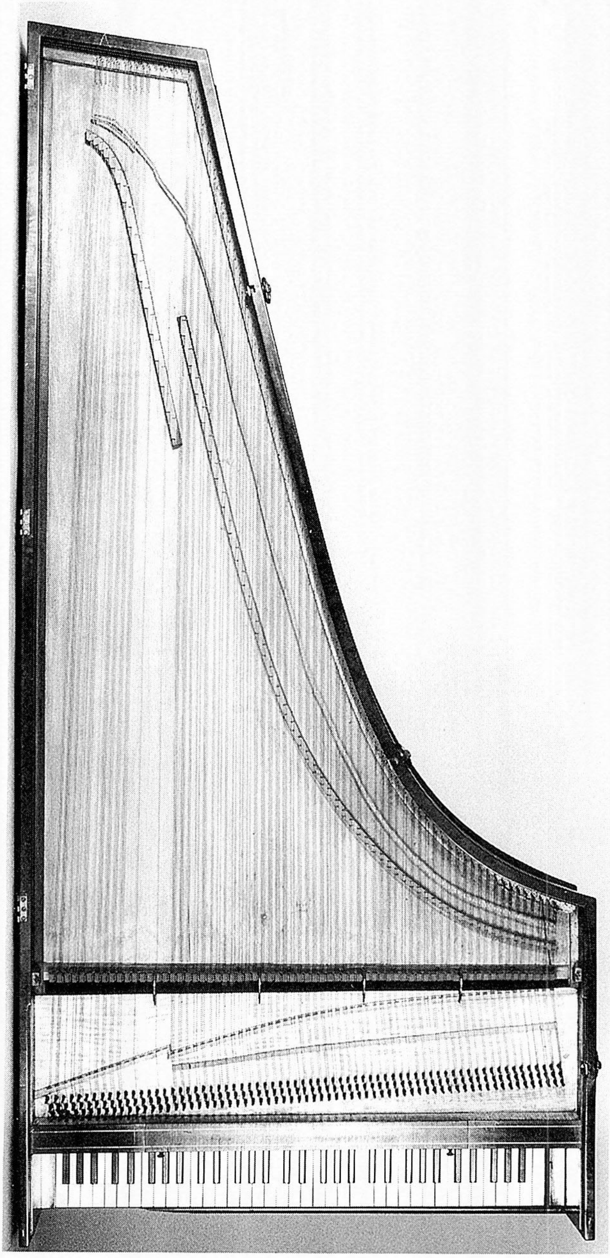

FIGURE 2. Grand piano by Matthew and William Stodart, London, 1795. The Shrine to Music Museum, Vermillion, South Dakota (cat. no. 5281; Rawlins Fund, 1992). Photo: Simon R. H. Spicer.

bridge occurred in the same place as the crossover from iron strings in the upper part of the compass to brass strings in the bass.[2]

Most treatises on piano building written after the instrument assumed its modern form in the 1860s specify three principles as important factors of good design. First, the tension of the strings should be as close to equal as practicable throughout the compass. Second, the points at which the strings are struck by the hammers should, thoughout much of the compass, be placed according to a certain constant ratio of the string lengths (except in the extreme treble). And third, the bridge should be divided so that the bass strings pass over a section separate from that for the treble strings.[3] Histories of the piano commonly treat the introduction of the divided bridge by John Broadwood in the late eighteenth century as if the third principle were so closely related to the first and second that all of them were developed simultaneously.[4]

The theoretical basis for the supposed desirability of specific striking-point ratios was not established until 1800, when use of the divided bridge was already well established in English piano making. Although Broadwood seems to have experimented with the concept of a rational striking point during the early years of the nineteenth century, these efforts were evidently soon abandoned, not to be revived by piano makers until the middle of the century. The history of equal tension is similarly discontinuous. Although harpsichords had long been made without major differences in tension from note to note, this practice

2. Throughout this article, the term "brass" will, unless otherwise noted, mean "yellow brass," i.e., the normally used brass containing about 70% copper and 30% zinc. ("Red brass" is approximately 90% copper and 10% zinc.) Although eighteenth-century writers refer to their ferrous strings as "steel," modern metallurgical analysis has established that eighteenth-century "steel" music wire was, in fact, iron. See Martha Goodway and Jay Scott Odell, *The Metallurgy of 17th- and 18th-Century Music Wire,* The Historical Harpsichord, vol. 2 (Stuyvesant, NY: Pendragon Press, 1987), 27.

3. Regarding equality of tension and rational striking point, see, for example, Siegfried Hansing, *The Pianoforte and Its Acoustic Properties,* 2nd rev. ed., translated by Emmy Hansing-Perzina (Schwerin: The Author, 1904), 83 and 159; William B. White, *Theory and Practice of Pianoforte Building* (New York: Edward Lyman Bill, 1906), 35 and 54; and S. Wolfenden, *A Treatise on the Art of Pianoforte Construction* (Hayes, Middlesex: The Author, 1916), 19 ff. and 51. To the authors of these works, the division of the bridge, present in all their designs, seems to have been so standard and obvious a feature that they did not explicitly allude to its necessity.

4. See, for example, Derek Adlam and William J. Conner, "Pianoforte" (§ I, 4: England and France to 1800), *The New Grove Dictionary of Musical Instruments,* edited by Stanley Sadie (London: Macmillan, 1984), 3:81.

was abandoned in pianos with divided bridges. Equality of tension was not widely accepted as a principle of piano making until the late nineteenth century.

Two nineteenth-century accounts contain the sum of what historians of the piano have known about the invention of the divided bridge.[5] One of these explicitly links the new form of the bridge to the introduction of equalized tension and rational striking points. After reevaluating the accuracy of these brief reports, the present article will clarify the history of important aspects of piano scaling and design through an examination of historical pianos themselves as well as an investigation of the early scientific literature. Among the latter sources is a previously unknown eighteenth-century manuscript written by John Dovaston, an obscure country gentleman with musical and scientific interests. Careful interpretation of the evidence will show that the bridge was divided for reasons unrelated to striking point or equalized tension: indeed, the tension was made decidedly unequal. Examination of later instruments further suggests that the scaling techniques devised by Broadwood and his scientific advisors survived into modern piano making.

Most writers have credited pupils of the Saxon instrument maker Gottfried Silbermann with founding the English piano industry.[6] Thus, the eventual division of the bridge by British makers would be regarded as the solution to a problem (to be explained below) originating in Silbermann's use of iron strings in the treble and brass strings in the

5. *Some Notes Made by J. S. Broadwood, 1838, with Observations & Elucidations by H. F. Broadwood, 1862* (London, 1862), 12–13; and A. J. Hipkins, quoted by Alexander J. Ellis in his translation and edition of Hermann L. F. Helmholtz, *On the Sensations of Tone as a Psychological Basis for the Theory of Music,* 2nd English ed. (London, 1885; facs. reprint, New York: Dover Publications, 1954), 77. Raymond Russell, in *The Harpsichord and Clavichord, an Introductory Study* (London: Faber and Faber, 1959), 81, vaguely refers to "MS notes in the possession of Messrs. Broadwood" that discuss the subjects of equalized tension and rational striking point, but David Wainwright, author of *Broadwood by Appointment: A History* (London: Quiller Press, 1982), a work based on extensive research in the Broadwood archives, has informed me in a private communication that he knows of no eighteenth-century Broadwood documents referring to these subjects or to the divided bridge. Wainwright suggests that Russell might have been referring to a notebook which Wainwright concluded had been compiled by Hipkins, although he cannot now recall any reference in it to these subjects. Alternatively, it seems possible that Russell was referring misleadingly to J. S. Broadwood's notes published in 1862.

6. See, for example, David Wainwright, *The Piano Makers* (London: Hutchinson & Co., 1975), 30–31; and Edwin M. Good, *Giraffes, Black Dragons, and Other Pianos* (Stanford, California: Stanford University Press, 1982), 63.

bass of his grand pianos. A remark in the Dovaston manuscript, however, suggests that the earliest English grand pianos were strung entirely in brass. This, as well as certain other technical details of extant instruments and the lack of historical sources linking any British maker with Silbermann, can be taken as allowing the possibility that the English design stemmed from pianos made by the Italian or Iberian followers of Bartolomeo Cristofori. Thus, although the English makers' subsequent adoption of iron treble stringing, which soon led to the division of the bridge, resembled Silbermann's earlier practice, it might well have been an independent development.

Two Nineteenth-Century Accounts

The recollections of James Shudi Broadwood (1772–1851), made in 1838 and published by his son Henry Fowler Broadwood in 1862, contain the earlier of two previously known nineteenth-century accounts of the invention of the divided bridge.

> John Broadwood . . . through the patronage of his friend *Muzio Clementi,* who was continually pointing out the defects of his instruments, and ever stimulating him to avail himself of the assistance of his scientific friends, . . . obtained the assistance, amongst others, of [Tiberius] Cavallo (well known by his Treatise on Acoustics and other works), who calculated, from the monochord, the length and due tension of the strings, a paper on which he afterwards read to the Royal Society—and the valuable services of Dr. [Edward Whitaker] Gray, late of the British Museum, who, by his experiments, established the due proportions in the gravity and vibration of the brass and steel strings, and thereby led to the division of the bridges on the sounding-boards of Grand Pianos. When John Broadwood succeeded in establishing his reputation as a maker of these instruments, the improvements, suggested by Signor Cavallo and Dr. Gray, were adopted by all makers—a proof of their value.[7]

J. S. Broadwood, son of John Broadwood, started working in the family business in 1785 and would have been present when the divided bridge was introduced.[8] Although his comments date from about fifty years after the events and were made only fleetingly, in the context of a twelve-page history of English stringed-keyboard instruments, there is

7. *Some Notes Made by J. S. Broadwood,* 12–13.

8. Biographical details about the Broadwoods are provided in Wainwright, *Broadwood by Appointment.*

no reason to doubt his basic claim that the division of the bridge had something to do with the tension and length of brass and iron strings and that John Broadwood received assistance from a number of scientists, two of whom are named. It can be confirmed that there was indeed a professional and personal connection between Clementi and the Broadwoods; that Clementi, in later years when he was a manufacturer himself, urged his employees to improve the firm's pianos; and that Gray and "Carvalo" were customers of Broadwood in the 1780s.[9] Even J. S. Broadwood's assertion that "the improvements . . . were adopted by all makers" is not merely the idle boast of a proud son. Among the early London piano makers there seems generally to have been close cooperation, or at least unfettered copying of the most useful innovations, which often were not patented. Just as most makers of English grand pianos used virtually identical actions, extant instruments such as the Stodart in fig. 2 show that the divided bridge and associated concepts of stringing and scaling were almost immediately applied by other makers in a manner virtually identical to Broadwood's.

In contrast to James Shudi Broadwood's recollections which mention only factors such as string material, length, and tension, and say nothing at all about the point at which the hammers strike the strings, modern histories of the piano usually associate the division of the bridge with adoption of a rational striking point.[10] These accounts stem directly or indirectly from the work of Alfred James Hipkins (1826–1903), who wrote:

> John Broadwood, about the year 1788, was the first to try to equalise the scale in tension and striking place. He called in scientific aid, and assisted by Signor Cavallo and the then Dr. Gray of the British Museum, he produced a divided belly [i.e., soundboard[11]] bridge, which shortening the too great

9. Ibid., 58–59, 62, 65, and 72. Regarding "Carvalo," it should be noted that names were often spelled phonetically in early Broadwood records. Michael Cole has suggested to me that J. S. Broadwood's wording of "his scientific friends" might well refer to Clementi's friends rather than Broadwood's. A contemporary source (quoted in Leon Plantinga, *Clementi: His Life and Music* [London: Oxford University Press, 1977], 155) refers to Clementi's dedication "to the mechanical and philosophical [i.e., scientific] improvement of piano fortes," and Plantinga's biography repeatedly attests to Clementi's intellectual interests.

10. See Rosamund E. M. Harding, *The Piano-Forte: Its History Traced to the Great Exhibition of 1851* (Cambridge: Cambridge University Press, 1933), 66; Wainwright, *Broadwood by Appointment,* 72; and Adlam and Conner, "Pianoforte," 3:81.

11. Robert S. Winter, in "Striking It Rich: The Significance of Striking Points in the Evolution of the Romantic Piano," *Journal of Musicology* 6 (1988), 272, quoting Hipkins, incorrectly states that the "belly bridge" is the nut. "Belly" was the traditional English

> length of the bass strings, permitted the establishment of a striking place, which, in intention, should be proportionate to the length of the string throughout. He practically adopted a ninth of the vibrating length of the string for his striking place, allowing some latitude in the treble. This division of the belly-bridge became universally adopted, and with it an approximately rational striking place.[12]

Although Hipkins evidently wrote this passage shortly before its publication in 1885, its validity as history cannot be dismissed solely on account of its late date. Because Hipkins, a distinguished early historian of the piano, had worked at the Broadwood firm since 1840, his information might well have come directly from J. S. Broadwood, who would have had no compelling reason to include such technical details in his own historical sketch of 1838.[13]

Nevertheless, it is evident that Hipkins was mistaken, both historically and conceptually. Contrary to his statement that the bass strings

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term for the soundboard, and Hipkins elsewhere, as in his *A Description and History of the Pianoforte and of the Older Keyboard Stringed Instruments,* 3rd ed. (London: Novello, 1929; facs. reprint, with an introduction by Edwin M. Ripin, Detroit: Information Coordinators, 1975), 24 and 27, uses the terms "wrest-plank bridge" for the nut and "belly-bridge" for the soundboard bridge.

12. Quoted, as a private communication from Hipkins, by Ellis in his 1885 edition of Helmholtz, *Sensations of Tone,* 77. An earlier version of Hipkins's text is in his "Observations on the Harmonics of a String struck at one-eighth of its Length," *Proceedings of the Royal Society* 37, no. 234 (1884): 366. (Ellis read this paper to the Royal Society on Hipkins's behalf.) It is significant that this version differs in some slight details from the text later published by Ellis: the division of the bridge is here said to have occurred "in 1788" (not "about the year 1788"); the word "practically" is absent; and Broadwood exercised "much latitude in the treble" (not "some latitude"). A few sentences about the division of the bridge are also in Hipkins's article "Pianoforte" in *A Dictionary of Music and Musicians,* 1st ed., edited by Sir George Grove (London, 1877–1889), vol. 2 (issued in 1880). Here (on pp. 717 and 723) Hipkins says nothing about striking points and adduces only circumstantial (and, in hindsight, unpersuasive) evidence for dating the event to about 1788. Another brief treatment of the subject is in Hipkins's article "Pianoforte" in *The Encyclopaedia Britannica,* 9th ed., edited by T. S. Baynes and William Robertson Smith (Edinburgh, 1875–1889), vol. 19 (issued in 1885, according to Michael Cole, whom I thank for sending me a photocopy of the relevant page 74). Here 1788 is mentioned only as the date of Cavallo's article, which is misleadingly said to contain "calculations of the tension." The variations in Hipkins's several accounts written nearly simultaneously suggest that he did not have as firm a grasp on the facts as might be supposed if only one of these is read without reference to the others. Later historians of the piano have taken Hipkins's date of 1788 as gospel. The nearest that I can come to confirming it is to note that I have seen a Broadwood grand piano of 1787 with an undivided bridge and one of 1792 with a divided bridge.

13. Biographical information about Hipkins is found in Ripin's introduction to Hipkins, *Description and History of the Pianoforte.*

were too long before Broadwood's innovations, extant instruments show that early English grand pianos without divided bridges have bass strings about the same length as, or sometimes even shorter than, the strings of later English pianos with divided bridges (see Table 1). Further, even with an undivided bridge it would be perfectly possible to adopt a striking-point ratio consistent throughout the compass. The piano designer need only put, say, one-ninth of the chosen length of each string in front of the straight line of hammer heads and eight-ninths behind, place the nut and bridge accordingly, and draw a suitable case outline around these. Indeed, it is more difficult to equalize the striking point when the bridge is divided: in order for the top brass and lowest iron strings to be struck at the same ratio of their respective lengths, the nut must also be divided so that the nut pins for the top brass-strung note are closer to the hammer heads than the nut pins for the lowest iron-strung note.

Lastly, as Robert S. Winter has noted, Hipkins was wrong in that measurements of historical pianos bear out neither the adoption of a strike ratio of one-ninth nor even a consistent ratio throughout the compass.[14] Although Winter provided information from only two English pianos, both from the nineteenth century, his conclusions are largely confirmed by further striking-point data that I have collected, for example, from two Broadwood pianos of the 1790s, made only a few years after the introduction of the divided bridge. In Table 2 these are compared with three earlier grand pianos with undivided bridges. (Ratios are given as the string length divided by the distance from the nut to the striking point. Thus, for example, a ratio of 9.0 indicates a striking point of one ninth.) It is apparent that the striking-point ratios of instruments with divided bridges are at least as variable throughout the compass as those in earlier instruments. The only evidence that makers of instruments with divided bridges were concerned with maintaining a somewhat consistent striking point is their division of the nut between G♯ and A. Just as the A strings are longer than the G♯ strings, the striking-point distance is longer at A than at G♯. Even so, the striking point ratios of the two notes are not nearly equal, and, in fact, are more unequal than in instruments with undivided bridges and nuts. Thus, the instruments show that Hipkins's account of a rational striking point as the reason for the development of the divided bridge is not credible.

14. Winter, "Striking It Rich," 283–84.

TABLE 1. Bass string lengths of typical early English grand pianos

Maker	Date	Location	Bridge	Length of FF Strings in mm
A. Backers	1772	Russell Collection, Edinburgh	Undivided	1741
R. Stodart	1784	Heaton Hall, Manchester (data from M. Cole)	Undivided	1712
Broadwood (serial no. 69)	1787	Private Collection, England (data from M. Latcham)	Undivided	1709
R. Stodart	1790	Smithsonian Institution, Washington, D.C. (data from M. O'Brien & E. McCullough)	Undivided	1706
Broadwood	1792	Metropolitan Museum of Art, New York	Divided	1725
M. & Wm. Stodart	1795	Shrine to Music Museum, Vermillion, South Dakota	Divided	1743
Broadwood	1796	Museum of Fine Arts, Boston	Divided	1872

Table 2. String Lengths in mm (L), Striking Points in mm (S), and Ratios (L/S) of Five English Grand Pianos

	R. Stodart, 1784 Undivided Bridge			J. Broadwood, 1787 (serial no. 69) Undivided Bridge			R. Stodart, 1790 Undivided Bridge			J. Broadwood, 1792 Divided Bridge			J. Broadwood & Son, 1796 Divided Bridge		
Note	L	S	**L/S**	L	S	**L/S**	L	S	**L/S**	L	S	**L/S**	L	S	**L/S**
c^4	—	—	—	—	—	—	—	—	—	—	—	—	74	7	**10.6**
f^3	104	8	**13.0**	104	10	**10.4**	100	16	**6.2**	108	8	**13.8**	101	8	**12.6**
c^3	140	12	**11.7**	136	17	**8.0**	139	19	**7.3**	141	13	**10.8**	132	11	**12.0**
f^2	207	19	**10.9**	201	23	**8.7**	210	22	**9.5**	210	19	**11.0**	203	15	**13.5**
c^2	279	23	**12.1**	270	31	**8.7**	280	27	**10.4**	278	24	**11.6**	275	22	**12.5**
f^1	420	36	**11.7**	406	44	**9.2**	411	43	**9.6**	415	39	**10.6**	412	35	**11.8**
c^1	564	40	**11.5**	543	54	**10.1**	539	54	**10.0**	554	55	**10.1**	551	50	**11.0**
f	843	69	**12.2**	830	81	**10.2**	804	77	**10.4**	824	84	**9.8**	821	78	**10.5**
c	1030	86	**12.0**	1085	102	**10.6**	1036	95	**10.9**	1088	119	**9.1**	1098	108	**10.2**
A	—	—	—	—	—	—	1169	105	**11.1**	1296	142	**9.1**	1300	130	**10.0**
G♯	—	—	—	—	—	—	1212	107	**11.3**	1074	134	**8.0**	1071	127	**8.4**
F	1461	114	**12.8**	1440	132	**10.9**	1348	117	**11.5**	1257	141	**8.9**	1260	132	**9.5**
C	1610	133	**12.1**	1629	155	**10.5**	1562	141	**11.1**	1536	154	**10.0**	1551	140	**11.1**
FF	1712	162	**10.6**	1709	184	**9.3**	1706	170	**10.0**	1725	176	**9.8**	1872	154	**12.2**
CC	—	—	—	—	—	—	—	—	—	—	—	—	1955	162	**12.1**
Location	Heaton Hall, Manchester(data from Michael Cole)			Private Collection, England (data from Michael Latcham)			Smithsonian Institution (data from M. O'Brien and E. McCullough)			Metropolitan Museum of Art, New York			Museum of Fine Arts, Boston		

A Newly-Discovered Eighteenth-Century Account

An explanation of the theory of the divided bridge, more nearly contemporaneous, more extensive, and far more technically detailed than J. S. Broadwood's account, exists in a privately-owned manuscript written by John Dovaston (1740–1808) of West Felton, near Oswestry, Shropshire.[15] According to his obituary, Dovaston was "a gentleman of learning, science, and ingenuity," whose "turn of mind was principally directed to Antiquities, Natural Philosophy [i.e., the physical sciences], Music, Mechanism, and Planting." He "left a set of philosophical and musical instruments made by his own hands; among which [was] . . . an organ on a new principle."

The Dovaston musical manuscript is a small (188 × 120 mm) leather-bound book of 80 numbered pages (preceded by a front flyleaf and two other unnumbered leaves, all of which are also used for writing) plus several additional sheets pasted in.[16] The second of the three unnumbered leaves at the front of the book bears on its recto the inscription "Jn°: Dovaston's/1765." Under this is noted an amount ("0.1.0," or one shilling) that presumably indicates the original cost of the blank book (see fig. 3). Inside the front cover is the bookplate of Dovaston's son, John Freeman Milward Dovaston. A very similar manuscript book recording the senior Dovaston's sporadic practice as a lawyer and other legal matters is at the Harvard Law School Library.[17] It bears an identical bookplate and signature, as well as a date (1780) and cost (two shillings, for about twice the number of pages). The entire contents were obviously written by the same hand as the entire contents of the music manuscript. Although in both books the handwriting used for the main text differs from that of Dovaston's formal signature, the appearance of both styles of writing in both manuscripts and the reference in Dovaston's obituary to his many unpublished works in manu-

15. A microfilm of the manuscript is at The Shrine to Music Museum, Vermillion, South Dakota. The principal source of information about Dovaston is his obituary, signed "P.," in *The Gentleman's Magazine* 78 (new series 1), no. 6 (June 1808), 563–64. It is quoted in full in *Letters from Lambeth: The Correspondence of the Reynolds Family with John Freeman Milward Dovaston, 1808–1815,* introduced and edited by Joanna Richardson (London: Boydell Press for The Royal Society of Literature, 1981), 155–56.

16. Three of these sheets unfold to show tables, while two others contain the account of bridges for keyboard instruments which will be transcribed and discussed below. Pages 79–80 are actually the end flyleaf, and writing continues onto the inside of the back cover as well.

17. The book, headed "The Origin and practise of the county court," is catalogued as MS 5415 of the Special Collections department.

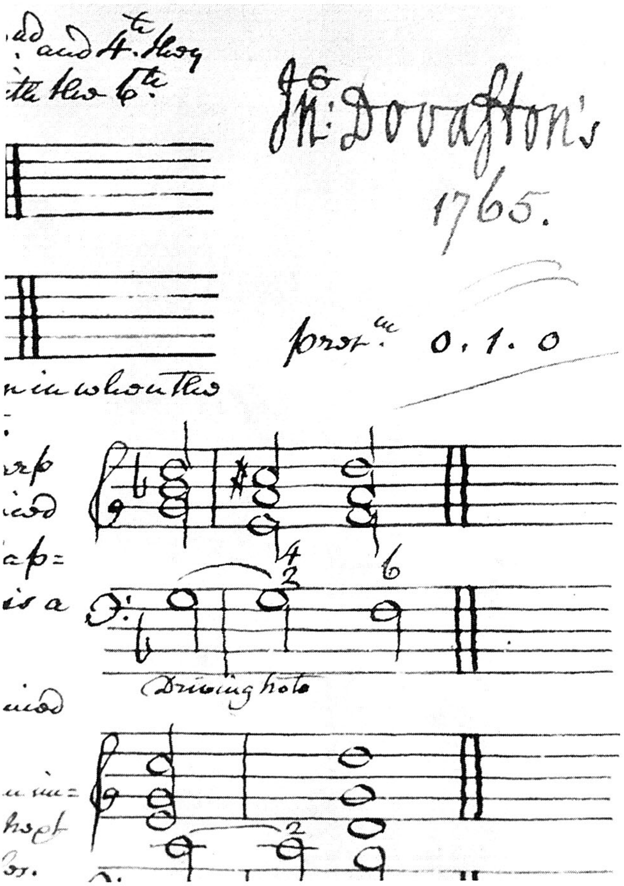

FIGURE 3. John Dovaston's signature at the beginning of his musical manuscript.

script form are consistent with the assumption that he indeed wrote both of them himself.

The music manuscript, like the legal one, was evidently written over an extended period of time. The bulk of its contents is concerned with music theory, including explanations of notes, rests, figured bass, ornaments, and the like. Dovaston copied much of this word for word from such standard didactic works as Peter Prelleur's *The Harpsichord Illustrated and Improv'd* (London, 1730; also issued as part of his *Modern Musick-Master* in 1731). This is of lesser interest than the contents of two leaves (that is, four pages) inserted between pages 44 and 45. On them, in Dovaston's hand, and graced by a diagram (see fig. 4), appears the following essay (slightly ungrammatical in places):

> An Improvement on the construction of Harpsichords and piano Fortes, with two Bridges instead of one was made by Broadwood & Son Harpsichord & piano forte makers London, one bridge for the Brass & the other for y[e] steel strings.
>
> In stringing of Harpsichords & piano fortes two sorts of metal are made use of viz[t] Brass & steel. The reason is that the tone produced by a steel wire of a given length & thickness is higher in its pitch than that of brass wire, the same length & thickness the tension of both being supposed equal; and the tone of the steel is not only higher but it also possesses a brilliancy which is not to be obtained from Brass wire.
>
> But if a piano Forte was to be strung entirely with steel the lower notes would require the Instrum[t] to be made some feet longer than the usual length.
>
> If strung entirely with brass (which formerly was the common practice) the consequence is, that the upper notes want that brilliancy, which as was before observed is produced from steel. This will not appear extraordinary when it is considered that steel is superior to every other metal in hardness and elasticity.
>
> These different property of the two metals render brass wire more proper for the lower notes of Harpsichords & piano fortes, and steel ones more proper for the higher ones, but it must be obvious that they also render it necessary that any note or notes of y[e] Instrument if meant to be strung with brass must be made shorter than if meant to be strung with steel, the difference in length which cannot be obtained without having a separate bridge for each metal this difference in length by which each metal has its proper tension; the first note strung with brass is several inches shorter than the last note strung with steel. Whereas in piano Fortes without two bridges of the common construction the first brass note, instead of being shorter than y[e] last steel one, is obliged to be made longer than it, and the manner in which the two mettals are brought to meet each other on the bridge is as follows: the lower steel notes are gradually shortened so that the last of all is several inches shorter than it ought to be, and the first brass note is several inches too long. The consequence is, that in this part of the Instrument the steel notes have a bad tone because they are too loose or slack, and the brass ones are bad because they are too tight. That what is here stated is really true, any person may convince himself by a very easy and decisive Experiment. Viz[t] let the lowest steel note of any piano forte of the common construction be drawn up half a note higher than its usual pitch and the tone will be found to be much Improved; the tone of the first brass note, on the contrary, will be improved by being let down half a note or even a whole tone lower than usual. This shows that the one is much too loose, and the other in a still degree greater too tight. By the simple expedient of two bridges on the sound board, one for the steel strings, and one for the brass ones, the forementioned de-

fects are entirely removed; each metal being thereby made to have that length which it requires in order to produce the best tone. In these piano Fortes & Harpsichords also, not only the requisite proportion between the two metals is preserved, but the length of every string, is determined with such accuracy, that the degree of tension throughout the Instrument is proportionately equal, from this equality of tension, the following very important advantages are derived.

1[.] The general tone of the instrument is improved and it is rendered so equal throughout, that the difference between the two mettals is hardly to be perceived. 2. These Instruments continue much longer in tune, than those of the common construction, in which, as has been shown some

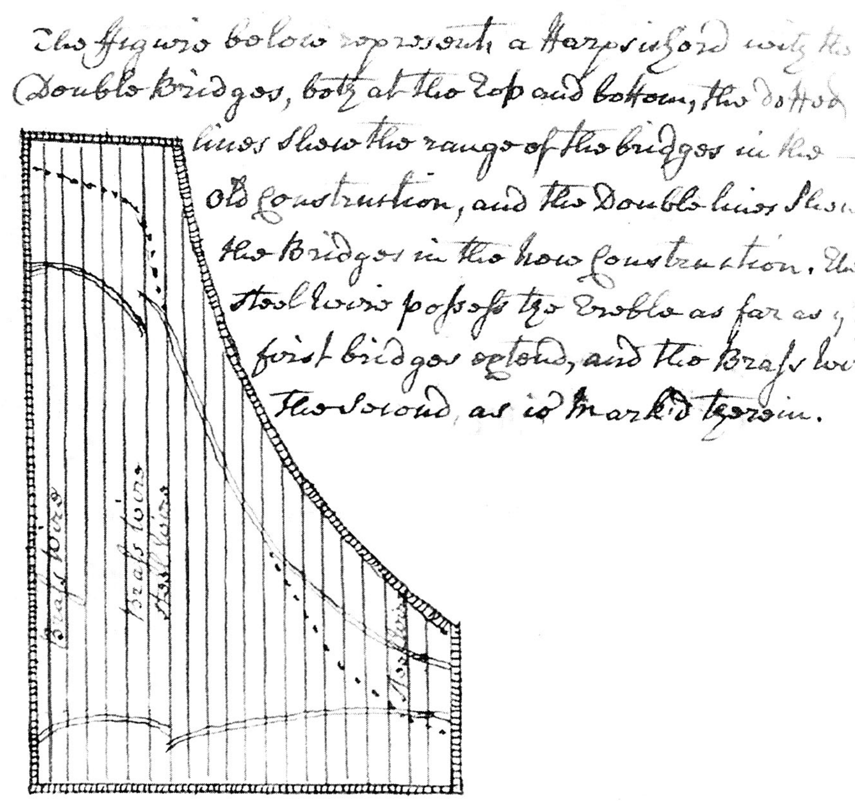

FIGURE 4. Dovaston's diagram of a "Harpsichord" with divided bridge. The older design with undivided bridge and short treble scaling is shown in dotted lines.

strings are too loose, & some too tight. 3. The breaking of the higher brass strings so common in other Instruments from their being too tight, is entirely prevented. Indeed the breaking of any of the strings is a very rare circumstance.

The figure below [i.e., fig. 4] represents a Harpsichord with the double bridges, both at the top and bottom [i.e., both bridge and nut are divided], the dotted lines show the range of the bridges in the old construction, and the Double lines show the Bridges in the new construction. The steel wire possess the treble as far as y^{e} first bridges extend, and the Brass wire the second, as is mark'd therein.

Although Dovaston could certainly have composed this essay himself, it is just as likely that he was merely its copyist. In either case the information in the essay clearly stems from someone directly involved with Broadwood and the development of the divided bridge. Even if Dovaston copied an earlier text, however, its designation of "Broadwood & Son," a partnership that was formed in 1795, provides a *terminus post quem,* while Dovaston's death in 1808 provides a *terminus ante quem.* The essay's implication that the divided bridge is a novelty suggests that it was composed at the beginning of this period, that is, shortly after 1795. This hypothesis is strengthened by the pasted-in sheets of paper upon which Dovaston wrote the essay, which bear a watermark containing the date 1799 (the last digit is partially obscured by ink and might be "5"). In any case, the document supplies important contemporary evidence confirming that the divided bridge was indeed originally introduced by the Broadwoods.

Dovaston writes of the divided bridge as applicable to both harpsichords and pianos. However, no known English harpsichord contains such a bridge, except for that shown in the drawing of a combined harpsichord-piano patented by James Davis in 1792 and a very similar instrument at the Smithsonian Institution, both of which are essentially normal grand pianos with added jack actions.[18] It is possible that Broad-

18. English patent no. 1887; see *Patents for Inventions: Abridgments of Specifications Relating to Music and Musical Instruments, A.D. 1694–1866,* 2nd ed. (London, 1871; facs. reprint, London: Tony Bingham, 1984), 27. A lithographic facsimile of Davis's drawing was issued by the patent office in 1856; I have consulted a photocopy of this in the archives of the late Edwin M. Ripin at the Museum of Fine Arts, Boston. Regarding the Smithsonian instrument, see *A Checklist of Keyboard Instruments at the Smithsonian Institution,* prepared by the Division of Musical Instruments, Museum of History and Technology (Washington, D.C.: Smithsonian Institution, 1967), 30–31, 44–45, and 70; and

wood made one or two experimental harpsichords with divided bridges, but the firm is believed to have ceased making harpsichords entirely after 1793.[19] The inclusion of harpsichords in Dovaston's account, written during this period of transition, need not obscure the primary significance of this account for the history of the piano, rather than the harpsichord. In any case, the piano is emphasized in Dovaston's longest paragraph, in which he proposes a "decisive Experiment" on "any forte piano of the common construction."

Dovaston's description of how the division of the bridge affects an instrument's scaling can be supplemented by a consideration of string lengths in representative instruments of the period. Table 3 gives these measurements for a grand piano by Robert Stodart, 1790 (at the Smithsonian Institution, Washington, D.C., shown in fig. 1), exemplifying "the common construction," i.e., with an undivided bridge, and a Broadwood grand piano of 1792 (at the Metropolitan Museum of Art, New York), in which the bridge is divided.[20] While the treble and extreme bass scalings of the two instruments are quite similar (as shown by the measurements of the FF, C, and c^2 strings), the lowest iron-strung note of the Broadwood (A) is significantly longer than the same note of the Stodart, while its highest brass-strung note (G♯) is significantly shorter. The effect of the divided bridge can also be seen by considering the c^2-equivalent scale, that is, the length that a string would have if it were adjusted to sound c^2 with all other factors remaining unchanged. (For example, the c^2-equivalent scale of a string sounding c^1 is one-half its measured length, while the c^2-equivalent scale of a string sounding c^3 is twice its measured length.) With the divided bridge, the lowest

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Frank Hubbard, *Three Centuries of Harpsichord Making* (Cambridge: Harvard University Press, 1965), 163. I am grateful to the staff of the Division of Musical History at the Smithsonian Institution for providing me with additional information about this instrument.

19. Nevertheless, they were occasionally called "harpsichord-makers" for some time thereafter: see Wainwright, *Broadwood by Appointment,* 79. (About the use of "harpsichord" and similar terms to encompass the meaning "piano," see Eva Badura-Skoda, "Prolegomena to a History of the Viennese Fortepiano," *Israel Studies in Musicology* 2 (1980), 77–99; and "Komponierte J. S. Bach 'Hammerklavier-Konzerte'?" *Bach-Jahrbuch* 77 (1991), 159–71.) Indeed, as late as 1819 Charles Burney's discussion of the history of the piano appeared as part of the entry "Harpsichord" in *The Cyclopaedia,* edited by Abraham Rees (London, 1819), vol. 17, unpaginated.

20. I thank Michael O'Brien and Elizabeth McCullough of the Smithsonian's staff for taking various measurements of the 1790 Stodart for me.

TABLE 3. Comparison of string lengths in grand pianos with undivided bridge (by Robert Stodart, 1790) and divided bridge (by John Broadwood, 1792)

	String Length in mm		c^2-equivalent Scale in mm	
Note	Stodart	Broadwood	Stodart	Broadwood
c^2	280	278	280	278
c	1036	1088	259	272
A	1169	1296	246	272
G♯	1212	1074	240	213
F	1348	1257	225	210
C	1562	1536	195	192
FF	1706	1725	142	144

iron-strung note has almost exactly the same c^2-equivalent scale as the treble strings, and the c^2-equivalent lengths of the brass strings show their scaling to be much less variable between C and G♯ than in the instrument with the undivided bridge.

Dovaston's text and James Shudi Broadwood's later recollections substantially agree about the reason for the introduction of the divided bridge. Together with instruments from the 1780s and 1790s, they provide a historical basis for rejecting the accuracy of Hipkins's account that the bridge was divided in order to secure a rational striking point.

Tiberius Cavallo and his "Great Object" of Piano Design

Because of his justified skepticism about Hipkins's account, Winter, who did not cite J. S. Broadwood's narrative, regarded Cavallo and Gray as "mysterious" figures "straight out of Sherlock Holmes."[21] One need not be much of a detective, however, to find the lives of these noted scientists of the period outlined in such standard sources as the *Dictionary of National Biography*.[22] That Edward Whitaker Gray (1748–1806)

21. Winter, "Striking It Rich," 273.

22. See Robert Hunt, "Cavallo, Tiberius," *Dictionary of National Biography*, 22 vols., edited by Sir Leslie Stephen and Sir Sidney Lee (Oxford: Oxford University Press, 1921–1922), 3:1246–47; John L. Heilbron, "Cavallo, Tiberius," *Dictionary of Scientific Biography*, edited by Charles Coulston Gillispie (New York: Charles Scribner's Sons, 1971), 3:153–54; George Simonds Boulger, "Gray, Edward Whitaker," *Dictionary of National Biography*, 8:450; and Wainwright, *Broadwood by Appointment*, 72–73, where Gray's portrait is reproduced.

was primarily active as a botanist does not mean that, in that age of universal learning, he might not also have been capable of experimenting with a monochord. With Tiberius Cavallo (1749–1809) one is on very firm ground indeed. Although the paper mentioned by J. S. Broadwood that Cavallo read to the Royal Society in 1788 has nothing to do with the divided bridge, string tensions, or striking points,[23] and although there is no evidence that he ever wrote a work actually titled "Treatise on Acoustics," he did publish a four-volume work, *The Elements of Natural or Experimental Philosophy* (London, 1803). This includes two chapters on acoustics, totaling 86 pages, which constitute a treatise on the subject and contain an extensive exposition of the theory of strings.[24] Cavallo mentions here that he possessed "a set of tuning-forks, for all the 13 sounds of an octave, which were tuned by one of the best piano-forte makers in town,"[25] and he recounts an experiment with a brass harpsichord string undertaken "in the presence of a very intelligent friend."[26] Both of these may be references to John Broadwood. Cavallo explicitly states his own interest in piano design:

> The strings of piano-fortes, harpsichords, etc. were they all of the same thickness, could not conveniently be made of the proper lengths; therefore, by making them of different sizes, and by stretching them differently, their lengths are suited to the commodious size of the instrument. Now the great object in adjusting the sizes and lengths of such strings, is to contrive that each string be stretched by a force proportionate to its thickness and length; otherwise the instrument will not have a uniform voice.—Few makers of such instruments pay sufficient attention to this particular.[27]

The last remark, of course, implies that some makers, presumably including Broadwood, had indeed paid attention to what Cavallo advocated.

Cavallo's comments about the scaling of stringed keyboard instruments are not a part of his formal exposition of the laws of strings but rather are a footnote to a catch-all series of "remarks concerning the

23. "Of the Temperament of those musical Instruments, in which the Tones, Keys, or Frets, are fixed, as in the Harpsichord, Guitar, &c.," *Philosophical Transactions of the Royal Society of London* 78 (1788), part 2: 238–54.

24. Cavallo, *Elements,* 2:309–95; chaps. 11, "Of Sound, or of Acoustics," and 12, "Of Musical Sounds."

25. Ibid., 389.

26. Ibid., 363.

27. Ibid., 389–90.

effects which are attributed to musical sounds." Thus the precise theory by which his "great object" of a "uniform voice" was to be achieved by "adjusting the sizes and lengths of . . . strings" is not stated with mathematical precision. The placing of these remarks along with other inadequately-explained phenomena such as consonance and the effect of the *tarantella* on tarantula-bite victims suggests that a rigorous explanation of the "great object" was beyond the capabilities of science in Cavallo's day. Thus both he and Dovaston would have been forced to write in qualitative, not quantitative, terms.

Hipkins wrote that the object was "to equalise the scale in tension," a conspicuous goal of modern piano design. Cavallo, by contrast, seems to advocate just the opposite, observing that makers stretch strings "differently" and that "each string [should] be stretched by a force *proportionate* to its thickness and length" (my italics). This is *not* the same as saying that each string should be stretched by a force *equal* to that of the other strings. Language similar to Cavallo's appears in the Dovaston manuscript: "the degree of tension throughout the Instrument is *proportionately* equal" (my italics).[28] This is echoed by J. S. Broadwood, who speaks of "due proportions" and of "due [i.e., not necessarily equal] tension." Dovaston enriches his exposition by including the factor of string material, such that "each metal has its proper tension." This, again, is not the same as saying that the brass and iron strings were made to have equal tension.

Having examined Cavallo's, Dovaston's, and J. S. Broadwood's accounts, we can reconstruct the significance of their texts and present in a more rigorous manner what they did not or could not explain. To do so, quantitative data from instruments of the period must be analyzed according to both historical and modern scientific understanding.

The basic physical laws that describe the musical behavior of strings were well understood and widely known in eighteenth-century England. The relationship between string length and pitch whereby, for example, a string will sound an octave higher if it is halved in length, was known to the ancient Greeks. Investigations by Giovanni Battista Benedetti, Vincenzo Galilei, Galileo Galilei, Marin Mersenne, and others in the late sixteenth and early seventeenth centuries explored the effects of tension and string mass or density and established the cor-

28. This phrase is followed immediately by "this equality of tension," which in the context should be understood to mean "relative (or proportional) equality of tension."

respondence between pitch and vibrational frequency.[29] The mathematical descriptions of the relationships between these individual factors of frequency, length, tension, and string mass or density are still known as Mersenne's Laws.[30] These can be combined into one general equation, sometimes called Taylor's formula after the English mathemetician, Brook Taylor, who published a proof in 1713.[31] In a modern form used by Rose and Law in their study of the stringing of early keyboard instruments[32] it is:

$$T = \frac{\pi\,\rho\,F^2 L^2 D^2}{9.81 \times 10^{12}}$$

in which:

T = tension in kilograms (i.e., kg-force; 9.81 newtons)
F = frequency in Hertz (cycles per second)
L = string length in millimeters
D = string diameter in millimeters
π = 3.14159 . . .
ρ = density of string material in kg/m^3.

Cavallo's chapters on acoustics contain a thorough exposition of the laws governing strings. Analyses of historical harpsichord string tensions presented by Bakeman,[33] O'Brien,[34] and Rose and Law demonstrate

29. See A. Wolf, *A History of Science, Technology and Philosophy in the 16th & 17th Centuries,* 2nd ed. (New York: Harper & Brothers, 1959), 1:282–83; Claude V. Palisca, "Scientific Empiricism in Musical Thought," in *Seventeenth Century Science and the Arts,* edited by Hedley Howell Rhys (Princeton: Princeton University Press, 1961), 91–137; and Sigalia Dostrovsky, "Early Vibration Theory: Physics and Music in the Seventeenth Century," *Archive for History of Exact Sciences* 14, no. 3 (1975): 169–218.

30. See Marin Mersenne, *Harmonie Universelle* (Paris, 1636; facs. reprint, Paris: Éditions du Centre National de la Recherche Scientifique, 1965), 3:123–26 (i.e., "Livre Troisiesme des instrumens à chordes," prop. 7); in Roger E. Chapman's translation, *Harmonie Universelle, the Books on Instruments* (The Hague: Martinus Nijhoff, 1957), 176–80.

31. Brook Taylor, "De motu Nervi tensi," *Philosophical Transactions* [of the Royal Society of London] 28 (1713; facs. reprint, New York: Johnson Reprint Corporation and Kraus Reprint Corporation, 1963): 26–32. An English translation of Taylor's paper is quoted in full by Cavallo in *Elements* 2:364–72.

32. Malcolm Rose and David Law, *A Handbook of Historical Stringing Practice for Keyboard Instruments, 1671–1856* (Lewes, East Sussex, and Long Compton, Warwickshire: The Authors, 1991), 192.

33. Kenneth Bakeman, "Stringing Techniques of Harpsichord Builders," *The Galpin Society Journal* 27 (1974): 95–112.

34. G. Grant O'Brien, "Some Principles of Eighteenth Century Harpsichord Stringing and Their Application," *The Organ Yearbook* 12 (1981): 160–76.

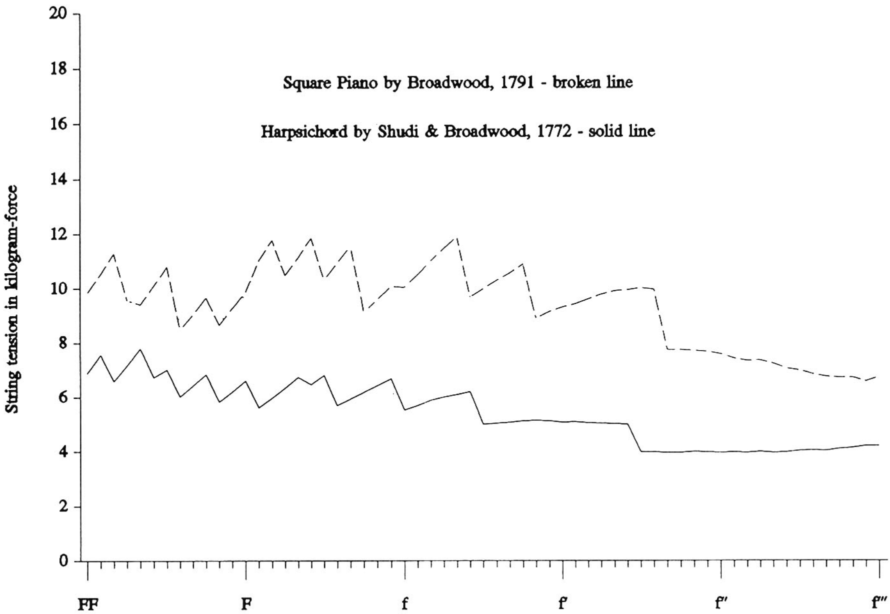

FIGURE 5. String tensions of the longer unison strings in a harpsichord by Shudi and Broadwood, 1772, and a square piano by Broadwood, 1791.

that, long before the late eighteenth century, makers achieved results apparently based either on knowledge of some or all of these laws or on an equivalent empirical knowledge of the several variables that affect string tension. That is, despite difficulties of foreshortened scaling (i.e., c^2-equivalent scales that become relatively shorter with each lower note in the bass) and varied string materials (in northern Europe usually iron in the treble, yellow brass in the bass, and red brass for the lowest notes), makers were able to secure an approximately equal tension throughout the compass. (Of course, inevitable jumps occurred when changing from gauge to gauge, and usually builders reduced tension gradually from tenor to treble.) That John Broadwood was capable of stringing instruments according to the traditional practice of consistent tensions is shown in fig. 5, based on a two-manual harpsichord at the Museum of Fine Arts, Boston, inscribed "Burkat Shudi et Johannes Broadwood . . . 1772" (i.e., made by Broadwood the year after Shudi's retirement) and a Broadwood square piano of 1791 at the Shrine to

Music Museum, Vermillion, South Dakota (cat. no. 1217).[35] The relative evenness of the tension in the 1791 square piano and other early English instruments of this type[36] is all the more impressive given their use of covered strings for the lowest bass notes, which greatly complicates the determination of tensions, whether calculated mathematically or determined experimentally on a monochord. Thus, in grand pianos, which had no covered strings, Broadwood and his colleagues could no doubt have achieved equal tension throughout the compass had they wished.

Brass is denser than iron. Thus, as Dovaston writes, "the tone produced by a steel wire of a given length & thickness is higher in its pitch than that of brass wire, [of] the same length & thickness[,] the tension of both being supposed equal." Northern European harpsichord makers

35. In this graph, for each instrument the tensions of the longer set of unison strings are shown. They are calculated at a pitch of a^1 = 425 Hz, which is used by Rose and Law for calculating piano tensions and which is virtually the same as Cavallo's reckoning of a^1 = 428 Hz as the current "concert pitch." (See Cavallo, *Elements* 2:384 and pl. 14. Because he could not measure frequency directly, Cavallo calculated the frequency from the known weight, length, and tension of a string tuned to A. He admits that the calculated frequency might be "a little higher than the truth" because he did not compensate for air resistance, but this is probably a negligible factor. The c^1 = 256 Hz reported by Thomas Young in *A Course of Lectures on Natural Philosophy and the Mechanical Arts* [London, 1807], 1:396, is almost identical to Cavallo's calculated pitch. One might note that a harpsichord made by Joseph Kirckman in 1798 [now at the Shrine to Music Museum, cat. no. 3328], presumably designed for the same prevalent pitch reported by Cavallo and Young, has scalings quite similar to those of the 1772 Shudi and Broadwood harpsichord.) My calculations also follow the values for densities (7769 kg/m^3 for steel; 8536 for yellow brass; 8769 for red brass) used by Rose and Law (see their *Handbook,* 4). Unless otherwise noted, I use these standards of pitch and density for all subsequent calculations in this article.

My calculations for the Broadwood harpsichord of 1772 follow the string materials and diameters indicated by the original gauge numbers on the nuts, which I have published elsewhere (see John Koster, *Keyboard Musical Instruments in the Museum of Fine Arts, Boston* [Boston: The Museum, 1994], 130). I employ Grant O'Brien's interpretation of the eighteenth-century English wire-gauge system (as given in "Some Principles of . . . Harpsichord Stringing," 166), which is consistent with old strings on the 1772 harpsichord. My calculations for the Broadwood square piano of 1791 are based on its many presumably original strings. Some of the transitions of diameter and material (covered strings from FF to F, yellow brass from F♯ to e, and iron for the remainder) were adopted from a Broadwood square piano of the same model and year in the collection of G. Norman Eddy, Cambridge, Massachusetts, on which the maker indicated string gauges and materials.

36. See Rose and Law, *Handbook,* passim.

therefore traditionally had used brass strings in the bass, where the scalings are foreshortened; and they normally used the even denser red brass for the lowest notes. The Dovaston manuscript explains clearly that the divided bridge was introduced to provide each string with what we would call a c^2-equivalent scale appropriate to its material, especially at the crossover point between brass and iron. One might therefore suppose that the scaling of the brass-strung notes was determined by taking the scaling of the iron strings and shortening it by the amount necessary to compensate for the greater density of brass. According to this hypothesis, in designing, for example, the 1792 piano at the Metropolitan Museum of Art, Broadwood would have taken the length of the lowest iron string, A (1296 mm), and multiplied this by the frequency ratio of a semitone (1.0595 in equal temperament) to obtain the hypothetical length (1373 mm) for the G♯ string according to the iron scaling. To convert this to the appropriate brass scaling based solely on the difference in density between brass and iron, he would have multiplied 1373 mm by the square root of the ratio of the densities, i.e., the square root of 7769 ÷ 8536, which is 0.954, thereby obtaining a length for G♯ of 1310 mm. Broadwood would not, of course, have worked in the metric system and he might have determined the scaling with a monochord and weights rather than with pencil and paper. Nevertheless, he would have come to the same result: the hypothetical length of the brass G♯ string reckoned solely on the difference in density would still be slightly *longer* than the iron-strung A. At 1074 mm, the actual G♯ string in the 1792 piano is far shorter than the A string. This shortness of the G♯ string is absolutely typical of early English grand pianos with divided bridges, as may be seen in Table 4. It is therefore clear—contrary to what Dovaston seems to imply by his discussion of the difference in pitch between brass and iron strings of the same length, diameter, and tension—that Broadwood and his fellow makers did *not* calculate scalings and divide the bridge in order to compensate for the different densities of the two materials.

The relative shortness of the brass G♯ strings is such that to maintain a tension equal to that of the iron A strings they would have to be 22% thicker. There is, however, considerable evidence that for the highest brass notes the makers used strings of about the same diameter as, or even slightly thinner than, those for the lowest iron notes. Because English grand pianos lack written gauge numbers, one must rely on measurements of strings thought to be original, such as those on the

TABLE 4. Comparison of A and G♯ string lengths in seven English grand pianos with divided bridges

Maker	Date	Location	String lengths in mm: A	G♯ (actual)	Hypothetical G♯ = A × 1.0595 × 0.954
J. Broadwood	1792	Metropolitan Museum of Art, New York	1296	1074	1310
M. & Wm. Stodart	1795	Shrine to Music Museum, Vermillion, South Dakota	1319	1119	1333
J. Broadwood & Son	1796	Museum of Fine Arts, Boston	1300	1071	1314
J. Broadwood & Son	1804	Museum of Fine Arts, Boston	1307	1079	1321
J. Broadwood & Sons	c. 1808	Metropolitan Museum of Art, New York	1306	1080	1320
J. Broadwood & Sons	1817	Neumeyer Collection, Bad Krozingen, Germany	1304	1077	1318
Wm. Stodart	c. 1818	Shrine to Music Museum, Vermillion, South Dakota	1222	1080	1235

1795 instrument by Matthew and William Stodart at the Shrine to Music Museum. To this may be added information collected from several Broadwood pianos by Rose and Law, Derek Adlam,[37] and Hugh Gough,[38] as shown in Table 5. Although the conclusion that a set of strings is original must ultimately rest on subjective judgements about the style and consistency of the hitch-pin loops and wrest-pin wrappings, it is quite unlikely that the above observations would be so consistent if many of them were incorrect.[39] If we therefore assume that the choice of closely similar string gauges at the crossover point was deliberate, calculation using the typical string lengths of the Metropolitan Museum of Art's 1792 Broadwood piano (see Table 2) and standard values for frequency and density shows that the tension of G♯ would be only 67% the tension of A.[40] A similar disparity is evident in the data and calculations from several Broadwood grand pianos presented by Rose and Law,[41] and from the Matthew and William Stodart piano of 1795 at the Shrine to Music Museum (see fig. 6). Evidently, this drastic inequality of tension at the crossover point was intentional.

37. As reported by Martin Skowroneck in "Praktische Überlegungen und Beobachten zur Frage der Saitenstärken von frühen Hammerflügeln," in *Studia Organologica: Festschrift für John Henry van der Meer zu seinem fünfundsechzigsten Geburtstag,* edited by Friedemann Hellwig (Tutzing: Hans Schneider, 1987), 441.

38. Personal communication. The data were gathered by Mr. Gough during his practice as a restorer in England during the 1930s to 1950s.

39. One further conceivable objection to the validity of these observations should be addressed, namely that under decades or centuries of tension the brass strings might have been permanently stretched (by the phenomenon known to engineers as "creep") with a consequent reduction in their diameters. If the brass strings had stretched significantly more than the steel strings on an instrument, one would expect to find more windings of brass wire than of steel wire around the wrestpins. But such evidence of stretching is not to be observed in instruments with extant early strings, for example, the 1791 Broadwood square piano and 1795 Stodart grand at the Shrine to Music Museum, in which, moreover, the diameters of the ends of the brass strings wrapped around the wrestpins (where there is no great tension) are the same as the diameters of the vibrating portions of the strings. It is possible, however, that a new brass wire nominally of the same gauge as a steel wire was slightly thinner because of the manufacturing process. That is, as a brass wire and a steel wire were pulled through identical draw-plate holes, the lower elastic limit of brass might result in some stretching. Also, one would expect that a draw-plate hole used for steel wire would become more quickly enlarged by wear than one used for brass.

40. This is calculated as follows: $T_{A\ (steel)} = 47.2 \times D^2$; $T_{G\sharp\ (brass)} = 31.7 \times D^2$; when the former is divided by the latter, the result is 0.67.

41. Rose and Law, *Handbook:* 25, 28–29, and 159–60.

TABLE 5. Comparison of diameters of presumably original G♯ and A strings in seven English grand pianos with divided bridges

Instrument	String Diameter in mm: Brass . . . G♯	String Diameter in mm: Steel A . . .	Source of Data
M. & Wm. Stodart, 1795	.54	.58	J.K., Shrine to Music Museum
J. Broadwood & Son, 1796	.51	.53	Adlam
J. Broadwood & Son, 1798	.53	.56	Gough
J. Broadwood & Son, 1799	.61	.58	Gough
J. Broadwood & Son, 1802	.597	.597	Rose & Law, *Handbook,* 28
J. Broadwood & Son, 1806	.635	.584	Rose & Law, *Handbook,* 29
W. Frecker, 1812	.66	.65	Gough

FIGURE 6. String tensions in a grand piano by Matthew and William Stodart, 1795.

In the same group of grand pianos by Broadwood and Stodart a further inequality of tension is evident, i.e., the gradual reduction of tension from the lowest iron-strung notes toward the treble. This inequality (similar to that traditionally found in the treble range of harpsichords) must also have been deliberate. Because the scaling of the iron strings in pianos with divided bridges is just, i.e., the c^2-equivalent scale is more or less constant from A to the top note, equal tension could easily have been achieved by using only one size of iron wire. Instead, smaller diameters were used in the treble.[42] In the following section, we shall attempt to explain why Broadwood and his fellow makers did not maintain an equal tension throughout the compass and especially why there is such a disparity of tension where the bridge is divided.

42. A scheme of Robert Wornum in 1820 (English patent no. 4460) provides further conclusive evidence that eighteenth- and early-nineteenth-century English makers did not intend to scale and string their instruments for equal tension throughout the compass, since Wornum's claim to do just that was promoted and patented as an innovation, apparently without objection from other piano makers. See "Mr. Wornum's Patent," *The Quarterly Musical Magazine and Review* 2, no. 7 (1820): 305–07; and *Patents for Inventions: Abridgments,* 86–87.

Scaling and Timbre

Cavallo wrote that "the great object" was to adjust the tensions, diameters, and lengths of the strings in order for the instrument to have a "uniform voice," i.e., timbre and loudness balanced throughout the compass. In a similar vein, Dovaston wrote even more clearly that with the divided bridge "each metal [is] thereby made to have that length which it requires in order to produce the best tone" and "the general tone of the instrument is improved and . . . rendered . . . equal throughout." One can relate Dovaston's statement, in essence that the scalings were determined by an utterly subjective judgement as to what sounded best, to Mersenne's observation that "if strings of the same material are different in length, the one that is longer and tuned in unison with the shorter yields a sweeter tone (*un son plus doux*)."[43] That is, the timbre of a string will change as the c^2-equivalent scale is changed.

In historical harpsichord design, as it is now understood, the longest practicable scales were used. Strings were stretched close to their breaking points, i.e., close to the limits of their tensile strength, with allowance for a margin of safety. The Broadwood harpsichord of 1772, cited above, provides an example of traditional harpsichord scaling. In the treble the iron-strung notes of its longer 8′ choir have a c^2-equivalent scale of about 345 mm; the top brass-strung note of this choir, A, 1308 mm long, has a c^2-equivalent scale of 275 mm. The scaling of the brass-strung notes must be shorter because brass has lower tensile strength than iron.[44] For each material, the maximal c^2-equivalent scale is such that the strings were tuned approximately a semitone flatter than the pitch at which they would break.

In early English grand pianos with divided bridges all the iron strings have c^2-equivalent scales of about 275 mm, while the top brass-strung

43. Mersenne, *Harmonie Universelle,* 3:12 (i.e., "Livre premier des Instruments," prop. 4); Chapman's translation, 25.

44. At a pitch standard of a^1 = 425 Hz, iron wire of the diameters used in the treble, about 0.25 mm, has a "breaking scale" of about 360 mm, above which length a string tuned to c^2 would break. (This is based on tensile strengths of about 105 kgf/mm^2, which have been found in samples of eighteenth-century wire found in English and French harpsichords: see Goodway and Odell, *Metallurgy,* 59. I have converted the results from this and other sources from Mpa or psi units into kgf/mm^2.) Old brass wires vary considerably in tensile strength (see the data assembled in Cary Karp, *The Pitches of 18th Century Strung Keyboard Instruments with Particular Reference to Swedish Material,* SMS-Musikmuseet [Stockholm], Technical Report no. 1 [1984], Table 6, p. 117) but a typical value of 75 kgf/mm^2 would result in a breaking scale of about 290 mm.

note, G♯, has a c^2-equivalent scale of about 215 mm. One cannot fail to notice that these scalings are considerably shorter than the scalings for brass and iron strings in harpsichords. An explanation might be proposed based on the fact, well-known both then and now, that wire gains in tensile strength as it is drawn thinner, a phenomenon known as "tensile pickup."[45] Thus, the use of thicker strings in pianos might be thought to necessitate very short scales. Data from historical wire, however, do not entirely support this explanation. For iron wire about 0.50 mm in diameter, a typical value for piano strings in the period under consideration, tensile strengths of about 80 kgf/mm^2 could be achieved.[46] This corresponds to a breaking scale of 315 mm and to a safety margin of more than two semitones for a c^2-equivalent scale of 275 mm. Further evidence that the iron-string scalings of English grand pianos were significantly shorter than necessary according to the tensile strength of the wire, even when allowing for a generous safety margin, is provided by square pianos, in which the iron strings are approximately the same diameters as those in grand pianos despite their longer treble scalings. The Broadwood square piano of 1791 at the Shrine to Music Museum, for example, has a c^2 string length of 305 mm.

Similar but even more definite conclusions can be reached regarding the brass scaling of English grand pianos. The phenomenon of tensile pickup is less pronounced with brass than with iron.[47] Historical brass wire about 0.50 mm in diameter, approximately the thickness of the highest brass strings in English grand pianos in the period under consideration, often had tensile strength of about 70 kgf/mm^2.[48] This corresponds to a breaking scale of about 280 mm. Thus, with a c^2-equivalent scale of about 215 mm, the highest brass-strung note in early English grand pianos with divided bridges was tuned four or five semitones below the pitch at which it would break. A privately-owned Matthew and William Stodart grand piano of 1793, with an undivided bridge,[49] confirms that makers could have used longer brass scales. Here, according to Rose and Law, the top brass note, G♯, is 1233 mm long, thus having a c^2-equivalent scale of 245 mm.

45. See Goodway and Odell, *Metallurgy,* 61–65.

46. Measurements published by C.-A. de Coulomb in 1784 show that iron wire 0.50 mm in diameter had a tensile strength of 81.7 kgf/mm^2: see ibid., 52. I have converted this value from the units used by Goodway and Odell to kgf/mm^2.

47. Ibid., 59.

48. See Karp, *The Pitches of 18th Century Strung Keyboard Instruments,* Table 6, p. 117.

49. See Rose and Law, *Handbook,* 24.

It will be noticed that the brass and iron scales of grand pianos with divided bridges are each about the same proportion of the scalings traditionally used in harpsichords (i.e., for iron 275 ÷ 345 = 80%; for brass 215 ÷ 275 = 78%). This similar proportion might have been the genesis of Dovaston's writing that "the degree of tension throughout the Instrument is proportionately equal."

Mersenne's observation that longer-scaled strings sound "sweeter" is consistent with the traditional use of the longest practicable scales in harpsichord making. Dovaston's remark that on instruments with undivided bridges the lowest iron strings, with their short c^2-equivalent scales, "have a bad tone because they are too loose or slack" is consistent with conventional wisdom. In contrast, his following comment states that the relatively long-scaled highest brass strings sound "bad because they are too tight." This, along with the observation that the typical iron string scaling in English grand pianos is significantly shorter than required by the limits of the wire's tensile strength, shows that the standards of scaling pianos for optimal tone, even at this relatively early period, were different from those applied to harpsichords. That is, in pianos the timbre of slacker strings was preferred.

Investigations with modern pianos have shown that what is perceived as a certain "warmth" of tone is caused by upper partials (overtones) that are sharper in pitch than pure harmonics.[50] This results from the relative stiffness of the thick, short piano strings, which do not function in quite the same manner as theoretically ideal strings without any inherent stiffness. The comparatively thin and long strings of harpsichords are closer to the ideal and therefore sound with relatively pure harmonic upper partials. The degree to which the upper partials of a string are sharp can be calculated from a value called the "coefficient of inharmonicity" or "B."[51] If B is very high, the partials can be so out of tune that the tone sounds false. In such an extreme case it can be

50. See E. Donnell Blackham, "The Physics of the Piano," *Scientific American* 213, no. 6 (December 1965): 88–99. If the fundamental frequency is, say, 100 Hz, the second partial sounds slightly sharper than the pure octave of 200 Hz, the third partial is, by an even greater degree, sharper than 300 Hz, and so on.

51. B times the square of the number of any particular partial equals the sharpening of that partial in cents, i.e., hundredths of an equal-tempered semitone. If, for example, the fundamental frequency of a string is 100 Hz and the string's B is 0.2, the third partial will be 0.2×3^2 (that is, 1.8) cents sharper than 300 Hz.

understood that the string functions essentially as a clanging rod. For any given string, B is determined by the formula:[52]

$$B = 1.335 \times 10^8 \frac{D^2 E}{F^2 L^4 \rho}$$

in which the terms are as in the previous equation and:

E = elastic modulus of the material in newtons/m^2.

The values of E and ρ are inherent in the materials. The E of iron is about twice that of brass.[53] If the terms F, D, and L are equal, the inharmonicity of a iron string is something more than twice that of a brass string. Thus, a short brass string will have an acceptable tone, while an equally short iron string will sound false. This, far more than the difference in density between the two materials, accounts for the successful use of brass strings in the bass, where the scale is foreshortened.[54] Happily, the tensile strength of iron allows much longer scales to be used. Thus, the relatively large values of L, when entered into the formula above, result in reasonably low values of B for long-scaled iron strings.

The warmth of inharmonicity is a timbral characteristic of even the earliest pianos, a consequence of their shorter scaling and thicker stringing in comparison with harpsichords. It is instructive to calculate the coefficients of inharmonicity, B, for strings at the crossover point in pianos with divided bridges. Using typical values for string length (1300 mm for A; 1075 mm for G♯), diameter (0.52 mm), and the elastic moduli (18.5×10^{10} N/m^2 for iron; 9.5×10^{10} for brass), we find that the coefficient of inharmonicity is 0.0266 ¢/(partial number)^2 for the iron-strung A and 0.0295 for the brass-strung G♯. These values of B for the adjacent notes G♯ and A and the consequent inharmonicity of their

52. This equation is adapted from Robert W. Young, "Inharmonicity of Plain Wire Piano Strings," *Journal of the Acoustical Society of America* 24, no. 3 (May 1952): 268 (equation 8).

53. See, for example, the data in Goodway and Odell, *Metallurgy*, 107. An ingenious method for determining the value of E by measuring the longitudinal vibrational frequency of wire mounted on an instrument is described by Thomas W. Parsons in a letter in *The Galpin Society Journal* 23 (1970): 164–65. (Unfortunately, his equations are marred by typographical errors.) By this method, I have determined that E for one of the steel strings on the Shrine to Music Museum's Matthew and William Stodart piano of 1795 is 18.5×10^{10} N/m^2.

54. See Goodway and Odell, *Metallurgy*, 85.

upper partials can be regarded as virtually identical (and the calculated values of B would be even closer if they were based on a brass wire diameter slightly less than that of the iron). Because the precise tuning of the upper partials for both notes would therefore be virtually identical, the timbre of both strings would be virtually identical. If the makers had chosen to make the G♯ strings, say, 1200 mm long, the value of B (0.0190) would have differed significantly from that of the A strings, and their timbres could not be expected to be similar.

The apparent success of Broadwood and his collaborators in matching the inharmonicities at the crossover point, that is, in maintaining a uniform voice, is all the more remarkable in that the theory of inharmonicity was not to be developed for another century. Even the great Helmholtz, in the middle of the nineteenth century, seems not to have addressed this issue. The first inklings of an understanding, however, seem to have arisen in the late eighteenth century. Dovaston writes of the superior hardness and elasticity of iron as important factors of its tonal qualities. In the paper read to the Royal Society in 1788, in which he proposes a new temperament determined by the precise division of string lengths, Cavallo states that the "number of vibrations performed in a certain time principally depends on the thickness, length, and elasticity of the sonorous bodies."[55] The elasticity of bodies sounding as idiophones, such as xylophone bars and lamellaphone tongues, plays an important role in determining their pitch. Cavallo, like any competent scientist, must have known, however, that the inherent elasticity of a string under tension has nothing to do with its pitch. Thus, his inclusion of the term "elasticity" in a discussion about strings should be regarded as a slip of the pen.[56]

In 1800 the physicist Thomas Young wrote that "in some cases, a nice ear will discover a slight imperfection in the tune of harmonic notes."[57] Nevertheless, these observations were more qualitative than quantitative, and the theorists of this period did no better than to write vaguely

55. Cavallo, "Temperament," 238.

56. This might well have occurred because he was at the same time working on another scientific project, the collaboration with John Broadwood and E. W. Gray which, according to J. S. Broadwood, led to the division of the bridge. Here, as we have seen, the elasticity of the string material is indeed an important factor in determining its timbre.

57. Thomas Young, "Outlines of Experiments and Inquiries respecting Sound and Light," *Philosophical Transactions of the Royal Society of London* for the year 1800, part 1:139.

about proportionality. With musical instruments, of course, the decisive test is in the hearing, but it is heartening to demonstrate by modern analysis the acuity of the "nice ears" of early piano makers and the natural philosophers who advised them.

There is one further aspect of maintaining a uniform voice at the crossover point: loudness. One might expect the brass G♯ strings, which, as has been shown, are under considerably less tension than the adjacent iron A strings, to sound softer. The bass bridge, however, is farther from the edge of the soundboard than the bridge for the iron strings. Thus the structure of the bass bridge and soundboard is less rigid than the structure of the treble bridge and soundboard. The very division of the bridge, which if undivided would act as a stiff rib along the entire soundboard, also contributes to the flexibility of the soundboard in the bass. The less tense brass strings presumably drive their more flexible bridge with an overall efficiency approximately equal to that with which the tauter iron strings drive their more rigid bridge.[58]

From our observations of the instruments we can infer that Broadwood and his fellow British makers applied two general principles of design in dividing the bridge. First, bass strings of brass, being inherently less stiff than the iron strings in the treble, should be given a shorter c^2-equivalent scale in order to match the timbres of the two types of strings. Second, strings that pass over the bridge attached to a rigid area of the soundboard should be stretched with more tension than strings passing over the bridge attached to a less rigid area.

A final aspect of these makers' stringing technique is their reduction of string diameters in the treble. This practice, adopted from traditional harpsichord making, also makes acoustical sense. In the denominator of the formula for the coefficient of inharmonicity (B), the frequency (F) is squared while the length (L) is raised to the fourth power; hence the inharmonicity would increase by a factor of four at each higher octave if the string diameter remained the same. (The increase in F and inverse decrease in L as the compass ascends would cancel each other out if these terms were raised to the same power.) A decrease in string diameter offsets, to a certain extent, this fourfold increase. Further, because the ear is more sensitive to the higher frequencies

58. The theoretical bases for this supposition are discussed in Arthur H. Benade, *Fundamentals of Musical Acoustics*, 2nd rev. ed. (New York: Dover Publications, 1990), 328–32.

toward the top of the keyboard compass,[59] the reduction in transmitted acoustical energy on account of the thinner strings and stiffer soundboard would help to maintain an even level of perceived loudness. Thus, through a combination of traditional, ultimately empirical techniques and new scientific insight, eighteenth-century British makers designed grand pianos that can be shown to have been well conceived according to the standards of modern physical analysis.

Striking Developments

The string lengths of Broadwood grand pianos remained virtually unchanged from the early 1790s until about 1820. In contrast, the striking points and their ratios with the string lengths change quite significantly from instrument to instrument, as can be seen in Table 2 above and in Table 6. The seemingly arbitrary variation in striking-point ratios suggests either that workshop standards were lax or that makers were constantly striving for improvement. It is reasonable to assume that the latter is true. If so, neither the harpsichord-making tradition nor, initially, the science of the day would have been of much help to Broadwood.

From our twentieth-century perspective, it has long been established that a musical string sounds many upper partial tones (also sometimes called overtones or harmonics) in addition to its fundamental tone; that the timbre depends on the relative strengths of the various partials; and that these strengths are affected, in a manner that can be described mathematically, by the point at which the string is plucked or struck. Although these three concepts are closely related, they were discovered and described rigorously only gradually over a period of centuries. That different plucking points result in different timbres must have been known from the earliest times, but this necessarily remained an imprecise observation before the concept of upper partials was developed. In 1636, for example, as great an acoustical scientist as Marin Mersenne offered only a brief subjective report that the timbre of a lute string becomes harder (*plus dur*) as one plucks closer to the bridge.[60] Although harpsichord makers obviously fixed their plucking points with

59. Ibid., 228–31.

60. Mersenne, *Harmonie Universelle* 3:56 (i.e., "Livre second des instruments à chordes," prop. 3); in Chapman's translation, 84.

TABLE 6. String lengths in mm (L), striking points in mm (S), and ratios (L/S) of four Broadwood grand pianos

	1799			1806			c. 1808			1817		
Note	L	S	**L/S**	L	S	**L/S**	L	S	**L/S**	L	S	**L/S**
c^4	72	7	**10.3**	75	6	**13.6**	73	5	**14.6**	73	6	**12.2**
f^3	97	9	**10.8**	99	6	**16.5**	100	5	**20.0**	—	—	—
c^3	131	12	**10.9**	131	10	**13.7**	131	8	**16.4**	132	7	**18.9**
f^2	198	17	**11.6**	200	18	**11.4**	201	17	**11.8**	—	—	—
c^2	403	40	**10.1**	270	26	**10.4**	272	25	**10.9**	268	18	**14.9**
f^1	539	56	**9.6**	409	42	**9.6**	413	42	**9.8**	—	—	—
c^1	814	88	**9.2**	542	59	**9.2**	548	57	**9.6**	544	51	**10.7**
f	1098	120	**9.2**	814	91	**8.9**	864	90	**9.6**	—	—	—
c	1100	124	**8.9**	1091	120	**9.0**	1096	118	**9.3**	1105	110	**10.0**
A	—	—	—	1305	138	**9.4**	1306	135	**9.3**	1304	129	**10.1**
G♯	—	—	—	1076	130	**8.3**	1080	125	**8.6**	1077	120	**9.0**
F	1271	139	**9.1**	1267	136	**9.3**	1265	135	**9.4**	—	—	—
C	1551	152	**10.2**	1551	148	**10.4**	1540	146	**10.5**	1524	135	**11.3**
FF	1724	170	**10.1**	1723	167	**10.3**	1720	165	**10.4**	—	—	—
CC	—	—	—	—	—	—	—	—	—	1926	163	**11.8**
Location	Royal College of Music, London (data from Elizabeth Wells)			Colonial Williamsburg, Virginia (data from John Watson)			Metropolitan Museum of Art, New York			Neumeyer Collection, Bad Krozingen, Germany		

great skill, these points seem to have been determined empirically, that is, by what sounded well, or according to some principle unrelated to nineteenth-century concepts of rational striking points in pianos.[61] A. J. Hipkins, finding plucking-point ratios varying radically throughout the compass of typical harpsichords, commented that they were "all without apparent rule or proportion" and that "no attempt appears to have been made to gain a uniform striking [i.e., plucking] place throughout the scale."[62] Indeed, there would have been no reason to make such an attempt in that the scientific theory as to how a particular plucking-point ratio affects a string's timbre did not exist in the heyday of the harpsichord.

As noted earlier in this article, Hipkins thought that John Broadwood, upon the advice of the scientists Tiberius Cavallo and E. W. Gray, had applied a consistent one-ninth striking point to grand pianos around 1788. Our Tables 2 and 6 show, on the contrary, that no such consistent ratio is to be found in his instruments of the period. Indeed, a consideration of the development of the scientific theory reveals that, while some important groundwork had been done in the seventeenth century, it remained insufficiently advanced in 1788 for Cavallo and Gray to have been any more enlightened than harpsichord makers had been.

Mersenne seems to have been the first to publish a clear account of the observation that a string, in addition to its fundamental tone, simultaneously sounds other tones at the octave, twelfth, superoctave, and seventeenth.[63] In 1677 John Wallis reported experiments which would help to establish, more firmly than Mersenne had attempted to demonstrate, that a string can vibrate not only along its entire length

61. Harpsichord makers might commonly have followed procedures combining empiricism with a mathematical scheme similar to that described in Johann Philipp Bendeler's *Organopoeia* (Frankfurt and Leipzig, [1690]; facs. reprint, Amsterdam: Frits Knuf, 1972), 45; a translation of this passage is in Hubbard, *Three Centuries of Harpsichord Making,* 279. Bendeler recommended that a pleasant-sounding plucking distance for c^1 be determined by ear; this distance was then halved for c^3 and doubled for C. It is noteworthy that the ratios of the string lengths with the plucking distances were not considered at all. Only in Flemish virginals of the *muselar* type does one find a consistent plucking-point ratio of about half the string length (44% or 4/9) throughout the compass. This, however, can be considered a special case dependent upon the unique timbre of center-plucked strings.

62. Quoted by Ellis in his 1885 edition of Helmholtz, *Sensations of Tone,* 77.

63. Mersenne, *Harmonie Universelle* 3:208–11 (i.e., "Livre quatriesme des instruments à chordes," prop. 9); in Chapman's translation, 267–71.

but also in sections corresponding to integer divisions of the length.[64] That is, as we would say today, that a string vibrates not only at its fundamental frequency but also in integral multiples of that frequency. Wallis even went so far as to note that the sound of a string was less clear when it was "struck" at one of the resting places (today called nodes) between the sections of the string, that is, for example, at its midpoint between the two halves vibrating at the octave or at the one-third point, between sections vibrating at the twelfth. He suggested that the perceived lack of clarity was caused by the motion of points that would otherwise be at rest between the vibrating sections. This type of inquiry, however, seems to have been abandoned for more than a century.

Cavallo, in the acoustical section of his *Elements of Natural or Experimental Philosophy,*[65] included a footnote referring to a paper published by Thomas Young just three years previously, in 1800. Young's paper, written in the form of a letter to none other than Edward Whitaker Gray, Secretary of the Royal Society, contains descriptions of the different closed curves that a single point on a string follows:

> Take one of the lowest strings of a square piano forte, round which a fine silvered wire is wound in a spiral form; contract the light of the window, so that, when the eye is placed in a proper position, the image of the light may appear small, bright, and well defined, on each of the convolutions of the wire. Let the chord [i.e., string] be now made to vibrate, and the luminous point will delineate its path, like a burning coal whirled round, and will present to the eye a line of light, which, by the assistance of a microscope, may be very accurately observed. . . . [W]hen a chord vibrates freely, it never remains long in motion, without a very evident departure from the plane of the vibration; and . . . it is thrown into a very evident rotatory motion, more or less simple and uniform according to the circumstances. Some specimens of the figures of the orbits of chords are exhibited in Plate VI. Fig. 44 [see fig. 7a]. At the middle of the chord, its orbit has always two equal halves, but seldom at any other point. The curves of Fig. 46 [see fig. 7b], are described by combining together various circular motions, supposed to be performed in aliquot parts of the primitive orbit: and some of them approach nearly to the figures actually observed. When the chord is of unequal thickness, or when it is loosely tended [i.e., under low tension] and forcibly inflected, the

64. "Letter to the Publisher, concerning a new Musical Discovery," *Philosophical Transactions* [of the Royal Society of London] 12 (23 April 1677; facs. reprint, New York: Johnson Reprint Corporation and Kraus Reprint Corporation, 1963): 839–42. Joseph Sauveur independently published similar results in 1701: see Albert Cohen, *Music in the French Royal Academy of Sciences: A Study in the Evolution of Musical Thought* (Princeton: Princeton University Press, 1981), 28.

65. Cavallo, *Elements,* 320–21.

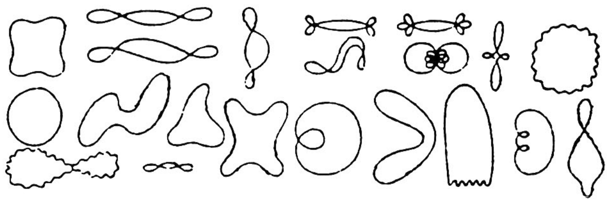

FIGURE 7A. Orbits of a point of a vibrating string observed by Thomas Young.

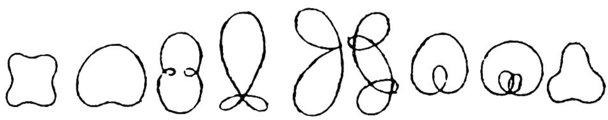

FIGURE 7B. Similar orbits that Young constructed mathematically. Reproduced from *Miscellaneous Works of the Late Thomas Young,* edited by George Peacock (London, 1855), vol. 1, figs. 104 and 106.

> apsides and double points have a very evident rotatory motion. The compound rotations seem to demonstrate to the eye the existence of secondary vibrations, and to account for the acute harmonic sounds which generally attend the fundamental sound. There is one fact respecting these secondary notes, which seems intirely to have escaped observation. If a chord be inflected at one-half, one-third, or any other aliquot part of its length, and then suddenly left at liberty, the harmonic note which would be produced by dividing the chord at that point is intirely lost, and is not to be distinguished during any part of the continuance of the sound.[66]

As would seem to be typical of much of Young's writing,[67] the ideas in this passage are rather awkwardly and obscurely expressed, and the concepts in adjacent sentences are not always directly related. Nevertheless, it is clear enough that he describes a technique for the analysis of periodic motion similar to those developed later in the nineteenth century, such as J.-A. Lissajous's figures, Charles Wheatstone's kaleidophone, and the vibration microscope.[68] The circular motion of the

66. Young, "Sound and Light," 135–38. In his footnote, Cavallo quotes the first two sentences of this passage.

67. See Edgar W. Morse, "Young, Thomas," *Dictionary of Scientific Biography,* edited by Charles Coulston Gillispie (New York: Charles Scribner's Sons, 1976) 14:568–69; and Isaac Todhunter, *A History of the Theory of Elasticity and of the Strength of Materials,* edited and completed by Karl Pearson (Cambridge: The University Press, 1886) 1:82–83.

68. See John Tyndall, *Sound,* 3rd rev. and enlarged ed. (New York: D. Appleton, 1897), 160–64 and 410; and Helmholtz, *Sensations of Tone,* 80–82.

string (i.e., a rotation around the center of the string at rest, similar to the rotation of a child's jump rope), presumably at the fundamental frequency, combines with the vibratory motions at the frequencies of the upper partials to form the curves described. By means of observing these complex curves, the harmonic components of a string's vibration could be visualized and analyzed.[69]

The last sentence in the above passage from Young's paper is of critical importance. The work that led Young to this observation was inspired by Wallis's paper of 1677: Young mentions that the "observation of DR. WALLIS [concerning the lack of clarity in the tone of a string activated at its nodes] seems to have passed unnoticed by later writers on harmonics."[70] Young's clearly stated discovery that (in modern language) an upper partial will not sound if the string is activated at a node of that partial was an important advance beyond Wallis's subjective report, and became known as "Young's Law."[71] According to this law, for example, the plucking of a string at its midpoint prevents the sounding of any partial with a node at that point: the octave, fifteenth, nineteenth, and so on, are absent, leaving a strong fundamental, twelfth, seventeenth, and so on. The ear perceives this sound, in subjective terms, as full and hollow.

The passage in Cavallo's *Elements* to which he appends the footnote referring to Young is as follows (to which I have added italics to distinguish information that is not mentioned by Young):

> [T]he strings of musical instruments in their vibrations, *especially at first,* form curves somewhat different from each other, according to the different methods by which they are caused to vibrate, viz. whether they be struck in

69. The "rotatory motion" of the apsides and double points evident to Young in certain instances would have been caused by inharmonicities or by the increase in tension and consequent rise in pitch when a string was plucked too strongly. When the fundamental tone and upper partials are in perfect tune with each other their frequencies are in simple integral numerical relationships, and the apsides and double points are formed at exact intervals of one-half, two-thirds, one-quarter, one-fifth (etc.) of the fundamental vibrational period of the string. They therefore form stable figures with two-, three-, four-, or five-fold (etc.) symmetry, or more complex multiple combinations. When the upper partials are not exactly in tune, the intervals are slightly shorter (or longer) than these simple fractional relationships, and the figures traced by the spot of light do not "close": successive tracings of the apsides or double points progress in one direction or the other around the center, that is they appear to rotate.

70. Young, "Sound and Light," 139.

71. See, for example, Helmholtz, *Sensations of Tone,* 52.

> the middle or close to one end; whether by the application of *a finger, or a quil* [sic], or a bow, *&c.*[72]

Thus, it would seem that Cavallo conducted his own experiments using Young's methodology. Obviously, Cavallo would have been familiar with Young's Law, and some of his experiments might well have explored its implications. Further, he or Dr. Gray, the Royal Society's official recipient of Young's paper, might have advised Broadwood to contrive a striking-point ratio of one-ninth so as to suppress the supposedly discordant harmonic that is three octaves and a whole tone above the fundamental.[73]

That Broadwood, for a short time, might actually have heeded such advice is suggested by three pianos of 1804, in which a ratio close to one-ninth is found in the central three octaves of the compass, from about F to f^2, as shown in Table 7. Thus, it is possible to distinguish two phases of scientific influence on Broadwood's work, the first in the late 1780s, when the bridge was divided in order to match the timbre of the brass and iron strings, and the second, concerning a rational striking point, shortly after 1800. The two episodes might well have become conflated in James Shudi Broadwood's memory by the time he would have recounted them to Hipkins decades later. (Alternatively, perhaps there was an ongoing decades-long collaboration between the Broadwoods and their scientific colleagues. Frequent consultations might have been deemed necessary as thicker and thicker stringing schemes were introduced over the years.) If J. S. Broadwood had mentioned to Hipkins something about the adoption, long before, of a one-ninth

72. Cavallo, *Elements,* 2:320.

73. Pianos made before the discovery of Young's Law in 1800 are occasionally found to have rather consistent striking-point ratios. An example by Robert Stodart, 1784, in which the ratio is about one-twelfth throughout much of the compass, is shown in Table 2. Another, by Pascal Taskin, Paris, 1787, with a ratio of about one-seventeenth, is descibed in my "Two Early French Grand Pianos," *Early Keyboard Journal* 12 (1994): 27. Indeed, the striking-point ratios of pianos are in general much more consistent throughout their compass than the plucking-point ratios of harpsichords, which are typically about one-tenth or one-twelfth in the bass but gradually increase to about one-half in the extreme treble. In pianos, however, an efficient transfer of energy from hammer to string requires that the point of contact be relatively close to the end of the string throughout the compass. Some makers seem to have conceived a systematic solution to this mechanical necessity by adopting a more or less constant striking-point ratio, with the particular ratio determined empirically, according to the tone quality that was desired.

TABLE 7. String lengths in mm (L), striking points in mm (S), and ratios (L/S) of three Broadwood & Son grand pianos made in 1804

	Serial no. 2851			Serial no. 2861			Serial no. 3027		
Note	L	S	**L/S**	L	S	**L/S**	L	S	**L/S**
c^4	71	7	**10.1**	72	7	**10.3**	68	6	**11.3**
f^3	99	9	**11.0**	101	10	**10.1**	98	8	**12.2**
c^3	133	11	**12.1**	134	13	**10.3**	132	12	**11.0**
f^2	206	22	**9.4**	205	21	**9.8**	203	22	**9.2**
c^2	277	30	**9.2**	275	29	**9.5**	273	31	**8.8**
f^1	415	50	**8.3**	413	47	**8.8**	411	46	**8.9**
c^1	552	64	**8.6**	549	63	**8.7**	547	62	**8.8**
f	824	96	**8.6**	829	95	**8.7**	823	94	**8.8**
c	1101	126	**8.7**	1103	123	**9.0**	1100	124	**8.9**
A	1310	144	**9.1**	1310	141	**9.3**	1307	138	**9.5**
G♯	1085	132	**8.2**	1083	130	**8.3**	1079	127	**8.5**
F	1272	138	**9.2**	1268	138	**9.2**	1265	138	**9.2**
C	1553	154	**10.1**	1544	149	**10.4**	1550	150	**10.3**
FF	1729	180	**9.6**	1723	167	**10.3**	1722	160	**10.8**
Location	Private Collection, England (data from M. Latcham)			Private Collection, The Netherlands			Museum of Fine Arts, Boston		

striking-point ratio, Hipkins, evidently not bothering to examine and measure the strings of obsolete pianos, would not have known that this practice was soon discontinued. Further, he seems to have misinterpreted J. S. Broadwood's talk of "due tension" as "equal tension": according to the later nineteenth-century principles of piano design known to Hipkins, due tension was indeed equal tension.[74]

The adoption of a somewhat consistent one-ninth striking point ratio evident in the instruments of 1804 was apparently a short-lived experiment. Although a Broadwood piano of 1805 (in the collection of Marlowe Sigal, Newton Centre, Massachusetts, whom I thank for information about it) has quite similar striking points to those used in 1804, as early as 1806 (see Table 6) the one-ninth ratio was beginning to be abandoned, at least in the treble. The Broadwoods evidently soon reverted to the traditional practice of determining striking points by what sounded best to their ears, an approach they seem to have followed also in the determining of appropriate string lengths and tensions.

This method, one must realize, is more scientific than the application of such naïvely rational standards as equal tension or striking points set at a simple numerical ratio. The piano is not just strings and striking points. It is part of a complex musical system that begins in the mind of the composer and ends in the mind of the listener. Analysis according to modern acoustical science can begin to explain some aspects of this system and to demonstrate reasons for the success of the early makers' efforts. The Broadwoods' early rejection of a strictly mathematical approach in determining striking points should not obscure the significant truths that the foundations of modern acoustical science were well established by about 1800 and that the piano makers put this knowledge to practical use in their instruments.

Later Developments

To view the Broadwoods' achievements in perspective, we should briefly consider some later developments in the nineteenth-century history of striking-point ratios, the divided bridge, and associated techniques of stringing and scaling. In 1885, Hipkins, in the same text in which he discussed the history of the divided bridge and rational striking point, noted that "the present head of the firm of Broadwood (Mr.

74. This is discussed below.

Henry Fowler Broadwood) has arrived at the same conclusions as Kützing with respect to the superiority of the ⅛th [striking point] distance, and has introduced it in his pianofortes."[75] That Hipkins reported this correctly is shown by a Broadwood grand piano of about 1876 (at the Shrine to Music Museum; cat. no. 4186) in which the striking-point ratios are *exactly* one-eighth from AAA to about c^2. Thus, what Hipkins wrote misleadingly about John Broadwood—"he practically adopted a ninth of the vibrating length of the string for his striking place, allowing some latitude in the treble"—could, merely by changing "ninth" to "eighth," be applied correctly to the work of his grandson.

During the 1820s, as the historical progression of stringing pianos with heavier and heavier gauges of wire continued in an effort to increase the loudness of the instrument, a point was reached in which the thick, relatively short brass strings crossing over the bass section of the divided bridge in grand pianos became too stiff to sound well. That is, the rigidity of these strings caused the inharmonicity of the tone to increase beyond tolerability. The requisite flexibility of the bass strings was restored by using covered strings consisting of a thin, flexible core wire with a second wire wrapped around it to increase the weight (as had been done in square pianos since the 1760s). Data from a Broadwood grand piano of about 1837 analyzed by Rose and Law[76] suggest that when the Broadwoods did this they preserved the traditional relationship that we have observed in earlier instruments with divided bridges: the top note (D♯) with covered strings has a total tension of about 100kgf, while the total tension of the first note (E) strung with plain iron (or steel) wire is nearly 150 kgf. By about 1880, however, Hipkins wrote that piano makers "should be guided by . . . equality of tension as far as the scale will admit."[77] In a pamphlet of 1885 he lists the tension for each note of Broadwood's top-of-the-line "Iron [i.e., iron-framed] Concert Grand Piano."[78] Here, one assumes, he intended

75. Quoted by Ellis in Helmholtz, *Sensations of Tone,* 77. Carl Kützing was a Swiss theorist of piano design who in the early 1840s determined that a striking-point ratio of one-eighth was "indisputably the best": see his *Das Wissenschaftliche der Fortepiano-Baukunst* (Bern, Chur, and Leipzig, 1844), 41.

76. Rose and Law, *Handbook,* 49 and 170.

77. Hipkins, "Pianoforte," in Grove's *Dictionary,* 1st ed., 2:723.

78. *International Inventions Exhibition, Division – Music, John Broadwood & Sons* (exhibition catalogue; London, 1885), 35–36. Although this pamphlet was published anonymously, an autographed copy on which Hipkins designates himself as the author is in my possession.

to illustrate the practical application of the equality principle. His data show that, except for the nine lowest notes, the tensions deviate by less than 9% from a median value of 204 kgf and that the tension falls by less than 12% at the crossover point from plain steel to covered strings, where the bridge is divided (between C♯ and D). The equality of tension advocated by Hipkins was (except for a fleeting application by Robert Wornum about 1820, mentioned in note 42 above) evidently an innovation of the third quarter of the nineteenth century. This concept was later promoted as a basic principle by twentieth-century theorists of piano design.[79] In adopting this principle, the late-nineteenth-century Broadwood firm seems to have abandoned one of the basic precepts that we have inferred was originally associated with the division of the bridge in the eighteenth century, i.e., that the tension of the strings crossing the section of the bridge in a less rigid area of the soundboard should be less than that of the strings crossing the bridge in a more rigid area.

Although the Broadwood piano described by Hipkins in 1885 had the traditional straight-strung layout, already in 1859 Henry Steinway, Jr., had obtained a patent for over-strung (also called "cross-strung") grand pianos.[80] In these, the bass section of the bridge was moved to the area of the soundboard between the main bridge and the bent side, with the covered bass strings crossing over the plain steel strings. Nevertheless, the traditional scaling relationship, in which the highest bass string is shorter than the lowest plain steel (formerly iron) string, was retained: in a Steinway grand piano of 1867 at the Shrine to Music Museum (cat. no. 3173), for example, C♯ is 1641 mm long, while D is 1795 mm. Arthur H. Benade has calculated the tensions and inharmonicities of the adjacent covered and plain strings at the crossover point of a modern over-strung Steinway piano.[81] Although he found that the

79. See, for example, Hansing, *The Pianoforte and Its Acoustic Properties,* 83; White, *Theory and Practice of Pianoforte Building,* 54; and Wolfenden, *Treatise on the Art of Pianoforte Construction,* 19 ff. There remains some question as to exactly what the concept of equal tension meant to each theorist and maker. In the Broadwood Concert Grand Piano described in Hipkins's pamphlet of 1885 (see footnote 78 above) the total tension of each *note* is approximately equal to the others, whether it be unichord (AAA to EE), bichord (FF to GG), or trichord (GG♯ to a^4). Some of the later writers specify equality for each *string.* (However, this question is irrelevant to early English instruments: square pianos were bichord throughout their compass, grands were trichord.)

80. See Cynthia Adams Hoover, "The Steinways and Their Pianos in the Nineteenth Century," this JOURNAL 7 (1981), 54 and fig. 13.

81. Benade, *Fundamentals of Musical Acoustics,* 345–46.

inharmonicities match quite closely, just as we have found at the crossover points of late-eighteenth-century English pianos, he discovered that the tension of the covered strings was considerably higher[82]—a situation that is the reverse of the early English practice. Nevertheless, the modern Steinway practice of setting the tensions at the crossover point is in principle essentially the same as John Broadwood's. As Benade observed, because the Steinway piano's bass strings are associated with a bridge-soundboard system which is stiffer than that for the treble strings, the bass strings must be higher in tension in order to maintain an even voice. Therefore, Steinway's design is just a rearrangement and reversed application of what we have observed in early Broadwood pianos with divided bridges: the strings crossing the section of the bridge in the less rigid area of the soundboard are still stretched by a lesser tension.

Steinway's introduction of the over-strung design into their grand pianos, long regarded as a decisive event in the development of the modern instrument, should be seen as the echo of a previous and even more decisive innovation, John Broadwood's introduction of the divided bridge, accomplished about seventy years before Steinway's patent of 1859. At the conclusion of Benade's analysis of "the problem of making a smooth transition from the full-length plain wire strings to the sequence of shortened wound strings that function for the lowest notes" in a modern Steinway piano, he wrote that we "have here a good example of the way in which painstaking traditional craftsmanship has learned over many years of experience to meet musico-acoustic requirements, some details of which we have come to recognize only in recent years."[83] It is astounding for us now to realize that the essential technical elements of the solution to the problem were devised more than two hundred years ago by John Broadwood and his scientific advisors.

Back to Backers and Before

As we have seen, Broadwood divided the bridge to alleviate a problem caused by the use of two different string materials, brass and iron. Dovaston's parenthetical remark that stringing "entirely with brass . . .

82. Wolfenden, in *Treatise on the Art of Pianoforte Construction,* 22, describes a similar deliberate increase in tension for the upper covered strings in order to equalize their flexibility and hence their tone with the flexibility and tone of the lowest plain strings. Paul Poletti has pointed out to me that some modern Steinway models do not have the same change of tension at the crossover point as that observed by Benade.

83. Benade, *Fundamentals of Musical Acoustics,* 346.

formerly was the common practice" suggests that there was an earlier phase of English grand piano making in which iron strings were not used. Dovaston's allusion to an all-brass phase probably refers to the work of Americus Backers, whose role as the virtual creator of the English grand piano has been confirmed by recent scholarship.[84] That Backers was remembered as such in the Broadwood circle from which Dovaston's information must have originated is shown by a letter in *The Gentleman's Magazine* of January 1812, signed by "C. J. S.," who quotes a letter that he had received from James Shudi Broadwood, stating that "the first maker of the Grand Piano Forte was H. Baccers, a Dutchman, who in 1772, invented nearly the mechanism [i.e., the standard English action], by which it is distinguished from the instrument with that name in Germany."[85]

The earliest extant English grand piano was indeed made in 1772 by Americus Backers (as his name appears on the nameboard and in J. S. Broadwood's memoirs of 1838), and is now at the Russell Collection in Edinburgh.[86] Its treble strings are rather short in comparison with those of other early English grand pianos with undivided bridges—Backers's c^2 length of 259 mm, for example, is 20 mm shorter than that in the Robert Stodart piano of 1784 shown in Table 2—suggesting a scaling more appropriate for brass than for iron strings. Thus we might infer that some time in the late 1770s or early 1780s a deliberate decision was made to improve the deficient tone of brass-strung treble notes by lengthening their scalings and switching to iron wire, which, Dovaston observed, "possesses a brilliancy which is not to be obtained from Brass." This may have been done by Backers in his later work (no example of which is extant), or perhaps more likely by Stodart, as the principal British maker of grand pianos between Backers's death in 1778 and the time when Broadwood seems to have begun making large numbers of grand pianos in the latter half of the 1780s.[87]

84. See Warwick Henry Cole, "Americus Backers: Original Forte Piano Maker," *The Harpsichord and Fortepiano Magazine* 4, no. 4 (October 1987): 79–85, a fundamentally important source for authoritative information about Backers's life and work.

85. "A Series of Letters on Acoustics . . . Letter I," *The Gentleman's Magazine* 82 (new series 5), no. 1 (January 1812): 11.

86. The instrument is described by Sidney Newman and Peter Williams, *The Russell Collection and other Early Keyboard Instruments in Saint Cecilia's Hall, Edinburgh* (Edinburgh: Edinburgh University Press, 1968), 52–53; and by Warwick Henry Cole, "Americus Backers," 80–83. I have also examined the instrument.

87. This historical sequence (Backers to Stodart to Broadwood) is reported in *Some Notes Made by J. S. Broadwood,* 12.

It has long been recognized that the English grand piano action, which was already present in an almost fully developed form in the Backers instrument of 1772, is a simplified derivative of the action found in the several earliest extant pianos, made by Bartolomeo Cristofori in the 1720s.[88] Those writers who have considered how Backers might have learned about the Cristofori action have suggested or even assumed that Backers, who was said to have been of Dutch or German birth, was familiar with the work of Gottfried Silbermann, whose piano actions are of the Cristofori type.[89] However, exhaustive compilations of documents concerning Silbermann's career[90] do not contain the name, among his apprentices or journeymen, either of Backers or of any of the other London piano makers, such as Johannes Zumpe, who are said (or, rather, presumed) in modern sources to have learned their craft with Silbermann. Further, a comparison of Backers's work with earlier Continental grand pianos indicates that his style is closer to Cristofori's than it is to Silbermann's.[91] Thus, it would seem that Back-

88. See, for example, Good, *Giraffes, Black Dragons, and Other Pianos,* 63–64.

89. See, for example, Hipkins, "Pianoforte," in Grove's *Dictionary,* 1st ed., 2:715; Philip James, *Early Keyboard Instruments from their Beginnings to the Year 1820* (London, 1930; reprint, London: Tabard Press, 1970), 54; and Wainwright, *The Piano Makers,* 28. (Cole, in "Americus Backers," 82, errs in writing that J. S. Broadwood stated that Backers had worked for Silbermann.) Cristofori's and Silbermann's extant pianos are described by Stewart Pollens in *The Early Pianoforte* (Cambridge: Cambridge University Press, 1995); see also Pollens's "Gottfried Silbermann's Pianos," *The Organ Yearbook* 17 (1986): 103–21, and "The Pianos of Bartolomeo Cristofori," this JOURNAL 10 (1984): 32–68.

90. See especially Werner Müller, *Gottfried Silbermann, Persönlichkeit und Werk: eine Dokumentation* (Frankfurt am Main: Verlag Das Musikinstrument, 1982).

91. Silbermann's checks are turned back so that they seem to function more as hammer-head rests, while Backers's checks, like Cristofori's, actually function as checks, catching the rebounding hammer heads. Silbermann's hammer shanks are of pearwood, whereas Cristofori's and Backers's are of softwood (that is, wood from a conifer, probably spruce or fir for Cristofori, redcedar [*Juniperus* sp.] for Backers). Cristofori's and Backers's pianos have gap-spacing struts between the wrest plank and belly rail, but Silbermann's pianos have no such reinforcement. Silbermann's pianos are rather long scaled (c^2 ranges from 310 to 320 mm in length, with their transposing keyboards at the higher pitch) and are strung in iron in the treble, while Cristofori's scaling, like Backers's, is suited for brass strings throughout the compass. No specific evidence regarding Cristofori's string materials has survived (I do not agree with Pollens's suggestion, in *The Early Pianoforte,* p. 92, that Cristofori might well originally have strung his pianos with "iron wire throughout most of the compass"). However, fragments of brass wire have been found on a harpsichord-piano by his pupil Giovanni Ferrini (see Luigi Ferdinando Tagliavini, "Giovanni Ferrini and his harpsichord 'a penne e a martelletti'," *Early Music* 19 [1991]: 406), and I have found green stains from the corrosion of brass strings on the bridge and nut of a piano by Manuel Antunes, Lisbon, 1767 (at the Shrine to Music Museum, Vermillion, South Dakota, cat. no. 5055), which was obviously patterned after Cristofori's instruments.

ers was influenced by a purer form of the Cristofori style than that represented by Silbermann's work.

Although the precise avenue by which the Cristofori tradition was transferred to Backers will probably never be discovered, there are several possibilities. First, Warwick Henry Cole has found an advertisement of 1774 for the sale in London of a "Piano Forte Harpsichord made in Florence."[92] This "Piano Forte," as it was also called in the same notice, had been owned by the late conductor Stefano Carbonelli, who had come to London from Rome as least as early as 1719. Thus, if he already owned his Florentine piano before arriving in England, it might well have been made by Cristofori himself; if Carbonelli brought the piano to England later, it might have been made by Cristofori's pupil Giovanni Ferrini. The arch-shaped iron gap-spacing struts in the Backers piano of 1772 are remarkably similar to the struts in a combined piano-harpsichord made by Ferrini in 1746.[93]

A "large" piano made in Rome by an English monk named Wood represents another way by which knowledge of Italian piano-making practice could have come to London. This instrument was brought to England by Samuel Crisp, certainly before 1747, when Charles Burney saw it. Wood had presumably copied an Italian grand piano, and Burney tells us that his piano was, in turn, copied in England by Roger Plenius.[94] A third possibility, enhanced by the existence of strong

92. Quoted by Stewart Pollens in "Three Keyboard Instruments Signed by Cristofori's Assistant, Giovanni Ferrini," *The Galpin Society Journal* 44 (1991): 93.

93. Backers's struts, which are also similar to those in later English grand pianos, are visible in the photograph in Newman and Williams, *The Russell Collection,* 52; Ferrini's are shown in Luigi Ferdinando Tagliavini and John Henry van der Meer, *Clavicembali e Spinette dal XVI al XIX secolo: Collezione L. F. Tagliavini* (exhibition catalogue; Bologna: Cassa di Risparmio in Bologna, 1986), 188, and in Tagliavini, "Giovanni Ferrini," 398. Pollens, in "Three Keyboard Instruments . . . by . . . Giovanni Ferrini," 84, seems to imply that the four iron struts in the Ferrini instrument might not be original because the construction of the piano action suggests that Ferrini intended there to be seven struts. I believe that Ferrini undoubtedly did intend at first to supply seven struts, but that other unquestionably original features of the instrument (such as the layout of the harpsichord keyboard) show that only four struts were actually installed when Ferrini completed the instrument. Perhaps Ferrini reduced the number when he decided to use iron rather than wood.

94. See Charles Burney, *Memoirs of Dr. Charles Burney, 1726–1769,* edited by Slava Klima, Garry Powers, and Kerry S. Grant (Lincoln, Nebraska, and London: University of Nebraska Press, 1988), 72–73; and Burney, "Harpsichord," in Rees's *Cyclopaedia,* vol. 17 (unpaginated). Rosamond E. M. Harding (whose account in *The Piano-Forte,* 53 must stem from the latter source, although it is not cited) surely errs in stating that Wood made the piano in 1711. This is the date of Scipione Maffei's account of Cristofori's pianos, cited by Burney in the same paragraph as his account of Wood's instrument.

commercial ties between England and Portugal, is that there might have been some link between Backers and piano makers in Lisbon, who followed the Florentine tradition much more closely than did Gottfried Silbermann.[95]

If, then, the introduction of iron stringing instead of brass in the treble of English grand pianos was not derived from Silbermann's use of iron strings, the idea must have come from some other source. We need not look far: English harpsichords of the period, most notably those of Kirckman and of Shudi, were designed for treble strings of iron, as were English square pianos from their beginnings in Johannes Zumpe's work of the mid-1760s. Remarkably, Broadwood's eventual solution to the problems introduced by the use of two string materials, i.e., the divided bridge, might, like the English grand piano itself, have been derived more or less directly from Cristofori's work. Both Cristofori and his pupil Ferrini had made instruments with divided bridges.[96] These were of two types. In their harpsichords and pianos, the lowest bass strings passed over one or more small separate bridges, evidently contrived to make the soundboard more flexible and responsive to low frequencies. (These divisions do not seem to have been associated with any change in stringing material, although red brass might have been used for these low notes.) In Cristofori's and Ferrini's *cembali traversi,* as well as in the two-foot choir of a harpsichord by the former, there were jumps, associated with divided bridges and nuts, from short-scaled brass

95. See Pollens, *The Early Pianoforte,* 136–56 and Pollens, "The Early Portuguese Piano," *Early Music* 13 (1985): 18–27, in which grand pianos by Henrique Van Casteel, Lisbon, 1763, and by an anonymous maker (in the collection of Harold Lester, London) are described and compared with Cristofori's work. The Van Casteel piano is also described by L. A. Esteves Pereira in "A Forte-piano at the Instrumental Museum, Lisbon," *The English Harpsichord Magazine* 3, no. 4 (April 1983): 67–70. (I thank Christopher Nobbs for providing me with additional information about it.) A third early Portuguese grand piano is the one by Manuel Antunes mentioned in note 91 above.

96. Cristofori instruments with divided bridges are described in Hubert Henkel, *Kielinstrumente,* Musikinstrumenten-Museum der Karl-Marx-Universität, Leipzig, *Katalog* 2 (Leipzig: Deutscher Verlag für Musik, 1979), nos. 84, 85, and 86; and in Pollens, *The Early Pianoforte,* pp. 82 (fig. 3.30) and 105 (fig. 4.12). See also Pollens, "Three Keyboard Instruments . . . by . . . Giovanni Ferrini." It is likely that Cristofori had been influenced by the small separate bridges provided for the tenor and bass strings in Italian Renaissance clavichords, an example of which I have described in *Keyboard Musical Instruments in the Museum of Fine Arts, Boston,* 22–26. A clavichord attributed to Cristofori has multiple separate bridges for the bass strings: see *Die Musik in Geschichte und Gegenwart,* 2nd ed., Sachteil 2 (1995), s.v. "Clavichord," *Abb.* 2.

strings in the major part of the compass to longer-scaled steel strings for the top octave or so. (The longer scaling was undoubtedly intended to provide enough space between the bridges and nuts for the rows of jacks in the crowded treble area.) As we have seen, Italian-made pianos were present in London, and Broadwood might first have seen a divided bridge in one of these. Alternatively, two of his associates, Clementi and Cavallo, were natives of Italy, where they might have become familiar with the Florentine instruments with divided bridges. Even so, there was considerable inventiveness in the application of the divided-bridge technique to the English piano, where the idea of a jump in the scale at the change from brass to steel (which the Florentine makers did in the treble) was combined with the idea of a separate, more responsive bass bridge.

In summary, there would seem to have been four stages in the development of the grand piano in eighteenth-century England. During the first, entirely putative stage, instruments were made in a relatively pure Cristofori style. In the second, represented by the 1772 Backers piano, the instruments were, like their Italianate predecessors, short-scaled and presumably strung entirely in brass. Their actions, similar in principle to Cristofori's but simplified by the removal of the intermediate lever, were essentially of the fully developed English grand type. The third stage is represented by the early grand pianos of Stodart and Broadwood, which used longer treble scalings with iron strings in an effort to gain brilliance. The fourth and final stage is that of the divided bridge, introduced by John Broadwood in the late 1780s. Indeed, it could be argued that modern piano making remains in this fourth stage, as shown by the lasting use not only of this feature but also of concepts of rationally determined striking points first developed at the beginning of the nineteenth century as a result of the continuing collaboration between British scientists and piano makers.