Journal of the American Musical Instrument Society

VOLUME XXXVI • 2010

Gold- and Silver-Stringed Musical Instruments: Modern Physics vs Aristotelianism in the Scientific Revolution

Patrizio Barbieri

As early as the outset of the seventeenth century—above all in Italy, but also in Spain and occasionally elsewhere—we hear of gold-stringed spinets, and continue to do so up to the end of the century. Such stringing was rather expensive, so the practice was confined to aristocratic circles. Silver-stringed spinets are also mentioned, albeit less frequently.

Aside from their prestige, such strings provided an indubitable advantage. Since the density of gold is about twice that of copper alloys and iron, its use made possible a significant reduction in the length of the bass strings, thus giving rise to easily transportable 8′ instruments, especially spinets, but also harps and citterns; only at the end of the century were these expensive strings replaced by the newly invented overspun type. The use of gold was also thought to have a favorable impact on two acoustic parameters: intensity level and "sweetness" of sound. These were subject to sometimes discordant estimations by musicians of the time, as also by natural philosophers belonging to the two phases of the Scientific Revolution, Galileo and Descartes included.

This article explores the use of gold and silver strings from both historical and technical points of view. Section 1 gathers the extant documentary sources, in order to draw information regarding the diffusion of such stringing and the reasons for choosing it. Section 2 discusses sixteenth- and seventeenth-century drawing technology, together with the related mechanical properties of the drawn strings. Section 3 deals with the innovative proposals by the natural philosophers of the Scientific Revolution regarding string acoustics. Their achievements concerning vibration frequency, intensity level, and what was then called "sweetness" of sound are compared to modern quantitative definitions. In sections 4–5, these quantitative definitions and the mechanical properties of section 2 are applied to gold and silver strings, to provide objective information on their real acoustic behavior. Section 6, based on the material gathered in section 1, documents the replacement of gold and silver strings with overspun ones. Section 7 gathers information on recent use of these noble metals on harps and harpsichords. My findings are summarized in section 8.

1. The Documentary Sources

1600. In this year, Giovanni Maria Artusi provides us with the first evidence of gold and silver stringing:

> if you use gut strings on the harpsichord, its case is so large that, losing itself inside, the sound becomes mute. If you use silver strings, according to the alloy they will produce sounds one more sonorous than the other, which will however always be somewhat muted; if of gold, that of Spain, because the alloy is harder than that of Venice or elsewhere, used on citterns it will give a very sweet sound; but not all gold is good. In the harpsichord, these metals, gold and silver, used for strings produce a sound that is somewhat muted. This depends on nothing but the size of the instrument's casing, together with the nature of the metal.[1]

Artusi's rather confused observations suggest that both the loudness and the "sweetness" of sound depend on the particular alloy of the two noble metals, valuable information that will be discussed in the following sections. Inexplicable on the other hand is his observation regarding the size of the harpsichord's case.

1602. In an inventory of the Capilla Real in Madrid, we find recorded: "A small harpsichord, triangular, in the fashion of a claviorgan, with ivory keys, the soundboard of cypress, and gold strings, in a case covered [with the lid]."[2]

1. All translations in the present article are mine. Giovanni Maria Artusi, *L'Artusi ouero delle imperfettioni della moderna musica* (Venice: G. Vincenti, 1600), 6v: "se ponerete delle corde di budella sopra il clauacembalo, egli è tanto grande di corpo, che perdendovisi per entro, il suono s'ammutisce. Se adoperarete delle corde d'argento, secondo le leghe, faranno suono l'uno più sonoro dell'altro; ma tuttavia haurà sempre del muto: se d'oro, quello di Spagna, perché è di lega più dura di quello di Venetia, ò altri, poste sopra la cetra renderà suono molto soave; ma ogn'oro non è buono: Nel clauacembalo questi metalli oro, et lo argento renderanno ridotti in corde il suono, che haurà del muto; il che non può nascere da altro, che dalla grandezza del corpo dello instromento, e dalla natura del metallo insieme."

2. Madrid, Biblioteca Nacional, Papeles F. Barbieri, MS 14017/6, "Instrumentos de mussica. Tasados por Joan de Rojas Carriòn, violero en Madrid à 13 de Mayo de 1602," 2v: "Un clauicordio pequeño en triangulo à modo de clauiorgano con teclas de marphil, la tapa de cipres y cuerdas de oro en caxa cubierta." The inventory is countersigned by "Alonso de Morales, corneta de la Capilla de su mag.[d]; Joseph de Isassi, organista para los organos y clauicordios."

1604. A spinet with "gold strings" is found in Florence, at the Medici Court.[3]

1611. Sebastian Cobarruvias [Covarrubias] Orozco, author of the dictionary *Tesoro de la lengua Castellana, o Española,* remarks that some guitars, clavichords, and other keyboard instruments have strings "of silver, and if they were of gold, I think their sound would be [even] sweeter," without however providing any reasons for thinking so nor explaining what he means by "sweeter" (on this subject see §5 below).[4]

1615. From several letters of Cesare Marotta, musician to Cardinal Montalto, in Rome, a curious affair emerges, which is rather informative in this connection. Invited to a merry meeting of friends in the country, Marotta decided to take with him "our cardinal's little spinet with gold strings." After the company had listened to the precious metal strings, however, the latter were all pulled out and purloined by one of the servants. Marotta immediately took measures: "because in this city [Rome] nobody knows how to draw these gold strings, I wrote to Florence to the person who usually makes all the others installed in several spinets, and by now they have already been drawn, and it is important for me to have them soon so as to put the said spinet in order, before the Lord Cardinal comes to know about it." The payment to be sent to the "gold-drawer" (*tira l'oro*) in Florence was twenty *scudi*.[5]

This document tells us that in Rome at that time (1) no one was making these strings, and (2) the cost of the gold strings for a spinet was roughly equivalent to three months' wages for a workshop assistant, who

3. Piero Gargiulo, "Strumenti musicali alla corte medicea: Nuovi documenti e sconosciuti inventari (1553–1609)," *Note d'archivio per la storia musicale,* n.s., 3 (1985): 55–71, at 70: "Spinetta con incassatura d'ebano e corde d'oro n° 1."

4. Sebastian Cobarruvias [Covarrubias] Orozco, *Tesoro de la lengua Castellana, o Española* (Madrid: Sanchez, 1611), s.v. "Cuerda": "otras [cuerdas] son de arambre qui sirven a las citaras, monacordios, clavicordios: algunos destos instrumentos la tienen de plata, y si fuessen de oro, pienso que havian mas suave sonido."

5. See the original letters in John Walter Hill, *Roman Monody, Cantata, and Opera from the Circles Around Cardinal Montalto* (Oxford: Clarendon Press, 1997), 1:349–51: "perché in questa città [Roma] non vi è persona che sappi tirare queste corde d'oro, in tal caso ho scritto in Firenze al istesso che è solito fare tutte l'altre poste già in opera in più spinette, et à quest'hora sono già tirate, et m'importa haverle presto per potere ponere in ordine questa detta spinetta, prima che il Signor Cardinale ne sappi nulla." I thank Arnaldo Morelli for pointing out this source to me.

throughout the seventeenth century was paid 0.30 *scudi* per working day.[6]

1619. Giovanni Battista Ghivizzani, composer and keeper of musical instruments to Ferdinando Gonzaga, Duke of Mantua, was dismissed, and the duke wrote to the duchess his wife, informing her that Ghivizzani "has at home (I deem) several of my gold-strung harpsichords" and requesting her to take care to have them sent back.[7]

1622. A spinet "with gold strings" is recorded in an inventory of the princely Aldobrandini family, in Rome.[8]

1623. In his *Intavolatura di liuto, et di chitarrone,* Alessandro Piccinini remarks that "the chitarrone strung with cittern strings [i.e., metal], as is the use particularly at Bologna, gives a very sweet harmony." He adds that he has improved the instrument structurally, and has "replaced the fifth string, and the sixth, and the contrabass strings with silver threads": thus, even though the instrument is "not too big in size," it "has a very long-lasting and deep sound."[9] We do not know whether these strings were of solid silver or already of the overspun type; however, this is the first evidence bearing explicit witness to the use of a high-density metal to make it easier to go lower down. It is highly probable that Piccinini's experiments were inspired by the spinets and harps discussed in this study.

6. Whereas a *mastro* earned 0.60, and a boy (low-level assistant) 0.15 *scudi* per working day: Patrizio Barbieri, "Organi automatici e statue 'che suonano' delle ville Aldobrandini (Frascati) e Pamphilj (Roma): Monte Parnaso, Ciclope, Centauro e Fauno," *L'organo* 34 (2001): 5–175, at 30.

7. Warren Kirkendale, *The Court Musicians in Florence during the Principate of the Medici: With a Reconstruction of the Artistic Establishment* (Florence: Olschki, 1993), 335: "[Ghivizzani] ha in casa (mi pare) alcuni cimbali dalle corde d'oro di mio." I thank Pier Paolo Donati for bringing this source to my attention.

8. Franca Trinchieri Camiz, "Gli strumenti musicali nei palazzi, nelle ville e nelle dimore della Roma del Seicento," in *La musica a Roma attraverso le fonti d'archivio: Atti del Convegno internazionale Roma 4–7 giugno 1992,* ed. Bianca Maria Antolini, Arnaldo Morelli, and Vera Vita Spagnuolo (Lucca: Libreria Musicale Italiana, 1994), 595–608, at 603: "Una spinetta indorata con la tastatura d'avolio con corde d'oro con la cassa di legno bianca. . . ."

9. Alessandro Piccinini, *Intavolatura di liuto, et di chitarrone. Libro primo* (Bologna: Heredi di G. P. Moscatelli, 1623), 5: "havendogli rimesso la quinta corda, e la sesta, et li contrabassi di fila d'argento . . . tiene l'armonia lunghissima e profonda assai."

1624. The Duca d'Este having charged Count Carandini-Ferrari to procure for him, in Rome, a special kind of spinet known as the *tiorbino,* the latter replied that he had just sent the duke the instrument he wanted (Rome, January 10, 1624); he added that it had been strung in the traditional manner, "however, these musicians advise me that for these and similar instruments, and also harps, they have started to use gold strings, which they say give a sweeter tone."[10] The *tiorbino* was very probably a gut-stringed spinet.[11]

1635. In order to increase the differentiation of timbre in some of the registers of his "polyharmonic harpsichords" (all made in Rome), Giovanni Battista Doni advises the use of strings "of gold and silver, which should not be too pure, because it gives too mute a tone, but with some silver alloy."[12] In his *Annotazioni* (1640) he states that spinets made with pure (24-carat) gold "are not very lively and do not produce a good effect, except at night, when the air is calm and tranquil." He also states that he agrees with Artusi (1600) that "gold from Spain, or rather from the Indies, is better for this effect than that of Venice, or pure gold, which is too soft."[13]

10. Luigi Francesco Valdrighi, *Nomocheliurgografia antica e moderna ossia elenco di fabbricatori di strumenti armonici. . . .* (Modena: Società Tipografica, 1884), 278: "quantunque questi musici avisano essersi introdotto à questi, et simili instromenti, et anco alle arpe farvi porre le corde di oro che dicono dar maggior dolcezza al suono."

11. On this hypothesis, see Grant O'Brien and Francesco Nocerino, "The Tiorbino: An Unrecognized Instrument Type Built by Harpsichord Makers with Possible Evidence for a Surviving Instrument," *Galpin Society Journal* 58 (2005): 184–208.

12. Giovanni Battista Doni, *Compendio del Trattato de' generi e de' modi della musica. . . .* (Rome: Fei, 1635), 59: "in qualche parte del sistema adoprarne [corde] d'argento e d'oro: il quale non vuol esser puro, perché riesce troppo sordo; ma con qualche lega d'argento." Doni was probably referring to electrum, a natural gold-silver alloy used in ancient times, which elsewhere in his works he shows he is familiar with: on electrum see Herbert Maryon, *Metalwork and Enamelling: A Practical Treatise on Gold and Silversmiths' Work and Their Allied Crafts,* 5th ed. (New York: Dover Publications, 1971), 8. On the mechanical properties of gold-silver-copper alloys, see table 2 below.

13. Giovanni Battista Doni, *Annotazioni sopra il Compendio de' generi, e de' modi della musica. . . .* (Rome: Fei, 1640), 33: "Nel che si sono ingannati alcuni che hanno fatto fabricare spinette con le corde d'oro puro di 24 caratti, che riuscivano poco spiritose; et non facevano buon'effetto, se non di notte, quando l'aria è quieta, et tranquilla. Quindi è che come osservò l'Artusio l'oro di Spagna, o' più tosto dell'Indie è migliore per quest'effetto, che quello di Venetia, o' di zecchini, per esser troppo dolce."

1636–40. Doni belonged to the circle of Cardinal Antonio Barberini, whose inventories record “a spinet with gold strings.”[14] This kind of instrument must therefore have been known to Girolamo Frescobaldi, who was at that time under the patronage of the Barberinis; we have also seen that in 1620 a similar spinet was owned by the Aldobrandinis, in whose service he had been from 1610/11 to 1621.

1638. In his *Two New Sciences,* Galileo Galilei writes: “if a harpsichord is strung with gold strings and another with brass, if the strings are of the same length, size, and tension, since gold is almost twice as heavy, the tuning will be about a fifth deeper-pitched.”[15]

1644–45. Passing through Ferrara, Marin Mersenne visits Antonio Goretti’s *Wunderkammer,* where he admires three spinets made for didactic-scientific purposes, being strung with gold, silver, and steel strings respectively. He remarks that the deepest-pitched sounds are produced by the first of the three.[16] In 1646, the Jesuit physicist Nicola Cabeo noted of this gold-stringed spinet that, “although the instrument is very short, its strings, being of gold, emit a very deep sound, as if it were very large and provided with longer strings.”[17]

14. Marilyn Aronberg Lavin, *Seventeenth-Century Barberini Documents and Inventories of Art* (New York: New York University Press, 1975), 156: “Una spinetta con le corde di oro che S. Em.za fa tenere al S.r Carlo Eustachij.”

15. Galileo Galilei, *Discorsi e dimostrazioni matematiche intorno à due nuove scienze attenenti alla mechanica e i movimenti locali* (Leiden: Elseviri, 1638); modern edition in Galilei, *Le opere,* vol. 8 (Florence: Barbèra, 1933), 146: “accade che incordandosi un cimbalo di corde d’oro et un altro d’ottone, se saranno della medesima lunghezza, grossezza e tensione, per esser l’oro quasi il doppio più grave, riuscirà l’accordatura circa una quinta più grave.”

16. Marin Mersenne, *Novarum observationum physico-mathematicarum,* vol. 3 (Paris: Bertier, 1647), 165: “triplicem spinetam habet, quarum prima chordis aureis, secunda argenteis, tertia chalibeis instruitur.” See also Marin Mersenne, *Correspondance,* ed. Cornelis de Waard and Armand Beaulieu, vol. 13, *1644–1645* (Paris: CNRS, 1977), 433–34. Mersenne’s contradictory scientific ideas on the subject of pitch vs density of string material will be examined in §3.1.

17. Nicola Cabeo, *In libros Meteorologicorum Aristotelis commentaria et quaestiones,* vol. 2 (Rome: Eredes Francisci Corbelletti, 1646), 289: “cimbalum, cuius fides, quia sunt ex auro, quamvis instrumentum sit brevissimum, gravissimum edunt sonum, ac si esset valde magnum, et longarum fidium.”

1649. In the inventory of goods of Prince Pompeo Colonna, Rome, is registered a spinet with "gold strings."[18]

1653. At his death, Luigi Rossi left four harpsichords and three spinets, one of the spinets "with gold strings by Pesaro."[19] We are not told, however, whether it was strung this way when Domenico da Pesaro (fl. 1533–75) made it. In 1665 these instruments were in the hands of Giovan Carlo Rossi, Luigi's brother, who was also a musician.[20]

1665. In the inventory of Archduke Siegmund Franz, at Innsbruck, are recorded—one after the other—three "small cypress spinets," strung respectively with silver, steel, and gold.[21] The inventory does not state whether they were made for the same purpose of demonstration as those of Antonio Goretti.

1665. At his death, one Domenico Costa left in his house, in Rome, a spinet "with gold strings, according to the said signora Madalena" (Domenico's mother).[22]

1668. At Florence, a Medici inventory for the year 1700 records a spinet "levatora di cassa" (of the inner-outer type) "with gold strings," bearing the inscription "Hyeronimus de Zentis fecit Parisijs anno Domini 1668."[23]

18. Rome, Archivio di Stato, *30 Notai Capitolini,* uff. 13, vol. 316 (year 1649-II), fol. 74r, May 7, 1649: "Una spinetta coperta di velluto rosso cremesino con passaman[o] d'oro, et corde d'oro."

19. Alberto Ghislanzoni, *Luigi Rossi (Aloysius de Rubeis): Biografia e analisi delle composizioni* (Rome: Bocca, 1954), 168.

20. Alberto Cametti, "Alcuni documenti inediti su la vita di Luigi Rossi compositore di musica (1597–1653)," *Sammelbände der Internationalen Musikgesellschaft* 14 (October–December 1912): 1–26, at 24; also Rome, Archivio di Stato, *30 Notai Capitolini,* uff. 37, vol. 192, fol. 677r–v (inventory of Francesca Campana, wife of Giovan Carlo Rossi, June 26, 1665): "Una spinetta con corde d'oro del Pesaro."

21. Franz Waldner, "Zwei Inventarien aus dem XVI und XVII Jahrhundert über hinterlassene Musikinstrumente und Musikalien aus Innsbrucker Hofe," *Studien zur Musikwissenschaft* 4 (1916): 128–47, at 132: "Ein kleines Spinetl von Cypress mit silbernen Saiten . . ."; "Mehr ein dergleichen kleins Spinetl mit Stächlen [*sic*] Saiten, von Cypress . . ."; "Mehr ein anders kleins Spinetl mit goldlichen Saiten, von Cypress. . . ."

22. Rome, Archivio di Stato, *30 Notai Capitolini,* uff. 32, vol. 206, 31.8.1665 (inventory of the goods of Domenico Costa), fol. 397r: "Una spinetta con quattro piedi di colore di noce filettata d'oro con corde di oro per quanto disse detta signora Madalena."

23. Vinicio Gai, *Gli strumenti musicali della corte medicea e il museo del conservatorio "Luigi Cherubini" di Firenze* (Florence: Licosa, 1969), 7. The same instrument also

One could argue the credibility of this date, since Roman parish archives record Zenti's wife as a "widow" from as early as 1667.[24] The inventory states that the spinet had fifty-one keys, starting from *G′* (with bottom short octave and a split black key for the *B′/E♭*) and ending at *c‴*.[25] We know that Zenti had been called to Paris for the first time in 1660, on the occasion of the première of Francesco Cavalli's *Ercole amante,* performed the following year in the very large and "dead" Théâtre des machines, at the Tuileries. According to Henry Prunières, French harpsichords not being powerful enough, two large harpsichords, together with "a craftsman skilled in the art of making such instruments" (i.e., Zenti), were brought from Rome.[26]

1673. Christiaan Huygens, at this time living in Paris, notes in one of his manuscripts that "they put gold strings in small spinets to obtain a deeper-pitched bass, if the same cannot be obtained by sticking a piece of lead in the middle of the string."[27] This is the latest evidence concerning the employment of gold in solid strings.

1679. The inventory of goods of Duke Giuliano Mancini, Rome, lists a gold-strung spinet.[28]

1686. For the restoration of the harpsichords at the Court of Modena, Sebastiano Ossa procures "wire of silvered copper [silver-plated copper; see §2.1], brass wire, and steel wire."[29]

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appears in an inventory dated 1716, again at the same court: Leto Puliti, "Della vita del Ser.mo Ferdinando dei Medici Granprincipe di Toscana e della origine del pianoforte. . . ." *Atti dell'Accademia del R. Istituto musicale in Firenze* 12 (1874): 92–240, at 192.

24. Patrizio Barbieri, "Cembalaro, organaro, chitarraro e fabbricatore di corde armoniche nella *Polyanthea technica* di Pinaroli (1718–32): Con notizie sui liutai e cembalari operanti a Roma," *Recercare* 1 (1989): 123–209, at 155 (also at www.patriziobarbieri.it/pdf/pirrotta.pdf).

25. Barbieri, "Cembalaro, organaro, chitarraro," 137.

26. Henry Prunières, *L'opéra Italien en France avant Lulli* (Paris: Champion, 1913), 243.

27. Christiaan Huygens, *Oeuvres complètes,* vol. 19 (The Hague: Nijhoff, 1937), 366: "Comme l'on met des chordes d'or a des petites espinettes pour avoir des basses qui descendent bas, si on ne pourrait pas faire la meme chose en attachant un peu de plomb au milieu de la chorde."

28. Rome, Archivio di Stato, *30 Notai Capitolini,* uff. 29, vol. 252, fol. 381r, July 31, 1679: "Una spinetta depinta a fiori dentro, già detta delle corde d'oro."

29. Valdrighi, *Nomocheliurgografia,* 285: "filo di rame inargentato, filo d'ottone, e di ferro."

1689. At the death of Queen Christina of Sweden, the inventory at her Roman palace recorded a "spinet of cypress wood with two registers . . . with forty-nine gold strings," 4½ *palmi* long (about 100 cm) and nearly 2 *palmi* wide (about 44 cm).[30] This was probably an 8′ instrument.

1694. Bartolomeo Cristofori adjusts "a spinettina with gold strings" belonging to Grand Prince Ferdinando de Medici.[31]

1690–1700. In his manuscript description of musical instruments, James Talbot (1664–1708), mentions, for the bass strings of the harpsichord, "copper basses mellower than brass. Last wire argentern [lowest string of silver]."[32]

1700. A single-register spinet of the inner-outer type "with gold strings" and equipped with forty-five keys (*C/E–c‴*), is recorded in a Medici inventory.[33]

1701. An inventory of the possessions of the organist Nicolas Gigault includes "a square virginal at the octave of the tone with bass strings of silver."[34] Bearing in mind the terminology of the time, we cannot exclude the possibility that these bass strings may either have been "overspun" with silver or—recalling the document of 1686—of silvered copper.

Beginning of the eighteenth century. According to Angelo Furio of Todi (1687–1723), "the wing-shaped harpsichord furnished with strings of silver or brass demands a lower sound than the non-wing-shaped, or quadrangular spinet furnished with strings of steel."[35] Although the meaning

30. Trinchieri Camiz, "Gli strumenti musicali," 607: "una spinetta di cipresso a due registri con la statua [= tastatura] d'avolio e sopra tasti negri con sue corde d'oro n.o 49 con sua cassa di pero nero, longa palmi quattro, e mezzo, larga pal. due scarsi."

31. Raymond Russell, *The Harpsichord and Clavichord* (London: Faber and Faber, 1959), 126.

32. Frank Hubbard, *Three Centuries of Harpsichord Making* (Cambridge, MA: Harvard University Press, 1974), 262.

33. Gai, *Gli strumenti musicali della corte medicea,* 9: "Una spinetta levatora di cassa, a un registro solo, con le corde d'oro . . . con tastatura di bossolo et ebano senza spezzati che comincia in cisolfaut in sesta e finisce in cisolfaut con n. quaranta cinque tasti tra bianchi e neri. . . ."

34. Hubbard, *Three Centuries,* 316.

35. Friedmann Hellwig, "Strings and Stringing: Contemporary Documents," *Galpin Society Journal* 29 (1976): 91–104, at 103: "il cembalo codato e armato di corde

of this sentence is unclear, silver appears to be related to a lower pitch. Martin Skowroneck reports that solid silver strings were also used "in a historical clavichord by Krämer from Braunschweig, where beside the hitchpins of the two lowest string choirs (bottom *FF* and *FF♯*) the word *Silberdraht* [silver wire] was written in ink."[36]

2. Early Gold-Drawing: Technology and Alloys

2.1. Drawing technology. The art of *tira l'oro* (gold drawing) had already been described by Biringuccio in 1540 (fig. 1).[37] A gold rod was made to pass through plates provided with increasingly smaller, tapered holes, first using winches, then—when the diameter was sufficiently small—by bobbins turned simply by hand. Each time the string passed through a hole, its outer surface (the "skin") hardened, with consequent increase in the breaking stress of its whole cross-sectional area: the more the diameter is reduced, the more the "skin" increases percentage-wise as compared to the whole area. As a result, owing to the tensile pickup due to "skin-effect," the breaking stress increases progressively with the decrease in diameter (tables 1 and 2). When the wire has passed through a number of holes, it becomes hard and springy, with the danger of breaking: to prevent this, the work-hardening thus acquired is periodically lessened by annealing at suitable temperature and duration, as mentioned by Biringuccio (which, for sufficiently tiny diameters, is effected by heating the coil directly over a flame).[38] Tables 1 and 2 show that annealing considerably reduces the breaking stress and increases elongation (i.e. ductility), both for pure metals and for alloys. The final mechanical specifications of the wire thus largely depend on the number and procedure

d'argento o d'ottone richiede il suono più grave del non codato, o sia spinetta quadrangolata armata di corde d'acciaio." See the original document in Luigi Ferdinando Tagliavini, "Considerazioni sulle vicende storiche del corista," *L'organo* 12 (1974): 120–32, at 131–32.

36. Martin Skowroneck, "Recollections – Observations – Experiences," *Clavichord International* 9 (May 2005): 18–22, at 21. My thanks to Simon Chadwick and Francis Knights for this reference.

37. Vannoccio Biringuccio, *De la pirotechnia* (Venice: Roffinello, 1540), fols. 139–40.

38. On such operations, see also *Encyclopédie ou dictionnaire raisonné des sciences, des arts et des métiers,* ed. Denis Diderot and Jean le Rond d'Alembert, vol. 16 (Neufchastel: Faulche & Cie, 1765), 346–51, s.v. "Tireur d'or et d'argent" (in which, however, annealing is not mentioned, although certainly performed even at that period); Maryon, *Metalwork and Enamelling,* 42.

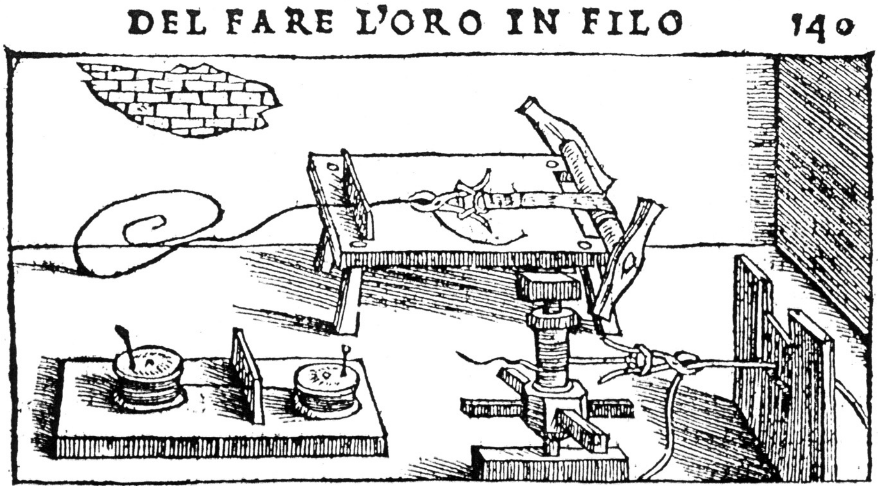

FIGURE 1. Three phases of gold drawing: initial (bottom right); intermediate (center); and final, with the string by now of very fine thickness (bottom left). Note that in the first two phases, the winch not only draws the string, but also automatically tightens the pincers on the string itself. From Vannoccio Biringuccio, *De la pirotechnia* (Venice: Roffinello, 1540), fol. 140.

of these operations, so that reliable historical data is best obtained by testing those specimens that have come down to us.[39]

From 1540 at the latest we find widespread production of the cheaper gilded silver wire—wire with a gold patina that, albeit very thin, completely covers the silver beneath. With this process, after numerous passes through the drawplate (up to about 140), diameters could be reduced to a hair's breadth and the product used to weave cloth of great value;[40] in the eighteenth century, the use of such wire was practically limited to this kind of application.[41] Like silvered copper (encountered

39. As was done by Martha Goodway and Jay Scott Odell, *The Metallurgy of 17th- and 18th-Century Music Wire* (Stuyvesant, NY: Pendragon Press, 1987), chaps. 1, 3, 5.

40. Biringuccio, *De la pirotechnia,* 140r–v describes the process. It is also described in the *Encyclopédie,* s.v. "Tireur d'or et d'argent," 347. See also Luigi Brenni, *L'arte del battiloro ed i filati d'oro e d'argento: Cenni storico-tecnici e 18 illustrazioni* (Milan: the author, 1930), 14.

41. In the *Encyclopédie,* s.v. "Tireur d'or et d'argent," the drawing of gilded silver wire is the only process described. On this type of wire, see also the shop inventory of the Roman Antonio Buti (see n44 below).

TABLE 1. Physical properties of pure gold and silver with different heat treatments and mechanical processing ("elongation" is measured at the breaking load). From Colin J. Smithells, *Metals Reference Book,* 4th ed. (London: Butterworths, 1967), 3:917 (original units for the stress: tons/inch^2).

Metal	*Breaking stress* (N/mm^2)	*Elongation* (%)
Gold, 99.99 %, soft, as cast	110	30
Gold, 99.99 %, hard, 60 % reduction	207	4
Silver, 99.9 %, soft, annealed at 600–650 °C	124	50
Silver, 99.9 %, hard	345	4

TABLE 2. Physical properties of a gold-silver-copper alloy ($Au_{750}Ag_{160}Cu_{90}$) with different heat treatments and mechanical processing. From Diego Pinton, *Tecnologia orafa: Processi produttivi, mezzi, strumenti* (Milan: Edizioni Gold, 2003), 217.

Property	*20% reduction, cold-worked*	*75% reduction, cold-worked*	*Annealed, 550 °C*	*[Quench-]hardened, 280 °C*
Breaking stress (N/mm^2)	650	800	500	550
Yield stress (N/mm^2)	550	720	300	350
Elongation (%)	2.5	1.2	35	35

in §1, 1686), not all strings declared to be "gold" were made completely of this metal: gilded silver strings were, for example, employed in 1700 by Jean Marius on his *clavecin brisé,* as we shall see in §6. However, solid gold or silver strings were certainly used, as they are clearly referred to in §1, in 1600, 1615, 1624, 1635, 1638, 1644–45, 1665, and 1673.

As far as the geographic distribution of Italian workshops is concerned, we have seen that in 1615 in Rome there were none (in that year Cesare Marotta had to send to Florence to replace the gold strings stolen from Cardinal Montalto's spinet). But as early as 1624 more than ten were recorded in the Eternal City.[42] In 1628 two Florentine artisans obtained permission from the Reverenda Camera Apostolica to introduce in Rome "the art of drawing gold and silver" according to the "use of

42. Brenni, *L'arte del battiloro,* 47–50.

Florence."[43] On the art of drawing gold and silver we have Carlo Stivani's engravings, which date from about 1640, when he too was operating in Rome (fig. 2).[44]

2.2. Alloys and mechanical properties. In gold coins, the alloying element most often employed was, and still is, copper.[45] Figure 3 shows that, among the metals known in ancient times, copper is the one that best increases the tensile strength of gold; both figure 3 and table 3 show that a content of 10% of this alloying element almost doubles the breaking stress. Even Mersenne (1636–37) confirmed that *l'or de travail* was then just 22 carats (916.7/1000), stating further that the remaining two carats were split in equal parts between copper and silver.[46]

The historical data are effectively limited to those left by Mersenne (1636–37), converted into modern units by Abbott and Segerman (1974) and by Goodway and Odell (1986).[47] According to the latter two authors, however, "these values [Mersenne's] are not credible," especially considering that (1) for gold, they surprisingly give a breaking stress higher than that of other metals now deemed better from this point of view (i.e., iron and copper alloys; see table 3); and that (2) the said value is the same both for pure gold and for its alloys (a statement

43. Rome, Archivio di Stato, *Notai della R.C.A.,* vol. 84, fol. 374, July 15, 1628. Giovanni Fontilaghi and Nicola Antonio Martinetto, both from Florence, "intendunt in Urbe introducere artem filandi aurum, et argentum ad instar bonitatis auri, et argenti quod venditum filatum in civitate Florentiae, et ad hunc officium aperire publice apotecam." On this document, see also Renata Ago, *Economia barocca: Mercato e istituzioni nella Roma del Seicento* (Rome: Donzelli, 1998), 13.

44. Brenni, *L'arte del battiloro,* 48. An interesting shop inventory of a *tira l'oro,* Antonio Buti (died Rome, October 7, 1696), can be found in Rome, Archivio di Stato, *30 Notai Capitolini,* uff. 9, vol. 563, fol. 132, 19.1.1706 ("negozio di fabrica di guarnitioni d'oro e d'argento fino, et arte afinaria, e di tira l'oro"); in it appears, among other items, "oro filato di Firenze" (137r); various metals and chemical substances (139r); a list of equipment (143v–144r), which includes "due molinelli all'italiana a due cannelle per filare l'oro, usati, *scudi* 8.00" and "due trafile d'acciaro con due razzi, et uno razzetto da tirar le verge, usato, si valuta *scudi* 15.00."

45. Albert Bordeaux, *L'or et l'argent* (Paris: Ballière & Fils, 1926), 69 (in which copper is responsible for the slight oxidation of the said coins).

46. Marin Mersenne, *Harmonie universelle* (Paris: Cramoisy, 1636–37), "Traité des instrumens à chordes," 51–52.

47. Dijlda Abbott and Ephraim Segerman, "Strings in the 16th and 17th Centuries," *Galpin Society Journal* 27 (1974): 48–73, at 57–59; Goodway and Odell, *Metallurgy,* 52–55.

FIGURE 2. Various *tira l'oro* operations by Carlo Stivani, Rome, ca. 1640. From Luigi Brenni, *L'arte del battiloro ed i filati d'oro e d'argento: Cenni storico-tecnici e 18 illustrazioni* (Milan: the author, 1930), 48. From left to right, and from top to bottom (in rather improper Italian, even for that time): "I am flattening the gold thread (*Io batto il filo di horo*); I draw the gold (*Tiro loro*); I overspin the gold on the silk (*Filo loro sopra la seta*); I melt the silver for the drawing operation (*Scuaglio largento per tiralou*); I hammer the silver bar (*Batto la verga dargente*); we draw the gold bar (*Tiramo la verga doro*)."

explicitly confirmed by Mersenne in 1648).[48] In 1600, Artusi had correctly noted that the gold of Spain is a harder alloy than that of Venice: indeed, the Venetian *zecchino* was almost pure gold (993/1000), whereas

48. Marin Mersenne, *Harmonicorum libri XII* (Paris: Baudry, 1648), 1:41. That, for musical-instrument strings, silver and gold have lesser tensile strength than steel and copper alloys is later emphasized by the Jesuit physicist Francesco Lana Terzi, *Magisterium naturae, et artis,* vol. 2 (Brescia: Ricciardi, 1686), 433: "[chordae] fieri possunt etiam ex auro, et argento, sed quia exiguo conatu extenduntur, praecipue si subtiliores sint, parum tensionis sustinent." Goodway and Odell, *Metallurgy,* 53, form the hypothesis that Mersenne followed "medieval theories regarding the properties of matter, which assumed the superiority of the noble metals gold and silver over the base metals brass and iron."

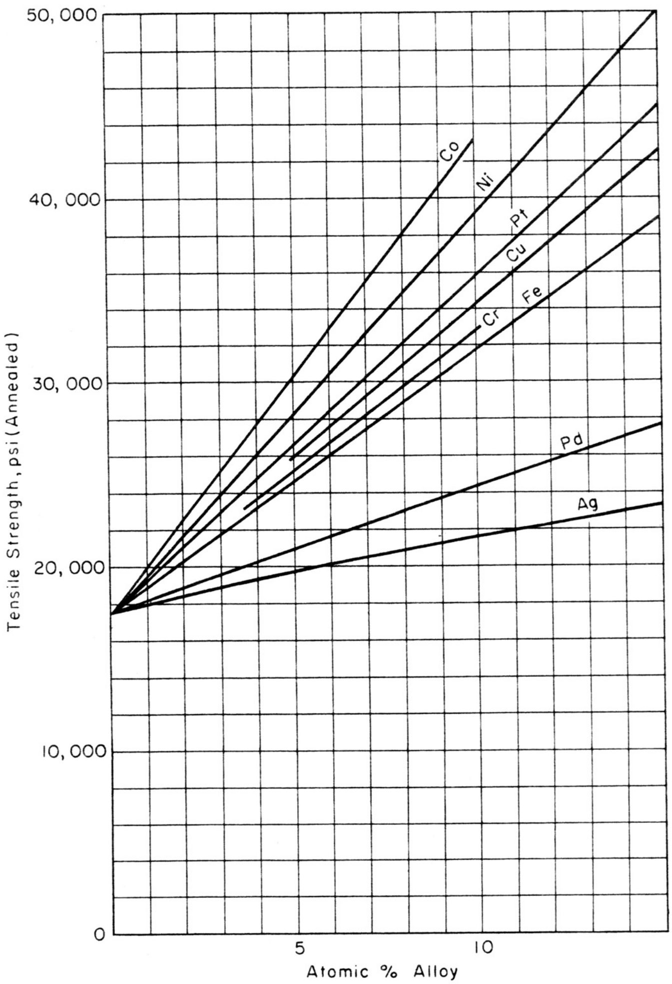

FIGURE 3. Effect of alloys on the tensile strength of gold. From Edmund M. Wise, ed., *Gold: Recovery, Properties, and Applications* (Princeton: van Nostrand, 1964), 89.

the Spanish *scudo* was made of gold alloy which, according to the mint, ranged from 875 to 917 parts per 1000.[49]

According to Athanasius Kircher (1650), the preferred gold in Rome was "aurum Hungaricum," that of the Austro-Hungarian florin, which

49. Angelo Martini, *Manuale di metrologia ossia misure, pesi e monete in uso attualmente e anticamente presso tutti i popoli* (Turin: Loescher, 1883), 819 (Venice) and 325 (Spain); Nicolò Papadopoli Aldobrandini, *Le monete di Venezia descritte e illustrate* (Venice:

TABLE 3. Physical properties of typical modern string materials. From Dijlda Abbott and Ephraim Segerman, "Strings in the 16th and 17th Centuries," *Galpin Society Journal* 27 (1974): 48–73, at 58. The values are purely indicative since, as we have seen, the properties vary greatly according to the extent of cold-working (diameter reduction) and annealing operations.

Property	*Gold*		*Silver*		*Iron*	*Copper*
	pure	$Au_{90}Cu_{10}$	*pure*	$Ag_{75}Cu_{25}$		
Density (g_m/cm^3)	[19.3]	17	[10.5]	10	7.9	8.9
Breaking stress ($\times 10^9$ dyne/cm^2)	2½	4½	3–3½	9	5½–8½	4–5
Breaking index (m × Hz)	60	80	85–90	150	130–165	105–120
Elastic modulus ($\times 10^{11}$ dyne/cm^2)	7¾	7¾	7¾	7¾	20½	10–12

was not only more ductile, but—he states surprisingly—also "purer and stronger" than others.[50] Kircher is not credible either, as his statement clashes with the previous evidence, the said coin being made of a 990/1000 alloy, almost pure gold, like the Venetian *zecchino*.[51] Furthermore, it may be observed that his association of purity with strength is clearly reminiscent of medieval theories.

For silver coins, an alloy with copper was used, mostly with a silver content of 925/1000 (i.e., "sterling" or "standard" silver); 958/1000 silver was not very widespread, owing to its low mechanical resistance.[52]

3. Vibration Frequency, Intensity Level, and "Sweetness" of Strings: The Scientific Revolution and Its Contribution to the Birth of a Quantitative Theory

3.1. On frequency: Descartes vs Galileo. It was indeed the use of gold strings in musical instruments—making possible a drastic reduction in

Tipografia Libreria Emiliana): pt. 2 (1907), 235, 246, 340, 435; pt. 3 (1919), 19. In the Republic of Genoa, on the other hand, the currency was the Genoese *scudo,* the use of the same name probably owing to the intense trade contacts between Genoa and Spain: see Giovanni Pesce and Giuseppe Felloni, *Le monete genovesi: Storia, arte ed economia nelle monete di Genova dal 1139 al 1814* (Genoa: Stringa, 1975), 314 (gold *scudo* at 911.5/1000), 312–13 (silver at 958.3/1000).

50. Athanasius Kircher, *Musurgia universalis,* vol. 1 (Roma: Eredi Corbelletti, 1650), 442: "Fila ex auro Hungarico maxime aestimantur; est enim huiusmodi aurum tractabilius, daefecatius, et robustius caeteris omnibus. Unde et omni alteri auro praefertur."

51. Martini, *Manuale di metrologia,* 116, 828.

52. Maryon, *Metalwork and Enamelling,* 11.

the instruments' dimensions—that stimulated the completion of the mathematical formula for the frequency of the vibrating string: density was, in fact, the final parameter to be included in it. The following summarizes the problem, as tackled in the first half of the seventeenth century by the natural philosophers, represented by Mersenne, Galileo, and Descartes.[53]

Until the Renaissance, it was believed that sound was generated "by the violent constriction of the air between the striking body and the struck body." Although this theory might appear valid for instruments such as the bell and the xylophone, it could not be correct for the vibrating string or the whip, since the location of the struck body was not clear. In *De anima,* Aristotle had hypothesized that, under particular conditions, this third body was constituted by the air itself: "this happens when the air after being struck resists the impact and is not dispersed. Hence the air must be struck quickly and forcibly if it is to give forth sound; for the movement of the striker must be too rapid to allow the air time to disperse."

The qualities that a string must have in order to be able to "strike the air quickly" are found not in Aristotle, but in the *Harmonics* of Ptolemy (AD 100–178). There, we read that a string strikes the air more quickly—and hence emits a higher-pitched sound—the more dense and hard its material. A copper string, all other conditions being equal, emits a higher sound than one of gut. Ptolemy adds, however, that hardness is more influential than density: copper, for example, emits a higher sound than lead because, though less dense, it is harder.

This theory was taken up by nearly all subsequent writers until the early seventeenth century. The first objection came from Mersenne, who claimed in 1626 that "experience shows that a string of hemp is lighter [i.e. has less density] and softer than one of copper alloy, yet it emits a higher sound." In the *Harmonie universelle* (1636–37) he stated that strings made with heavier metals "descend lower," without taking into account their "softness." However, experiments he himself had carried out in 1625 contained errors of measurement too large to allow him to deduce a law with any certainty. Only in 1638 was it clearly stated, in Galileo's *Two New Sciences,* that frequency is inversely proportional to the

53. With regard to what follows, all documentary references and major details can be found in Patrizio Barbieri, "'Galileo's' Coincidence Theory of Consonances, from Nicomachus to Sauveur," *Recercare* 13 (2001): 201–32, at 222–25 (also at www.patriziobarbieri.it/pdf/recercarexiii.pdf).

square root of density. As we saw in §1, he compared two harpsichords, one strung with gold and the other with brass, with equal string lengths, diameters, and tension, and he correctly affirmed that the brass strings sound about one fifth above, i.e. the ratio of their frequencies (f) is about $f_{brass} : f_{gold} = 1.5 : 1$.[54]

Descartes, on the other hand, remained wedded to the old Ptolemaic theory. Writing to Mersenne in October 1638, he commented on Galileo's *Two New Sciences:* "He says that the sound of gold strings is lower than that of brass strings because gold is heavier; but [instead] it is rather because it is softer." And surprisingly, Mersenne himself, in July 1643, agreed with Descartes's opinion (or maybe he felt obliged to submit to his authority); in a list of objections to *Two New Sciences,* sent "in the name of the mathematicians of Paris to the friends of Galileo in Italy" (Galileo having died in 1642), he writes that "the sounds of gold strings are not lower because of the greater weight of gold, but because of its greater softness."

3.2. Intensity level. Claude Perrault, the first to tackle the problem of the intensity level of a vibrating string, affirmed in 1680 that "metal-overspun gut strings" give a "much louder sound" than plain gut because the mass is greater: "And it is because of this principle [that] the die-drawn gold strings in harpsichords emit a sound almost twice as strong as copper strings, there being no material heavier and more ductile than gold. A steel string therefore makes a weaker sound than a copper string, because steel is less heavy and less ductile than copper."[55] Today we know that the energy W stored in the string at the moment of plucking is proportional to its tension T.[56] For the same frequency f, cross-sectional area

54. Assuming 19.3 g_m/cm^3 for the density of gold and 8.7 for that of brass, we would have: $(19.3/8.7)^{1/2} = 1.49$.

55. Claude Perrault, *Essais de physique, ou recueil de plusieurs traitez touchant les choses naturelles,* vol. 2 (Paris: Coignard, 1680), 157: "Et c'est par ce principle que les cordes faites d'or trait dans les clavecins, rendent un son presque une fois plus fort, que celui des cordes de cuivre, n'y ayant point de matiere si ductile et si pesante que l'or: Une corde d'acier rend aussi un son plus foible qu'une corde de cuivre, parce que l'acier est moins pesant et moins ductile que le cuivre." This problem was tackled again only in 1767, by Giordano Riccati; see Patrizio Barbieri, "Giordano Riccati on the Diameters of Strings and Pipes," *Galpin Society Journal* 38 (1985): 20–34, at 20.

56. The energy W stored in the string is equal to the work done by the jack at the moment of plucking. The work done in stretching a string by a small amount δL is $W = T\delta L$, neglecting the small change in tension: Michael Spencer, "Harpsichord Physics," *Galpin Society Journal* 34 (1981): 2–20, at 17n18. During the vibration, part of this W is transformed into sound energy, while the rest is dissipated as heat.

A, and length *L,* the tension *T* is proportional to the density ρ of the material. Therefore we may say that from a theoretical point of view Perrault was right;[57] we can only contest his mention of "ductility," of Ptolemaic memory.[58] The problem, however, is not that simple: as we have seen, the breaking stress (T_{br}/A) of gold is very low, so that any valuation of energy *W* depends on where the string is placed in the spinet, with higher tensions in the treble and lower tensions in the bass. Quantitative examples will be provided in §4.

3.3. "Sweetness": Inharmonicity and detuning. According to Roman musicians (1624), gold strings conferred "greater sweetness to the sound" (see also Artusi, §1, 1600). We find confirmation of this in 1665–73, in a manuscript by the Florentine Orazio Ricasoli Rucellai: "I know that in harpsichords gold strings provide a sweeter and pleasanter resonance than strings of any other metal and even gut."[59] We do not know what was meant by "sweetness of sound," nor whether these opinions were influenced by the greater "degree of perfection" that the ancient alchemic hierarchy attributed to this noble metal, of which some were convinced right up to the end of the eighteenth century.[60] However, Ricasoli

57. Indeed, from the vibrating string formula $f = [T/(4AL^2\rho)]^{1/2}$ it can be seen that, if the other variables are equal, if ρ increases, then *T* must also increase in the same ratio.

58. On Aristotelian and Ptolemaic reminiscences in Perrault, see Patrizio Barbieri, "The Jesuit Acousticians and the Problem of Wind Instruments (c. 1580–1680)," *Analecta Musicologica* 38 (2007): 155–204, at 176 (also at www.patriziobarbieri.it/pdf/analecta.pdf); Barbieri, " 'Galileo's' Coincidence Theory of Consonances," 225. The work of Mersenne and Galileo notwithstanding, the Ptolemaic theory continued to have followers throughout the seventeenth century; besides Descartes and Perrault, there was Kircher himself, theorizing in 1650 that a different air resistance was one of the main reasons for the disagreement between the physical properties of the materials tested by Mersenne and his own measurements: Kircher, *Musurgia,* 1:447.

59. Orazio Ricasoli Rucellai, "Segue il Timeo: Delle musiche proporzioni," Florence, ca. 1665–73. Florence, Biblioteca Nazionale, Ms. Cl. II.III.269, 4r: "Io sò, che le corde d'oro, ne' gravicimbali fanno più dolce, e più suave la risonanza, che non fanno le corde di tutti gli altri metalli, e delle minugie medesime." Ricasoli Rucellai, a neo-platonist philosopher and from 1635 a gentleman of Grand Duke Ferdinand II's chamber, in this work also discusses Galileo's theory on consonance: Barbieri, " 'Galileo's' Coincidence Theory of Consonances," 212–13.

60. On the assumed "degree of perfection" of gold, a metal that in medieval symbolism was associated with divine wisdom, see Patrizio Barbieri, "Alchemy, Symbolism and Aristotelian Acoustics in Medieval Organ-Pipe Technology," *Organ Yearbook* 30 (2001): 7–39, at 25 (also at www.patriziobarbieri.it/pdf/alchemy.pdf). In 1791, the

Rucellai was the first to examine the problem from a modern scientific point of view. In the same manuscript—in an ideal "dialogue" between the author and Raffaello Magiotti (1597–1656), one of the three favored pupils of Galileo—he opined that this "greater sweetness" should be sought in the internal structure of the gold, a metal that belongs to the category of those "that yield more, but then return" (che più cedono, ma poi ritornano); today we would say that it belongs to the category of elastic materials with low "elasticity modulus."[61] Science thus begins to glimpse the parameter later known as the "elasticity (or Young's) modulus," first clearly defined by Giordano Riccati in 1764–1782 and subsequently by Thomas Young (1807).[62] The existence of the inharmonicity of the vibrating string was first experimentally worked out by Jean Baptiste Mercadier in 1783, and the related mathematical problem solved in the nineteenth and twentieth centuries.[63] It is therefore natural to observe that Descartes certainly lost the moment to link the "softness" of the gold string to its timbre, rather than to its shorter vibrating length.

Nowadays, the degree of inharmonicity is expressed by the "sharpness factor" (S), the parameter that determines by how much the overtones are sharpened compared to those of an ideal string, one without stiffness.

Frenchman Delorthe used a monochord strung with gold strings, a metal that was perfect in his eyes, to demonstrate the validity of a just-intonation scale he had invented. He submitted his invention to the Parisian Academy of Science, but was unsuccessful (he was even removed from the room when only halfway through his dissertation): Gabriel-Antoine Delorthe, *Moyens de rectifier la gamme de la musique et de faire chanter juste* (Paris: the author, 1791), 10–11, 16.

61. Ricasoli Rucellai, "Segue il Timeo," 3v–4r.

62. Patrizio Barbieri, "Giordano Riccati fisico acustico e teorico musicale: Con una memoria inedita di acustica architettonica," in *I Riccati e la cultura della Marca nel Settecento europeo: Atti del convegno internazionale di studio* (Castelfranco, Veneto, 5–6 aprile 1990) ed. Gregorio Piaia and Maria Laura Soppelsa (Florence: Olschki, 1992), 279–304, at 280. Riccati is also the first author to carry out experiments on this parameter: in 1770 he noted the ratio between the elasticity modulus of steel and that of bronze, obtaining the correct value of 2.18: James F. Bell, *The Experimental Foundations of Solid Mechanics* (New York: Springer-Verlag, 1973), 161; Patrizio Barbieri, *Acustica accordatura e temperamento nell'Illuminismo veneto* (Rome: Torre d'Orfeo, 1987), 50.

63. Patrizio Barbieri, "The Inharmonicity of Musical String Instruments (1543–1993); With an Unpublished Memoir by J.-B. Mercadier (1784)," *Studi musicali* 27 (1998): 383–419, at 385, 393, 396 (also at www.patriziobarbieri.it/pdf/inharmonicity.pdf); Italian version: "L'inarmonicità degli strumenti musicali a corda (1543–1993): Con una memoria inedita di J.-B. Mercadier (1784)," in *Strumenti, musica e ricerca: Atti del convegno internazionale, Cremona, 28–29 ottobre 1994,* ed. Elena Ferrari Barassi, Marco Fracassi, and Gianpaolo Gregori (Cremona: Ente triennale internazionale degli strumenti ad arco, 2000), 255–92.

It is the more reduced the thinner and tenser the string and the lower the elasticity modulus of the material of which it is made.[64] Some modern authors maintain that the sharpness factor is likely to be less important than detuning due to plucking, owing to the plucking displacements usually found on harpsichords.[65] When the jack raises the string, it gives rise to a δT increase in string tension, producing—in the attack transient—an increase in frequency δf as compared to the proper f value to which the string adjusts.[66]

The small lead ball mentioned by Huygens as used to ballast the bass strings (§1, 1673) not only reduced the fundamental frequency, but made the sound emission inharmonic, and string vibration aperiodic as a consequence—but these properties were not understood by scientists of the time.[67] In Huygens's case, the lump was attached at the center of the string: with this disposition Lord Rayleigh verified on trial that the even harmonics were undisturbed, whereas the odd ones were lowered, though still constituting a harmonic series.[68]

Table 4, from the 1788 edition of the *Encyclopédie méthodique,* lists the various materials then used for strings, classified in increasing order of "sweetness" (*douceur*). "Copper strings" (used in the bass range, if brass ones "do not speak well") "are more touching and more harmonious than the yellow [i.e., brass] strings."[69] For the same vibrating length, the

64. The "sharpness factor" is $S = \pi^3 D^4 E/128 L^2 T$, with E = elasticity modulus, and D, L, T respectively the diameter, length, and tension of the string. See Spencer, "Harpsichord Physics," 17n20.

65. Spencer, "Harpsichord Physics," 5.

66. Such "detuning" is given by $\delta f/f = AE\delta L/2LT$, with A, L, T respectively as the cross-sectional area, length, and tension of the string, and E = elasticity modulus: Spencer, "Harpsichord Physics," 16n15.

67. The first to raise the problem of the string without a constant section was Lagrange, in a paper printed in the 1760 memoirs of the Academy of Sciences of Turin. There he correctly concludes that such a string cannot vibrate with constant frequency: Giuseppe Luigi Lagrange, "Nouvelles recherches sur la nature et la propagation du son," *Miscellanea Taurinensia* 2 (1760–61), repr. in Joseph-Louis Lagrange, *Oeuvres,* vol. 1, ed. J.-A. Serret (Paris: Gauthier-Villars, 1867), 151–316, at 237–38: "Des vibrations des cordes inégalement épaisses."

68. John William Strutt, Baron Rayleigh, "Acoustical Notes, VIII," *Philosophical Magazine* 16 (1908): 235–46. Rayleigh, however, adds that with the load of the ball conveniently chosen and the tension of the string suitably adjusted, all the partial tones may be brought to form a harmonic series.

69. *Encyclopédie méthodique: Nouvelle édition enrichie de remarques dédiée à la Sérénissime République de Venise,* vol. 4, pt. 1 (Padua, 1788), 40, s.v. "Arts et métiers mechaniques": after prescribing stringing with "yellow strings" (i.e., brass) for the bass, the author adds that such strings "peuvent être de cuivre rouge, si les jaûnes ne parlent pas bien,"

greater "harmoniousness" of red brass over normal yellow brass can today be justified by its having a lower "sharpness factor," since it has a lower elastic modulus and greater tension (table 5).[70] This source assigns maximum *douceur* among the metals to gold (see table 4).

3.4. "Sweetness": A hypothesis on internal friction. Other parameters, not taken into account until the twentieth century, contribute to aesthetic judgments on the "pleasantness" of the sound. The previous formulas did not, for example, consider the damping due to internal friction associated with the flexing of the wire. It is probably thanks to lesser internal losses that the sound of iron strings is richer in high overtones and has a longer decay time than that of the copper alloys;[71] this—despite iron's higher inharmonicity (or even thanks to it, at least according to some recent psychoacoustic theories)—was often the reason for its being preferred, as shown by the following authors (all, it should be noted, from northern Europe):

1636–37. Mersenne states that the "harmonie" of the psaltery "is very pleasing, because of the clear and silvern sounds emitted by the steel strings" (on this statement see §5 below).[72]

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and "on se sert aussi quelquefois, pour le ravalement, de cordes de cuivre rouge, marquées de même 000, 00, 1, 2; ces cordes sont plus touchantes et plus harmonieuses que les cordes jaûnes."

70. Among the alloys used for harpsichord stringing, "yellow brass" is about 25–30% zinc, whereas "red brass" is about 10–15% zinc; *The New Grove Dictionary of Music and Musicians,* 2nd ed. (London: Macmillan, 2001), s.v. "Harpsichord," §1, by Edwin M. Ripin, Howard Schott, and John Koster; see also table 5 below. As explained in n. 69 above, "red" brass strings, being of higher density, can more easily descend into the bass range than the "yellow," when they are of the same length. For this reason, the former were sometimes preferred in smaller-size instruments; Mersenne, *Harmonie universelle,* "Traité des instrumens à chordes," 158, describing an octave-spinet, says, for example, that in the low octave the strings are of brass ("jaunes") and the other of iron ("blanches"); twelve years later (1648), describing the same instrument, he says, on the contrary, that in the low octave the strings are of red brass ("fidibus aeneis fulvis"): Mersenne, *Harmonicorum libri XII,* "Liber novus," 63.

71. On these two qualities of iron strings see *The New Grove Dictionary of Music and Musicians,* 2nd ed. (London: Macmillan, 2001), s.v. "Harpsichord," §2.i, by Denzil Wraight. See also the typical loss factors in the audio frequencies listed in J. Soovere and M. L. Drake, *Aerospace Structures Technology Damping Design Guide,* vol. 3, *Damping Material Data* (n.p.: Lockheed-California Co Burbank, Air Force Wright Aeronautical Laboratories, Flight Dynamics Laboratory, 1985), 491.

72. Mersenne, *Harmonie universelle,* "Traité des instrumens à chordes," 175: "Certes l'harmonie de ce psalterion est fort agreable, à raison des sons clairs et argentins que rendent les chordes d'acier."

TABLE 4. String materials, in growing order of "sweetness" of sound (central column), as deduced from the original text (side columns). From *Encyclopédie méthodique: Nouvelle édition enrichie de remarques dédiée à la Sérénissime République de Venise*, vol. 4, pt. 1 (Padua, 1788), 50, s.v. "Arts et métiers méchaniques."

Original French	*Resulting "sweetness" (in growing order)*	*English translation*
On doit observer que les cordes en boyau ont un son plus agréable et plus doux que les cordes en soie; 2°. que les cordes en métal ont un son plus aigu, plus clair et moins doux que les cordes tirées du regne végétal ou animal; le fil de fer a un son plus aigu que celui de laiton; le fil de cuivre rouge et ceux d'argent ont encore le son plus doux; le fil d'or rend encore un son plus doux; les fils de cuivre filés en cuivre, ont un son très-doux et mou; les fils de métal tordu ou croisé, ont un son très harmonieux et de longue durée; ils sont excellens pour les basses.	Iron Brass Red brass – Silver Gold Copper wound on copper Twisted wires Silk Gut	It should be noted that gut strings have a sound more agreeable and sweeter than those of silk; 2. That metal strings have a more penetrating, more bright, and less sweet sound than strings made from vegetal or animal matter; iron wire has a more penetrating sound than brass; red-copper strings and silver ones have a still sweeter sound; gold strings give an even sweeter sound; copper strings overspun with copper have a very sweet and mute sound; strings of twisted or [and] intertwined metal have a very harmonious and long-lasting sound; they are excellent for bass strings.

TABLE 5. Mechanical properties of some commercial metals and alloys. From David R. Lide, ed., *CRC Handbook of Chemistry and Physics* (Boca Raton, FL : CRC Press, 2003), sec. 12, p. 234. To facilitate comparison, the units have been converted to those of table 3.

Material	*Elasticity modulus* ($\times 10^{11}$ dyne/cm^2)	*Breaking stress* ($\times 10^{9}$ dyne/cm^2)
Copper, electrolytic	12.0	3
Yellow brass (high brass)	10.0	3–8
Red brass, 85%	9.0	3–7
Iron (ingot)	20.5	—

1699. Claas Douwes reports that the harpsichord is strung not only with brass and copper, "but mostly with white [i.e., iron] strings, because the white are fine and clear in tone."[73]

1739. According to Quirinus van Blankenburg, writing of harpsichords, copper strings "do not sound as clear as iron ones in the treble."[74]

1768. Jakob Adlung too affirms that he prefers iron to brass, because, among other considerations, it "sounds more lovely."[75]

If, on the contrary, the internal damping assumes a high value, the sound will be less rich in treble overtones, and thus "sweeter" (see the case of gut strings).[76] On gold, no considerations can so far be put forward, the related data being uncertain and noted only in relatively recent times (e.g., §7).[77] One might also observe that a lower emission power of the string would be equivalent to the effect of greater damping, since some of the higher overtones would inevitably fall below the hearing threshold.

4. Gold Strings: Acoustic Features

Sections 4 and 5 provide some objective acoustic data on gold and silver strings. The calculations are based on the formulas discussed in §3, using the mean values of the mechanical properties relating to typical modern materials, listed in table 3. Any comparison with historical alloys and with brass has been avoided, in view of the wide spread of data relating to their tensile strength.

String length. With equal diameter, tension, and fundamental frequency, two strings, one of gold alloy with 10% of copper (*Au*) and the other of

73. Hubbard, *Three Centuries,* 235.
74. Ibid., 240.
75. Ibid., 280.
76. Neville H. Fletcher and Thomas D. Rossing, *The Physics of Musical Instruments,* 2nd ed. (New York: Springer, 1998), 54–56.
77. See, for example, the data published in Benjamin J. Lazan, *Damping of Materials and Members in Structural Mechanics* (Oxford: Pergamon Press, 1968), 214–15, 35. Besides damping due to air friction, a metal string is subject to further damping due to internal losses. Charles-Augustin Coulomb was the first to prove this experimentally, in his famous "Memoir on Torsion," dated 1784.

iron (*Fe*), would have the respective lengths L in the ratio $L_{Au} : L_{Fe} = 0.68 : 1$.[78] This, however, is not a working ratio, since gold has a lower breaking stress than iron, so that its operating tension must be kept lower, leading also to a decrease in L_{Au}. Taking that into account, the ratio descends to 0.54.[79]

Intensity level. In the treble: making, by way of example, a comparison between the alloy $Au_{90}Cu_{10}$ and iron, operating at breaking stress and with identical diameters, we have: $W_{Au} : W_{Fe} = 0.64 : 1$ (= 1.9 decibels of attenuation), a ratio which, if pure gold were used, would go down to 0.36 (–4.5 dB). According to the above figures, the use of gold instead of iron would thus involve a drop in loudness, in accordance with the evidence of Artusi and Doni.

In the bass, so that instruments are not impracticably long, the L is "foreshortened" with respect to the Pythagorean scaling usually adopted in the treble, with the result that stress (T/A) is also lower. In such cases, the use of a high-density material makes it possible to keep the T, and consequently the W, higher.[80] Thus a passage from iron to brass, and from brass to copper has often been seen.[81] Huygens in 1673 reported the use of gold strings in the bass.

Gold strings have recently been employed in the bass range of some low-headed Gaelic harps, on which it was necessary to go down as far as $G = 98$ Hz with a rather limited length: $L = 61.0$ cm (fig. 4).[82] By way of

78. Ratio deduced from the formula $L_{Au}/L_{Fe} = (\rho_{Fe}/\rho_{Au})^{1/2}$, where ρ = density.

79. Value obtained simply through the ratio of the breaking indexes in table 3. The breaking index is a parameter calculated to match the breaking stress, and it provides the maximum fundamental frequency f that can be emitted by a string of length L. For the alloy $Au_{90}Cu_{10}$, for example, we have $Lf = 80$ Hz m, so that $f = 80/L$ (which means that a string one meter long could be stretched until it emits an $f = 80$ Hz, and stretching it more, it would break; if the string were two meters long, on the other hand, it could only reach 80/2 = 40 Hz).

80. See n57 above.

81. See, for example, Barbieri, *Acustica accordatura e temperamento,* 43–44 (in Rome, 1638), 44–45 (in England, 1774); Hubbard, *Three Centuries,* 234–36 (in Holland, 1699); §1 above, 1686 (Modena). There is much historical evidence showing that in harpsichords, going toward the bass, the strings change from iron to brass and lastly to red brass (on red brass, see n70 above).

82. Measurements kindly provided by Simon Chadwick (St. Andrews, Fife, Scotland), with reference to a replica of the medieval "Queen Mary" harp. The rationale for this is mentioned in Simon Chadwick, "The Early Irish Harp," *Early Music* 36 (2008): 521–31, at 526.

FIGURE 4. Copy of the "Queen Mary" harp. The original instrument is believed to have been made in the fifteenth century in the west of Scotland, and is preserved in the National Museum of Scotland, Edinburgh. The copy was made for Simon Chadwick (in the photo) by the sculptor and instrument maker Davy Patton, Co. Roscommon, Ireland, in 2006–7. Photo by Ealasaid Gilfillan.

example, if copper (see table 3) had been used to descend into the bass, for the G a stress of 1297 kg/cm^2 would have been obtained, typical of a slack string; with the alloy $Au_{90}Cu_{10}$ on the other hand, the value rises to 2477 kg/cm^2; in the latter case, the energy ratio is favorable to the use of gold: $W_{Au} : W_{Cu} = 1.91 : 1$ (= 2.8 dB increase). This may be the case to which Perrault was referring (see §3.2 above), the more so because he compares the gold strings with overspun ones.

Inharmonicity and detuning. We shall now calculate both the sharpness factor and the detuning under the two operating conditions mentioned above for spinets and harps. In the treble, working at breaking stress we would have, for the alloy $Au_{90}Cu_{10}$ (*Au*) and iron (*Fe*):[83] $S_{Au} : S_{Fe} = 2.0 : 1$, $\delta f/f_{Au} : \delta f/f_{Fe} = 1.08 : 1$. Passing from iron to gold, in the treble range the sound is not only weaker, as already seen above, but also more inharmonic. The only way of decreasing inharmonicity would be to reduce the diameter of the gold string, but this would further reduce the level of its sound emission.

In the bass: for $G = 98$ Hz on the Gaelic harp mentioned above, we should have: $S_{Au} : S_{Cu} = \delta f/f_{Au} : \delta f/f_{Cu} = 0.37 : 1$. This time, the "harmoniousness" of the sound is overturned, being decidedly in favor of gold.

5. Silver Strings: Acoustic Features

Under the operating conditions already described (using for these calculations the properties in table 3), in the bass, silver is less favorable than gold, both as regards acoustic intensity and "sweetness" of sound. In the bass range of instruments, gold is thus decidedly superior.[84]

In the treble, when both metals are operating close to breaking stress, the balance tends to be decisively in favor of silver, from every acoustic aspect.[85] If then—always under equal conditions—we compare it to iron, silver alloy emits a slightly superior sound energy, to which is added the decided advantage of much less inharmonicity and detuning, since its elasticity modulus is much lower.[86] In this connection, it is curious to

83. The comparison, as for the previous ones, is made between two strings of the same diameter and same frequency. The elasticity modulus *E* remains practically unchanged in passing from pure gold to its alloys: apart from table 3, see also Diego Pinton, *Tecnologia orafa: Processi produttivi, mezzi, strumenti* (Milan: Edizioni Gold, 2003), 70.

84. Indeed, with equal length, diameter and fundamental frequency, we have, for the two materials, both in the form of alloy: $W_{Au}/W_{Ag} = 1.7$; $S_{Au}/S_{Ag} = \delta f/f_{Au} : \delta f/f_{Ag} = 0.59$.

85. With the same diameter and frequency and with both materials working at breaking stress, the following values are obtained. Pure gold and pure silver: $L_{Au}/L_{Ag} = 0.69$; $W_{Au}/W_{Ag} = 0.77$; $S_{Au}/S_{Ag} = 2.76$; $\delta f/f_{Au} : \delta f/f_{Ag} = 1.90$. Gold and silver, both as alloys: $L_{Au}/L_{Ag} = 0.53$; $W_{Au}/W_{Ag} = 0.50$; $S_{Au}/S_{Ag} = 7.03$; $\delta f/f_{Au} : \delta f/f_{Ag} = 3.75$.

86. With silver alloy and the mean values for the two qualities of iron indicated in table 3, we have: $L_{Ag}/L_{Fe} \approx 1$; $W_{Ag}/W_{Fe} = 1.29$ (= +1.1 dB); $S_{Ag}/S_{Fe} = 0.28$; $\delta f/f_{Ag} : \delta f/f_{Fe} = 0.29$.

note that the timbre of iron (or even steel), which as we have just seen is the antithesis of silver, was described as "silvern" by Mersenne in the document cited in §3.4. Psychoacoustic or cultural factors unknown to us must have contributed to such an opinion.

In 1611 a Spanish author, writing of instruments strung with silver, stated that he thought their sound would have been still "pleasanter" had they been strung with gold: the same conviction appears in table 4. But we may affirm that such a conjecture clashes with what has now emerged, at least in the treble range of the instrument. The Spanish author's statement was probably suggested by a preconceived idea linked to the greater "degree of perfection" that the ancient alchemic hierarchy attributed to the gold.

6. Solid-Gold Strings vs Overspun

In §1 we saw that documentary references to gold strings became progressively fewer from the mid-seventeenth century and finally disappeared. Toward the end of that century, reports began to appear of twisted or overspun strings used in the bass range of keyboard instruments (overspun strings having already been used for some decades in viols). In this range, the new strings, besides providing all the acoustic and dimensional advantages of gold, were much cheaper.[87]

We shall now examine some of the main documentary evidence relating to the application of this innovatory technique to keyboard instruments.

1673. According to Huygens, in Paris gold strings were employed on small spinets due to the "foreshortening" of the bass strings: that the Dutch physicist recalled as an alternative the use of a small lead ball in the middle of the string demonstrates that the overspun type had not thus far been adopted in such instruments.

87. A string of length L, tension T, and linear density ρ_L emits the fundamental frequency $f = [T/(4L^2\rho_L)]^{1/2}$. If ρ_L is increased (by adding overspinning), f decreases, so that—to bring it back to its original value—T has to be increased; in n56 above we saw however that the acoustic energy emitted by a string is proportional to T, so that the intensity level will also rise (in agreement with Perrault's observations in 1680). As regards inharmonicity, it is contained, since the core not only remains that of the original unspun string, but draws greater benefit from the increase in T (see the "sharpness factor" in n64 above).

1690. In Rome, for the bass strings of a harpsichord belonging to Antonio Ottoboni, Tomasso Mandelli used "saltaleoni grossi," made—according to other evidence—of two twisted copper strings.[88] The twisted strings provided less inharmonicity than a single string with a section equal to the sum of the two;[89] thus, according to the *Encyclopédie méthodique* (1788), strings of a twisted type were also characterized as having a longer decay time (table 4).

1700. Overspun and double-overspun strings were reported in Paris in the *clavecin brisé* of Jean Marius. Indeed, in this very year, Denis Dodart reported to the Académie des sciences: "With regard to string length, Mr. Marius is known to make folded harpsichords which, when open, are only two-and-a-half feet long at the most, and of which the bass strings—of brass, wound or double-wound, or of copper, or of silver, or of gilded silver in order to lower the pitch more and more—are in unison with the longer bass strings of seven-foot-long harpsichords, so that it can be deduced that, with this device, 1 sounds like 3."[90] It is unclear whether the said copper, silver, and gilded silver refer to the strings themselves or to the material used for overspinning.

88. Teresa Chirico, "New Information about Harpsichords and Harpsichord Makers Employed in Rome by Cardinal Pietro Ottoboni and His Father Antonio," *Galpin Society Journal* 62 (2009): 101–15, at 104. Twisted strings are already mentioned for citterns in the *Breve e facile instruction pour apprendre la tabulature, a bien accorder, conduire, et disposer la main sur le cistre* (Paris: Adrian Le Roy and Robert Ballard, 1565); see Howard Mayer Brown, *Instrumental Music Printed before 1600: A Bibliography* (Cambridge, MA: Harvard University Press, 1965), 1565_3. With thanks to the anonymous reviewer for this reference. Two brass wires twisted together were also used in the eighteenth and nineteenth centuries for the third string of the Neapolitan mandolin (the fourth string was of copper wound on a silk core): see Patrizio Barbieri, "Roman and Neapolitan Gut Strings, 1550–1950," *Galpin Society Journal* 59 (2006): 147–81, at 178.

89. On calculating the elasticity modulus of a twisted string, see Abbott and Segerman, "Strings in the 16th and 17th Centuries," 65–69.

90. Denis Dodart, "Memoire sur les causes de la voix de l'homme, et de ses differens tons," *Histoire de l'Academie royale des sciences: Avec les memoires de mathematique et de physique, pour la même année,* 1700, 2nd ed. (Paris, 1719), "Memoires de mathematique et de physique," 244–93, at 192: "Quant à la longueur des chordes, on sçait que M. Marius fait des clavessins brisés, qui déployés, n'ont que deux pieds et demi dans leur plus grande longueur, et dont les basses de leton guippées ou surguippées, ou de cuivre, ou d'argent, ou d'argent doré pour baisser de ton de plus en plus, sont à l'unisson des basses les plus longues des clavessins de sept pieds de long, d'ou il s'ensuit que par cet artifice, 1 sonne comme 3."

1724. In a workshop book started in this year, the organ maker Johannes Creutzburg (1686–1738), working in Thuringia, noted the details of the stringing of his clavichords. These show that, for the bass notes, he employed an iron or brass core overspun with silver. In 1732, he noted that in the stringing used on clavichords by a certain Mr. Ohaus, the bass strings were also overspun with silver.[91]

1768. Jakob Adlung states that, on the harpsichord, one can overspin from the bass up to *c;* but, according to Agricola: "However the quills soon rub off the overspinning. Therefore many hold that it is better not to use overspun strings on the harpsichord."[92] Pianos, on the other hand, were clearly immune from such an inconvenience.

1773. Peter N. Sprengel observes that the bass strings on harpsichords are longer than those of the clavichord, for which reason "unspun bass strings are chosen for the harpsichord."[93]

7. Modern Gold- and Silver-Strung Instruments

The following experiments started in September 1983 for low-headed Gaelic harps (carried out by Jay Witcher of Maine, a harp maker as well as an engineer, who also made the calculations for the stringing requirements) and around 1980 for quilled keyboard instruments. The information, mostly in private communications, is due to the kindness of Cynthia Cathcart, Simon Chadwick, and Ann Heymann (for the harps), and Barthélémy Formentelli and David Kinsela (for the keyboards).

7.1. Gaelic harps. In the low-headed types, gold strings have been employed (by Simon Chadwick and Ann Heymann) mainly to make up for the lack of sound intensity in the bass without resorting to wound or twisted strings (see §§4–5).[94] On the 2006–7 replica of the famous

91. Lothar Bemmann, "*Wie man ein Cor Thonig Clavicortium beziehen sol* – The Organ Maker Johannes Creutzburg (1686–1738) and His Workshop Book," *De clavicordio VIII: The Clavichord on the Iberian Peninsula,* ed. Bernard Brauchli, Alberto Galazzo, and Judith Wardman (Magnano: Musica Antica a Magnano, 2008), 145–56, at 150–54.

92. Hubbard, *Three Centuries,* 280.

93. Ibid., 278.

94. The original argument for silver and gold strings was made in Ann and Charlie Heymann, "Strings of Gold," *Historical Harp Society Journal* 13, no. 3 (Summer 2003):

medieval harp of Mary, Queen of Scots (preserved in the National Museum of Scotland, Edinburgh), tuned to *a′* = 440 Hz, Chadwick uses:[95]

for the bass: dead-soft yellow 18-carat gold. Bottom note, *G:* string length 61 cm, diameter 1 mm.

for the mid-range: spring-hard sterling silver (silver 92.5%, copper 7.5%). *c′:* string length 33 cm, diameter 0.7 mm.

for the treble: yellow brass. *c″:* string length 19 cm, diameter 0.6 mm.

Some of these harps have also been strung in gold throughout the entire range (for example, by Ann Heymann), using a change in hardness and carat to overcome the big changes in scaling; for example, dead-soft 18-carat gold in the bass through spring-hard 14-carat (or also spring-hard 18-carat) in the treble. It is also possible to resort to a whole-silver stringing, both for historical and financial reasons.[96] On the use of gold in the bass, Chadwick observes:

> Overwound bass strings produce a good strong tone, but do not blend well with the higher monofilament strings, and are very unpleasant to touch and pluck with the fingernails. Also they are of course not historically correct for the 15th century when these harps were built. Twisted strings are also not so comfortable to feel with the nails, are probably not correct for the 15th century, and their sound is very dull.[97]

Experiments made by Cynthia Cathcart confirm that "wrapped, wound or twisted strings give inferior sound when compared to monofilament [silver] strings." This is probably due to their thickness (in the low-headed harps these may be made from two wires of red brass, each 0.75 to 1.0 mm thick) and to the loss of energy at high overtones caused by

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9–15, reprinted with emendations at www.annheymann.com/gold.htm (accessed July 27, 2007). See also the website of Simon Chadwick, St. Andrews, Fife, Scotland: http://www.earlygaelicharp.info/emporium/wire/.

95. Simon Chadwick, *Clàrsach na Bànrighe: A Recording of Historical Scottish Music Performed on a New Replica of the Famous Medieval Harp of Mary, Queen of Scots, Preserved in the National Museum of Scotland, Edinburgh,* recorded at St. Andrews, Fife, 2008, EGH 1, compact disc (see http://www.earlygaelicharp.info/emporium/CDs/).

96. See, for example, Cynthia Cathcart, "The Silver Report: Precious Metal Strings on the Wire-Strung Harp," *Folk Harp Journal* 143 (Summer 2009): 34–43. In the article's "Conclusions" are also mentioned experiments suggesting that full hard silver-rich gold ("Electrum"), at 18 carats (75% gold and 25% silver) may produce superior sound.

97. Simon Chadwick, message to the author, June 28, 2010.

friction of the two wires when vibrating,[98] a modern observation that is in disagreement with table 4.

In §4 we saw that gold strings emit a louder and less inharmonic sound compared to the other metals, but we still lack quantitative data regarding the number and intensity of their overtones: thus we cannot know what older sources meant when they reported that gold emits a "more sweet sound." So far, the only measurements at our disposal are those of fig. 5; these compare the frequency spectrum of two strings of the same length and frequency, one of 18-carat gold and the other of brass: the decay slope of the harmonics is different, but the emission of overtones of gold is at least comparable to that of brass.[99] With regard to timbre, it is difficult to draw general conclusions from data of this kind, mainly because today instruments—in order to obtain uniform timbre and loudness throughout the whole compass—are strung "by ear" with gold of different carats (from 9 to 22) and different types of work-hardening.

Finally, one must consider the cost of using gold strings on musical instruments. As in 1615 (see §1), gold strings are today very expensive. On July 5, 2010, the price per ounce of gold was $1209.90, whereas the price of an ounce of silver was $17.83: the ratio of prices gold/silver being thus about 68/1.[100] This has obvious reflections on the cost of strings. In Simon Chadwick's pricelist, gold strings cost "anything up to £200 or more per string, probably over £1000 for the whole bass octave," whereas silver strings cost £19–23 per meter and brass and iron ones £1.50.[101]

7.2. Quilled keyboard instruments. The first modern instrument to be strung with noble metals was a Cristofori-style harpsichord, $a' = 415$ Hz

98. Cathcart, "The Silver Report," section "Current practice." On the twisted strings for an eighteenth-century high-headed harp, see Robert Evans, "A Copy of the Downhill Harp," *Galpin Society Journal* 50 (1997): 119–26, at 124–25.

99. These graphs confirm a statement by Cynthia Cathcart, "Excuse Me, But is That a Harp?" accessed January 17, 2011, http://www.cynthiacathcart.net/excuseme.html, first published as "Wire Harp 101," *Harplight* 3 (Spring 2001): "While some players believe gold gives a better bass sound than brass, experiments to date show that gold strings produce more 'upper harmonics' than the other metals, and thus can sound thin as they resonate."

100. Source: Kitco, Inc., "New York Spot Price," accessed July 5, 2010, http://www.kitco.com/market/.

101. Simon Chadwick's Early Gaelic Harp Emporium, accessed January 1, 2011, http://www.earlygaelicharp.info/emporium/wire/.

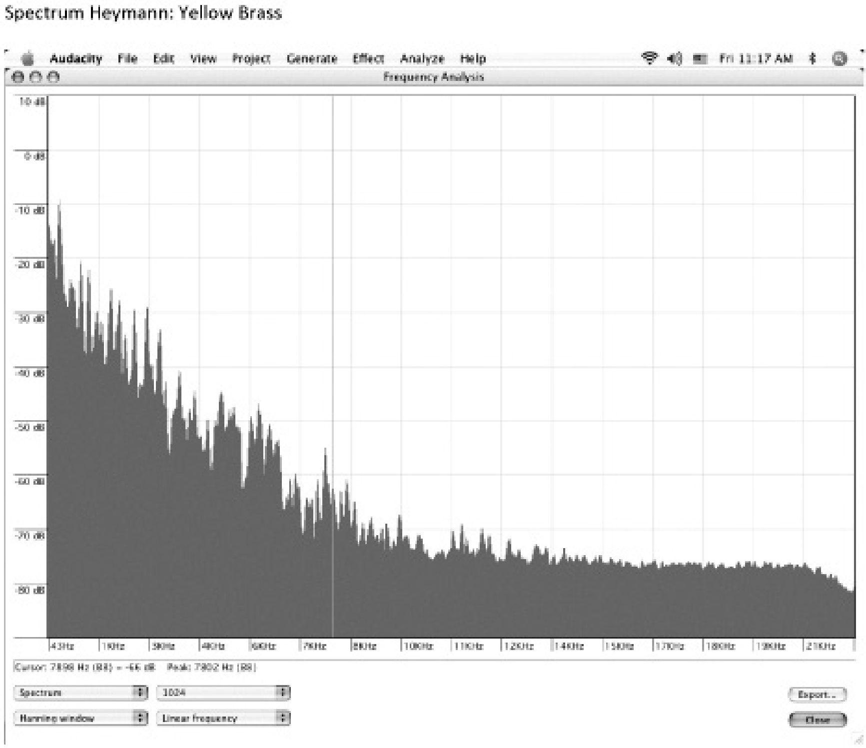

FIGURE 5. Emission spectra of two strings, stretched on an unstrung David Kortier Queen Mary model harp, sounding an approximate C = 65.4 Hz, both with length = 24.25″ (61.6 cm) and diameter 0.035″ (0.89 mm), of two different alloys: yellow brass and 18-carat gold. Frequency band shown: 43 Hz–21 kHz (Audacity audio analyzer). The two strings have been struck by hand, using as closely as possible the same procedure. Data kindly supplied by Ann Heymann (Winthrop, MN), author of the experiment.

pitch, keyboard range G'–c'''. Around 1980 Barthélémy Formentelli (Pedemonte, Verona, Italy) used these alloys:

Bottom octave: gold, probably low-carat
Mid-range, about two octaves: silver alloy
Treble: brass and bronze

The above stringing is no longer extant, but Formentelli remembers (2010) that the sound of gold was fully satisfactory ("loud and mellow").

The next keyboard instrument was the clavicytherium made in 1991 by David Evans (United Kingdom) and sent to David Kinsela (Padding-

Spectrum Heymann: Gold 18k

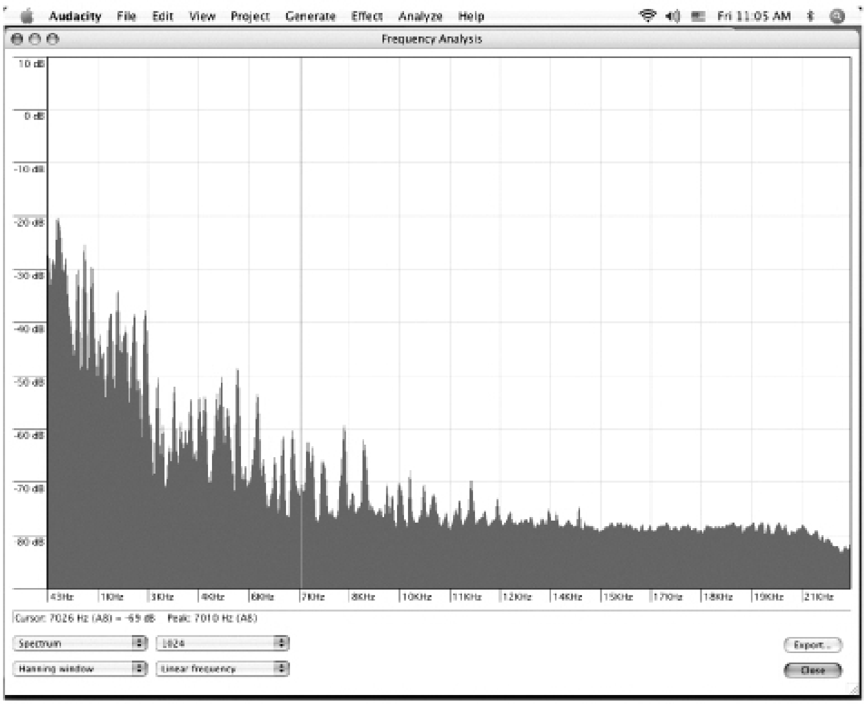

FIGURE 5. continued

ton, Australia), initially strung in brass, at $a' = 415$ Hz. In 1995 Kinsela invited Evans to come to Australia and to restring it in gold, whole compass. The work was done in August of the same year, without shifting the bridge (fig. 6). After unsuccessful attempts with 24-, 22-, and 18-carat gold (the strings were breaking before reaching the operation pitch), it was decided to go down to a circa 9-carat gold, having recourse to a dental-alloy business (Kinsela recalls that "my being an engineer and having had a dentist as father was helpful"). The exact composition was 37.5% gold, 37.5% copper, 12.5% zinc, and 12.5% nickel (specific weight = 11.1 g/cm^3).[102] On the sound obtained, Kinsela observes: "The gold-alloy strings were much darker in tone that the brass,

102. The cost of the new strings amounted to "a little under 1000 Australian dollars, the Australian dollar being worth about 80% of the USA dollar." On the mechanical properties of dental gold-alloys see Edmund M. Wise, ed., *Gold: Recovery, Properties, and Applications* (Princeton: van Nostrand, 1964), 228–33. E = 11–15 million psi.

FIGURE 6. Clavicytherium made in 1991 by David Evans for David Kinsela, and strung in gold four years later. Photo courtesy of David Kinsela.

but much stronger in fundamental as well as louder." Kinsela produced three CDs playing on his clavicytherium.[103] In 2010, he reported that "the instrument is detuned, but three strings have broken nevertheless."

103. One of them, produced in 2002, is *Fundamentum: The Birth of Keyboard Repertoire,* David Kinsela playing the gold-strung Evans clavicytherium, recorded July 1999, ORO 202, compact disc (www.organo.com.au).

8. Conclusions

1. From the documentation presented, it emerges that the number of spinets and harps strung with gold or silver was anything but negligible, amounting to at least a few dozen, and almost all used in aristocratic circles. In the seventeenth century, gold stringing was successful both for reasons of prestige and, more particularly, because the length of the strings could be reduced spectacularly, by as much as 50%. Such a reduction was especially useful in the bass compass of spinets, in which string length was limited by the instrument's dimensions. This fact certainly adds a new complication to the already much-debated problem concerning the string-scaling of quilled keyboard instruments produced in Italy in the sixteenth and seventeenth centuries.

2. Starting around 1690 in Italy, overspun or twisted strings began to be used for the bass range of the harpsichord, allowing the dimensions of the instrument to be reduced without recourse to gold. By then, gold was no longer reported for solid strings, probably on account of its cost (solid silver would continue to be employed, but only for overspinning). Modern experiments show that twisted strings emit a duller sound than equivalent monofilament gold strings.

3. In the medieval alchemic and symbolist hierarchy, gold enjoyed a special ranking over other metals. As gold strings became fashionable at the dawn of the Scientific Revolution, their use in spinets and harps was thus inevitably involved early in research on string acoustics. Stimulated by gold's performance, Galileo was, for example, the first to include the density of the material correctly in the general formula on vibrating string frequency, provoking the opposition of Descartes, who was still tied to the ancient Ptolemaic theory.

4. With regard to the use of the two noble metals for stringing musical instruments, evidence that has come down to us also concerns two other parameters: intensity level (on which the evidence is conflicting) and "sweetness" of sound (on which all the sources agree in stating that gold improved it). Hypotheses (that proved to be correct) regarding these two parameters were advanced by Orazio Ricasoli Rucellai (on "sweetness," 1665–73) and Claude Perrault (on intensity level, 1680).

5. On the basis of modern acoustic theory, several theoretical verifications have been carried out on intensity level and "sweetness" of sound, leading to the following conclusions: (1) thanks to its high density and low elasticity modulus, gold is superior to other metals in both

inharmonicity and detuning ("sweetness" of sound) and in sound intensity in the bass compass of the instrument, where string tension is low, owing to the "foreshortening" of the strings; and (2) in the treble, tension is much higher, so that using high-carat gold, which has a rather low breaking stress, would be much less satisfactory in all three parameters than the materials usually employed. Silver is shown to be superior in the treble to the other metals, including iron and gold, from all points of view: a behavior not pointed out by any historical source, but today taken into account in the stringing of harps and keyboard instruments.