Chapter 2
Description of String Instruments for Classical Music

Contents

Since the first quarter of the twentieth century the concept of culture associated with the post enlightenment world generated a keen interest in rediscovering Baroque music and specific instruments required for its performance. This takes the form of continuity on the one hand and contrast on the other. The composers returned to aesthetic precepts of the "classicism", embodied in order, balance, clarity, and emotional restraint, by using a new and innovative musical approach, introducing a very rich instrumental texture. By rediscovering the manuscripts of the early 18th

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century French composers Lully (1632–1687), Couperin (1668–1733) and Rameau (1683–1764) with dance forms such as sarabands, pavans, minuets, etc., Debussy (1862–1918), Ravel (1875–1937) and Poulenc (1899–1963) took inspiration from genuinely refined French models, in contrast to the grandiloquence of Germanic music. Stravinsky (1882–1971) in contact with Parisian artistic life composed in 1920 the ballet "Pulcinella" strongly inspired by Pergolesi's (1710–1736) music and by the Neapolitan commedia dell'arte of the 17th century (Ford 2004). In Germany neoclassicism proceeded from Busoni (1866–1924) and was later represented by Hindemith (1895–1963). Other composers were very famous for their neoclassical compositions were: Respighi (1879–1936) in Italy, de Falla (1876–1946) in Spain or Villa–Lobos (1887–1959) in Brazil, and many others (Sadie and Tyrrell 2001).

In this cultural and musical context interest in the myth of the "secrets" governing the manufacture of Baroque violins was growing in the scientific world. Utilising the most advanced scientific equipment of their time, scholars in Germany (Backhaus 1930, 1931; Meinel 1937; Lottermoser and Meyer 1957) and US (Saunders 1937, 1946, 1953) visualised the modes of vibration of violin bodies (Hutchins 1983). Since 1963, under the impulse of CM Hutchins violinmakers started to discuss and publish their "secrets" in the Journal of Catgut Acoustical Society. At the same time in his monumental monograph, Sacconi explained the traditional Cremonese techniques for violin making, arguing that there are no secrets for Stradivari's violins (Sacconi 1979). At the beginning of the 1970s we entered the modern era of violin research. Academic studies initiated at Berlin Technical University by Professor Cremer were synthesised after 20 years of research activity by the publication in 1984 of the reference book "The Physics of the violin" (Cremer 1984). The physics of other instruments is also a passionate subject of study as demonstrated by Fletcher and Rossing in their monumental book —"The Physics of musical instruments" (Fletcher and Rossing 1998 first edition and second edition in 2010). Acoustical aspects of musical instruments were emphasised by Chaigne and Kergomard in the recent publication in French of their handbook "Acoustics of musical instruments-Acoustique des instruments de musique" (Chaigne and Kergomard 2013 second edition).

Musical instruments are cultural objects; their sounds characterise a specific historical era or geographical area and are "symbolic and emblematic of peoples and of places as any other musical phenomenon" (Dawe 2003). Therefore the study of musical instruments is as much a cultural study as it is about the physics, the acoustics and the materials used for their construction. The manufacturing of musical instruments, their shape, their decoration and their iconography is characteristic of the aesthetics of the musicians they serve and of the society in which the musicians live (Randel 2003).

On the one hand this chapter is intended to illustrate some aspects related to the historical evolution of string instruments representative of Western classical musical practice: the instruments of the violin family, violin, viola, cello and double bass, the classical guitar, the concert harp and the grand concert piano. To the studies of these instruments we have to include the harpsichord as an instrument for

Baroque orchestra and also an instrument of the contemporaneous classical music ensembles.

This introduction will be followed by an organologic description relative to the geometry and the constitutive parts of the instruments. On the other hand, the other important point to be raised is related to the technology for the construction of these instruments as is used by the craftsman. Being a constitutive part of the symphony orchestra it is interesting to analyse, in the last section of this chapter, the directivity of string instruments, which constitute the majority of the members of the orchestra.

2.1 Evolution of String Instruments

2.1.1 Short Historic Overview

The origin of stringed instruments played by a bow is related to India and the Far East. These instruments known under the name of two families rebec and vielle, migrated to Europe following the paths of different tribes. The instruments from the rebec family are characterised by a pear-shape, arched at the bottom, have three strings tuned in fifths and no nuts at the base of the peg box. One of the well known instruments from this family is the lyra (with a rectangular body pierced by two sound holes) which is reminiscent of the ancient lyre known in Greek and Roman Antiquity. From the 12th to the 16th centuries in Europe families of four or six instruments were grouped and corresponded to human voices-soprano, alto, tenor and bass. At the end of 15th century lira da braccio (held in the arms) tuned in fifths appeared in Italy, as can be seen in many paintings of the Renaissance. A complement in the bass register was lira da gamba (held between the legs). These instruments with f-holes and without frets were suited for celebrations, dances and balls, and were the ancestors of the violin family instruments. These instruments were painted between 1530–1540 by Gaudenzio Ferrari on the cupola of the cathedral of Saronno, north of Milan in Italy (Fig. 2.1).

(a) **Violin Family**

The emergence in the sixteen century of the violin family had an enormous impact in Western music, for its practice and its aesthetics. The exact date of this event is not known, but it is supposed to be the consequence of the evolution of rebec and lira da braccio determining the construction of the viola, from which the other members of the violin family developed in various pitch-sizes. The violin family developed in the form of classic quartet–violin, viola and violoncello. The double bass appear later as a modified orchestral variant from the viol family (Marcuse 1975). The considerable acoustical development of the instruments from violin family is due to the great Cremonese masters. The difference in sound of the members of violin family is due to the major structural changes produced as a

Fig. 2.1 Angels playing musical instruments from the violin family, painted circa 1530–1540 by Gaudenzio Ferrari (1475–1546) on the cupola of the cathedral of Santa Maria dei Miracoli of Saronno, north of Milan in Italy (http://upload.wikimedia.org/wikipedia/commons/4/4d/Gaudenzio_Ferrari_002.jpg. Access 17 November 2014)

consequence of the increasing of technical demands imposed by the new aesthetics of Baroque music and later by Romanticism.

It seems that the word violin was used for the first time in 1538 when Pope Paul III (1468–1549) was negotiator of the Truce of Nice for the Italian war between 1536–1538, and where he took the "violini Milanesi" to participate in the ceremonies involving Francis I, King of France (1515–1547) and Charles V, Emperor of Holy Roman Empire (1515–1547).

The Valois Kings of France, under the influence of Catherine de Medici (1519–1589)-married to King Henry II (1519–1559) and mother of Charles IX (1550–1574)-from 1550 commissioned 38 instruments (24 violins, 6 violas, 8 cellos) from Andrea Amati (1505–1578). These instruments were housed in the royal chapel in Versailles until 1790 and many disappeared during the French revolution (Markevitch 1984). Only eight of them survived: three violins, one viola and two cellos. One of the cellos, known as the "King" is definitely dated 1572, and is now in National Museum of Music—US. The other cello is probably from 1769 and belongs to the Belgian baroque virtuoso Wieland Kuijken (1938–). These instruments are superb art works, richly decorated with the French coat of arms and the motto PIETATE ET IVSTITIA (Piety and Justice).

These new Italian instruments replaced the luth, rebec and viole which were mainly used until then for court ceremonies and other important events. A scene was pictured by Jacques Paris (Fig. 2.2) in which we can probably see the royal couple, the courtiers and the musicians playing a violin consort composed of only four instruments. As noted by Dipper (2005a, b) "the violin was propelled by the

Fig. 2.2 Ball at Valois Kings of France, unknown painter, circa 1580 (now in Musée des Beaux Arts de Rennes, France). http://commons.wikimedia.org/wiki/File:Ball_at_the_Valois_court,_c._1580.jpg

dance masters' ability to adapt the old musical genres to the new, fashionable court dances". "These dance masters would have been in a position to nurture further Amati violin commissions from the courts and noble families of Europe". It is probable that a consort of these five painted instruments made by Andrea Amati for Charles IX was played at his marriage with Elisabeth of Austria in 1570. Before the end of the Baroque era the instruments of the violin family arrived at their perfect constructive shape and after Antonio Stradivari's death in 1737, no more effective modification of the corpus geometry or of the constitutive parts was produced. The instruments manufactured in Cremona or Brescia during the 16th and the 17th century are considered today the peak of the luthier's art.

After 1550 Andrea Amati (1570–1576) was probably the first to make violins with four strings. The development of Western music was closely linked to the development of techniques for playing violins enriching the colourfulness of music. Violins and later other members of the violin family were played by professional musicians and Italian musicians introduced these “new” instruments to a wider audience at different European courts. The golden age of the violin was probably between 1600 and 1750. The Cremonese School of violin makers was led by Amati’s sons and grandsons until the death of Nicola Amati (1596–1684). His pupil Andrea Guarneri (1626–1698) and later Giuseppe Guarnieri “del Gesu” (1698–1744) and of course Antonio Stradivari (1644–1737) were the most outstanding exponents of the Cremonese School. The design of Stradivari’s violins was accepted as the definitive reference by later generations of violin makers. The Brescian School was also well known with craftsmen such as Gasparo da Salo (1540–1609) and his pupil Maggini (1580–1632). Modern masters try continuously to reproduce these models and to introduce new materials and testing methods for quality assessment of modern instruments played in very big concert halls.

North of the Alps countries have famous violin making schools as for example in the Tyrol where Jacob Steiner (1621–1683) built violins played by JS Bach (1685–1750) among others. Matthias I Klotz (1656–1743) was the renowned founder of the Mittenwald school of violin making in Bavaria, and his brother Aegidius Klotz is said to have made Mozart’s (1756–1791) personal violin. The Austrian musician Eduard Melkus (who from 1982 to 1995 was professor of violin, baroque violin, viola, and historical performance practice at the Vienna Academy of Music and head of the Institute for Viennese Sound Style) played an unaltered violin by Aegidius Klotz, made in around 1760 and has been recorded by Deutsche Grammophon. In Vienna, Austria, the first violin maker of repute was Joseph Stadlmann (1720–1781), while in France the first violin maker of repute was Nicolas Médart (1628–1672). He was followed after a century by Nicolas Lupot (1758–1824) and Jean Baptiste Vuillaume (1798–1875) who modelled his instruments on Stradivarius and worked with the French scientist Felix Savart (1791–1841). England had Barak Norman (1678–1740), and so on in other countries of Europe. After 1800 the art of violin making founded by the aristocracy declined in favour of modernized instruments in which the bridge was raised, the tension in strings increased, the angle of the fingerboard was modified, the neck and the fingerboard were lengthened, the bass bar and the soundpost were reinforced, etc. In 1820 the composer Louis Spohr (1784–1859) invented the chin-rest to facilitate the sliding movement of the left hand. Since then the chin-rest has continuously been used for violins and violas.

In about 1800 structural modifications completely altered Cremonese instruments by utilising four operations: replacing the bass bar with a new longer one, lengthening the finger board, raising the height and camber of the bridge, and lengthening the neck. These “innovations” had a major effect on the design of the great Cremonese instruments irreversibly altering their original design. Was this “catastrophic” for their sound, or did it improve it? Do we know what it sounded like? It is impossible to know.

During the second half of the 20th century the art of violin making was again much prized. Modern masters try continuously to reproduce Cremonese models and work together with scientists to introduce new materials and testing methods for quality assessment of modern instruments played in very big concert halls. They also seek improvements by the invention of new instruments in the violin family such as the violin octet by Hutchins-Schelleng (Bissinger 2010) or the guitar family developed by Caldersmith (1995)

(b) **The Classical Guitar**

Andalusia in Spain was to the classical acoustic guitar what Cremona was to violins. The Spanish vihuela built during the Renaissance (1400–1600) is chronologically the first important guitar-type instrument. Such an instrument can be seen at the Musée Jacquemart-André, in Paris. The Baroque classical guitar was built between 1600 and 1750. This instrument had four gut strings or four courses (two or more adjacent strings closely spaced) and movable gut frets. Such an instrument made by Josef Dörfler can be seen at the Edinburgh collection in the UK. Another preserved example of a five course guitar, beautifully made with ivory Cocho having a flat back, is the guitar built in 1582 by Belchior Diaz of Lisbon—today in the collection of the Royal College of Music, London (Coates 1985). The end of the five course tradition was between 1752 and 1775. An important step in guitar construction was the introduction of six single strings, which underwent alterations in shape (broadened at the lower and upper bouts and narrowed at the waist), the fixed fret and the peg board replaced by the machine heads. During more than two centuries the design of the body outline had changed very little. Between 1750 and 1800 the instrument "remained outside the musical mainstream" (Wade 2001). At the beginning of the 18th century two composers, the Catalan Fernando Sor (1778–1839) and the Italian Mauro Giuliani (1781–1829) made an outstanding contribution to the classical guitar musical repertoire. Paganini (1782–1840) also composed for the guitar, as well as Berlioz (1803–1869) and many others. In spite of this splendid repertoire, in the 1850s the guitar declined in popularity, mainly probably because it lacked sound loudness for the requirements of the romantic repertoire and of new socio—economic conditions unfavourable to the aristocracies.

However, the 19th century marked an important step in classical Spanish guitar evolution and culminated in the mid-nineteen century with the instruments made by Antonio de Torres (1817–1892). He fixed string length at 65 cm, refined the outline and introduced fan bracing of the top that enhanced the sound. Torres produced guitars of unsurpassed beauty having very elegant proportions, a sculptured heel, a profiled head and inlayed sound holes and ribs with splendid mosaics (Jahnel 1981; Sloane 1989). This tradition of building remarkable concert guitars was continuously developed in the 20th century. In the late seventies the Australian classical guitar luthier Greg Smallman (1947–) invented a very innovative structural system of bracing using a lattice framework composed of balsa wood and carbon fibre on a very thin top made of Western red cedar (*Thuja plicata*) (Fig. 2.3). The highly arched thick back is made in Madagascar rosewood (*Dalbergia maritima*). This technical solution invented by Greg Smallman was adopted by numerous luthiers all over the world. These instruments are more appropriate for the acoustics of modern concert halls. At the beginning of the 21st century, the classic guitar is well established as a creative force in modern

(a) (b)

Fig. 2.3 Smallman guitar—the most important innovation of the 20th century in guitar building. *Legend* **a** bracing using a lattice framework composed of balsa wood and carbon fibre; **b** The ribs and the back in Madagascar rosewood, the fingerboard in ebony (Photo Greg Smallman—A Smallman guitar, Saturday 28 Nov 2009 (http://www.abc.net.au/radionational/programs/intothemusic/a-smallman-guitar/3064766. Access 25 April 2014)

musical life illustrated by the activity of numerous recitalists of virtuosic ability and by the expansion of guitar teaching from the elementary to the academic level.

(c) The Concert Harp

Among the chordophone instruments, the harp has a very distinctive characteristic related to the position of the strings, at a large angle to the resonance box. The strings are supported by a frame having a long vertical pillar which is much decorated for concert instruments. Harps have been known since Egyptian and Greco-Roman antiquity. In Europe harps of Scottish, Irish and French origin are known from their representations in a ninth century Utrecht Psalter, penned between 816 and 835 AD. Medieval harps had a triangular shape, had metallic strings, no pedals and were played with two hands in the same way as the modern harps (Marcuse 1975). Primitive pedal harps were developed in the Tyrol–Austria. An important contribution to harp construction was made by the French Sébastien Erard (1794–1810). He was active in France and England where he commercialised patents, the first one in 1794 for the harp was for a single action instrument with a mechanism allowing the strings to be shortened by one semitone. A second patent was in 1810 for a double movement seven pedal action allowing each string to be shortened by one or two semitones. This mechanism is still in use for modern concert harps in the Western classical symphony orchestra. (http://www.piano-tuners.org/history/erard.html. Access 19 April 2014, Montagu 2002).

(d) The Grand Piano

The grand piano in the Western symphony orchestra is probably the instrument needing the most technology for its manufacture. The history of this instrument is relatively recent. Around 1700 the fortepiano was invented in Florence by Bartolomeo Cristofori (1655–1731) curator of the collection of musical instruments at the Medici court. The fortepiano has strings struck by hammers, while the harpsichord has plucked strings. Pollens (1995) noted that three pianos made by Cristofori have survived to the present day and are dated from the 1720s. A detailed discussion about the mechanism of sound production by the modern piano is given in Chap. 15. To the ears of a contemporary listener these instruments sound similar to modern harpsichords.

In the contemporary symphony orchestra the grand piano is used in two distinct ways. Its first use is as a soloist instrument, for the interpretation of the enormous repertoire of concerts written for this instrument since the Baroque era. A second function of the grand piano is as a rank instrument seated near the harp and the percussion instruments, as will be seen in the next section of this book. In this manner the grand piano is used mainly in symphonic repertoires of the 20th century.

(e) **The Harpsichord**

During the 20th century the harpsichord revived in contemporary music animated by exceptional interpreters and renamed composers and builders. Pleyel et Cie, company in Paris built in 1927 the modern harpsichord at the request of Wanda Landowka (1879–1959). This instrument is today in the collection of the musical instruments museum in Berlin. Several elements derived from the technology of piano building were introduced in the construction of this instrument such as a metallic frame to increase the stability of tuning, an additional set of strings that played an octave below pitch, etc. Since the mid 20th century harpsichords builders followed the historical principles with thinner cases and traditional disposition of choirs of strings.

The revival of the harpsichord was determined by an extraordinarily rich repertoire of chamber music due to the composers of the 20th century, introducing a new image to the modern harpsichord, with new striking sonorities. Casting off the weight of tradition and using new ideas and modern technology, imaginative composers discovered the potential and the rich expressiveness of this old instrument (Chojnacka 2008). Over 80 new works were dedicated to the most appreciated harpsichordist for contemporary music, Elisabeth Chojnacka. Another important phenomenon was the migration of modern harpsichord from classical music to jazz and pop music.

2.1.2 String Instruments and the Symphony Orchestra

In Europe, the emancipation of instrumental music from vocal music took place between the 14th century and the 17th century. This was one of the most outstanding events in music history. Keyboard instruments evolved into polyphonic chords as early as the 14th century followed by the lutes in the 15th century. The invention of the particular tablatures was a big step forwards, the music was written in several parts, each one intended to be played by an individual musician and adapted to his instrument (Praetorius (1614–1619). Composers created new instrumental forms different from those for voices, the instruments became polyphonic. Orchestration was first considered in the second half of the 16th century. A specific composition for instruments and voices/singers involving more than two groups was specified in detail. Giovanni Gabrieli (1554–1612) in Venice was the first to specify the instruments required for the written score (Arnold 1980). "The new delight in timbre acted as a strong stimulus in making instruments" (Sachs 1940). The musical instruments in all their sizes are depicted by Pretorius in his second volume of *Syntagma musicum* (written in German) *De Organographia*, in which instruments are referred to in Brunswick feet (1 foot = 289 mm). Another reference book was written in French by Mersenne (1636) and the construction of the instruments has been explained. In the Renaissance epoch musical instruments were also appreciated for their own beauty as decorative objects. Drawing musical instruments in correct proportions for a realistic representation and depicting them in art works was of major interest. Dürer (1471–1528) explained the principles of perspective drawing using a lute (Fig. 2.4) (Silver and Smith 2011). Dürer strongly believed in the importance of proportions and numbers for artistic design as can be seen from a letter to humanist Wilibald Pirkheimer (1470–1530) "For this doctrine of proportions, if rightly understood, will not be use only by painters alone, but also by sculptors in wood and stone, goldsmiths,….. as well to all those who desire to make figures" (Coates 1985). (We note that wood carving is the main skill of a luthier).

At the beginning of the Baroque era a most significant innovation in musical life took place in Florence, when drama and music were put together by three composers Jacopo Perri (1561–1633), Giulio Caccini (1551–1618) and de Cavalieri (1563–1602), belonging to the Florentine Camerata. This group of humanists, musicians, poets, and artists was interested to discuss and guide trends in music and drama and arts in general. The first surviving score of the Italian opera is Euridice, by Jacopo Perri—"creatore del melodrama". This opera was performed in Palazzo Pitti in Florence, on 6 October 1600 for the weeding of Maria de Medici to Henry IV, King of France. The interest for musical art was transmitted to their son, Louis XIII

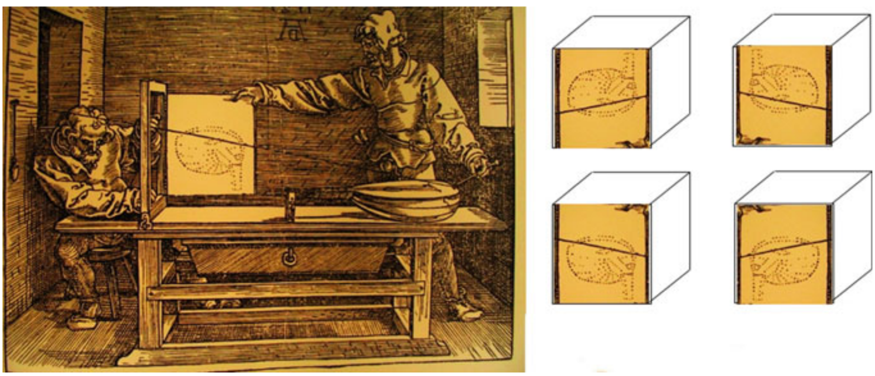


Fig. 2.4 Drawing a lute in perspective as explained by Durer (http://photos1.blogger.com/x/blogger/3242/2391/1600/227622/Renaissance%20Durer.jpg. Access 17 November 2014)

Table 2.1 Instruments composing the orchestra in different historic periods

Orchestra type	Years	Description	Major contributions (a selection)	Instruments
Baroque	1600–1750	1 Harpsichord of the maestro di capella. 2 Harpsichord of the accompanist (of the recitative); 3 Violoncelli; 4 Contrabassi; 5. First violins; 6. Second violins, with backs to theatre [the stage];7. Oboes; 8 Flutes, the same. a. Violas, the same. b. Bassoons. c. Hunting Horns. d. A platform at each side, for the timpani and trumpets. ___________ 2 Flutes 2 Oboes 2 Oboes d'amore (an early oboe with a slightly lower range) 2 Oboes da caccia (another early oboe, shaped like a hunting horn) 3 Trumpets 2 Corni da caccia (hunting horns) Timpani Strings Continuo (bassoon, cellos, string bass, and organ)	Dresden Hofkappelle __________ J.S. Bach Christmas Oratorio	Acoustical instruments
Classic	1750–1830	2 Flutes, 2 Oboes, 2 Clarinets 2 Bassoons, 2 (or 4) Horns 2 Trumpets,Timpani, Strings (violins I and II, viole, cellos and double bass)	Beethoven Symphonies	
Romantic And Post-romantic	1830–1950	2 Flutes (one doubling piccolo) 2 Oboes (one doubling English Horn), 2 Clarinets (doubling on A, Bb, C, and Eb)	Berlioz 1830 Symphonie fantastique	

(continued)

Table 2.1 (continued)

Orchestra type	Years	Description	Major contributions (a selection)	Instruments
		4 Bassoons, 4 Horns, 2 Cornets 2 Trumpets, 3 Trombones 2 Ophicleides (obsolete bass brass instruments), Timpani Percussion (including Bass Drum, Snare Drum, Cymbals and Bells), 2 Harps, Strings		
Modern for film, radio, television and concerts	1950 to the end of XXth century. and XXIth century	The piece is scored for: Solo piano and—ondes Martenot • Woodwind: piccolo, 2 flutes, 2 oboes, cor anglais, 2 clarinets, bass clarinet, 3 bassoons; • Brass: 4 horns, 3 trumpets, 1 trumpet in D, cornet, 3 trombones, 1 tuba; • At least 8 and up to 11 percussionists, playing: vibraphone, keyed or mallet glockenspiels, triangle, temple blocks and wood block, cymbals (crash and three types of suspended), tam tam, tambourine, maracas, snare drum, Provençal tabor, bass drum, and tubular bells; • celesta, and strings (32 violins, 14 violas, 12 cellos and 10 double basses)	Messian 1948 (revised 1990) *Turangalîla-Symphonie*, piano solo, ondes Martenot solo, orchestra	Acoustical instruments and Electronic instruments

(1601–1643). He was the patron of the French Court ensemble, known as 'Les 24 Violons du Roy', composed of 6 dessus (violins), 4 haute-contre or haute-contre taille (alto violas), 4 taille (tenor violas), 4 quinte or cinquiesme (more violas), 6 basse (violoncellos). Keyboards—harpsichords have been used as "continuo", as described in 1637, by Mersenne in "*Traité d'harmonie universelle*". Similar instrumental ensembles arose in other European courts during the 17th century and continued to develop in the next two centuries covering the baroque orchestra to the classic, romantic and modern orchestra (Sptizer and Zaslaw 2004; Peyser 1986). The instruments composing these orchestras are listed in (Table 2.1). The major figures of the Classical period were Haydn (1732–1809), Mozart and Beethoven (1770–1827). They developed orchestral composition very significantly and after 1800 the orchestra became the grandest and most powerful tool of musical expression, with a great timbral variety (Raynor 1978). One of the possible orchestra seating charts for a modern configuration is shown in Fig. 2.5. The violins are to the left of the conductor, the violas in front of him and the cellos and the double basses to the right. The wind and the percussion instruments are placed to the rear. Directivity of symphony orchestra instruments is different; the brass instruments radiate in the direction of their bell, while the directivity of strings and the woodwinds is affected by playing dynamics (Patynen and Lokki 2010; Meyer 2009).

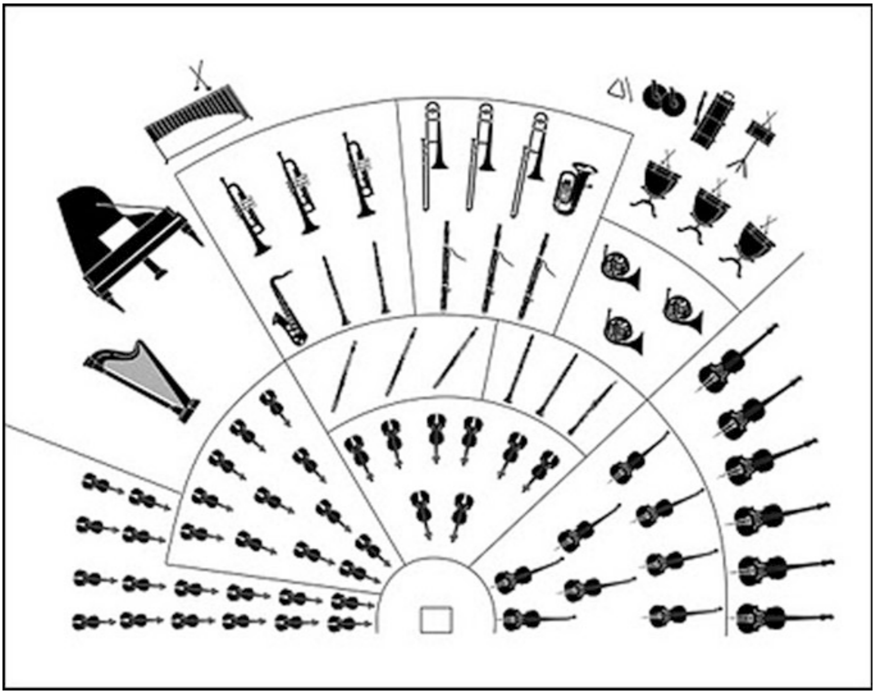


Fig. 2.5 One of the possible orchestra seating charts for a modern configuration (http://media.composerfocus.com/articles/artofmidi/orchestra.jpg. Access 4 November 2011). *Legend* ϒ conductor; 1—first violin; 2—second violin; 3—viola; 4—cello; 5—double bass; 6—harp; 7—piano; 8—oboe; 9—flute, 10—horn; 11—bassoon; 12—clarinet; 13—tuba; 14—trombone; 15—trumpet; 16—percussion (tympani, bass drum, cymbals, triangle and others); 17—marimba

2.2 String Instruments as Art Objects

> Let proportions be found not only in numbers and measures, but also in sounds, weights, times and positions, and whatever force there is. Leonardo da Vinci

Music which has always acted as a stimulus across a broad spectrum of the arts, can be created via instruments and of course via players. Elegantly dressed musicians playing splendid instruments have been represented in numerous pictures or sculptures from antiquity to the post romantic era. Studies on musical iconography have a very abundant literature reflected in famous journals such as *Imago Musicae* (eds Tilman Seebass and Tilden Russel, published in Basel-Switzerland by Durham, Bärenreiter-Verl.), *Musique-Images-Instruments*—French journal of organologie and musical iconography—ed. Florence Gétreau, published in Paris by CNRS Editions and the American journal *Music in Art, International journal for music iconography* published in New York, ed. Z. Blazekovic. A large database on musical iconography is accessible at http://www.ridim.org/database.php. Access 22 March 2014 (RIdIM = Répertoire international d'iconographie musicale).

Two particular art forms used in the service of Baroque musical instrument representation were painting and the inlay. The third art form widely used on musical instruments was sculpture. These three art forms were used to enhance their symbolic value and to emphasize the origins of these exceptional objects which are indispensable to the musical phenomenon. The fascinating sense of ornamentation of the craftsmen manufacturing these instruments was unsurpassed. Beside their acoustic functions as devices to produce sounds, some musical instruments are representative of the decorative arts. The painted representation of musical instruments and the sculptural decoration of these fine arts objects are complex subjects which need to be understood in the context of musical organology and of the decorative arts. Only three examples have been chosen here to illustrate the organologic as well as the decorative arts aspects.

(a) **Representation of musical instruments in painting**

Italian Baroque musical instruments (namely from Brescia) were extensively depicted by Evaristo Baschenis (1617–1677) and his pupils Bartolomeo e Bonaventura Bettera (1639–1688) (Rosci 1985; Milliot 1987). Some of their pictures today belong to the art collection of the Pinacoteca dell'Accademia Carrara in Bergamo. A portrait of Baschenis is reproduced in Fig. 2.6. Another painter active in Bergamo and known for still life with Italian string musical instruments was Cristoforo Munari (1667–1720). The instruments are realistically represented, equipped with all their accessories including the strings, the bridge, and the pegs.

(b) **Representation of musical instruments on intarsia**

Intarsia is a form of wood inlaying developed in Italy in Siena and its surrounding region, since the 15th century, for the decoration of religious buildings. Intarsia proceeds from marquetry applying pieces of veneer to form decorative patterns and from carpentry since these pieces are glued onto a solid wooden panel.

Fig. 2.6 Portraits of Evaristo Baschenis playing spinetta and Ottavio Agliardi playing the lute; other instruments are painted (arciliuto; mandola, chitarra, violone) (Photo Wikipedia.it http://it.wikipedia.org/wiki/Evaristo_Baschenis. Access 23 March 2014). Evaristo Baschenis, *Accademia musicale di Evaristo Baschenis alla spinetta e di Ottavio Agliardi con arciliuto;mandola, chitarra, violone, intavolatura per liuto*, 1665 circa. Olio su tela, 115 × 163 cm. Bergamo, Casa Agliardi. Sul bordo della spinetta si legge EVARISTUS/BASCHENIS/BERGOMI/P

The materials used were small pieces of wood veneer of various species, shapes and sizes. Each piece was individually finished. The natural grain of wood was selected to create the illusion of depth for the objects represented in perspective by axonometric projections. One of the most outstanding examples is the set of panels representing musical instruments by Fra Giovanni da Verona between 1502 and 1505, for the choir stalls of the church of Monte Oliveto Maggiore Abbey (26 km south of Siena, Tuscany, Italy). Figure 2.7 shows two recorders, a cittern, a lute with visible detached strings and a sheet of a musical score. The instruments are represented in real size and the different structural components are made from the same wood species as the real instruments.

(c) **Sculpture**

The scroll at the end of the neck of string instruments (plucked or bowed) was the structural element mostly decorated with carvings inspired from architectural design. Floral patterns or zoomorphic heads were also used for scroll decoration. The scroll of the harp having a large surface was one of the features mostly

Fig. 2.7 Intarsia with musical instruments by Fra Giovanni da Verona (cca 1457–1525) with two recorders, a cittern, a lute with visible detached strings and a sheet of a musical score made 1502–1505 for the choir stalls of the church of Monte Oliveto Maggiore Abbey (26 km south of Siena, Tuscany, Italy www.monteolivetomaggiore.it/lang1. Access 20 April 2014)

decorated with floral patterns (Fig. 2.8). The famous masters of that time were the Parisians Cousineau (1733–1800) and Nadermann (1734–1799).

Another interesting example is in Fig. 2.9 showing details of the scroll of a cittern, made in Brescia by the violin maker Girolamo Virchi (cca 1520–?) well known as the father of Paolo Virchi (1551–1610) the composer and musician at the court of Alfonso II d'Este, Duke of Ferrara (1533–1597). No doubt judging by the beauty and elegance of its proportions this scroll is the work of a professional sculptor. On the other hand this work reflects the artistic climate of decorative arts at the Italian courts dominated at that time by the famous goldsmith and sculptor Benvenuto Cellini (1500–1571), himself the son of a violin maker in Florence.

Italian harpsichords were decorated with the most extraordinary sculptures of the exuberant Baroque style, as for example the legs of the instrument made by Michele Todini (1616–1690) displayed in the Metropolitan Museum in New York or that made by Grimaldi in Sicily in 1697, with a range of 4 1/2 octaves now in the Germanisches National museum in Nuremberg, Germany (Fig. 2.10). The outer case and the legs of the Grimaldi harpsichord are covered in gold leaf. The keyboard naturals are in ivory with ebony topped accidentals.

Fig. 2.8 Harp made in 1775 by the Parisian maker Cousineau (1733–1800). *Legend* The scroll and the pillar are decorated with *carved* flowers, leaves and garlands. Polychrome Chinoiserie is painted on a black background (Photo courtesy http://www.onlinegalleries.com/art-and-antiques/detail/louis-xvi-harp/90703. Access 20 April 2014)

2.2.1 Utility and Beauty, Inseparable Concepts for Baroque Musical Instrument Building

Richly decorated musical instruments are art objects and at the same time artefacts reflecting their long cultural history, craftsmanship and the materials used. Musical instruments with sumptuous decorations were not the norm and we have to consider the instruments' history and commissioning, in their sociological context. Since the Renaissance the decoration of European musical instruments has had three main functions: *the social* and psychological function, restricted to aristocratic milieus; the *aesthetic function* of interior design, in the aristocratic salon and in the bourgeois drawing room (i.e. the clavichords, harpsichords and pianos, a combination musical instrument and furniture such as spinet/secretaire, harpsichord/dresser, spinettino/needlework box); the *stimulative function* of player on the listener.

Among the musical instruments the keyboards were decorated most. The inside surface of the lids was painted with trees, landscapes, ruins, etc. The outer surface of the lid and the sides of the outer case were largely decorated with heraldic devices, musical scenes, musical instruments, flowers, inlaid in ivory, tortoiseshell, precious stones, gold leaf, etc. The motto on the lid was in Latin, testifying to the artist's or patron's humanistic education. (i.e. MUSICA DVLCE LABORVM LEVAMEN—Sweet music, light work or MUSICA MAGNORUM SOLAMEN

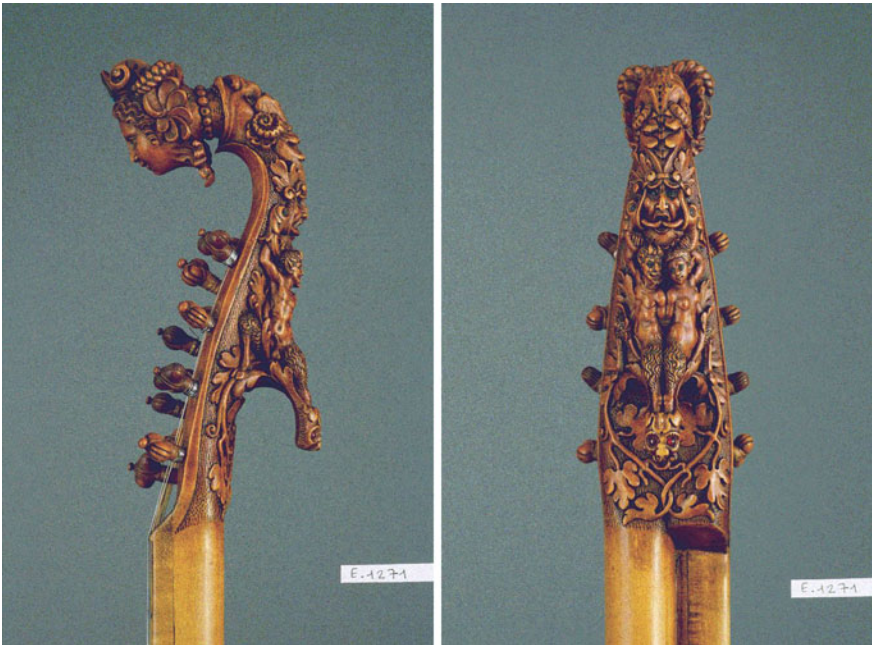


Fig. 2.9 Cittern-detail of the neck and scroll by Girolamo Virchi–Brescia 16th century (Cité de la Musique – Musée – Paris inv. E 1271, Photo J M Angles) (http://www.mimo-db.eu/media/CM/IMAGE/CMIM000019554.jpg. Access 20 April 2014)

DULCE LABORUM—Music is the sweet consolation of great labours) or SINE SCIENTIA ARS NIHIL EST—Without science art is nothing).

The legs of the keyboard instruments were also an important part of the decoration (Fig. 2.11). The legs were carved or gilded and decorated with caryatides, atlantes, tritons in the Rococo period or luxuriant foliage in the Art Nouveau period (Rueger 1982).

The string instruments having smaller surfaces were less decorated. However the flat top the guitars (Fig. 2.12) and the fretted fingerboard were particularly decorated with inlaid precious wood species and ivory (Fig. 2.13).

The surfaces of violin family instruments particularly decorated were the end of the neck, the tailpiece and the back, which was carved, painted or inlaid. A unique example of painted instruments having a relatively big surface is the bassetto, known today as the “King” cello made by Andrea Amati for the royal French court of King Charles IX (1560–1574) (Fig. 2.14). This cello was among the five instruments comprising a consort, made by Amati for the French court around 1566. The instruments of the consort were: violin piccolo (body length 34.2 cm), violin (35.4 cm), viola contralto (40.8 cm), viola tenore (47.1 cm) and 3-string bassetto (78.5 cm).

Fig. 2.10 Harpsichord by Carlo Grimaldi, made in Messina, Sicily in 1697 now in the Germanisches Nationalmuseum, Nürnberg, Germany (Photo Germanisches Nationalmuseum www.gnm.de/. Access 21 April 2014)

Unfortunately in the early 1800s, this cello was reduced in size and the painted decoration mutilated, as can be seen at the central crest of the armorial showing the area of cutting down the centreline. The decoration entails the motto in Latin capital letters PIETATE ET IVSTITIA (Piety and justice) around each of the twin ionic columns in gold and silver leaf (the gold one is barely visible, probably because of wear by playing), the armorials of the king, the letter "K" (Karolus in Latin = Charles) surmounted by a crown flanked by a floral motif, at the lower bout, the royal fleur de lys of France (with three petals recalling the Trinity) at the four corners at the purfling point. In the centre between the C-bouts several are separate motifs, the arms of France surmounted by the crown and surrounded by the chain and medallion of the order of St. Michael. To the right of the arms is the figure of Piety (in a very bad condition, only the face and the foot on a cloud being visible) and to the left the figure of Justice with sword in hand, a sacred relic of the kings of France, used in their ordinations. The painted decoration by an unknown artist is

Fig. 2.11 Harpsichord made in 1643 by Andreas Ruckers II (1601–1667), Antwerp 1643 (Photo Bill Willroth Sr., National Museum of Music, The University of South Dakota, US. http://orgs.usd.edu/nmm/Keyboards/RuckersHarpsichord10000/Ruckers1643.html. Access 25 March 2014)

Fig. 2.12 Virginal "à la quinte" made in 1583 by Hans Ruckers (1540–1598)—Paris Musée de la Musique. nr. E.986.1.2). The instrument sounds a fifth higher than standard pitch, A 440, and it is the only virginal with this pitch, that has been preserved (Photo Albert Giordan. http://collectionsdumusee.philharmoniedeparis.fr/0130260-virginale-ruckers.aspx)

Fig. 2.13 Baroque guitar by Matteo Sellas made probably between 1630 and 1650. *Legend* size: 26.9 × 95.6 cm. *Materials* spruce, bone, parchment, snakewood, ivory (Metropolitan Museum of Art http://commons.wikimedia.org/wiki/File:Baroque_guitar_(ca.1630-50),_Matteo_Sellas,_The_Met,_NYC.jpg)

laid on a ground coat of varnish. A copy of this splendid instrument is shown in Fig. 2.14b.

Dipper (2006) emphasised that Andrea Amati probably invented and certainly constructed the consort of instruments for Charles IX of France to be played together as an ensemble. "While the "King" cello is certainly the precursor of the modern cello, the Charles IX consort of instruments, as a whole, and the underlying ideas of harmony and proportion that are implied in their design, may be seen as the basis and foundation stone of the structure of the modern string orchestra".

2.2.2 Precious Materials for Baroque Musical Instruments

Venice was recognised as the world leading centre of musical instrument making of the 16th century. Decoration of musical instruments or furniture with gemstones was practised in Rome from 1550 and in Florence since 1588. Milano was and still is a leading centre for furniture manufacturing. Precious materials used for surface decoration of Baroque musical instruments were: gold, silver, gems and hardstones, ivory and tortoise shell. In this section we will present several instruments of historical importance and high artistic decorative value.

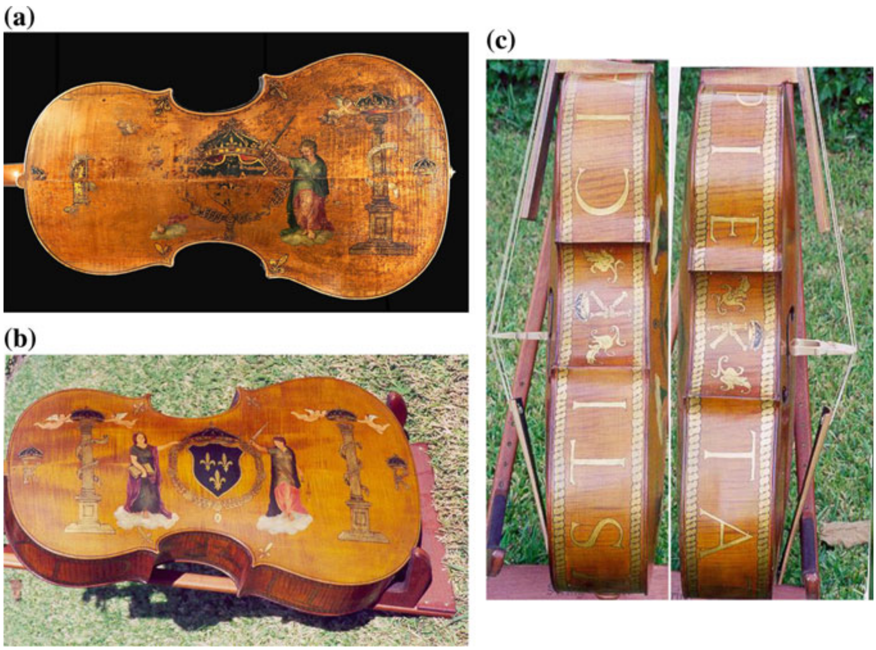


Fig. 2.14 The "King" cello by Andrea Amati. **a** Original instrument and its painted decoration on the back (Photo Bill Willroth Sr., National Music Museum, The University of South Dakota, US. http://orgs.usd.edu/nmm. Access 23 March 2014). **b** A modern copy with reconstituted decoration (http://www.cello.org/heaven/masters/king.htm. Access 20 March 2014). **c** Side view (*Note* letter K—Karolus in Latin for Charles)

(a) Decoration with gems

The virginal made by Annibale de'Rossi in Milano in 1577 is now in the Victoria and Albert Museum in London (Fig. 2.15). As noted in the technical note of the museum, "the instrument is decorated with 1928 precious stones (857 turquoises, 361 pearls, 103 lapis lazuli, 28 amethysts, 58 topazes, 6 carnelians, 40 emeralds, 32 sapphires, 117 garnets, 242 small garnets and rubies, 4 crystals, 9 agates, 52 jaspers, and 19 small jaspers and agates). However many of these appear to be much later additions. Only the stones in the keyboard and some of the lapis lazuli panels are certainly part of the original scheme. During conservation in 2012 ebony inlay was found underneath some of the applied ivory, and inlaid jasper panel." "The soundboard in cypress contains a wooden rose of exceptionally large diameter (145 mm), carved in relief with strap work cartouches…". (http://collections.vam.ac.uk/item/O61533/the-rossi-virginal-virginal-rossi-annibale/).

(b) Decoration in Moresque sgraffito on a lustrous gold background

One of the instruments of that era made in Venice was the spinet belonging to Queen Elisabeth I of England (who reigned from 1558 to 1603), today in the

Fig. 2.15 Virginal superbly decorated with gems made by Annibale de'Rossi in Milano in 1577 is now in the Victoria and Albert Museum in London (http://collections.vam.ac.uk/item/O61533/the-rossi-virginal-virginal-rossi-annibale/. Access 18 April 2014)

Victoria and Albert Museum in London. The spinet was made by Giovanni Antonio Baffo, but the artist who decorated the instrument is supposed to be a professional unknown painter. The very rich decoration of this spinet includes superb ornamentation in red and blue glazes of gold, keys inlayed with various precious woods, ivory or bone and key fronts decorated with embossed and gilded paper. The most unusual and unique part of the decoration is the Moresque sgraffito in blue and red on a lustrous gold background (Fig. 2.16). Sgraffito is a decorative technique based on several layers of contrasting colour on which a pattern is scratched through the upper layer to reveal the colour underneath.

(c) **Decoration with ivory**

Joachim Tielke (1641–1719) active in Hamburg made lutes, mandoras and guitars richly decorated with ivory inlaid (Fig. 2.17). Ivory, relatively easy to carve, was used to cover the neck, the fingerboard or the pegboxes. The pegs were in ivory. As we can see today, the artistic quality of ivory work by Tielke was very high.

(d) **Decoration with tortoise shell**

Tortoise shell used for decoration of musical instruments and of very fine furniture is obtained from a marine turtle (*Eretmochelys imbricate*) living in warm water around the equator. The shield has a complex shape. To be used as a raw material, the shield should be separated into thin sheets and reconstituted in thick blocks with thin layers of gold leaf or coloured paper. Joachim Tielke made instruments decorated with this material and among them we cite two, a violin with the back in tortoise shell (Hellwig 2007) as well as a viola da gamba superbly decorated with inlay of ivory and tortoise shell, gold, mother of pearl, and precious stones, today in the collection of the Stiftelsen Musikkulturens Främjande in Stockholm (Fig. 2.18).

Fig. 2.16 Moresque sgraffito in blue and red on a lustrous gold background on the spinet made in Venice by Giovanni Antonio Baffo for Queen Elisabeth I of England (Victoria and Albert Museum, London. www.vam.ac.uk. Access 15 April 2014)

Fig. 2.17 Head of baroque instruments made by Joachim Tielke (1641–1719) decorated with inlaid ivory, tortoise shell, gold and precious wood species (http://www.tielke-hamburg.de/htm_english/instr_zupf.htm. Access 16 April 2014)

(e) Instruments in marble

Marble or limestone was a material only accidentally used for musical instruments. Limestone is a mosaic of carbonate crystals and has an orthotropic symmetry, as does wood. The big difference between these two materials is their density—400 kg/m^3 for resonance wood and 2500 kg/m^3 for marble. Hellwig (2007) cited two instruments, a harpsichord of 1686 (Fig. 2.19) and a guitar of 1680 made by Michele Antonio Grandi (1635–1707) at the request of Francis II d' Este Duke of Modena (1660–1694), and today in the Modena collection. The history of these instruments was described by Meucci (2005). The harpsichord is made in Carrara

Fig. 2.18 Carved head of viola da gamba, side view inlaid in ivory and tortoise shell (Stiftelsen Musikkulturens Främjande-Nydahl Collection, Stockholm, Sweden www.nydahlcoll.se)

Fig. 2.19 Marble harpsichord made by Michele Antonio Grandi in 1686 at the request of Francis II d′ Este duke of Modena, today in the Modena collection-Galleria Estense, Palazzo Communale (http://thegravicembalo.blogspot.com.au/2013/07/marble-harpsichord.html. Access 16 April 2014)

white marble and is equipped with an action made of wood which suggests that the instrument was played. The guitar is made in white Carrara marble, splendidly decorated and inlaid in black marble.

(f) Instruments in porcelain

Musical instruments were reproduced as decorative objects in porcelain, majolica or faience. These instruments were not made to be played. A violin in Delft porcelain is shown in Fig. 2.20. "When the violin was a record amount of 1500 guilders bought in 1876 by the collector John Loudon, he was regarded as the absolute highlight of the production of Delftware. The modeling and paintings make this an exceptional object" Dutch Rijks Museum Copenhagen

Given the limited space in this book for this subject, the selection of the instruments presented here is representative only of the personal opinion of the author. Without doubt for their extraordinary beauty of materials and craftsmanship other instruments deserve to be included in this list.

Fig. 2.20 Violin in porcelain by an anonymous artist, ca 1705–1710—today in the Dutch Rijks Museum Copenhagen (www.rijksmuseum.nl/. Access 16 April 2014)

2.3 Organologic Description of String Instruments of a Symphony Orchestra

Musical organology which is a subset of musicology and art history involves academic study of the art and science of musical instruments and embraces the musical instruments' history, the iconography of musical instruments, the classification of musical instruments and the descriptive aspects of their construction and acoustics.

In this chapter we focus our attention on the geometry of string instruments and the constitutive parts of string instruments.

2.3.1 Geometry of String Musical Instruments

Geometry has played an important role for the craft of instrument manufacture since antiquity. Construction of any geometric figure was possible using only the ruler and the compass. At the beginning of the thirteenth century a distinctive geometry was recognised under the label *geometria fabrorum*, taught by oral tradition and used in masonry and carpentry. Violin makers used a compass and a relatively short ruler. For keyboard instruments the basic tools were the compass, the large beam compass (trammel), the straightedge, the long ruler and the square (Birkett and Jurgenson 2000). These simple tools are illustrated in a French reference book for woodworking such as "L'art du menuisier"—the art of the cabinet maker-by Roubo (1769) and in "L'Art du facteur d'Orgue"—the art of the Organ builder—by Dom Bedos (1776).

Since Renaissance times the cabinet maker (ébeniste in French or ebenista in Italian) was no longer a craftsman but an artist making case furniture veneered or painted as fine art objects. The furniture created by Boulle (1642–1732), Chippendale (1718–1779), Maggiolini (1738–1814), Van Risenberg (1730–1767), David Roentgen, Majorelle (1859–1926) are testimonies to their art. Cabinet makers and violinmaker are craftsmen or artists of the highest level in woodworking and wood carving.

In the next section we discuss the geometry of the violin, guitar, harp and piano.

2.3.1.1 About the Geometry of the Violin

The perfection of the geometry of the violins made by Amati was without precedent. Mairson (2013) based on the "Traite de Lutherie" published by Denis (2006) and on the old book of Bagatella (1782) demonstrated that for the design of the instruments from the violin family Amati probably used only a compass and a ruler, and, the Euclidean geometry which was the theoretical basis of Renaissance architecture.

Music, architecture and mathematics were strongly linked in the philosophical approach of the life of Renaissance cultured spirits. However Brescian mathematician Tartaglia (1499–1557) published the first Italian translation of Euclid (Linehan 1913). He is known for teaching mathematics and geometry to the craftsmen of his native town of Brescia (Houssay 2008). Therefore it is not surprising that Amati constructed the profile of his violins with a ruler and a compass and without doubt the profile of the violin was not the result of an empirical evolution of the instrument from viola da braccio.

Outline violin design of Cremonese instruments was studied by Coates (1985) with four instruments dating from 1564 to 1703, by McLennan (2008) with copies of a Baroques violin and more recently using advanced procedures available with computer science by Stroeker 2010, Mairson 2013 and Muratov (2008). The subject is really of great interest and we have selected only a few examples for comment.

The outline of the violin corpus can be included in a big rectangle composed of four identical small rectangles, having edge sizes of the golden ratio. Figure 2.21 shows the possible design of the violin outline using the golden ratio and the Fibonacci numbers. (Fibonacci (1170–240) was an Italian mathematician in Pisa; in

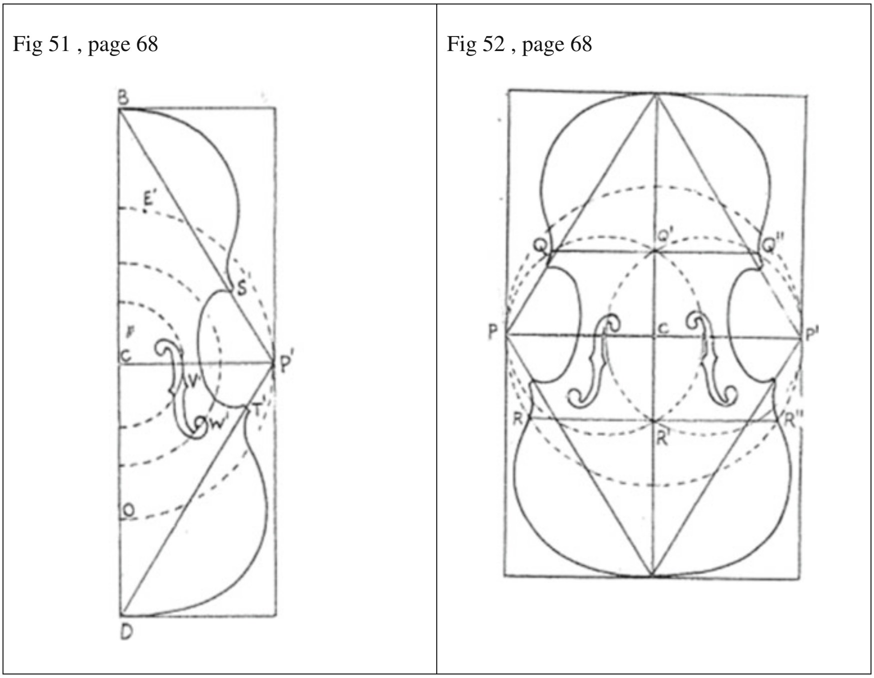


Fig. 2.21 Design of violin outline based on the golden ratio (Coates 1985, Fig. 51, p. 68 and Fig. 52, p. 68 with permission). *Legend* CV′ is the radius $\varphi_{3;}$ CW′ is the radius $\varphi_{4;}$ the body length is $\varphi_{5;}$ the diagonals BP′ and DP′ pierce the corners S′ and T′. The f hole and the position of the corners S and T′ (Fig. 51, p. 68). Intersection QQ′Q″ and RR′R″ for the outline of the violin (Fig. 52, p. 68)

the Fibonacci series 1, 1, 2, 3, 5, 8, 13, etc., each term is the sum of the two preceding terms, i.e. 3 = 2 + 1; 5 = 3 + 2, etc.).

The golden ratio φ and its progression is: 0.618; 1; 1.618; 2.618; 4.236 etc. Coates (1985) explained the use of φ series as follows (Fig. 2.21 a): A circle of radius φ_3 centre C, pierces the f-hole at its centre V′ between the middle notches, whilst a circle of radius φ_4, also centre C, pierces the lower centring W′. The φ_5, …, is shown here as arc E′P′O which together with the body length defines the hypothetical vertical aggregation of four φ rectangles (for clarity, only half the symmetrical plan is shown), whose diagonals, BP′ and DP′, pierce the corners S′ and T′ respectively. The establishment, in this way, of point P′ (and, of course, its lateral inversion, P) is of great importance in determining the vector which is to complete the plotting of middle and lower bouts". This vector is 2/3 of $\varphi 5 = 2/3 \times 106$ mm = 70.7 mm, commensurable with the body length

By drawing a rhomb (known as "*vesica piscis*") inscribed in the big rectangle (Fig. 2.21b), we can define the shorter diagonal PP′ which is the diameter of the circle with centre C. The lines of intersection Q Q′ and Q″ and R R′ and R″ are important points of the outline geometry. Coates (1985) demonstrated that other relationships between the outline of the violin and geometric considerations were established and illustrate the idea that violin design was the result of the aesthetics of the Renaissance derived from Antiquity and governed by the golden proportions.

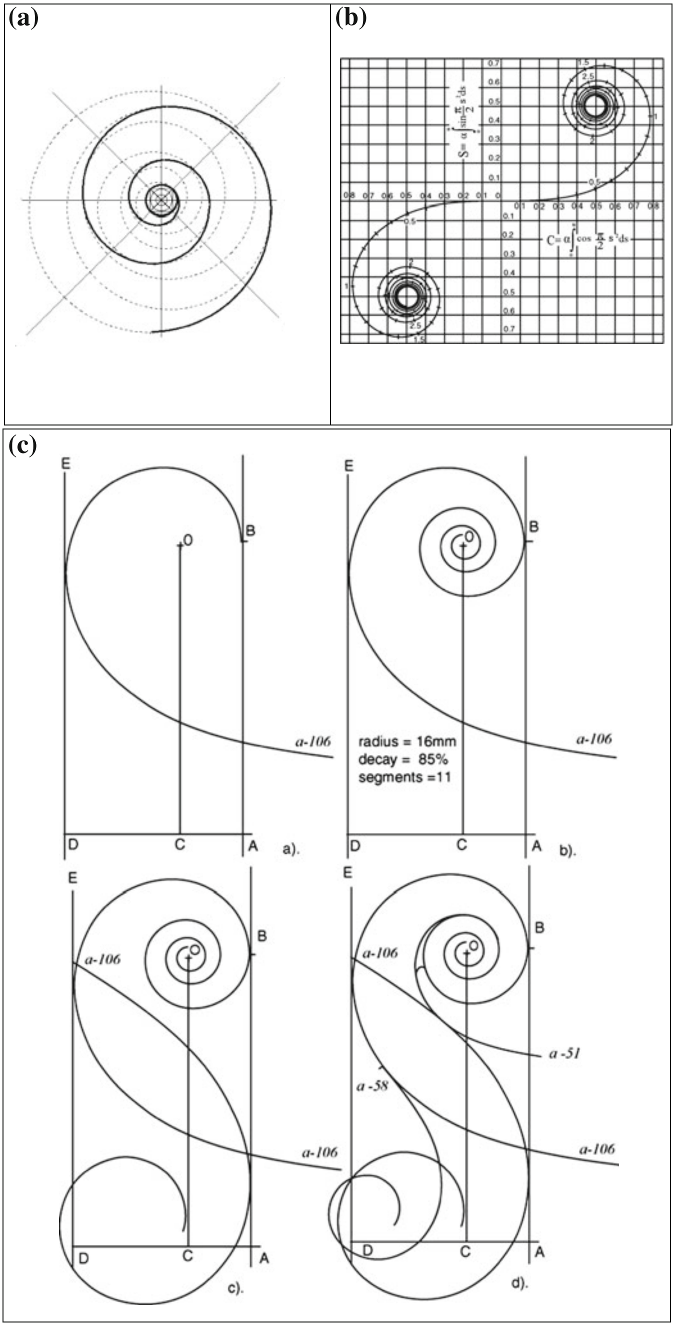
However the shape of the violin established by Andrea Amati can hardly be improved, and very elaborate computational methods such as parametric cubic splines (developed for aircraft and shipbuilding industries) used to establish the nice curvature of the violin shape need suitable guide points established by the human eye, preferably that of a master (Stroeker 2010).

Violin family instruments have the same shape, with one exception, the double bass. It has sloping shoulders, basically in the shape of a viol.

The scroll of the violin is another interesting example of the application of knowledge of geometry transmitted from Antiquity. We refer here to the golden spiral, created by drawing circular arcs and connecting the opposite corners of the Fibonacci tiling

The size and the proportion of the violin scroll were the subject of interesting discussions. The first idea was to approximate the spiral curve of the scroll to the profile of an Ionic volute, drawn with a compass (Coates 1985). Another idea was to refer to the golden spiral, created by drawing circular arcs and connecting the opposite corners of the Fibonacci tiling and using squares of the sizes such as 1, 2, 3, 5, 8, 13, 21 and 34 (Fig. 2.22a).

Muratov (2008) suggested a more complex curve, namely the clothoid (or the Cornu spiral, named after the French physicist Marie Alfred Cornu (1841–1902) used in optics and engineering for connecting and transiting the geometry between a tangent and a circular curve. (ex: the design of highways or to form the railways with series of straight lines and flat circular curves). The Cornu spiral is shown in Fig. 2.22b. This curve can be drawn by hand or drawn and calculated with a personal computer. The design of the violin scroll was made up of "segments of clothoids joined in such a way that the curvature is continuous throughout", as


(a)
(b)
$S=\alpha\int \sin\frac{\pi}{2}s^2ds$
$C=\alpha\int \cos\frac{\pi}{2}s^2ds$
(c)
E
B
O
a-106
radius = 16mm
decay = 85%
segments =11
D
C
A
a).
b).
c).
d).
a -51
a -58

◀ **Fig. 2.22** Different curves used to recreate the scroll and the pegbox of the Cremonese violins. **a** Golden spiral created by drawing circular arcs connecting the opposite corners of squares in the Fibonacci tiling. http://en.wikipedia.org/wiki/Golden_spiral. The circles are tangent to the squares. The diameter of each circle equals the side of the square size i.e. 1, 1, 2, 3, 5, 8, 13, 21 and 34. **b** The Cornu spiral. http://en.wikipedia.org/wiki/Cornu_spiral. **c** Four different steps for the geometric reconstruction of the scroll and the peg box (Muratov 2008, Fig. 10, p. 11)

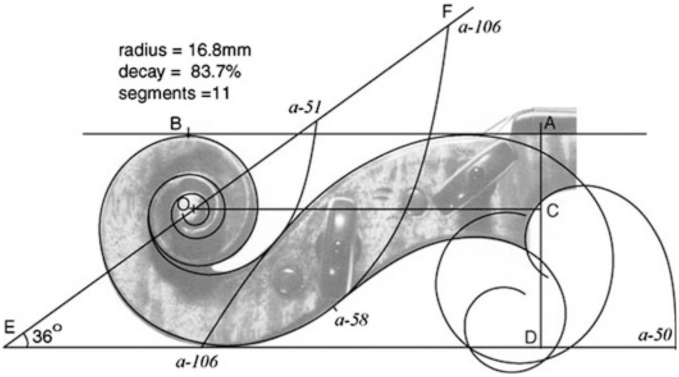


Fig. 2.23 Superimposition on a photograph of a real violin made by Stradivari in 1715 of the geometric reconstruction of the scroll and peg box (Muratov 2008, Fig. 11, p. 11). (http://samlib.ru/img/m/muratow_s_w/violin_design/ 19/01/2014). sergeimuratov@bigpond.com

shown in Fig. 2.22c, for four successive phases of geometric reconstruction of the scroll. Figure 2.23 shows a good coincidence by superimposition of the geometric reconstruction on the scroll and the peg box of a real Cremonese violin. However, Muratov (2008) noted that this approach “only helps to describe the configuration of different parts of a violin and do not confirm that the luthiers of the past used the clothoid”.

Thus far, in the light of previous comments, there is no doubt that the outline of the scroll and peg box was design by the Cremonese luthiers having a high understanding of geometry serving aesthetics.

2.3.1.2 About the Geometry of the Classical Guitar

We have seen in a previous section that the rise of the guitar in Western music coincides with the decline of lute playing during the Renaissance. However since the 17th century the guitar was played by the amateur musicians of the aristocratic society in Spain, Italy and France (Sachs 1940).

Musical iconography related to the guitar and characters playing the guitar is quite rich, one of the most representative artists were Watteau (1684–1721) in France and Vermeer (1632–1675) in the Low Countries (Mirimonde 1962a, b; 1963a, b).

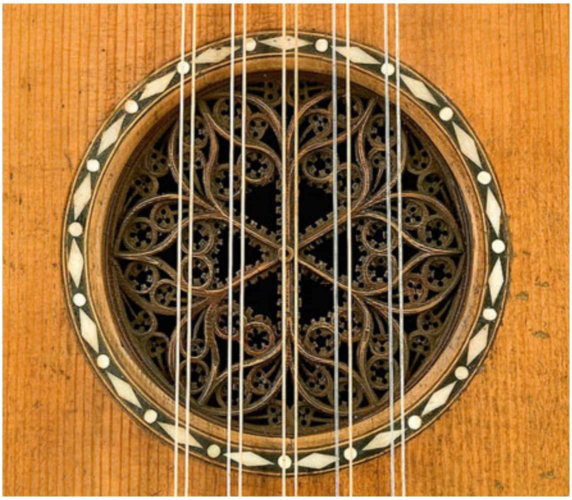


Fig. 2.24 Detail of the rose of the "Rawlins" guitar made in Cremona 1700 by Stradivari (Photo Bill Willroth Sr., National Music Museum The University of South Dakota US, http://orgs.usd.edu/nmm/PluckedStrings/Guitars/Stradivari/3976StradguitarrosecontextLG.jpg. Access 10 April 2014)

Since the 1970s modern lutherie contributed to the rapidly growing modern revival in instruments for early music repertoires and reference books were published on the art of building classical guitars (Edwards 2013; Sinier and de Ridder 2000).

Baroque and early romantic guitars (1700–1880) had five double strings. Among the Baroque guitars those built by Stradivari are highly valued. The "Rawlins" guitar made in Cremona 1700 has a superb rose of Gothic inspiration, a testimony to Stradivari's high skill in woodwork (Fig. 2.24). The wood grain for the top of this guitar is not as fine and uniform as we can see on his violins. The acoustic requirements for guitars are less severe than those for the violin, which justify the utilisation of this kind of wood. Some of the French baroque guitars such as those made in Paris by Jean Baptiste Voboam (1658–1731) were sumptuously decorated (Fig. 2.25). An extensive documentation on French guitars made by the luthiers from the Voboam family active for a century in Paris (1640–1740) was published by Gétreau (2005, 2010). The instruments reserved for aristocratic players from the close entourage of the king were richly decorated with a large variety of sumptuous materials such as tortoise and mother of pearl included in *godrons*—oval motifs in shape of a pod and *pistogne*—a diagonal pattern in ebony and ivory inlayed at the edges of the soundboard, back, fingerboard, rose and on the front side of the peg-box. Other French guitar luthiers (Jean Christophle in Avignon, Robert Chéron in Paris and others) embellished the side of the instruments with ebony, walnut, mahogany, ivory and diamonds in ivory inlays.

Fig. 2.25 Guitar decorated with tortoise shell and mother pearl, made in 1697 in Paris by Jean Baptiste Voboam (Metropolitan Museum of Arts New York http://www.metmuseum.org/toah/works-of-art/1989.147. Access 18 April 2014)

Modern classical guitars had six catgut strings; in our days the strings are made of nylon or other polymers, with a fine wrap on the bass strings. The design of the modern classical guitar was established by Antonio de Torres (1817–1892). Some of his splendid well preserved guitars are exhibited in the Museu de la Musica in Barcelona-Spain.

The oblong shape of the early guitars has many similarities with those of violins. Modern classical guitars have more power created by the larger area of the top plate. However, this has to be balanced with stiffness and air volume to give acoustic resonance at an appropriate frequency, with a complex technique of brassing. However the outline of these guitars can be constructed using the golden proportion, and a compass and a liner, after selection of module size as selected in Fig. 2.26.

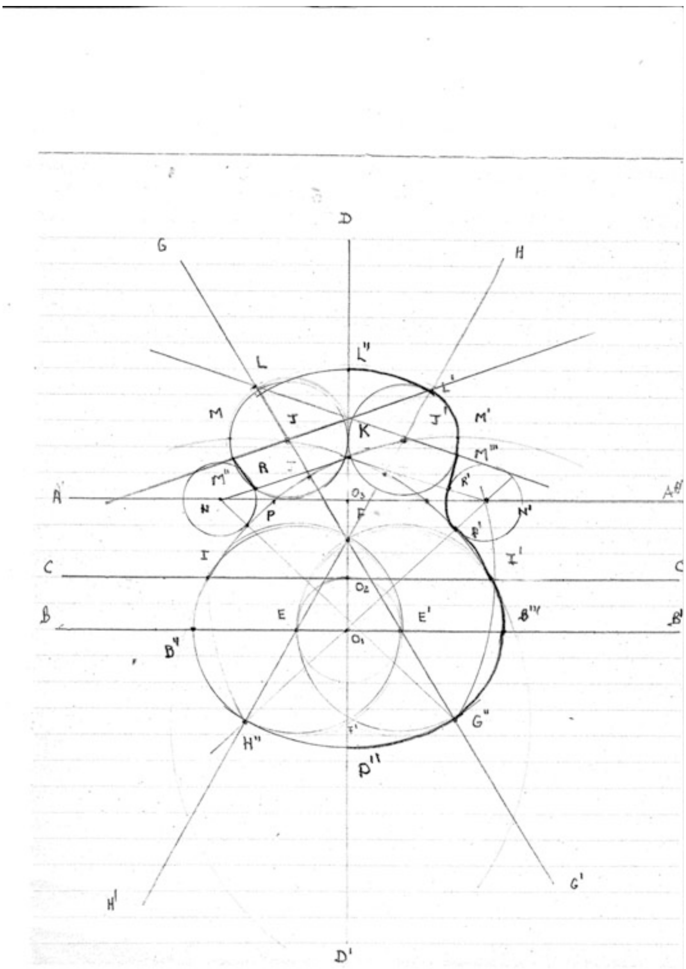


Fig. 2.26 Outline of a modern classic guitar constructed with a compass and a drawing rule (figure Otis ~ *Stringed Instruments* ~ *The Drawing Board* ~ http://www.fiddletree.com/drawing_board/drawing_board.htm. Access 3 April 2014; with explanations by D Spandonide 2014 and Tosolini 2014)'. Legend the golden ratio can be seen as for example in O_1O_2/O_1O_3

The corresponding 36 steps necessary for the construction of the guitar outline by ruler and compass are explained as follow (Spandonide 2014; Tosolini 2014)

(1) Draw a construction line AA′ parallel to a second construction line BB′ at a separation of d

(2) Draw construction line CC′ between these two lines and parallel to them at a separation of 0.6d from AA′

(3) Draw the centreline DD′ perpendicular to AA′, intersecting BB′ at O_1 and CC′ at O_2

(4) With centre O_1 draw a circle of radius O_1O_2 which intersects BB_1 at E and E′
(5) With centre E and radius EE′ draw a circle intersecting BB′ at B″
(6) With centre E′ and radius EE′ draw a circle intersecting BB′ at B‴
(7) Let these circles intersect DD′ at the points F and F′
(8) Construct HH′ by extending EF in both directions and intersecting the circle with centre E at H″
(9) Similarly extend E′F to construct GG′ intersecting circle centre E_1 at G″
(10) With centre B″ and radius B″B‴ draw an arc which intersects DD′ at L″
(11) With centre B‴ and radius B″B‴ draw an arc which intersects DD′ at L″
(12) With centre F and radius FL″ draw an arc intersecting GG′ at L and HH′ at L′
(13) Extend G″ E to meet the circle with centre E at I
(14) Extend H″E′ to meet the circle with centre E′ at I′
(15) With centre H″ and radius H″I′ draw an arc to meet DD′ at K
(16) With centre G″ and radius G″I draw an arc to meet DD′ at K
(17) Let the arc with centre G″ and radius G″ I intersect HH′ at J′
(18) Let the arc with centre H″ and radius H″I′ intersect GG′ at J
(19) Draw a circle with centre J and radius JL
(20) Draw a circle with centre J′ and radius J′L′
(21) Extend the segment LJ′ to intersect the circle with centre J′ at M‴
(22) Extend the segment L′J to intersect the circle with centre J at M″
(23) Draw an arc with centre F and radius FL to intersect DD′ at L″
(24) Draw an arc with centre I and radius IG″ to intersect AA′ at N′
(25) Draw an arc with centre I′ and radius I′H″ to intersect AA′ at N
(26) Let the circle with centre E intersect BB′ at B″
(27) Let the circle with centre E‘intersect BB′ at B‴
(28) Join NG″ to intersect the arc with centre G″ at P
(29) Join N′H″ to intersect the arc with centre H″ at P′
(30) Draw a circle with centre N and radius NP
(31) Draw a circle with centre N′ and radius N′P′
(32) Join NK and let it intersect the circle with centre N at R
(33) Join N′K and let it intersect the circle with centre N′ at R′
(34) Join M″ to R with straight line segment M″R
(35) Join M‴ to R′ with straight line segment M‴R′
(36) With centre F and radius FG″ draw the arc G″H″ to meet DD′ at D″
By joining the constructed sections
D″G″B″I′P′R′M″M′L′L″
Half of the guitar outline can be traced, the other half being symmetrical with it.

2.3.1.3 About the Geometry of the Concert Harp

The shape of the harp schematically shown in Fig. 2.27a could be included in a rectangle having the edge sizes of ratio 2:1, with a module noted S and $S = 1$. The rectangle is composed of two squares of size S. The harmonic curve of the neck

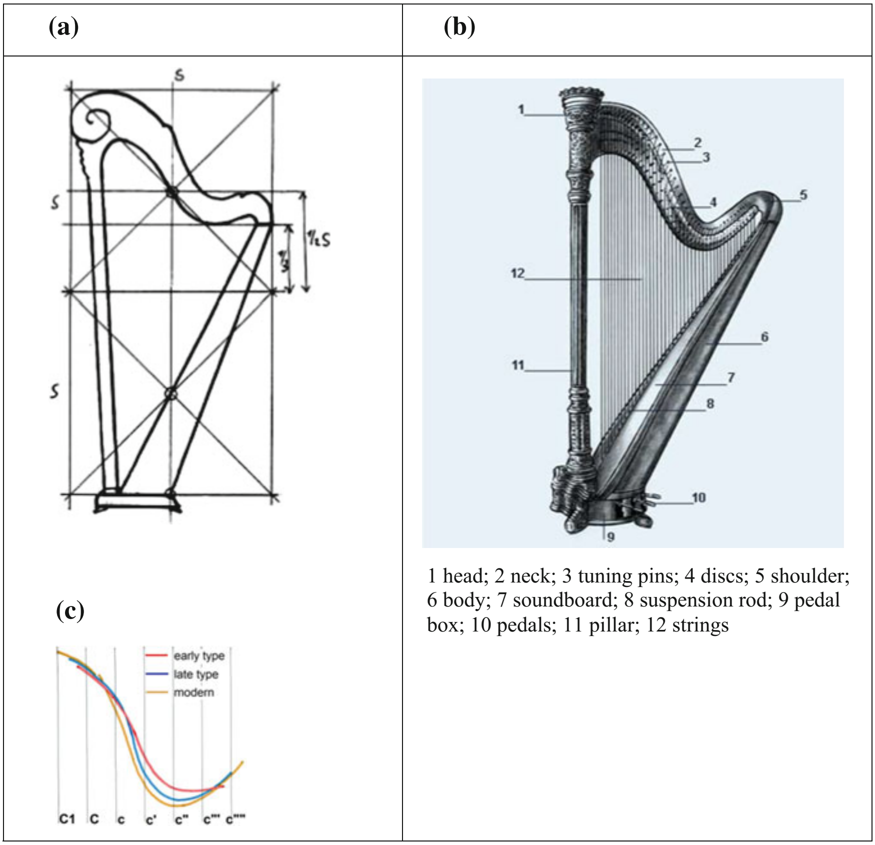


Fig. 2.27 Concert harp. *Legend* **a** Outline of a concert harp (figure B. Wolf http://www.beatwolf.ch/. Access 3 April 2014); **b** aspect of the concert harp; **c** Evolution of the neck curves figure courtesy B Wolf: *Neck Curves Red* Wolter-harp c.1780; *blue* Wolter, c.1810; *yellow* modern double-action harp, Erard, 1905. http://www.harpspectrum.org/historical/wolf_long_updated.shtml #Picture 2 Access 3 April 2014)

running from the crown to the shoulder has a first reference point at 1/2 S, at the intersection of the diagonals of the upper square and a second reference point in the upper square at 1/3 S limiting the lower outline of the harmonic curve.

The neck curve evolved relatively few during about two centuries, as can be seen from Fig. 2.27b.

2.3.1.4 About the Geometry of the Grand Piano

The geometric layout method for the construction of two Viennese fortepianos built by JA Stein in 1783, the first one which is today in the Boston museum of Fine Arts

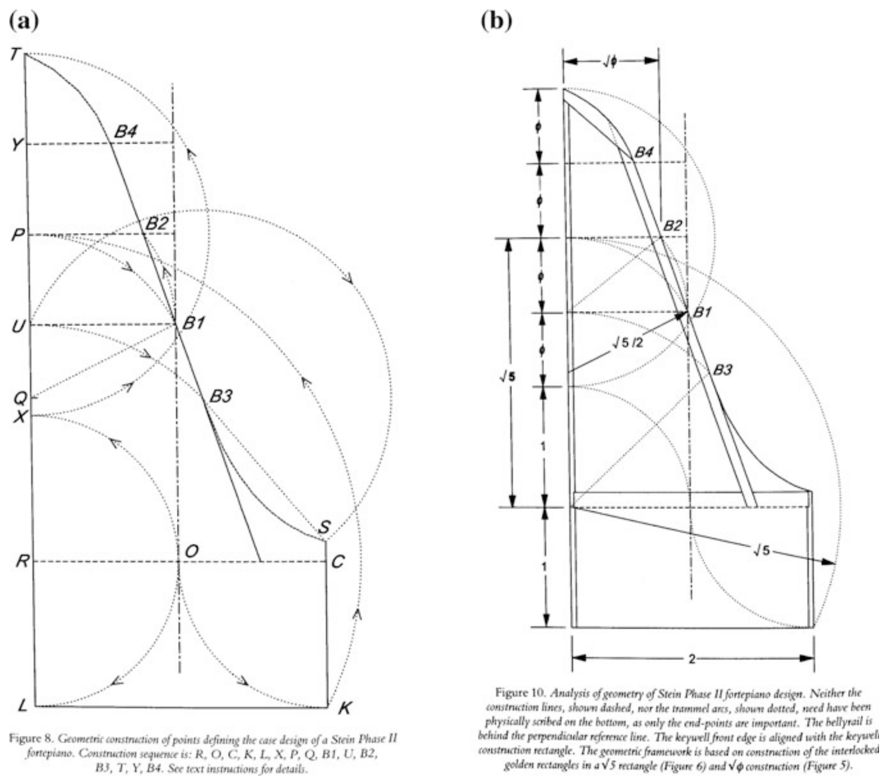


Fig. 2.28 Geometric construction for Viennese fortepianos made by J A Stein in 1783, *Legend* **a** Stein soundboard made in 1788, today in the Germanisches Nationalmuseum in Nurenberg (Birkett and Jurgenson 2000, Fig. 2.8 with permission). **b** fortepiano today in the Wuerttembergisches Landesmuseum, Stuttgart-Germany (Birkett and Jurgenson 2000, Fig. 2.10)

and the second one in the Wuerttembergisches Landesmuseum, Stuttgart-Germany as discussed by Bikett and Jurgenson (2000) is shown in Fig. 2.28. The inner liner and the framing of the piano are clearly visible for both instruments. Haydn, Mozart and Beethoven wrote piano music for this kind of instrument.

The construction points are located on the bottom boards extending to the outside edges of the shaded liners. The construction is based on the most common proportions, $\sqrt{2}$ and $\sqrt{5}$ (the hypotenuse of a triangle of edges 1 and 2), the golden mean $\Phi = 0.618$ rather $\sqrt{5} - 1 = 2\Phi$ (half of the hypotenuse of the right triangle) and the golden rectangle. The main reference is defined on the front edge of the bellyrail.

Establishing the modular dimension is a key step in piano construction and is a function of several elements such as string spacing, keyboard dimensions, structural case width, long case dimension and geometry and string lengths (Bikett and Jurgenson 2001)

The half—width modular dimension was 465 mm. The other dimensions used for the construction are: $465\sqrt{5} = 1040$ mm; 1040/2 = 520 mm; 465 (1 + Φ) = 752 mm; Φ = 0.618 the golden mean. The overall predicted length of the bottom board of the fortepiano in Boston is 2080 mm and is the sum of these numbers (575 + 575 + 465 + 465). The overall length of the bottom board of the fortepiano in Nuremberg is 547 + 1040 + 520 = 2107 mm, excluding "mouldings". The successive phases of the construction are given by the points B_1, B_2, B_3, B_4. Experimental comparison between the calculated data for the fortepiano in Nuremberg and the underside of the soundboard removed from the a fortepiano made in 1788 is shown in Fig. 2.28b It is evident that the five octave fortepiano geometry constructed with the compass using constructive geometry is perfectly superposed onto the existing soundboard. The validity of constructive geometry was verified for another keyboard instrument, a virginal made in 1552.

As a conclusion of this section we can note that the shape of the musical instruments was derived from three main considerations: acoustics, ergonomics and aesthetics. Acoustics is related to the string length, bridge position, the volume of air encapsulated in the resonance corpus and the materials used for the soundboard and other parts. Ergonomics relates playing functions such as the angle of the neck, the height of the bridge, the length of the fingerboard, the incurved middle bouts and the weight of the instrument. Aesthetics harmonizes the requirements of acoustics and ergonomics by using the geometry and the harmony of proportions (Coates 2008). There is no doubt that the geometry and the golden proportion system have been used by the luthiers of 16th, 17th and 18th centuries. Their design has been guided by practical, aesthetical and metaphysical considerations. The beauty of the instruments' form was derived from the perfection of geometry and proportions related to the spiritual approach of discovering the TRUTH.

2.3.2 Constitutive Parts of String Instrument

Now we have to describe the constitutive parts of string instruments.

2.3.2.1 Instruments of the Violin Family

The violin family is composed of the following instruments: the violin, the viola, the cello and the double bass (Fig. 2.29). The external aspect of the violin family instruments is symmetrical, but we will see that the internal structure is asymmetrical and has a huge influence on the tone quality.

Since the late 18th century the string quartet (two violins, viola and cello) has been one of the most prominent chamber ensembles in classical music. The setting of the instruments on the stage during the performance is shown in Fig. 2.30. During the performance the directivity of the cello or of the viola can be preferred,

Fig. 2.29 Instruments of the violin family (http://lemaitredemusique.wordpress.com/category/string-instruments-violin-family/. Access 14 April 2014). *Note* the size and mass of the instruments from the violin family are given in Appendix 1 and Appendix 2 respectively.

depending on the position of the instruments on the stage (i.e. first violin, second violin, cello and viola or, first violin, second violin, viola and cello). These two variants are currently used, depending on the musical taste of the performers, on the piece played and on the acoustics of the concert hall. The string quartet can be modified by introducing a second viola or a second cello and forming a string sextet or an octet by introducing a double bass and another instrument.

Figure 2.31 describes the constitutive elements of the instruments of the violin family, illustrated for a cello, such as

- The top usually made in spruce has variable thickness, being thinner at the edge than in the centre. The top has two f-holes which allows the air to flow freely from the interior of the body.
- The back is usually made in maple, sometimes for Baroque instruments in poplar or willow. The thickness of the back is non uniform.
- The ribs, which hold together the top and the back, are in maple and consist of six rectangular bands shaped over a hot iron mould to conform to the outline of the top and back. The ribs are evenly lined by the counter-sides.
- The neck is in maple supporting the fingerboard and the nut is commonly in ebony. On top of the neck are the scroll and the peg box.
- The pegs are holes by the peg box and fix the upper ends of the strings. The lower ends of the strings are fastened to the tailpiece in ebony.
- The bridge is made in maple (*Acer campestre*) and is found between the two f-holes.

(a)

(b)

Fig. 2.30 Setting of the instruments for string quartet performance. *Legend* **a** from left to right—first violin, second violin, cello, viola; **b** first violin, second violin, viola and cello. **a** Tokyo string quartet © Photo by Lois Siegel. **b** «Ebene» string quartet at summer festival in 2011—Wissembourg, Alsace, France. https://www.youtube.com

- The purfling consists of three very fine sheets of wood inserted in the top and back, and has an important function in preventing cracking of the top and back.
- The bass bar in the interior of the box, lying lengthwise, is glued under the left foot of the bridge, reinforcing the top and enhancing the sonority of the instrument.
- The soundpost is a small cylinder in spruce wedge (never glued) between the back and the top, slightly below the right foot of the bridge.

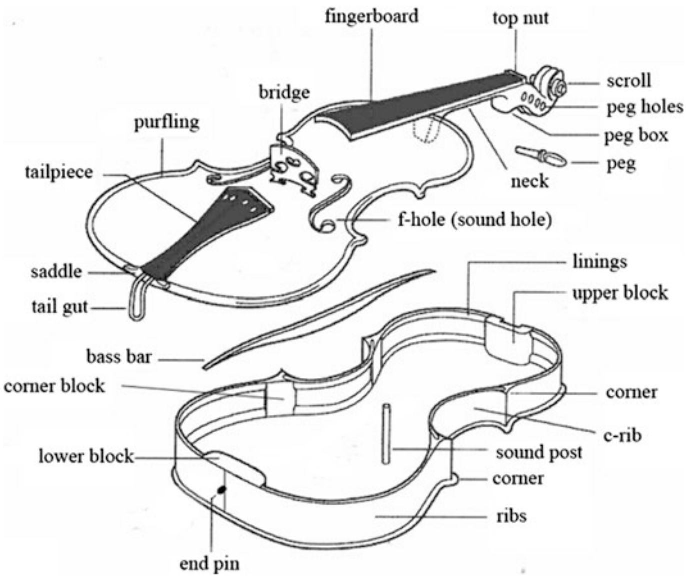


Fig. 2.31 Structural components of an instrument from violin family instruments illustrated for cello (figure courtesy http://schoolworkhelper.net/violin-parts-string-instruments/. Access 30 March 2014, with permission)

- The top and bottom blocks and the corner wedges are small blocks of spruce or willow glued to the inner surface of the back and top for solidity of the box.
- The endpin is in metal and is part of the tail button.

The size and the weight of each instrument are important ergonomic parameters. The sizes of the instruments from violin family are given in Appendix 1. The weight of some instruments is given in Appendix 2.

2.3.2.2 The Classical Guitar

The constitutive elements of a classical guitar are described in Fig. 2.32:

- The top is usually made in spruce or red cedar, and has a constant thickness of about 2 mm. the top has two acoustic holes. On the internal face of the top plate are fixed several braces made from the same wood as the top.
- The braces give more rigidity to the top plate and their disposition is a determinant of the sonority of the instrument. Fan bracing is the standard pattern for the classic acoustic guitar since it was proposed by Antonio de Torres. Several other patterns exist such as those shown in Appendix 3
- The back is made in rosewood (*Dalbergia spp*). A highly regarded species for the back is Brazilian rosewood (*Dalbergia nigra*). Other species are selected for their decorative value such as mahogany or species having decorative curly

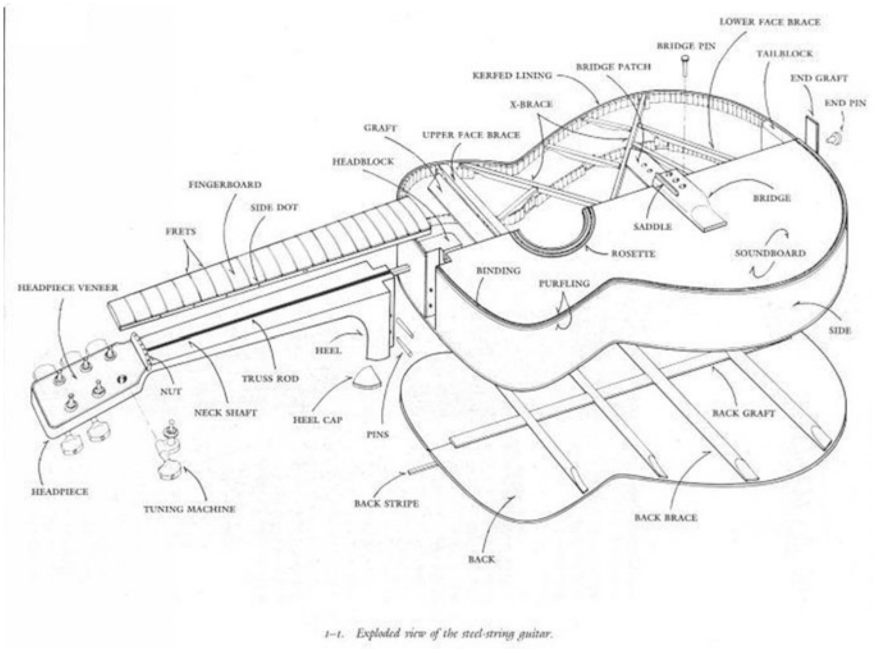


Fig. 2.32 Classical guitar—Exploded view showing typical construction. (Kozinn and Santoro 1984. Fig. (no number), p. 25)

structure. Back bracing is simpler than top bracing; the braces are parallel to each other and perpendicular to the strings.

2.3.2.3 Concert Harp

The constitutive elements of the concert harp as described in Fig. 2.33 are: the pillar, the neck, the soundbox, the strings, the pedal box and the pedals. The soundbox and the soundboard have a determinant role in the acoustics of harps. The soundbox has four or five soundholes. Pedals are mounted in the pedal box. The inventor of the pedal harp was Jakob Hochbrucker (1673–1763) from Donauwörth. One of his instruments built in 1720 is displayed in the Kunsthistorisches Museum in Vienna on which can be seen: the sound box composed of 7 ribs; the spruce soundboard with horizontal grain; the single action pedal mechanism with 7 pedals; the head shaped as a volute. The pedal mechanism of the instrument was improved by Nadermann, Cousineau and Erard in Paris. A single action pedal and later a double action pedal allowed raising the pitch of a string. Around 1790 the height of the harps called Louis XVI harps, was 170 cm and had 37 strings. The double action pedal harp is the standard instrument used in classical symphony orchestras.

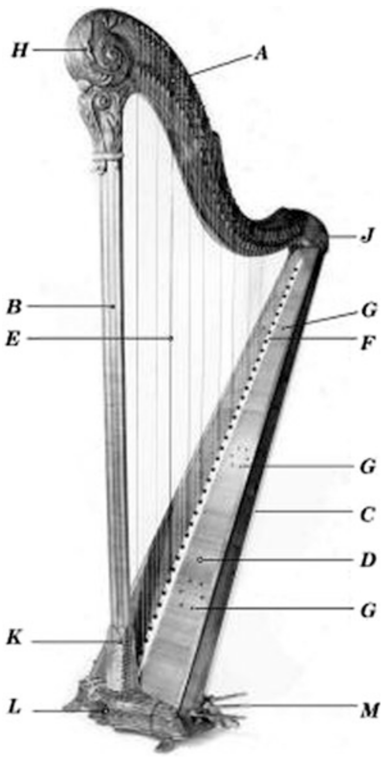


Fig. 2.33 Constitutive elements of a concert harp (B Wolf http://www.harpspectrum.org/historical/wolf_long_updated.shtml. *Legend A* Neck; *B* Pillar, forepillar; *AB* Frame; *C* Sound box; *D* Soundboard; *E* Stringing; *F* Bridge rail; *G* Sound holes; *H* Volute (head, scroll); *J* Shoulder, cutaway; *K* Base of Pillar; *L* Pedal box; *M* Pedals

2.3.2.4 Grand Piano

Modern concert grand pianos have over 2500 constituent parts. The main constitutive ensembles of the modern piano are: the keyboard, the action, the soundboard, the cast iron frame (sometimes called plate), the strings mounted in the case. The modern piano is made from a very large diversity of materials. Wood is used for the soundboard, parts of the keyboard and action, and the case of the instrument. Metallic components are used for strings and cast iron frame

The main structural elements of a grand piano are the soundboard, the keyboard, the case, the pinblock, the cast iron plate and the strings and the action (Fig. 2.34a). The most important role in the acoustics of the instrument is played by the soundboard made of spruce. Over the two bridges of the soundboard are fixed the strings. The simplified piano action mechanism, hammer and string are shown in Fig. 7.34b. The key pressed by the player set the hammer in motion toward the string. The jack slips of the hammer before the collision with the string, allowing the hammer to move freely before and after the contact with the string. The hammer set in motion the string, which transmits the vibration to the soundboard which sets the surrounding air into motion, producing pressure waves which are the sounds of the piano. The soundboard, the piano action mechanism and the cast iron plate are

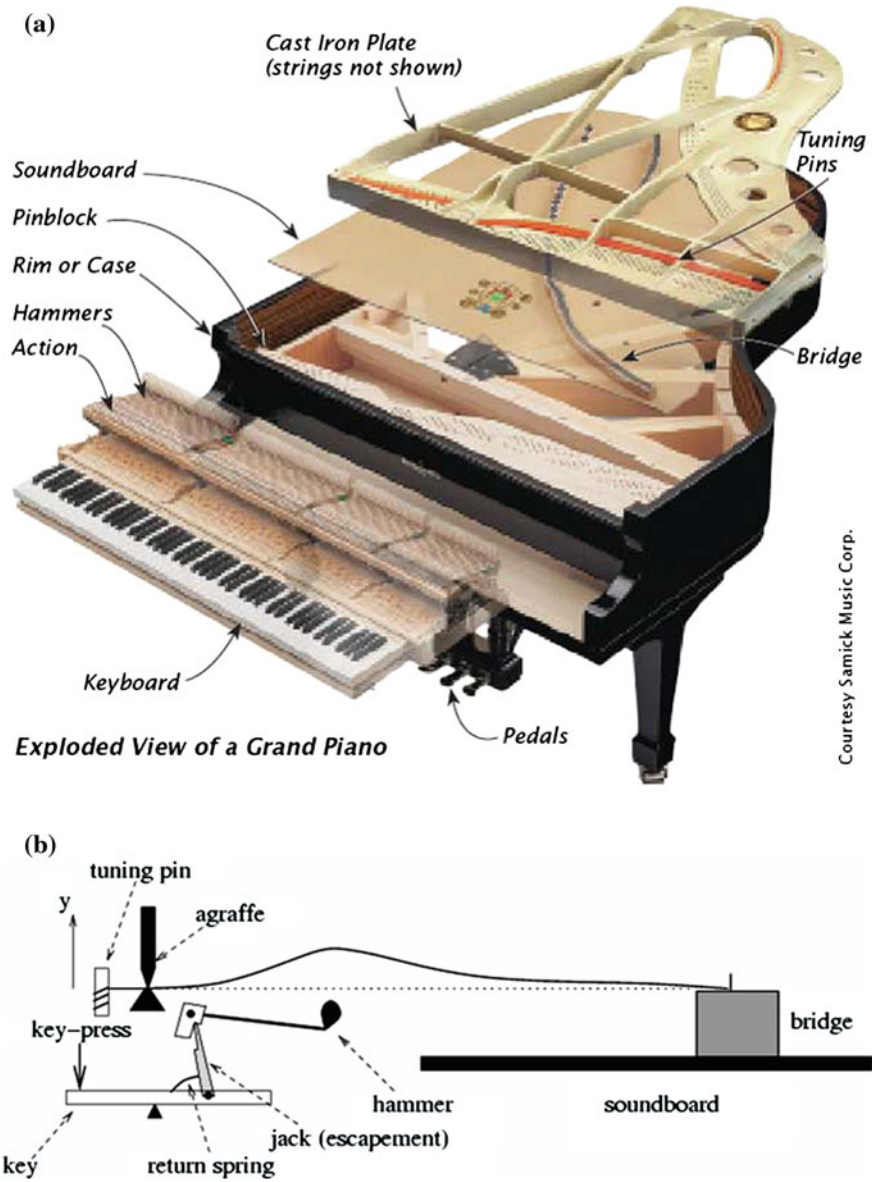


Fig. 2.34 Grand Piano **a** Exploded view of a concert grand piano (http://www.pianobuyer.com/fall11/14.html. Access 5 August 2014). **b** Sketch of the piano action, hammer, string, bridge and soundboard (Giordano 2010, Fig. 20.2, p. 355, with permission)

fixed into the piano case. At the end of the 19th century the cases of several instruments were magnificent pieces of furniture sumptuously decorated with marquetry of exotic wood species, mother of pearl and other precious materials. More details about the construction of pianos are given in Chap. 15.

2.3.2.5 Modern Harpsichord

The design of the case of the contemporaneous harpsichord was also revised and modernised in agreement with the contemporaneous technology for furniture making (Fig. 2.35). However the structural elements of a Baroque instrument were reproduced identically and with turned legs and strands, the domestic decoration of Baroque furniture was reinterpreted. The Baroque decoration of one of the most famous French harpsichord made in Paris by Pascal Taskin (1723–1793) is shown in Fig. 2.36.

The structural elements of the Baroque harpsichord are described in Fig. 2.37. The case of the instrument holds the following elements: the soundboard, the pinblock, the hitchpins, the keyboard and the jack action. The bottom of the case and the internal bracing, maintain its shape and prevent the warping under the tensions of the strings. The case stands alone on legs, styled in the manner of period furniture, or can be placing on a table. Flemish instruments have cases greatly in weight rather Italian and French harpsichords are of lighter construction as described in reference books (Kottick 2003; Vermeij 2004).

Fig. 2.35 Harpsichord built in 2010 by John Phillips, Berkeley California, based on the original built in 1722 by Johann Heinrich Gräbner, Dresden. http://www.philharmonia.org/october%E2%80%93harpsichord-john-phillips/. Access 3 August 2014

Fig. 2.36 A great example of an Italian harpsichord by Giuseppe Mondini (1701), now in the collection of Museum Für Kunst und Gewerbe Hamburg. Case 270 × 83.5 × 21.3 cm. http://www.mkg-hamburg.de/en/sammlung/schwerpunkte/musikinstrumente/cembalo. Access 25 November 2015

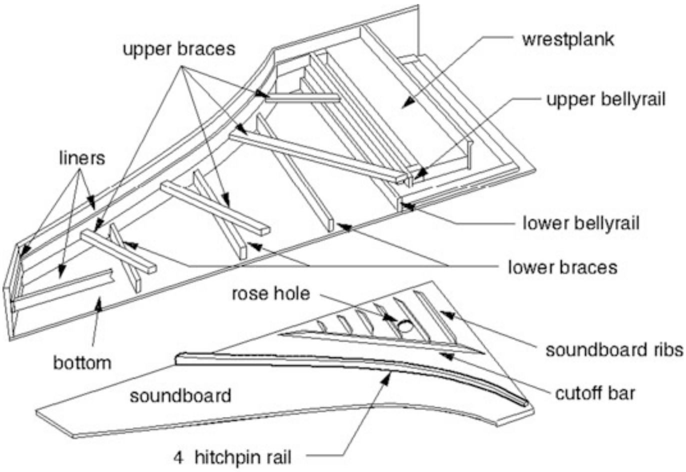


Fig. 2.37 Exploded view of the structure of a typical Flemish harpsichord (Fletcher and Beebe 2010, Fig. 8.7, p. 131 with permission). Fletcher and Beebe (2010) Harpsichord and clavicord. In T.D. Rossing Ed. *The science of string instruments*. Springer, New York, p. 123–143

Fig. 2.38 The strings, the tuning pins, the bridge, the soundboard decorated with flowers and the keyboard of a Spanish harpsichord (Photo Museo de la Musica Barcelona 041. http://fr.wikipedia.org/wiki/Clavecin#mediaviewer/Fichier:041_Museu_de_la_M%C3%BAsica.jpg. Access 2 August 2014)

As described by Fletcher and Beebe (2010) the plucking of the harpsichord strings is similarly to that of the psaltery. The strings are clamped rigidly at one end and at the other end the strings are coupled to the soundboard which radiates sound. The soundboard, the mechanics of the keyboard and the plucking action have a crucial effect on the acoustics of the instrument (Fletcher 1977; Thwaites and Fletcher 1981). Figure 2.38 shows some details of a Spanish harpsichord, the strings, the tuning pins, the keyboard and the soundboard decorated with painted flowers. The functioning of the action of a harpsichord is shown in Fig. 2.39. The strings are wound around the tuning pins fixed in the wooden block called wrest-plank. The strings pass on the nuts and on the bridge fixed on the soundboard. At the other end the strings are held by a brass pin. The bridge transfers the force of the vibrating string to the soundboard which vibrates. Each keylever rests upon a jack. Usually the harpsichord has more than one choir of strings. The jack is a piece of wood of rectangular section which sits in the vertical position on the end of the keylever. Four characteristic positions of the key are shown in Fig. 2.40 namely, the resting position, the key is pressed, the string is plucked and the key is released. The thin flexible quill was made originally from the spine of a crow or raven. In modern harpsichord the material used is an industrial polymer (deltin or celcon). The felt damper rests in contact with the wire inhibiting its vibration. “When the key is depressed, this raises the jack so that the damper is lifted and the quill displaces the string until it bends sufficiently for the string to slip off, after which the string vibrates freely. When the player’s finger is removed from the key, the jack returns

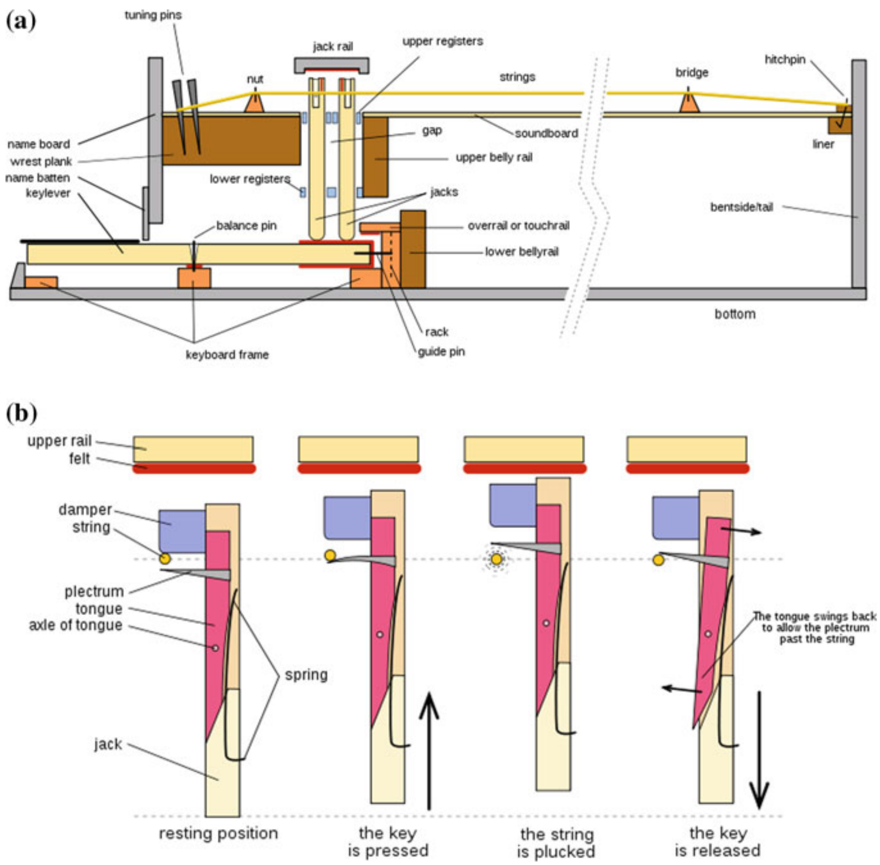


Fig. 2.39 The action of a harpsichord. *Legend* **a** cross section of the action; **b** four position of the the key (http://en.wikipedia.org/wiki/Harpsichord#mediaviewer/File:HarpsichordMechanism-EN.svg. Access 2 August 2014). **b** four characteristics aspects of the relative position of string and quill (plectrum), when the key is in resting position, pressed or released

by gravity, the tongue is deflected backward so that the quill flips easily under the string, and the felt damper stifles the vibration so that the sound ceases in a fraction of second" (Fletcher and Beebe 2010).

2.4 Craftsman's Technology for Construction of String Instruments

Understanding traditional procedures is a permanent source of inspiration for technological improvements of mass production in spite of the fact that a craftsman's technology for construction of string instruments is fundamentally different from industrial technology for mass production. In this section we will describe the principal operations required for the construction of string instruments.

2.4.1 Technology for the Manufacture of Instruments of the Violin Family

The operations required for manufacturing a violin are described in reference books by Heron-Allen (1885), Sacconi (1979) and more recently by Johnson and Courtnall (1999). During three centuries insignificant improvements were observed in manufacturing instruments from the violin family compared to the tools and technology used by Amati. The violin maker selects the pattern of the violin and prepares the mould in which the ribs will be bent. On the ribs are glued the lining and the corner blocks. The arching of the top and back plates is one of the most important operations in violin construction. The purfiling is introduced into a fine channel and glued several mm from the border of the plates. On the top plate two soundholes are cut with a sharp knife or with a wire saw. The bass bar is glued on the inner side of the top plate. Some aspects of violin building technology are shown in Fig. 2.40.

Tuning the plates is a key operation for good sonority of the violin. Traditionally the plates are tested by being twisted and flexed along and across the grain, and by tapping. Twentieth century technological advances allowed the introduction of a scientific approach to tuning violin plates. By using Chladni figures Hutchins (1981) proposed an experimental method for objective tuning of violin plates. By adjusting plates' thickness, the front and the back are tuned for vibration modes 1, 2 and 5 and the corresponding frequencies of 87, 175 and 350 Hz for the front and 115, 175 and 350 Hz for the back. This experimental technique which is a "classic" in today's violin maker's skill has been complemented by modal analysis, which requires expensive equipment and a very high academic training of the violin maker. However, as a matter of fact, simplified modal analysis can be done easily and cheaply using Chladni figures on a plate excited by loudspeaker beneath it driven by an oscillator, and using fine dust to produce the mode figures.

Manufacturing the violin neck and scroll, fingerboard and nut, tailpiece and button are operations related mostly to wood sculpture. The violin is assembled by gluing the top and the back to the ribs and to the neck on which the fingerboard was fixed. The next operation is varnishing. Drying of varnish requires a long period of time (several weeks, depending on the nature of the varnish). When the varnish is dry, the violin can be fitted with the tailpiece the bridge, the strings and the soundpost. Thereafter its sound can be adjusted by acting on the position of the soundpost.

Mould with glued upper and lower blocks and four corners, on which the ribs will be attached

Bending ribs into shape on a hot metallic surface

Arching the belly

Cutting the f-hole on the upper plate

Bass bar glued on the top

Viola in white with fingerboard not glued

Fig. 2.40 Some aspects of violin building (Photos violin master HH Uilderks—Lübeck Germany. http://www.geigenbauonline.com/violinmaking-New-Construction.html. Access 10 April 2014)

2.4.2 *Technology for Manufacturing a Concert Classical Guitar*

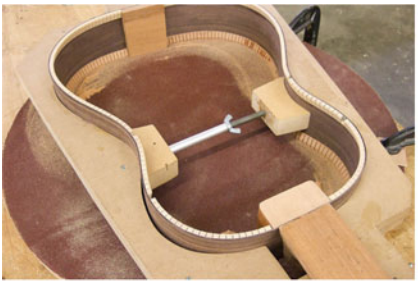
Guitar manufacturing has some common aspects with violin making, but at the same time some strong particularities. Guitar technology was described by Evans and Evans (1977), Jahnel (2000), Jansson (1983), Courtnall (1993), Wade (2010), French (2012) and by some Internet sites (Australian site of Caldersmith http://www.caldersmithguitars.com/tech.php, Smallman and Redgate http://www.ozemail.com.au/~redgate/; there are many other excellent sites in Italy http://www.mangore.com/bellucci-guitar-studio.html, Spain, France, etc.). Some aspects of guitar building technology are shown in Fig. 2.41.

The design of the guitar starts with the definition of basic parameters such as the string lengths (650 mm) and the body dimensions. The diameter of the soundhole is matched to the upper bout, being one third of its length. The ribs are the first elements constructed and are made in two separate strips 66 cm long, 82 mm wide, and 2 mm thick. The ribs and the back plate are made of the same wood species. The ribs are moisturised and shaped by bending on an iron until completely dried. This is a long and delicate process under humidity and temperature control to avoid cracking during bending. Then the lower block is inserted and glued. This operation is followed by the gluing of butt joints between the two ribs and by the gluing of curved linings. The linings are made in wood of low density such as obeche (*Triplochiton scleroxylon*) or aga umbrella tree (*Musanga cecropioides*). Instead of linings some makers uses small wooden blocks (tenteliones), glued at about 3 cm intervals, offering a better adherence to the surfaces of the top and back plates.

The top plate, or the soundboard, is made from two symmetrical halves of the quarter sawn piece. The wood species used for the top plate are: spruce (*Picea abies*) and fir (*Abies alba*) from Europe or North American Sitka Spruce (*Picea sitchensis*) and red cedar (*Sequoia sempervirens*) of fine grain (1–2 mm annual ring width). The soundboard has a critical role for the acoustics of the guitar. A stiffer soundboard is always preferred.

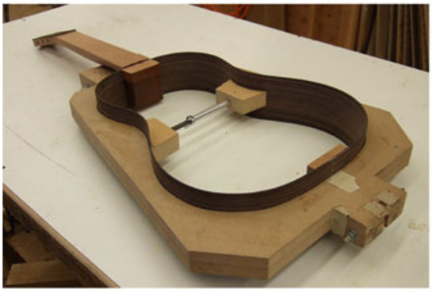
The outline of the top plate should match the shapes of the ribs. A cutting tool (router) is used to precisely cut the plate along the outline. The same type of tool is used to cut the soundhole and the 1 mm thickness rebate in which the rosette is inserted and glued, before the soundhole is cut. The rosette is inserted on the outer side of the guitar soundboard.

The underside of the soundboard is braced. Bracing patterns are very numerous (Appendix 3). Bracing design could be symmetrical or asymmetrical and in its design a luthier's particular style emerges. The struts are commonly made in the same wood as the top plate. Variations in top thickness and in struts' parameters (number, layout and size and thickness) are unlimited. However since early 1980 struts in carbon fiber–epoxy and balsa were proposed by the Australian luthiers Greg Smallman and Graham Caldersmith, and were successfully used all around the world.



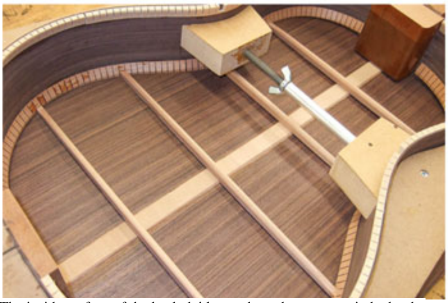
The kerfing on the top already levelled with the sides and notched the kerfing to receive the cross braces on the top.

What the inside of the guitar would look like with the back removed

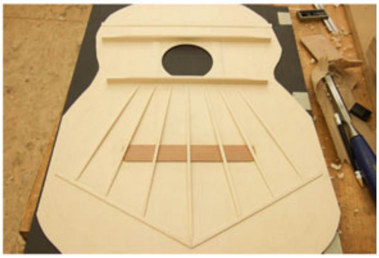


The tail block was made with a slight curve to match the form that was used for the guitar. The sides 1.8 mm thick were glued on to this tail block.

Rosette by Jose Romanillos
http://www.guitarplans.co.uk/pictures01.htm



The inside surface of the back, laid out where the centre strip had to be notched to receive the back braces, heel block and tail block.



The inside of the top after everything has been shaped. At this point, you can tap the top and hear a satisfying resonance that sounds like a tuned tom-tom.

Fig. 2.41 Main operation for building of a concert classical guitar (Photos http://lumberjocks.com/kem/blog/6089. Access 8 April 2014)

The back, initially of 2 mm thickness is usually worked in parallel with the soundboard, allowing tuning of their resonant characteristics. For concert instruments the back is slightly arched. This shape increases the strength of the instrument. Arching stiffens the plate and raises frequencies of vibrational modes (standing waves). The back has three cross struts and a centre fillet over the joint

Fig. 2.42 The guitar neck: view of the neck and the raw blocks (http://www.taylorguitars.com/guitars/acoustic/features/nt-neck. Access 8 April 2014)

between the two halves. The back is tuned in the same way as the top, by tapping and listening for harmonics. Brazilian rosewood or palisander (*Dalbergia nigra*) is the highly preferred wood for the top and ribs, but other species can be used as those cited further for the neck.

The neck is traditionally cut from Honduras mahogany (*Swietenia humilis*). However other species can be used such as maple (birdseye, flame), padouk (*Pterocarpus* spp.), purpleheart or amaranth *(Peltogyne spp)*, walnut (*Juglans nigra*), bubinga (*Guibourtia demeusei*), Acacia koa (*Acacia heterophylla)*, and Indian rosewood *(Dalbergia latifolia.)*. The neck requires a heel and a foot which are created with laminated layers (Fig. 2.42). The pegbox of the guitar is made in the same timber as the neck and is connected by a splice joint at an angle required for the correct connection of the head and the neck. As we can see in Fig. 2.43, the specific and distinctive carving of the pegbox is the luthier's signature related to its particular style (Friederich 1998).

The neck is glued to the corpus after which the purfiling is inlayed at the junctions between the top and ribs and between the ribs and back. The next operation is to fix the fingerboard on the neck. The fingerboard is made from a wood species of high hardness, like ebony, rosewood, bubinga and many other tropical species. Frets made in nickel silver wire, need special attention for very accurate positioning allowing guitar correct tuning.

The bridge made in rosewood inlaid with a mosaic matching the rosette is glued to the soundboard. The position of the bridge is of great importance as are the positions of the frets for guitar tuning. The saddle and the nut are made in ivory. The last operation is the varnishing applied on all guitar components with one exception, the fingerboard which is maintained in its natural state. The guitar is strung with six nylon strings tuned E2, A2, D3, G3, B3 and E4 with the corresponding frequencies of 82, 110, 147, 196, 247 and 330 Hz.

(a)

(b)

Fig. 2.43 The pegbox and the bridge of a guitar made by French luthier Daniel Friederich, built in 1967, the year in which he won the top prize of the Queen Elisabeth of Belgium (1876–1965) competition in Liege, Belgium. http://www.guitarsalon.com/p3367-1967-daniel-friederich-spcsar.html. Access 8 April 2014). **a** The pegbox. **b** the bridge

2.4.3 Technology for the Concert Harp

The concert harp is probably the only one contemporaneous musical instrument superbly decorated with carved floral or abstract patterns. We have seen that the structural elements of a concert harp are the post or the pillar, the neck and the soundbox. Some steps in harp manufacturing are shown in Fig. 2.44.

The strings are arranged at a large angle (about 45°) to the plane of the soundbox. The attachment points of the strings are the bridge—pins mounted on the neck and the soundboard. The soundboard is made in resonance spruce (*Picea abies)* for the harps made by Salvi in Italy or in Sitka spruce (*Picea sitchensis*) for the harps made in the US or Japan. The soundboard has a trapezoidal shape of about 1.4 m length, 0.5 m at the base and 0.1 m at top, the thickness is about 12 mm (bass) at the bottom and 2 mm at the top (treble). The soundboard is made of segments 3 to 8 cm wide glued together and covered with a spruce veneer. The grain direction is perpendicular to the strings' plane. Along the centreline of the soundboard two string bars in hardwood or laminated beech are mounted on the outer and inner face of the soundboard, for string connection. In addition on the inner face of the soundbox, harmonic bars made in beech are mounted parallel to the string bars to reinforce the soundboard. Soundbox shape is semi-conical and is covered with

Fig. 2.44 Some operations for the technology of the concert harp (Photos Salvi Harps http://salviharpsinc.com. Access 7 October 2015)

veneer of curly maple, walnut or precious wood species. On the back of the soundbox are four or five soundholes. One additional hole exists on the base of the soundbox. The function of these holes is acoustical but at the same time they give access for mounting or replacing the strings. The internal structure of the soundbox is shown in Fig. 2.45.

A concert harp has 46 or 47 strings ranging from C1 or D1 to G7. The top end of the strings are wrapped around a tuning peg and a bridge pin, which determine the unsharpened string vibrating length. Beneath the bridge are the sharping

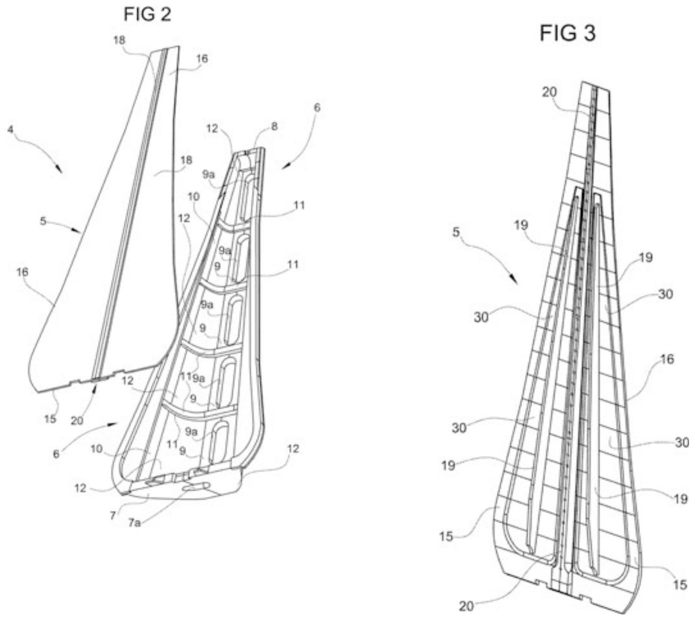


Fig. 2.45 Internal structure of a concert harp soundbox (Belmondo and Peirano 2013. US patent 2013/0074672A1, **a**, *sheet 2* and **b**, *sheet 3*. *Legend 5* soundboard; *6* body a half; *7* chest bottom *7a* opening; *8* upper block; *9* central longitudinal batten; *10* two symmetrical side battens; *11* transverse stiffening members or bridges; *12* outer shell; *13* wings; *14* splints; *15* main wooden board; *16* outer ply of veneer; *18* profiled string carrier member; *19* sound bar; *20* longitudinal profiled reinforced member

mechanisms controlled from seven pedals. (i.e.: As, Bs, Cs etc. can be played as flat, natural or sharp). The connection between the pedals and the sharping mechanism runs up the pillar into the neck. Because of strong mechanical stress the neck is made in laminated wood. The pillar is made in maple, walnut, mahogany or other precious wood species. The capitel of the pillar could be superbly carved and decorated and covered with gold leaf. The base of the pillar which incorporates the pedals could also be elaborately decorated (Fig. 2.46).

2.4.4 Technology for the Grand Piano Soundboard

The manufacturing technology for the grand piano soundboard is described in Fig. 2.47. The soundboard is made from several planed planks 2–3 m long, of rectangular section (1 cm thick and 8–14 cm wide) quarter sawn from logs of spruce tone wood (*Picea abies*) from the Alps or Carpathians mountains in Europe, namely from the Rumanian side of the mountains or, from Sitka spruce (*Picea sitchensis*) from Alaska in North America. There is no specific requirement for resonance

(a)
(b)

Fig. 2.46 The decoration of a contemporary concert harp (Apollonia) made by Salvi in Italy. *Legend* **a** general view; **b** detail of pedals (http://salviharpsinc.com/GoldHarpApolloniaSalvi.htm. Access 10 April 2014). **b** Details of pedals and the base of the pillar and the lower part of the soundbox

wood for piano soundboards that differentiate this material from the resonance wood used for other musical instruments. It is understood that the tonewood for piano soundboards is quarter-sawn, tight grained (1–2 mm annual ring width) and free of defects such as knots, cracks, decay, etc.

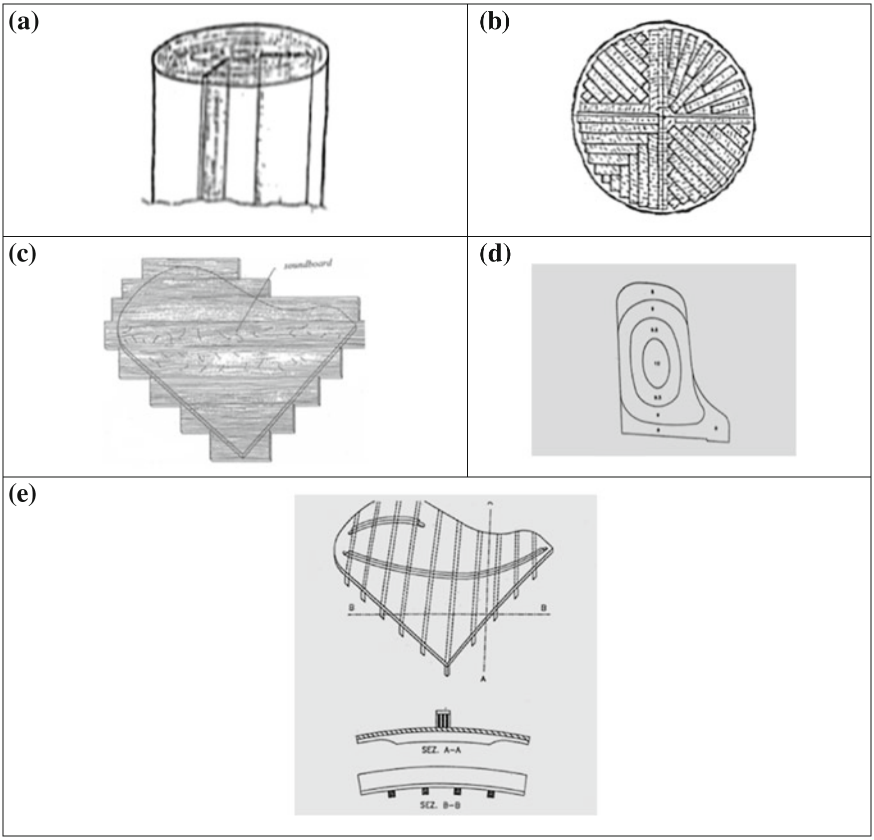


Fig. 2.47 Schematic representation of soundboard manufacturing technology **a** resonance wood selection; **b** quarter sawn log; **c** edge glued strips; **d** planing of the soundboard; **e** gluing of the bridges. (data from Fazioli 2002, pp. 108, 109, 110, 111)

Prior to soundboard manufacturing the quarter-sawn planks were dried naturally for a minimum of three years (preferably 10 years) and had about 10 % moisture content. In grand pianos the longitudinal axis of planks are oriented at an angle of 30–50° versus the direction of the keyboard in such a way that the grain direction of each plank is parallel to the direction of the long bridge.

After a very strict qualitative selection (sound velocity along the grain in planks of 5500–6000 m/s), the planks are edged glued to obtain a plate, which is shaped at the prescribed size for a grand piano or for an upright piano. Both sides of the plate are planed to obtain a plate having an approximately (about ±0.1 mm) parallel surfaces of variable thickness, of about 8–10 mm (for high quality pianos; for standard pianos for students the thickness of the soundboard is constant). Given its size, the soundboard at this stage is a very flexible plate. To reinforce its cross stiffness, several ribs are used. The ribs are mounted on the soundboard in the optimum direction for sustaining the curvature of the soundboard. The ribs made also in resonance spruce are glued on the upper part of the soundboard and perpendicular to the direction of the fibres of the strips.

The bridges have an important effect on the quality of piano tone production, loudness and duration. The bridges couple the strings' vibration to the soundboard in the plane of the soundboard and normal to the soundboard. Modern pianos have two bridges, a main long one labelled the treble bridge and a shorter bass bridge which are made from a laminated structure of maple and mahogany, having the top made in maple for the base and centre areas and in boxwood for the high treble zone. The bridges are glued on the upper side of the soundboard. For raising the bass strings the bass bridge is made about 3 cm taller than treble bridge.

Table 2.2 Operations for piano soundboard manufacturing (data from Fazioli 2002)

	Operation	Notes
1	Selection of resonance spruce of fine grain (Fazioli 2002 scheme A, p. 108)	Figure 2.47a
2	Quarter sawed (Fazioli 2002, scheme A, p. 108)	Figure 2.47b
3	Natural air drying	About minimum 3 years
4	Edge glued strips (Fazioli 2002, scheme B, p. 108)	Figure 2.47c
5	High precision planing of the soundboard of non-uniform thickness distribution (10 mm in the centre and 8 mm on the edge; ±0.1 mm) (Fazioli 2002, scheme D, p. 109)	Figure 2.47d
6	Ribs gluing to the underside of the board, perpendicular to fibres direction (Fazioli 2002, scheme C, p. 109).	Gluing is done in a cylindrical (or other) device with the board in an inverted position. See the convex shape of the completed board in section
7	Bridges gluing (Fazioli 2002, scheme E, p. 110)	Figure 2.47.e (Scheme E, p. 110 and G, p. 111)
8	Soundboard varnishing	Protection against variation of air moisture content in the atmosphere where the piano will be used
9	Soundboard conditioning at constant temperature and air humidity for about 3 years minimum	Moisture content in the soundboard is about 8 %

The extremities of the ribs are planed to obtain a characteristic profile as can be seen in the previous figure. The ribs are glued on the soundboard making a network. At this stage of fabrication the soundboard is slightly convex (1–2 mm). Usually for all piano types, the soundboard is slightly convex before stretching of the strings and becomes perfectly flat under playing conditions (Conklin 1996). The soundboard is again polished, covered with a thin layer of varnish and submitted to a long process of dimensional stabilisation for a minimum of three years at constant air temperature and relative humidity. Piano soundboard is mechanically connected with the case and the cast iron frame.

The case of the piano is the external structural component which combines the acoustics and engineering of the instrument with the aesthetics of its overall appearance in the room. Some of the XIXth century piano forte cases were magnificent pieces of furniture sumptuously decorated with marquetry of exotic wood species, mother pearls and other precious materials. In costly European instruments a favourite combination of wood species such as mahogany, walnut, cherry wood ornamented with marquetry. Modern piano case of technological design (Fig. 2.48) is produced with current technology for furniture making.

The history and evolution of cast iron frame was described by Doldge (1911). The cast iron frame for concert piano was patented in 1843 by Jonas Chickering, and sixteen years later, in 1859, Steinway and Sons in U.S. patented “the full frame for grand pianos with overstrung scale and disposition of the strings in the form of a fan”. London exhibition of 1862 promoted the cast iron frame and since then, piano builders in German speaking countries currently used it (Fig. 2.49). The upright

Fig. 2.48 Piano cases (Photo Wilhelm Schimmel Pianofortefabrik, GmbH, Braunschweig, Germany) (blog.livero.it/Amazzoneperforza/commenti.php?msgid=8050883&id=173365. Access 1 July 2014)

Fig. 2.49 Cast iron frame for a Steinway concert piano D 274 (http://en.wikipedia.org/wiki/Piano#Grand. Access 4 August 2014)

piano, with the strings arranged vertically appeared in 1828 and was mostly for amateurs and domestic usage. This instrument continued to develop during the 19th century in minor ways.

2.4.5 The Case of the Harpsichord

In this section we discuss some aspects related to the manufacturing of the case of the harpsichords. We know that the 20th century was characterised by a constant interest in Early Music revivals. More exactly, the period 1960s/70s has been characterised by an increasing interest of musicians (composers and performers) and instrument makers on harpsichords. During the last decades a large number of antique harpsichords have been restored to playing condition and new replicas of authentic instruments have been built. In Europe the harpsichord makers were famous in 16th, 17th and 18th centuries and superb instruments have been built by makers that today can be grouped around several schools—the Italian, the French, the Flemish, the German, the English and Irish and the Iberic (Spain and Portugal), the Dutch and the Scandinavian (Germainn 2002). The harpsichord is one of the

(a)

(b)

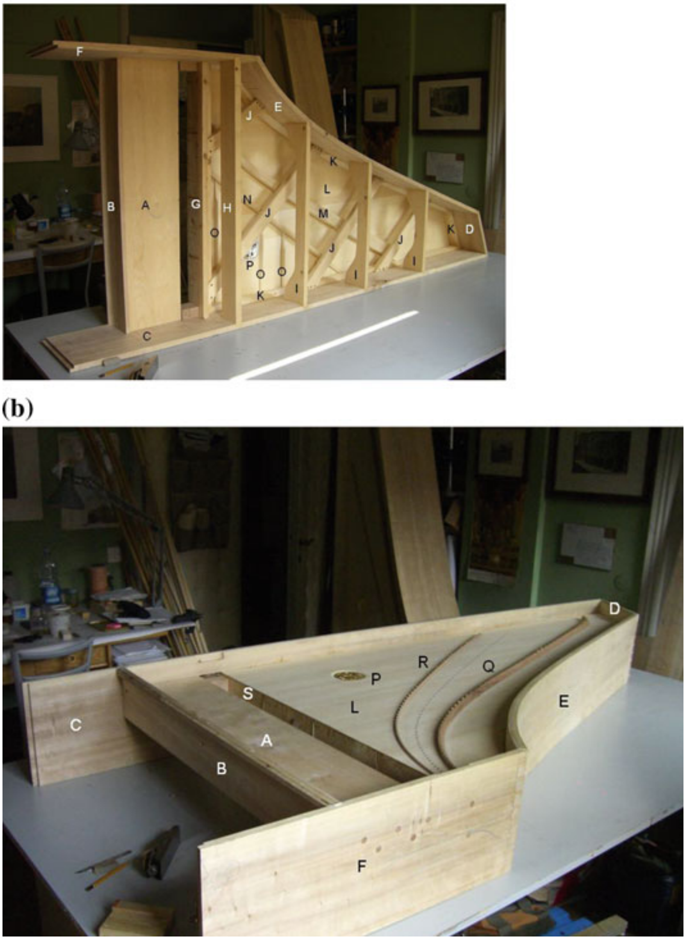


Fig. 2.50 Structural elements of a replica of a 18th century French harpsichord made by Taskin and recently built by Marco Brighenti—harpsichord maker in Parma—http://www.brighenti-harpsichords.com/images/foto/Taskin_soundb_01.jpg. Access 4 August 2014). *Legend* **a** internal structure; **b** upper view: *A* westplank; *B* nameboard; *C* spine; *D* tail; *E* bentside; *F* cheek; *G* upper bally rail; *H* lower belly rail; *I* lower frame; *J* arch; *K* liners; *H* lower frame; *L* soundboard; *M* 4'hitchpin rail; *N* cut-of-bar; *O* soundboard bars; *P* rosette; **a** Internal structure. *A* Sommier, *B* Barre de nom, *C* Echine, *D* Pointe, *E* Eclisse courbe, *F* Joue, *G* Contre-sommier, *H* Masse, *I* Barres de fond, *J* Arcs-boutants, *K* Contre-éclisses; *L* Table d'harmonie; *M* Boudin; *N* Grande barre; *O* Petites barres; *P* Rosace. **b** Upper view. *A* Sommier; *B* Barre de nom; *C* Echine; *D* Pointe; *E* Eclisse courbe; *F* Joue; *L* Table d'harmonie; *P* Rosace; *Q* Chevalet du 8 pieds; *R* Chevalet du 4 pieds; *S* Fosse. *A*-wrestplank, E-rib; F- L-soundboard Q-bridge 8′; R bridge 4′

richest decorated musical instruments in western music, with a very large selection of materials (wood, semi-precious stones, mother–of-pearl, tortoiseshell, applied metals-brass marquetry, ivory, bone, leather). Rich relief decoration and sculptures decorated the external part of the instrument, which was covered with cloths in velvets and brocades. The outer case of inexpensive and simpler instruments has been decorated with 'découpages'—less expensive printed papers glued on wood and covered with several layers of varnish. The lids have been painted in oil or gouache with landscapes, musical mythological or religious subjects, polychrome chinoiserie, etc. The stands were in furniture style, made in a great variety of forms. Contemporary builders simplified the decoration which is subordinate to the structure and the function of the instrument.

Wood is the main material used for the harpsichords. Different species have been used for the soundboard like cypress, spruce, fir, depending on local availability of lumber. For the bridge maple was preferred, for the spine maple, walnut or oak. The bentside was in maple or in coniferous veneered with mahogany. In harpsichord, the metallic elements are the strings and the ironware on the main lid and wrest-plank lid flap. Detailed description of materials used for specific historic harpsichords are given by Germainn (2002).

The structural complexity of a harpsichord made mainly in wood is illustrated in Fig. 2.50 with a replica of an 18th century French harpsichord made by Marco Brighenti,

2.5 Directivity of String Instruments

The radiation of sound by string musical instruments was systematically studied by Cremer (1984), Fletcher and Rossing (2010) and Gough (2012). Different vibrational modes of musical instruments are excited simultaneously by the players, but not all of them are important for the radiated sound. The sound emitted by the musical instruments propagates in air. The speed of sound depends on air temperature and humidity (343 m/s at 20 °C). Air temperature and humidity condition affect the playing pitch. The sound radiated by the instruments is characterised by its intensity. In free space, the sound from a localised source will propogate as spherical waves. The velocity and pressure differ in phase by an amount that depends on the distance from the source and the wavelength. In the near field, close to the source, the pressure and the velocity are in phase quadrature. In the far field the pressure is in phase with the velocity. The transition from the near to far field occurs at λ/π, where λ is the acoustic wavelength of the radiated sound, which means that at 440 Hz the distance will be about 15 cm. Therefore the player close to the source will experience a different sound from that heard by the listener in a big concert hall.

The sound pressure in the far field and the corresponding directional characteristics of a radiator can be calculated using the hypothesis that all dimensions of the sound source are small with respect to the wavelength. In the case of the violin the shortest wavelength corresponds to a frequency of 122 Hz, lower than the violin fundamental frequency, and in the case of cello, the limiting frequency is 57 Hz, which is also very low.

String musical instruments produce sound from the vibrations of their surface plates. The velocity of the transverse vibration of the thin plates of the front and back of an instrument increases with frequency as $\omega^{1/2}$. When the phase velocity in the plates is lower than the speed of sound in the air, the standing waves on the vibrating plates are inefficient radiators of sound. Above the crossover frequency the plates radiate sound efficiently. Cremer (1984) estimated the critical frequency of a violin plate of 2.5 mm thickness at 2 kHz and that of a cello plate of 4 mm thickness at 2.8 kHz.

The bowed string instruments numerically compose the most important group of instruments in a contemporary symphony orchestra. String players are sitting to the foreground of the stage having very few acoustical obstructions. Acoustical radiation of string instruments depends on the vibration of their plates expressed by the following parameters: frequency, amplitude and phase and, at low frequency by the sound radiated by air through the f-holes. Another important factor influencing the acoustical radiation of string instruments is the material of which they are made, namely wood. However, the instrument and the player have a shadowing effect on directional characteristics.

Meyer (1972, 2009) studied the directivity of instruments composing the contemporary symphony orchestra. For this purpose it was necessary firstly to define references, such as the principal radiation directions. Given their structural characteristics the instruments have been analysed in three separate groups, namely the bowed string instruments, the harp and the grand piano. In the case of the bowed string instrument, these principal radiation directions were defined with reference to the bridge plane and to the projection of the player and his instrument in the horizontal plane, at 0°, 90°, 180° and 270°, when 0° refers to the bridge.

The sound energy radiated from the harp is produced mainly by the upper surface of the resonance body. Three radiation planes have been defined: the horizontal, the plane of the strings, and the plane perpendicular to this plane.

Sound radiated from the piano is mainly produced by soundboard vibrations and is directed upward. However some important reflections are determined by the position of the lid, which can be closed, or open at an angle ranging between 10° and 37°, and the floor. Another influential factor is the location of the excitation in the lower, mid or high register. Two perpendicular planes of radiation were considered, the horizontal and the vertical.

Now, we can start to analyse the radiation regions of the string instruments following the sequence described previously.

Fig. 2.51 Radiation patterns in horizontal plane of a violin and a cello at different frequencies as specified (data from John Willet 2 May 2015) https://www.gearslutz.com/board/remote-possibilities-acoustic-music-location-recording/1003869-microphone-placement-violin-soloist.html

2.5.1 The Violin Family

The principal radiation regions for the bowed string instruments presented as frequency histograms are shown in Fig. 2.51. Three main frequency regions are represented on these graphs: low, medium and high (i.e. for violins low-up to 600 Hz, medium 700–2000 Hz, and high 2500–5000 Hz). Data from the histograms are synthetised in Table 2.3 such as:

- For violins below 400 Hz, there is no effect in the bridge plane. Maximum of concentration was observed in horizontal plane at about 1000 Hz. The violas have similar patterns.
- For cellos, below 200 Hz omnidirectional radiation was observed. Concentrated directivity in front of the player was observed between 500 and 200 Hz.
- For doublebasses at 100 Hz omnidirectional radiation was observed. At higher frequencies (400–500 Hz) we have an increasing radiation from the back.

Using more advanced technology and numerous microphones (44) in an anechoic chamber. Patynen and Lokki (2008, 2010) studied the directivity of string instruments with reference to three planes: from the front of the player (called median), from the lateral plane of the player (called lateral) and from above the player (called transverse). Sound power measurements in the far field were made as required by ISO 3745, with microphones positioned in a dodecahedron shape and with one player. The average distance of the microphones from the centre of the room was 2.13 m. Figure 2.52 shows the overall directivity of the violin, viola and cello and double bass. It is noticeable that the average sound radiation directivity for:

Table 2.3 Frequency range and radiation pattern for violin, viola, cello and double bass (data from Meyer (2009)

Instrument	Frequency range	Radiation pattern
Violin	Below 400 Hz, in bridge plane	No directional effect
	Around 425 Hz	Top plate radiation
	Around 500 Hz	Back plate radiation
	660–700 Hz	Higher values in the bridge plane at 90°, toward the back of the instrument
	1000–1250 Hz	Maximum concentration in horizontal plane
	3000–4000 Hz	Concentration at 270° in front of the payer
Viola		Similar to violin
Cello	Below 200 Hz	Omnidirectional radiation
	250–300 Hz	Radiation from the top plate resonances
	500–2000 Hz	Concentrated directivity in the front
Double bass	Low frequencies	Pronounced radiation
	100 Hz	Omnidirectional radiation
	400–500 Hz	Increasing radiation to the back.
	1000 Hz	Lateral directivity to the front half plane

- The violin, below 500 Hz octave band is omnidirectional, while between 2000 and 6000 Hz, the sound is radiated in front of the player. i.e.—the octave band above 1000 Hz—irregular pattern; the octave band 2000 Hz—sound radiated to the front region; 4000 Hz octave band–at–3 dB concentrated directivity oriented in front of the player (red line) occurs.
- The viola patterns are similar to that of the violin, but exhibit less directivity than the violin.
- The cellos, 500 Hz octave band in the median plane radiate strongly to the front. At higher octave bands radiations are mostly along the length axis of the instrument.
- The double bass (flat back) has some similarities with the overall directivity patterns of the cello. A cardioid shape pattern for the cello was observed in the 2000 Hz octave band, and an octave lower the double bass shows a similar pattern.
- The playing dynamics of all instruments do not significantly change the directivity pattern.
- The directivity patterns were measured for a single musician.

To help to clarify ideas regarding the four bowed string instruments it seems interesting to conclude that there were similarities in the radiation pattern. Depending on the instrument, it was observed that one or two frequency bands divide the contiguous regions of the radiation patterns.

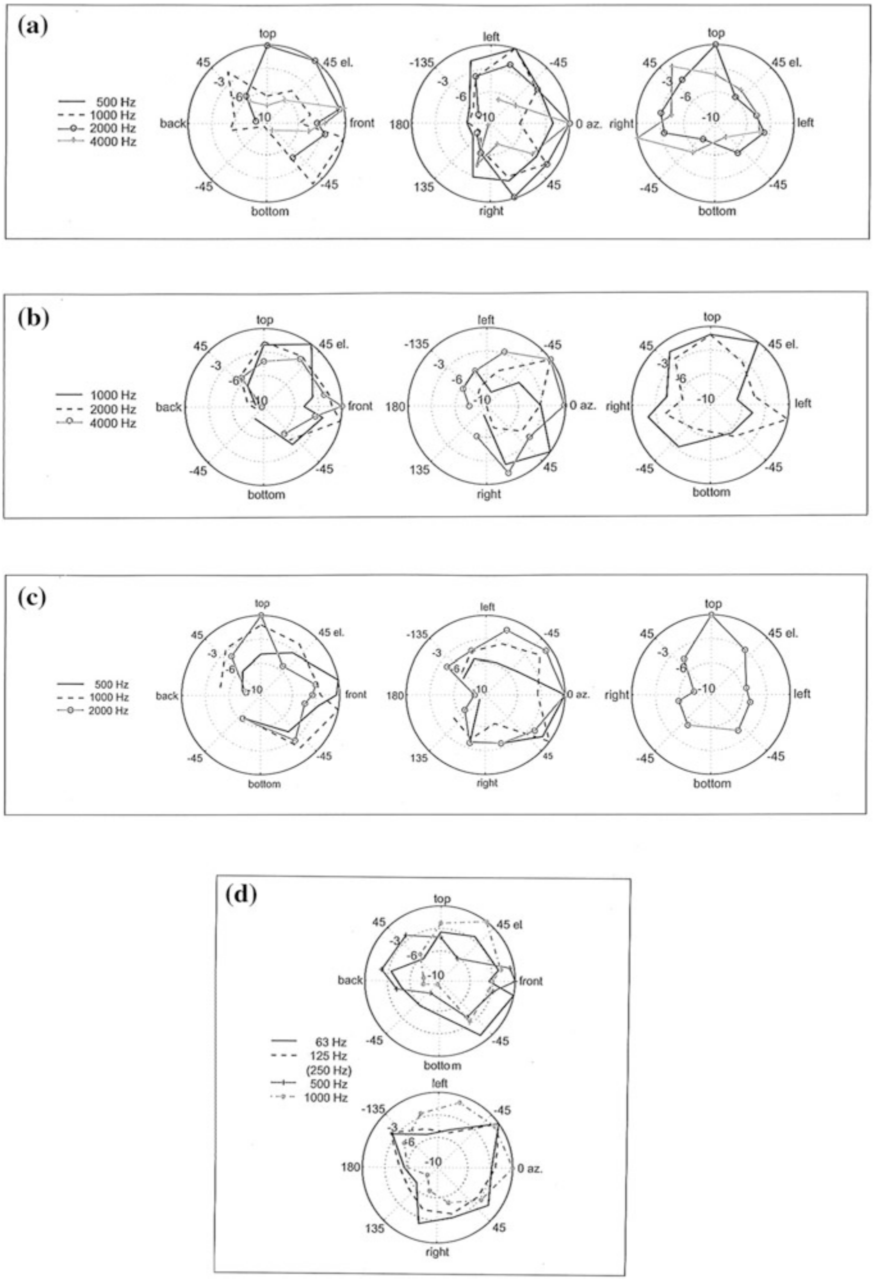


Fig. 2.52 Overall directivity of bowed string instruments (Pätynen and Lokki 2010). *Legend* **a**, **b**. **c** Overall directivity of the violin, viola and cello in three planes (median, lateral and transverse) at −3, −6 and −10 dB (Pätynen and Lokki 2010, Figs. 33. p. 159, 37, p. 161, 40, p. 163, with permission). **d** Overall directivity of the double bass in two planes (median and lateral) at −3, −6 and −10 dB (Pätynen and Lokki 2010, Fig. 43, p. 164)

Fig. 2.53 Current setting of the string players in Vienna Philharmonic Orchestra (http://www.musikverein-wien. Access 4 August 2014)

Meyer (2009) has discussed the effect of the seating order of the players in three versions

- The European/German version when the first violins are at the left of the conductor, the second violins at the right of the conductor, the violas and cellos between them, the double bass at the back of the stage, as for example Vienna Philharmonic (Fig. 2.53)
- The American version I—the first violins are at the left of the conductor, the cellos at the right of the conductor, the second violins near the first violins, so that the top of their instruments face towards the audience, giving good high frequency sound, while the violas are near the cellos; the double bass are at the back of the stage on the right wing. This setting was probably the one most frequently used during the second half of the 20 century, as for example Melbourne Symphony orchestra (Fig. 2.54)
- The American version II—the first violins are at the left of the conductor, the violas at the right of the conductor, between them the second violins and the cellos, as in the arrangement of the string quartet. The double bass is at the back of the stage.

It is generally accepted that there is no universally recognized optimum seating configuration for string players on a stage. Several factors are involved in the selection of one or another solution such as the space available on the stage, the acoustic circumstances of the concert hall or opera house, the subjective tonal

Fig. 2.54 Current setting of the string players in Melbourne Symphony orchestra (Photo courtesy of Melbourne Symphony orchestra performing Mahler 2nd symphony-Resurrection, conducted by Sir Andrew Davis on 13th November 2014. Hammer Hall, Art Centre Melbourne, Photo Matt Irwin)

perception of the conductor for the music played, the visual contact among the players, the performance practice, etc.

2.5.2 The Concert Harp

As regards the harp, Meyer (2009) citing Bell and Firth (1989) noted that in the horizontal plane the radiation is circular, at 400 Hz. Between 400 and 2000 Hz the radiation is concentrated in two regions towards the front and back. In the plane of the strings at about 1000 Hz there is a predominant radiation upward. In the third plane broad radiations were observed up to 1000 Hz. (The data are expressed as the maximum value of sound pressure level). On a concert hall stage the harp is placed on the left wing of the orchestra behind the violins. In the horizontal plane the sound radiation is mostly symmetrical, with one exception for the frequency range 400–2000 Hz, which is slightly non symmetrical.

For a soloist the optimal position of the harp is at 45° to the edge of the podium.

2.5.3 The Grand Piano

For the piano, the most interesting plane is the vertical one. Figure 2.55 shows the directional characteristics of a grand piano, lid open and the ideal microphone position for recording. Meyer (2009) studied the corresponding directional characteristics represented in polar coordinates, with the lid open and for excitation in lower, mid and high registers of the keyboard. The preferred radiation in the lower register was observed between 85° and 90° at 2000 Hz. In the middle register, due to the open lid, a maximum is observed at about 40° and another one around 140°, at 500 Hz and at 4000 Hz. In the higher region the strong influence of the open lid position is more apparent, at 4000 Hz and 25° for a grand piano soloist.

When the piano is used as an orchestral instrument with an open lid, its location is toward the back of the stage, to the left side of the orchestra. Sometimes the lid can be removed allowing a better visual contact with the conductor or with the harp, celesta and other percussion instrument players.

2.6 New Instruments

In this section we will analyze the major innovations of the 20th century related to classical musical instruments, namely the violin octet and the guitar family instruments

2.6.1 The Hutchins—Schelleng Violin Octet

The most interesting event in Musical Acoustics of the 20th century was the creation of a new violin family of scaled violins, known as the Hutchins—Schelleng violin octet (Bissinger 2010). This innovation was generated by discussions by Frederick Saunders, John Schelleng and CM Hutchins in 1958 with a musician, the American composer Henry Brant (1913–2008) (who taught at Columbia University and the Julliard School of Music) about stringed instruments able to cover the entire range of about five octaves. This was a fascinating challenge having in mind that violin masters from all times aspired to create a more homogeneous violin band.

The design of the new family of violins of eight instruments (Fig. 2.56) was guided by the theoretical scaling relationship called the general law of similarity. All instruments have the violin body shape and four strings, the smallest has a 280 mm body length and the largest bass of very massive body has a length of 1,300 mm. The body resonance of the scaled violins should be at the same relative pitches

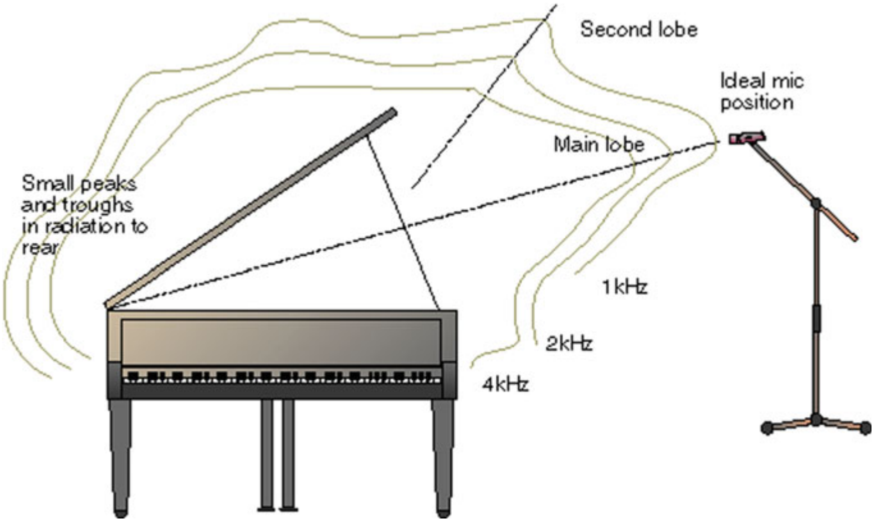


Fig. 2.55 Directional characteristics of a grand piano, lid open and the ideal microphone position for the recording (http://www.soundonsound.com/sos/may99/articles/recpiano.htm. Access 4 August 2014)

on each instrument. Schelleng proposed the violin as the standard instrument for the new family. The scaling targets were A0 and a combination of mode frequencies called "main wood", which included corpus resonances, namely B1 (Bissinger 2010), as represented in Fig. 2.57. We can see that the main wood resonance of the violin is close to note A5, which is again the pitch of the second highest string, on the baritone violin the second highest pitch is note D3, with the main wood resonance at this pitch, and so forth. The size and the tuning of each instrument from the new family compared with the instruments of the classic quartet are given in Table 2.4.

Bissinger (2003, 2005, 2007, 2010) performed experimental modal analysis of the Hutchins–Schelleng violin octet, combined with cavity mode analysis and room-averaged acoustic analysis. This analysis gives a highly detailed characterization of the dynamics for this experimental group of instruments of historic importance. All the "signature" modes in the open string pitch region—cavity modes A0 ("main air") and A1 (lowest longitudinal), CBR (first corpus bending), modes $B1^-$ and $B1^+$ (comprising the "main wood")—were observed for all instruments of the octet. A0 was always the lowest dominant radiator, below all corpus modes. A1 contributed significant acoustic output only for larger instruments, but was the dominant contributor for the large bass in the "main wood" region. Both $B1^-$ and/or $B1^+$ are the major radiators for all instruments.

Fig. 2.56 The instruments of the violin octet and the American artists of "The Hutchins Consort in 2006" Joe McNalley, artistic director (www.hutchinsconsort.org and http://www.danielpearlmusicdays.org/artist_detail.php?id=254). Access 30 January 2014

The violin octet produces a strong sound, quite different from that of conventional string ensembles. Players with special skill are required for mastering the technical demand of each family instrument. Today, after about 50 years from the conception of this group of instruments "The Hutchins Consort" successfully plays a large repertoire from early music to 21st century music (http://www.hutchinsconsort.org).

The materials used for these instruments are the same as traditionally used for the classic violin family, spruce for the top and curly maple for the back, ribs and neck. For small instruments specimens having very narrow annual rings were preferred, while for big instruments the specimens selected had large annual rings, without knots.

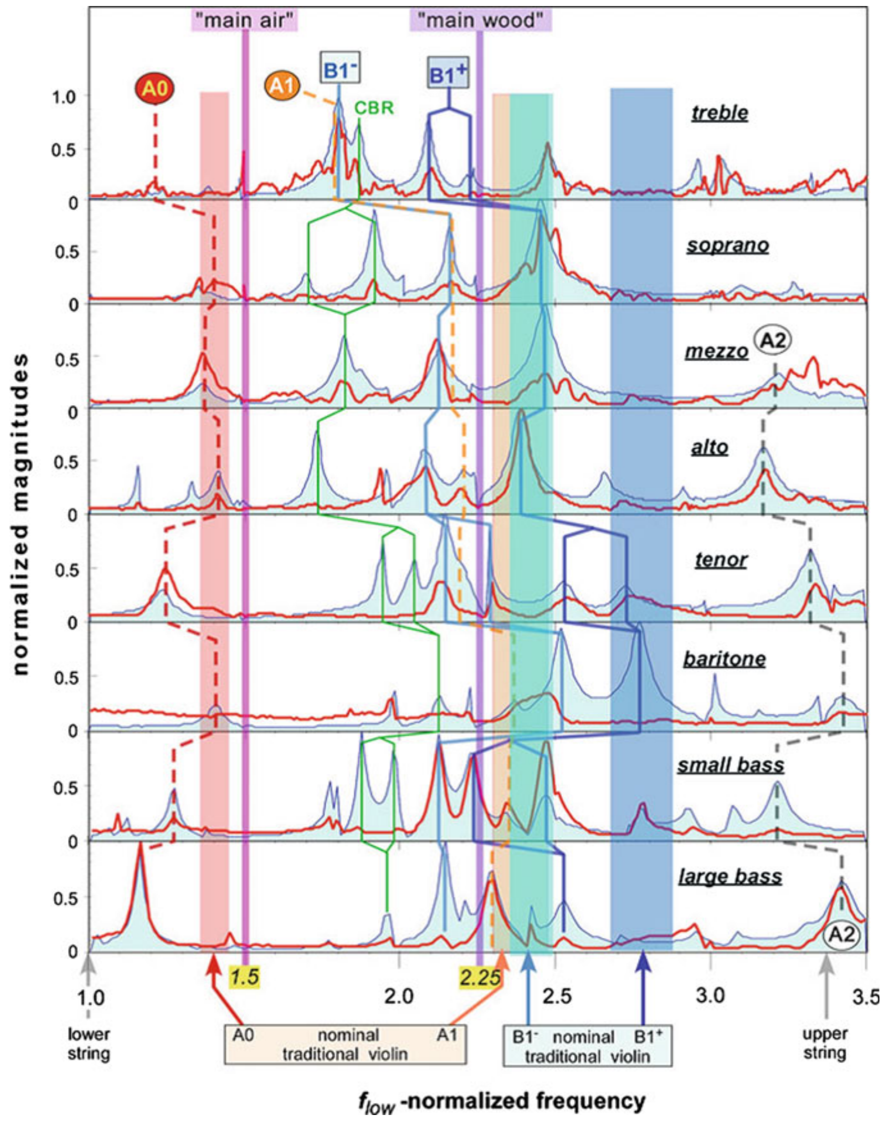


Fig. 2.57 Average corpus vibration (*blue shaded curve*) superimposed on room averaged radiation (*red curve*) for the "St Petersburg" violin octet, versus normalized frequency (*low string*). The scaling target: A0 at 1.5 × f_{low} and B1 at 2.25 × f_{low}. (Bissinger 2010, Fig. 18.5, p. 335)

Table 2.4 Measurements and scaling of the new violin family compared with conventional instruments (Fletcher and Rossing 2010, Table 10.2, p. 325, after Hutchins 1980)

Instruments			Length (cm)			Relative scaling factor		
Name	Tuning	Frequency (Hz)	Overall	Body	String	Body length	Resonance placement	String tuning
Treble	G_4, D_5, A_5, E_6	392, 587, 880,1319	48	28.6	26.0	0.75	0.50	0.50
Soprano	C_4, G_4, D_5, A_5	262, 392, 587, 880	54–55	31.2	30.0	0.89	0.67	0.67
Mezzo	G_4, D_5, A_5, E_5	196, 294, 440, 659	62–63	38.2	32.7	1.07	1.00	1.00
Violin	G_4, D_5, A_5, E_5	196, 294, 440, 659	59–60	35.5	32.7	1.00	1.00	1.00
Viola	C_3, G_4, D_4, A_4	132, 196, 294, 440	70–71	43.0	37.0	1.17	1.33	1.50
Alto	C_3, G_4, D_4, A_4	132, 196, 294, 440	82–83	50.2	43.0	1.44	1.50	1.50
Tenor	G_2, D_3, A_3, E_4	98, 147, 220, 330	107	65.4	60.8	1.82	2.00	2.00
Cello	C_2, G_2, D_3, A_3	65, 98, 147, 220	124	75.0	68.0	2.13	2.67	3.00
Baritone	C_2, G_2, D_3, A_3	65, 98, 147, 220	142	86.4	72.0	2.42	3.00	3.00
Small bass	A_1, D_2, G_2, C_3	55, 73, 98, 131	171	104.2	92.0	2.92	4.00	4.00
Double Bass	E_1, A_1, D_2, G_2	41, 55, 73, 98	178	109.0	104.0	3.09	4.00	6.00
Contrabass	E_1, A_1, D_2, G_2	41, 55, 73, 98	213	130.0	110.0	3.60	6.00	6.00

Note New violin family is scaling from 41 to 1319 Hz, on 5 octaves from E1 to E6
Classic quartet is scaling from C2 to E5, on more than 3 octaves

The sound of this octet was recorded in https://www.youtube.com/watch?v=ao5Ig02fwOk Meet musicians of the Hutchins Consort; The San Diego News Network YouTube Channel

https://www.youtube.com/watch?v=ISvKEbqUe5Y The Hutchins Consort (Concerto for Hutchins Violins) https://www.youtube.com/watch?v=IGZl3BN3aZo Introduction To The New Violin Family (1/3) by Robert Spear https://www.youtube.com/watch?v=70gjbrLtDD0 Introduction To The New Violin Family (2/3)

2.6.2 The Caldersmith Classic Guitar Family

Based on the same scaling principle described previously for the violin family, the Australian luthier/physicist Graham Caldersmith conceived a family of scaled classic guitars (Caldersmith 1995), having as reference the classic guitar with six strings E4, B3, G3, D3, A2, E2.

Guitar mode resonances depend of bracing system. An innovative bracing system proposed by Caldersmith is with internal frame and rectangular lattice used for concert classic guitar and for the treble guitar of scaled family. (Fig. 2.58).

The guitar family is composed of four members: treble, standard—tenor, baritone and bass (Fig. 2.59). The bass guitar has four strings tuned E1 (41 Hz), A1(55 Hz), D1(73 Hz), G1(98 Hz). The baritone guitar has six strings tuned a fifth below the standard with the compass from A1(55 Hz) to A3(220 Hz). The treble guitar has four strings and is tuned a fourth above the standard guitar from A2(110 Hz), to A4(440 Hz). The design of the instruments was documented with principle mode geometry, frequency response and playability, by keeping the lowest modes (air, 0.0; 0.1; 1.0; 2.0) of the new instruments in the same relation to the string frequency as for the standard guitar.

The frequencies of principal modes of the top plate, back plate and air cavity of classic guitar, fan-braced are given in Table 2.5. The lowest resonance, called improperly Helmholtz resonance is around 100 Hz, includes air resonance and motions of the top and back plates.

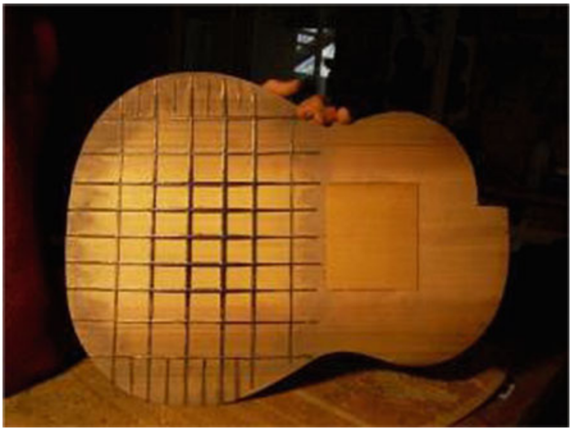


Fig. 2.58 Internal frame and rectangular lattice of a concert guitar made by Caldersmith (http://www.caldersmithguitars.com/concert.php. Access 7 February 2014)

Fig. 2.59 Australian quartet Guitar Trek 2012—Timothy Kain, Minh Le Hoang, Bradley Kunda and Matt Withers. Photo Jimmy Walsh (http://bradleykunda.com/gallery/#jp-carousel-317. Access 7 February 2014

Scaled guitar family was built with fan-braced geometry for standard, baritone and bass guitars. We have seen in Chap. 3 that mechanical behavior of plates in orthotropic materials is governed by four elastic moduli and density. The inertial force experienced by an element during oscillation is proportional to the frequency squared, to plate thickness and plate density. The mode frequency is proportional to plate thickness and inversely proportional to the square of plates dimensions (along and across the grain). Caldersmith (1995) noted that "to have the frequency of the natural modes for an instrument tuned an octave lower than the standard, the plate dimensions should increase by a factor of about 1.4 if plate thickness and brace

Table 2.5 Principal mode frequencies of scaled guitar family (Data from Caldersmith 1995)

Instrument	Air		Mode frequencies (Hz)			
	Resonance (Hz)	Ratio	0.0	1.0	0.1	2.0
Classical guitar	92	1.0	216	231	325	420
Treble long string	144	1.56	273	333	450	638
Baritone guitar	72	0.73	160	185	195	375
Bass guitar	63	0.68	137	146	187	286

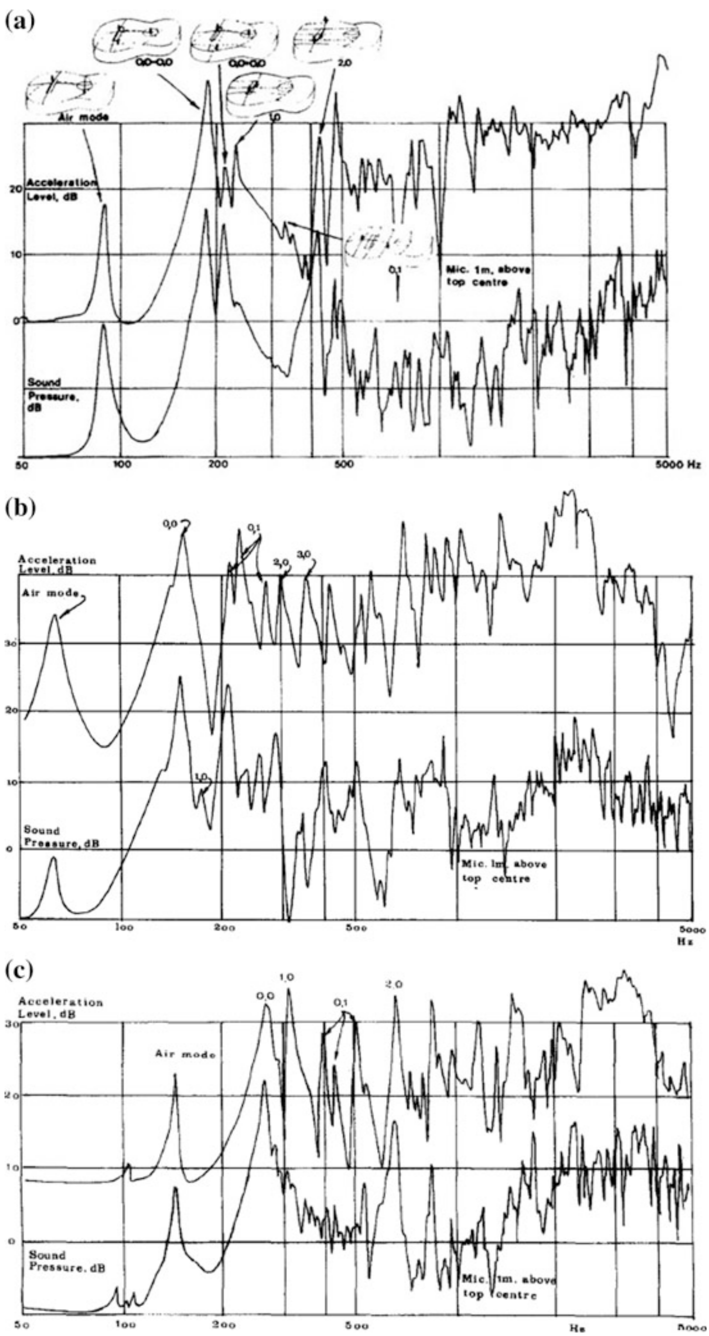


Fig. 2.60 Acceleration level (input) and sound pressure level (output) frequency responses of three instruments from guitar family (Caldersmith 1995, Figs. 1, p. 6, 4, p. 13 and 8, p. 16). *Legend* **a** classic guitar; **b** baritone guitar and **c** treble guitar

Table 2.6 Frequencies of principal modes of the top plate, back plate and air cavity of classic guitars—Kohno 30[a] (Data from Fletcher and Rossing 2010)

	Modes						
	0.0	0.1	1.0	0.2	1.1	2.0	1.2
	Frequency (Hz)						
Top plate	183	388	296	466	558	616	660
Back plate	206	285	368	417	537	646	856
Air cavity	A0	A1	A2	A4	A3		
	Helmholz	Mode 0.1	Mode 1.0	Mode 0.2	Mode 1.1	Mode 2.0	
	Frequency (Hz)						
	118	396	560	780	674		

[*]Masaru Kohno (1926–1998)—gold medal in Queen Elizabeth's concourse Belgium-international competition in guitar lutherie in 1967. He was the most important Japanese guitar luthier of the 20th century

sections remain the same". Because of playability restrictions the bass guitar is about 1.4 larger than the standard guitar. To keep the bass guitar modes an octave below the standard, the top thickness and brace height were 3.0 and 7.0 mm, compared with 2.5 and 5 mm for standard classic guitar.

Principal mode frequencies of instruments from scaled guitar family are given in Table 2.5. The reference instrument—the classic guitar, has air resonance of 92 Hz. Air cavity resonance for family instruments was scaled in following proportions: treble guitar 1.56; baritone 0.73 and bass guitar 0.68. Treble guitar has the frequencies of all modes higher than those of classic guitar; baritone guitar and bass guitar have all frequencies lower than those of classic guitar.

The frequency response of three instruments from the guitar family are shown in Fig. 2.60. The frequency response of baritone guitar shows a strong "resonance triplet" introduced by the coupling of the 0.1 top mode with the 0.0 back mode and with the air mode 0,1. Treble guitar has a "sharp, cutting tonality" with pronounced broad peak in the band 2–5 kHz. The smaller guitar body produces modes less than a fourth above the modes frequencies of standard guitar.

For comparison in Table 2.6 are given the frequencies of principal modes of the top plate, back plate and air cavity of classic guitars made by the Japanese luthier Kohno 30.

The musical repertoire of this guitar family is very large, from that of string quartets to new modern compositions. This guitar family enjoys a wide international audience and excellent reputation (http://www.caldersmithguitars.com/gtr.php. Access 1 February 2014). The sound of Melbourne guitar quartet was recorded and can be leased on https://www.youtube.com/watch?v=SfxJmDN77Pg

2.7 Summary

Musical instruments are cultural objects; their sounds characterise a specific historical era or geographical area. Therefore the study of musical instruments is as much a cultural study as it is about the physics, the acoustics and the materials used for their construction. The manufacturing of musical instruments, their shape, their decoration and their iconography is characteristic of the aesthetics of the musicians they serve and of the society in which the musicians live. This chapter is intended to illustrate some aspects related to the historical evolution of string instruments representative of Western classical musical practice: the instruments of the violin family, violin, viola, cello and double bass, the classical guitar, the concert harp and the grand concert piano—instruments of symphony orchestra. Three particular art forms used in the service of Baroque musical instrument representation were painting, intarsia and sculpture. These three art forms were used to enhance their symbolic value and to emphasize the origins of these exceptional objects which are indispensable to the musical phenomenon. The fascinating sense of ornamentation of the craftsmen manufacturing these instruments was unsurpassed. Beside their acoustic functions as devices to produce sounds, some musical instruments are representative of the decorative arts. The shape of the musical instruments was derived from three main considerations: acoustics, ergonomics and aesthetics. Acoustics is related to the string length, bridge position, the volume of air encapsulated in the resonance corpus and the materials used for soundboard and other parts. Ergonomics relates the playing functions such as the angle of the neck, the height of the bridge, the length of the fingerboard, the incurved middle bouts, the weight of the instrument. Aesthetics harmonizes the requirements of acoustics and ergonomics by using the geometry and the harmony of proportions. There is no doubt that the geometry and the golden proportion system have been used by the luthiers of 16th, 17th and 18th centuries. Their design has been guided by practical, aesthetical and metaphysical considerations. The manufacturing of musical instruments is described in terms of the principal operations required for their construction. In the last section of this chapter the directivity of string instruments is analysed. The bowed string instruments numerically compose the most important group of instruments in a contemporary symphony orchestra. String players are sitting to the foreground of the stage having very few acoustical obstructions. Acoustical radiation of bowed string instruments depends on the vibration of their plates and their directivity depends on frequency. The sound energy radiated from the harp is produced mainly by the upper surface of the resonance body. Sound radiated from the piano is mainly produced by soundboard vibrations and is directed upward. During the 20th century new instruments have been created using scale principle and derived from the geometry of the violin and of the classical guitar, namely the Hutchins—Schelleng violin octet and the Caldersmith guitar quartet

Appendices

Appendix 1: Sizes of the Instruments from the Violin Family

The sizes of the instruments from violin family (Data from Ron Pinkham-Woodsound Studio. http://woodsoundstudio.com/images/setup-charts/cello&bass-sizes.pdf. Access 28 April 2014

VIOLIN SIZES	4/4	3/4	1/2	1/4	1/8	1/16
MENC Designation	**STD.**	**INT.**	**JUN.**	---	---	--- *
Body Length, Nominal	356	335	310	280	255	230
String Length, Nominal	330	310	285	260	235	215
Bow Length, Nominal, Overall	745	690	630	550	500	450
Bridge Blank Width at Feet	41	38	35	32	29	27
Bridge Thickness at Feet	4.2	3.9	3.6	3.3	3.0	2.8
Bridge Thickness at Strings	1.3	1.2	1.1	1.0	0.9	0.9
Sound Post Diameter	6.0	6.0	5.0	5.0	4.0	4.0
Bar Length	277	260	241	218	198	179
Bar Width	5.5	5.1	4.7	4.3	3.9	3.6
Bar Height at Bridge	12	11	10	9.4	8.6	7.9
String 1-4 Spacing at Nut	16.3	15	14	13	12	11
String 1-4 Spacing at Bridge	33.5	31	29	26	24	22
String I FB Clearance, Gut	3.5	3.2	3.0	2.7	2.5	2.3
String I FB Clearance, Steel	2.5	2.3	2.1	1.9	1.8	1.6
String 4 FB Clearance, Gut	5.5	5.1	4.7	4.3	3.9	3.6
String 4 FB Clearance, Steel	4.0	3.7	3.4	3.1	2.9	2.6
FB Height Projected to Bridge	27	25	24	22	20	19
Fingerboard Length	270	250	230	210	195	180
Tailpiece Length	112	105	95	89	82	75
Pegbox to Peg Thumbpiece	16	15	14	13	11	10
Peg Thumbpiece Width	22	21	20	19	18	17

Suzuki 1/10, 1/16, approximate the traditional 1/16, 1/32.

VIOLA SIZES	LARGE	MED.	SMALL	3/4	1/2	1/4
MENC Designation	**STD.**	**STD.**	**STD.**	**INT.***	**JUN.***	**MINI***
Approximate:	17 in	16 in	15½ in	14 in	13 in	12 in
Body Length, Nominal	430	410	390	356	335	310
String Length, Nominal	390	375	355	(See	(See	(See
Bow Length, Nominal, Overall	750	740	740	4/4	3/4	1/2
Bridge Blank Width at Feet	50-52	48-50	46-50	vn.)	vn.)	vn.)
Bridge Thickness at Feet	5.5	5.3	5.0			
Bridge Thickness at Strings	1.5	1.5	1.4			
Sound Post Diameter	7.0	7.0	6.0			
Bar Length	334	319	303			
Bar Width	6.6	6.3	6.0			
Bar Height at Bridge	15	14	13			
String 1-4 Spacing at Nut	17	17	16.5			
String 1-4 Spacing at Bridge	38	37	36			
String I FB Clearance, Gut	4.5	4.3	4.0			
String I FB Clearance, Steel	3.5	3.3	3.0			
String 4 FB Clearance, Gut	6.5	6.3	6.0			
String 4 FB Clearance, Steel	5.0	4.8	4.5			
FB Height Projected to Bridge	32	31	30			
Fingerboard Length	305	300	290			
Tailpiece Length	135	130	125			
Pegbox to Peg Thumbpiece	18	17	17			
Peg Thumbpiece Width	25	24	24			

May be 4/4, 3/4, 1/2 violins specially strung. True violas (wider and deeper bodies) are preferable.

CELLO SIZES **MENC Designation**	**4/4 STD.**	**3/4 INT.**	**1/2 JUN.**	**1/4 --- ***	**1/8 --- ***
Body Length, Nominal	755	690	650	580	530
String Length, Nominal	695	635	600	535	490
Bow Length, Nominal, Overall	715	670	630	590	560
Bridge Blank Width at Feet	90	83	77	70	65
Bridge Thickness at Feet	11	10	9.3	8.6	7.9
Bridge Thickness at Strings	2.6	2.4	2.2	2.0	1.9
Sound Post Diameter	11	10	9.0	9.0	8.0
Bar Length	587	536	505	451	412
Bar Width	11	10	9.5	8.5	8.0
Bar Height at Bridge	25	23	21	19	18
String 1-4 Spacing at Nut	22	20	19	17	16
String 1-4 Spacing at Bridge	47	43	40	37	34
String I FB Clearance, Gut	5.5	5.1	4.7	4.3	3.9
String I FB Clearance, Steel	4.0	3.7	3.4	3.1	2.9
String 4 FB Clearance, Gut	8.0	7.4	6.8	6.3	5.7
String 4 FB Clearance, Steel	6.5	6.0	5.5	5.1	4.7
FB Height Projected to Bridge	81	75	69	63	58
Fingerboard Length	580	530	500	450	410
Tailpiece Length	235	215	200	180	160
Pegbox to Peg Thumbpiece	28	26	24	22	20
Peg Thumbpiece Width	38	36	34	32	30

*Suzuki 1/2, 1/4, approximate the traditional 1/4, 1/8. Suzuki 1/8, 1/10 are about 455, 400 mm long. (A viola with an end pin has also been used.)

BASS SIZES **MENC Designation**	**4/4 ---**	**3/4 STD.**	**1/2 INT.**	**1/4 JUN.***
Body Length, Nominal	1160	1110	1020	940
String Length, Nominal	1100	1060	975	900
Bow Length, French, Overall	725	725	675	675
Bow Length, German, Overall	750	750	710	710
Bridge Blank Width at Feet	160	150	138	127
Bridge Thickness at Feet	23	21	19	18
Bridge Thickness at Strings	4.9	4.5	4.2	3.8
Sound Post Diameter	18	17	16	15
Bar Length	932	855	792	726
Bar Width	25	23	21	19
Bar Height at Bridge	44	40	37	34
String 1-4 Spacing at Nut	33	30	28	25
String 1-4 Spacing at Bridge	87	80	74	68
String I FB Clearance, Gut	12	11	10	9.3
String 1 FB Clearance, Steel	7.6	7.0	6.5	5.9
String 4 FB Clearance, Gut	17	16	15	14
String 4 FB Clearance, Steel	9.5	8.7	8.0	7.4
FB Height Projected to Bridge	160	150	138	127
Fingerboard Length	890	850	780	730
Tailpiece Length	350	340	310	290
(Tuning "Machines")	---	---	---	---

* A cello is sometimes tuned an octave above the bass for children.

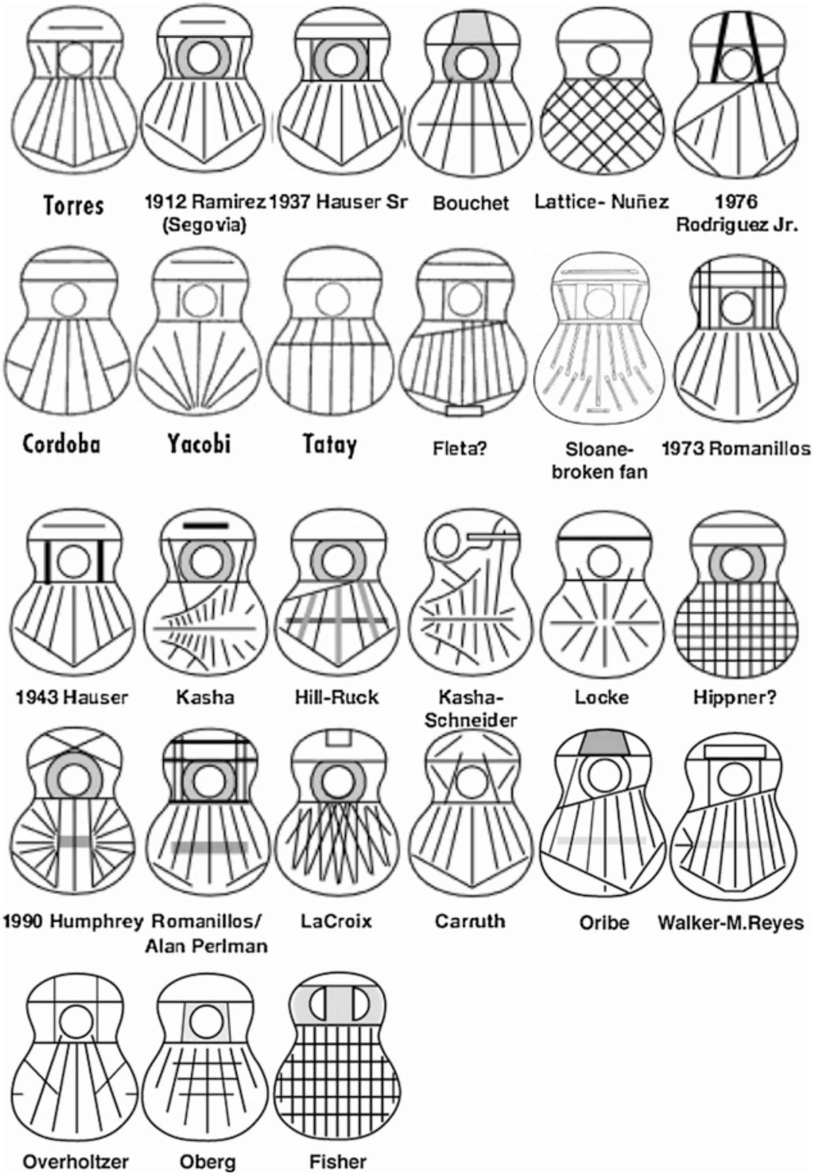
Appendix 2: Mass of Instruments from the Violin Family

Mass of instruments from the violin family

Maker	Location	Date	Description of fittings	Mass (g)
Violins				
Andrea Amati	Cremona	1577	No chin rest, all else ebony	353
Carlo Bergonzi	Cremona	1732	"Tarisio" no chin rest, all else boxwood	355
Mateo Gofriller	Venice	1715	Complete, all boxwood	395
Jacob Steiner	Absam	1668	Original Baroque condition, no chin rest, ebony fittings	
Antonio Stradivari	Cremona	1694	"Harrison", no chin rest, rosewood pegs, ebony	319
Antonio Stradivari	Cremona	1704	"Betts" complete, all boxwood	429
J.B. Vuillaume	Paris	1871	No chin rest, all else boxwood	378
Contemporary	Usa	XXth century	Complete—all else boxwood	454
Contemporary	Usa	XXth century	Complete—all ebony	384
Contemporary	Usa	XXth century	Complete—all rosewood	457
Viola				
Andrea Amati	Cremona	1577	No chin rest, all else ebony	576
Nicola Bergonzi	Cremona	1781	No chin rest, boxwood pegs, ebony	561
F. Gofriller	Venice	1730	No chin rest, all else rosewood	583
Jacob Steiner	Absam	1650	Original Baroque conditions, no chin rest, maple fingerboard &tailpiece	561
Contemporary	Usa	XXth century	Complete all ebony	615
Contemporary	Usa	XXth century	Complete all boxwood	666
Cello				
N. Gagliano	Naples	1752	7/8 size, complete—steel endpin	2597
D. Montagnana	Venice	1735	Complete, rosewood pegs, steel endpin	3000
Contemporary	Usa	XXth century	Complete, steel endpin, rosewood pegs	2870
Contemporary	Usa	XXth century	Complete, all ebony, steel endpin	2610

Appendix 3: Bracing System for Classical Guitars

Different bracing systems (G Weigert http://gidsguitars.wordpress.com/how-to-build-a-guitar-part-1/. Access 10 April 2014)



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