Introduction

Much of the information included in this manual is derived from a shop notebook that I compiled while serving as the musical instrument conservator of the Metropolitan Museum of Art between 1976 and 2006, and it is a reflection of the range of tasks that confronted me on a day-to-day basis. This manual has not been conceived as a "how to" textbook on musical instrument repair and conservation, but rather as a convenient alphabetically arranged reference work organized for the quick retrieval of useful information. I have, however, augmented the recipes, formulas, charts, and tables in that shop notebook with essays on procedures and practices that I feel are relevant to the care of musical instruments. I hope this manual will be of assistance to those who pursue musical instrument repair and conservation as their profession and to those who oversee such work.

During my thirty years as a museum-based conservator and as an outside observer of museums since my formal retirement, I have witnessed a number of significant changes within the profession. Around the time I entered the field, major museums throughout the United States were in the midst of altering their hiring policy: a foundation in practical craftsmanship was no longer deemed sufficient or even relevant, and in an effort to "raise standards" a master's degree in conservation from one of a coterie of university-based programs became a virtual requirement for a full-time staff position. Along with this alteration in hiring policy, the title "restorer" was changed to "conservator" – a semantic refinement ostensibly intended to signal a shift from a "glue-and-fix-it" approach to one based on scientific training. The new breed of conservator may be guided by such laudable precepts as "the preservation of cultural property," an "informed respect for cultural property," "preventive conservation," "documentation," the "stabilization of objects," and the "reversibility" of treatments (to paraphrase the American Institute for Conservation's 1994 *Code of Ethics and Guidelines for Practice* and the International Council of Museums' 2013 *Code of Ethics*), though their classroom experience may not equip them to tune a harpsichord or even to install a set of violin strings. In the specialty of musical instrument conservation, academic credentials in conservation must be supplemented by certain physical skills, such as those gained through a formal apprenticeship with an established instrument maker, as well as a modicum of musical training: in addition to being able to make an instrument, a musical instrument conservator should be able to play one.

In recent years there has been a spate of articles and books decrying the restoration of historic musical instruments (Barclay, 2005; Barnes, 1980; O'Brien, 2008), and a few collections have declared moratoriums on restoring their instruments because they believe that virtually any form of intervention destroys historical evidence. This policy is a reaction to many restorations, now considered ruinous, that were carried out in the course of the early music revival. At the other end of the spectrum are musical instrument departments that are called upon (or perceive it to be their responsibility) to serve as entertainment or fundraising divisions of their museums. Some of the most active departments do not even employ a staff conservator but instead rely upon musicians, musical instrument makers, and outside repairmen to maintain their instruments in playing condition. In such cases the standards of practice as defined in the bylaws of the American Institute of Conservation, for example, may be unknown to these individuals and therefore not observed. Despite their training and special expertise, staff conservators often exert very little authority within the museum hierarchy, and though they may be consulted as a matter of procedure, it is the curator, and not the conservator, who decides which objects are to be restored and how they will be used.

It is assumed that there is rhyme and reason behind the formation of collections, and that museums acquire objects on the basis of their relevance to the collection, historical importance, quality, and condition. However, most musical instrument collections gratefully accept virtually anything as a gift, and often such instruments arrive, and remain, in disrepair. Anyone who has ventured behind the scenes of the world's major collections has certainly been appalled both by the condition of many thousands of instruments crammed in their storerooms – dented and heavily corroded brass instruments; tarnished silver flutes; keyboard instruments with torn-off lids and missing everything from legs to ornamental hardware; stringed instruments lacking pegs, bridges, and strings – and by, in general, evidence of inadequate climate control and protection from dust, dirt, woodworm, and other pests, as well as the aftereffects of floods and burst water pipes. Faced with such a discouraging situation, it is surprising that some of the profession's most respected figures are so vehemently opposed to any and all forms of intervention. Certainly, much can be done to improve the appearance of many of these neglected instruments, and perhaps make them playable, with minimal or no compromise to their historical integrity. In general, I neither advocate nor disapprove of the restoration of historic musical instruments; rather, I believe that each instrument and proposed treatment must be considered on a case-by-case basis with consideration given to the requirements and needs of the collection or owner. The only requirement that I would insist upon is that such work be carried out by technically skilled and historically informed individuals who are cognizant of their ethical responsibility to preserve original material and respectful of the maker's concepts.

While this manual provides detailed instructions for employing the most up-to-date techniques, it also advocates a number of traditional procedures and materials that remain relevant and in some cases are preferable to their modern counterparts. For example, many of the modern synthetic materials that are widely employed in conservation work (such as the ubiquitous acrylic adhesives and varnishes) are often inappropriate, ineffective, and potentially harmful when used in musical instrument conservation, whereas a traditional material such as animal-hide glue is not only eternally "reversible" but ideally suited to certain tasks. Furthermore, some of the mainstays of modern conservation practice, such as the consolidation, stabilization, and impregnation of wood with synthetic resins and other substances, should be generally avoided in musical instrument work because they alter an instrument's acoustical and playing characteristics, and are, in fact, irreversible.

Throughout this work, I have retained the units of weight and measurement used in many of the original sources rather than converting everything into metric, as the fundamental proportions are often more easily recognized in their original units. For convenience, I have provided a table of equivalents (see MEASUREMENT SYSTEM CONVERSION). The references listed at the end of each section include the sources of the information found in those sections as well as recommendations for further reading.

Unless otherwise noted, all photographs and the conservation treatments represented in them are the work of the author.

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A

Acoustics (see also INTERVALS, MERSENNE'S LAW, TUNING AND TEMPERAMENT)

Acoustics, or the science of sound, is a broad subject that includes the study of vibration, noise abatement, room and architectural acoustics, the physiology and perception of sound, speech and hearing, the processes of recording and reproducing sound, sound reinforcement, hydrophonics, and ultrasonics, as well as musical acoustics. So-called "acoustical" musical instruments produce sound by causing bodies or columns of air, strings, rods, bars, reeds, plates, and membranes to vibrate at certain frequencies.

The science of musical acoustics advanced significantly in the twentieth century with the development of recording equipment, audio spectrum analyzers, high-speed computers, hologram interferometry, and the application of mathematical techniques such as Fourier transform, constant *Q* transform, and finite element analysis. Though modern science has increased our fundamental understanding of how musical instruments function, it has unfortunately provided little practical benefit to musical instrument makers, and the old, empirical "cut and try" approach still plays a large part in the design, construction, and adjustment of musical instruments. As conservators, our task is not to improve upon instruments but rather to preserve their characteristics; nevertheless, many of the published studies and readily available instrumentation, such as electronic tuning devices, frequency counters, and audio spectrum analyzers, can be used to optimize their setup and adjustment. For example, when replacing a missing fortepiano hammer, one might employ a Lucchi meter (an electronic device that measures the speed of sound in wood, which is proportional to its stiffness) in order to select a piece of wood that matches the properties of the neighboring hammers.

Acoustical knowledge up through the eighteenth century

The science of acoustics may be thought to have originated with the ancient Greek philosopher Pythagoras (*c.*570–497 BC), who is said to have discovered that simple arithmetic ratios underlie musical intervals while listening to the sounds produced by blacksmith's hammers striking an anvil (that is, hammers whose weights were in the ratio of 2:1 produced sounds an octave apart, and hammers whose weights were in the ratio of 2:3 produced sounds a fifth apart). The Roman philosopher Boethius (480–524 CE) maintained that Pythagoras invented the monochord for studying the pitch of vibrating strings. Although this assertion has been disputed, by Boethius's time the monochord was widely used to study musical intervals by physically dividing the length of its string into various ratios and proportions (a ratio is the relationship between two quantities; a proportion is the relationship among three or more quantities, such as the equality of two ratios). Thus, Pythagoras and his followers established a clear link between musical intervals, mathematics, and geometry.

The Roman architect, engineer, and author of *The Ten Books on Architecture* Marcus Vitruvius Pollio advised architects to study music because of its underlying mathematical rigor. He also described the design and construction of ancient theaters, which employed tuned niches and resonant bronze vessels positioned around the circumference of the stage to augment the voice of the speakers. These were "arranged with a view to musical concords or harmony, and apportioned in the compass of the fourth, the fifth, and the octave, and so on up to the double octave, in such a way that when the voice of an actor falls in unison with any of them its power is increased, and it reaches the ears of the audience with greater clearness and sweetness." The use of air resonance to accentuate certain frequencies remains critical in the design of musical instruments. Optimally, the air resonance of an instrument's body should lie at or below the lowest frequency that can be produced by the instrument. For example, at Baroque A=415 pitch, a violin's G string vibrates at around 185 Hz, though a typical violin body's air resonance is around 290 Hz, which is close to a

Baroque d♯[1]. Thus, the air resonance of a violin begins to support its D, or second string. The earliest violins were made with only three strings; the G string was evidently an afterthought added around the middle of the sixteenth century, though the body of the instrument was never enlarged to accommodate it acoustically (Pollens, 2011).

In the sixteenth century the astronomer Galileo Galilei (1564–1642, the son of the lutenist and music theorist Vincenzo Galilei, 1520–1591) demonstrated that a sounding body produces ripples, or vibrations, when placed in water, but the precise number of vibrations per second in musical pitches was not then known. It was not until the 1660s that the French mathematician, philosopher, and music theorist Marin Mersenne (1588–1648) conducted experiments that enabled him to estimate the number of vibrations per second produced by low-pitched organ pipes by comparing their pitches with measurable vibrations in strings that were approximately 18 feet in length. He made the first measurements of the speed of sound by timing the difference between a gun's muzzle flash and its audible report at a measured distance. Mersenne also codified the relationship between string length, string tension, and pitch (see MERSENNE'S LAW). In writing about the selection and testing of strings in his *Harmonie universelle* (1636), Mersenne advocated the tuning of soundboards and air resonances of instruments to the pitch of their strings:

> It is enough to conclude that one will know which string sounds better than all the others on a proposed instrument when one knows the pitch of the table [soundboard] of the instrument, for that [string] will produce the best sound which, having the requisite length and tension, will be in unison with the said table, and if one finds many of the same thickness, length, and tension, which are in unison, the one with more uniform parts will sound the better; and if all the parts of some are as even as those of the others, they will sound equally.
>
> If those who make as great a thing of a good string as of the whole instrument take the trouble of finding the tone of the soundboard, I feel that they will have some satisfaction in comparing these two unisons and they will admit that the unison is the most powerful and the most excellent of all the consonances, as I have proved in the Books of Theory, since the union made of the tone of the table with that of the string produces an exquisite harmony, for it builds almost a single tone from the two. Still, I do not wish to reject the other reasons that can be given for the goodness of strings, for example, that the air enclosed in the body of the instrument must be very well proportioned to the length of the string, which ought to find not too great a quantity of air to stir up.

The simplest means of determining the fundamental pitch of a musical instrument soundboard is to tap it and listen to the sound it produces. It should be noted that the actual frequencies of musical tones were not known until around 1700, when the French physicist Joseph Sauveur (1653–1716) employed the beat rate (which represents the difference in pitch between two notes) between two low-pitched organ pipes whose interval ratio was known to calculate the actual number of vibrations produced by both pipes. (For example, if we know that the ratio between two notes is 17:18, and that two pipes tuned to those notes beat at 5 cycles per second, then the pitch of the higher-pitched pipe can be obtained by multiplying the beat rate by 18, which gives 90 cycles per second, while the lower-pitched pipe is calculated by multiplying 90 by 17/18, or 85 cycles per second.) In Stradivari's day, violin makers may have tap-tested the front and back plates of their instruments, but it was not until 100 years after the death of Stradivari that the French physicist Félix Savart (1791–1841) wrote that the disassembled front and back plates of fine violins by Stradivari, Guarneri, and Vuillaume (the latter a contemporary of Savart) vibrated at particular frequencies when lightly tapped with a finger. Savart determined that the front plate of a Stradivari violin vibrated at 512 Hz (the equivalent of c^2 at A=430 Hz) and that the back plate was tuned about a half or whole tone higher. However, violin makers and theorists have not always agreed upon the optimal tap tones of violin plates. For example, the Russian theorist Anatoli Leman (1853–1913) notes in *The Acoustics of the Violin* (1903) that violin plates exhibit three tap tones located at the upper, middle, and lower sections of the front and back plates, and he proposed that the front plate's tap tones should be tuned to F, D, and B, while the back plate's tap tones should be tuned to G, E, and C♯. Mersenne's observations about the sympathetic vibration between tuned strings, wood, and air volume were published just before Stradivari was born, so it is possible that Stradivari used some method (perhaps tap tones) to establish the resonant pitches of the front and back plates of his instruments.

It is important to consider that pitch was not standardized in Stradivari's time, though in most locales it was generally somewhere between a whole and a half step lower than it is today (see PITCH). With higher pitch, there is more string tension as well as downward pressure exerted by the bridge on the front plate, which has the effect of raising the front plate's resonant frequency. However, most instruments made during Stradivari's time were later "regraduated" (a euphemistic term for "thinning"). This was primarily a timbre-altering procedure that was first carried out on a large scale in the third quarter of the eighteenth century and continues to this day. Though the thinning of front and back plates has the general effect of lowering their resonant frequencies, it does not fully compensate for the moderate rise in resonant frequency caused by the increased downward pressure on the top, but compounds the discrepancy between the plates' resonant frequencies and present pitch standards. Thus, if Stradivari somehow optimized the structure and resonances of his instruments to conform to pitch standards then in vogue, his instruments are not functioning optimally today (unless later restorers somehow surmised Stradivari's plate tuning principle and retuned the plates of his instruments to accommodate later pitch and string tension).

Mersenne also makes reference to the air resonance of an instrument's body (which is derived from the body outline, rib height, and f-hole dimensions). Though the rib structures of most of Stradivari's violins and violas have been reduced by a millimeter or two as a result of shrinkage and repair, many of his cellos have had their ribs deliberately reduced in height and their entire bodies cut down in length and width, often by as much as several centimeters, in an effort to render them more comfortable to play. With violins and violas, the rise in air resonance resulting from the slight reduction in body volume is not significant, but with cut-down cellos, the lowest notes are certainly affected.

The German historian and music theorist Athanasius Kircher (1601–1680) wrote extensively on the reflection, spreading, and compression of sound. An engraving in his *Phonurgia nova* (Kempten, 1673) illustrates the phenomenon of an ellipsoidal "whispering room." As an ellipse has two foci, if someone whispers at one focus, the sound will be clearly heard by someone else standing at the other. Kircher's use of ray tracing to explain the projection of sound may have stemmed from contemporary theories on the nature of light and optics that used similar diagrams to explain how light rays and images were brought into focus by lenses.

Francis Bacon also makes several references to room acoustics in his *Sylva Sylvarum* (1627) and describes the acoustical properties of an architectural beam that is comparable to a violin's soundpost:

> I remember in Trinity College in Cambridge, there was an upper chamber, which being thought weak in the roof . . . was supported by a pillar of iron of the bigness of one's arm in the midst of the chamber; which if you had struck, it would make a little flat noise in the room where it was struck, but it would make a great bomb [boom?] in the chamber beneath.

Bacon's *Sylva Sylvarum* includes a number of general remarks on the acoustical properties of musical instruments. For example, he describes the interaction between the "knot" (soundboard rose), the "board" (soundboard), and "concave underneath" (the volume of air enclosed by the instrument):

> The strings of a lute, or viol, or virginals, do give a far greater sound, by reason of the knot and board, and concave underneath, than if there were nothing but only the flat of a board, without that hollow and knot, to let in the upper air into the lower. The cause is the communication of the upper air with the lower, and penning of both from expense of dispersing.
>
> An Irish harp hath open air on both sides of the strings: and it hath the concave or belly not along the strings, but at the end of the strings. It maketh a more resounding sound than a bandora, orpharion, or citter, which have likewise wire strings. I judge the cause to be, for that open air on both sides helpeth, so that there be a concave; which is therefore best placed at the end.

> In a virginal, when the lid is down, it maketh a more exile sound than when the lid is open. The cause is, for that all shutting in of air, where there is no competent vent, dampeth the sound: which maintaineth likewise the former instance; for the belly of the lute or viol doth pen the air somewhat.
>
> The harp hath the concave not along the strings, but across the strings; and no instrument hath the sound so melting and prolonged as the Irish harp. So as I suppose, that if a virginal were made with a double concave, the one all the length, as the virginal hath, the other at the end of the strings, as the harp hath; it must needs make the sound perfecter, and not so shallow and jarring. You may try it without any sound-board along, but only harp-wise at one end of the strings; or lastly, with a double concave, at each end of the strings one.

Bacon also addresses the phenomenon of sympathetic vibration and the phenomenon as it applies to the viola d'amore:

> There is a common observation, that if a lute or viol be laid upon the back, with a small straw upon one of the strings, and another lute or viol be laid by it; and in the other lute or viol the unison to that string be strucken, it will make the string move, which will appear both to the eye, and by the straw's falling off. The like will be, if the diapason or eighth to that string be stricken, either in the same lute or viol, or in others lying by: but in none of these there is any report of sound that can be discerned, but only motion.
>
> It was devised, that a viol should have a lay of wire-strings below, as close to the belly as a lute, and then the strings of guts mounted upon a bridge as in ordinary viols: to the end, that by this means, the upper strings stricken should make the lower resound by sympathy, and so make the music the better; which if it be to purpose, then sympathy worketh as well by report of sound as by motion.

In his *Philosophical Essay of Music Directed to a Friend* (London, 1677), Francis North includes a section headed "How tones are produced, and of assistances to the sound by instruments," in which he comments on the contribution to the production of sound made by the sides of an instrument, the influence of mass on the bridge, and the function of the soundpost in the violin:

> In violins and harpsichords the tones are made wholly by the vibrating strings, but the frame of the instrument adds much to the sound: for such strings vibrating upon a flat rough board would yield but a faint and pitifull sound.
>
> The help that instruments give to the sound, is by reason that their sides tremble and comply with any sound, and strike the air in the same measure that the vibrations of the musick are, and so considerably increase the sound.
>
> This trembling is chiefly occasioned by the continuity of the side of the instrument with the vibrating string; therefore if the bridge of a violin be loaded with lead, the sound will be damp; and if there be not a stick called the soundpost to promote the continuity between the back and belly of the instrument, the sound will not be brisk and sprightly.
>
> Such a continuity to the nerve of hearing will cause a sense of sound to a man that hath stopped his ears, if he will hold a stick that touches the sounding instrument between his teeth.
>
> The sound of itself without such continuity would occasion some trembling, as may be seen by the moving the unison strings in the instance before given; but this is not considerable in respect of the other, though it be all the assistance that the structure of a chamber can give to musick, except what is by way of eccho.
>
> This tremble of the instrument changes with every new sound; the spring of the sides of the instrument standing indifferent to take any measure, receives a new impression: but a vibrating string can take no measure but according to its tension.
>
> Therefore instruments that have nothing to stop the sounding strings make an intolerable jangle to one that stands near, as bells to one that is in the steeple, and hears the continuing sound of dissonant tones; such is the dulcimer; but the harpsichord that hath rags upon the jacks by which the vibration of the string is staid, gives no disturbance by the sonorousness of the

> instrument, for that continues not the sound after the vibrations determined, and another tone struck, but changes and complies with the new sound.

North also discusses the properties of strings and the phenomenon of harmonics:

> A perfect string produces a clear sound by entire and equall vibrations, there being no inequality to hinder the motion from being uniform from one end to the other, according to the laws of a pendulum: but if the string hath any inequality toward one end, it will yield a jarring and distracted sound; for the resistances are not only at the ends of the string, but there are cross tugges that alter the course of the vibrations; which is evident in the manner whereby musicians try if their string be true: for if the string be true the vibrations will appear as a clear filme; but they will appear with cross threads if the string be false.
>
> It is common experience, that a great string struck near the bridge with a bow where the rosin takes but small hold, will whistle and break into chords above; which it were struck by the thumb that removes it out of its place, would give the true tone.
>
> The trumpet marine that sounds wholly upon such breaks, is a large and long monochord played on by a bow near the end, which causes the string to break into shrill notes. The removing the thumb that stops upon the string gives measure to these breaks, and consequently directs the tone to be produced. The jar at the bridge takes the same measure and makes the sound loud, in imitation of a trumpet, which otherwise would be like a whistle or pipe.

In 1724 the French mathematician Pierre-Louis de Maupertuis presented a paper to the French Royal Academy entitled "Sur la forme des instruments de musique," which explores how an instrument's shape affects the quality of sound it produces. In this paper, he proposes that wood fibers act like vibrating reeds, and that these reeds resonate at discrete frequencies according to their length. Maupertuis suggests that the shape of the violin's front plate and the position of the sound holes create a wide variety of reed lengths, permitting the violin to resonate at many frequencies, and he proposes that violins might benefit from being broken apart, thereby "freeing up the reeds," and then gluing them back together.

When an instrument maker continually experiments with new designs, it is clear that he has not come upon the ideal proportions and shapes by scientific means but is searching for a better means of achieving the tonal qualities he desires. Stradivari's wood forms provide ample evidence of this empirical approach. Four of his forms are graded in size and are inscribed, from largest to smallest, P, S, T, and Q, which likely stand for *prima* (first), *seconda* (second), *terza* (third), and *quarta* (fourth). Two of them, P and S, are roughly duplicated (see below), and the S forms have a slightly longer counterpart marked SL (probably an abbreviation for *seconda lunga*, or second, long). A form marked MB (possibly *modello buono*, or good model) is thought to be the earliest form and is said to be dimensionally similar in outline to violins made by Nicolo Amati. The forms marked P, PG (*prima grande*, or first, large), and G (*grande*, or large) are similar, though not identical in shape, and were used to make his esteemed grand-pattern violins. Two forms having slightly different dimensions are inscribed with the letter B, and the longer of these appears to have been used to construct the so-called "long-pattern" violins that were made primarily in the 1690s. This form is similar to the SL form, which he made the previous year (see dates below).

How important is the outline of a violin with regard to its tonal qualities? Clearly, Stradivari thought it was a critical aspect of design because he continually experimented and modified the size and shape of his violins, violas, and cellos. With the cello, he gradually reduced its overall dimensions during the course of his career, no doubt because of the gradual adoption of metal overwound strings (invented around 1660), which enabled him to shorten the string length and thus reduce the size of the instrument. After Stradivari completed the set of five instruments for the Medici court in 1690, he redesigned his contralto viola form by making it narrower, though retaining the original length. In a sense, this slimmed-down viola was a better visual and perhaps acoustical match for the elegant long-pattern violins that came into production around that time. Though the long-pattern violin was all but discontinued around 1700, Stradivari continued to use the slender 1690 contralto viola form for the rest of his life. With the demise of the long-pattern violin, he reverted to his earlier P form and to the PG and G forms derived from it that were used to make the "Alard" (1715), "Soil" (1714), and "Sarasate" (1724) violins. This variety of shapes and sizes, in some cases going in one direction (as in the cello and viola) or wavering between one basic design and another (in the case of the violin) is indicative of Stradivari's restless experimentation, an approach that typifies the work of many important historic makers.

Stradivari also experimented with arching, which is perhaps more critical to the tone of an instrument than the outline. His early instruments, in keeping with the work of his Cremonese predecessors, are highly arched, while his long-pattern and golden period instruments exhibit the flatter arching that contributed to a more penetrating tone. Violins made in his later years surprisingly exhibit a return to higher arching.

In the 1920s a cache of documents came to light in Italy that ostensibly included the workshop notebook of Antonio Stradivari. In court proceedings, these documents were declared fraudulent, and one of the perpetrators was imprisoned. It is unclear whether a manuscript entitled *Librem Segreti de Butteghа* is the workshop notebook that is mentioned in the inventory of these documents (see Peluzzi, 1978; Dipper, 2013). This manuscript is said to have passed into the hands of a book collector named Federico Patétta, who allegedly donated it to the Vatican; however, it is not currently listed in the Vatican's catalog and Vatican officials deny possession of it. The author's impression of this manuscript, based upon the single page that has been photographically reproduced by Peluzzi and Dipper, is that it is not in Stradivari's hand. Furthermore, aspects would appear to be derived from Antonio Bagatella's *Regole per la costruzione de' violini, viole, violoncelli e violoni: memoria presentata alla R. Accademia di Sienze Lettere et Arti di Padova*, which was first published in 1786 and went through innumerable editions into the twentieth century. The manuscript ostensibly provides geometric techniques for establishing the general dimensions, arching, and thicknesses of the violin's plates; however, its instructions are ambiguous at best. In all likelihood the *Librem Segreti*, if it exists or ever existed, would appear to be a twentieth-century fabrication and unworthy of further consideration.

One eighteenth-century document that does shed some light on the thought processes of contemporary makers regarding violin acoustics and design is a manuscript dated 1786 by the Bolognese violin maker Giovanni Antonio Marchi (1727–1807), which is preserved in the Biblioteca Comunale in Bologna (Ms. No. B3195). A transcription and English translation of this important and insightful document was published by Roberto Regazzi (1986). Another valuable work is the Abbé Sibire's *La Chélonomie ou le parfait luthier* (published in Paris in 1806 and reissued in Brussels in 1823), which is a treatise on violin making derived from the author's communication with the violin maker Nicolas Lupot (1758–1824), who worked in Orléans between 1768 and 1794 and subsequently in Paris until his death.

Acoustical science in the nineteenth century

Charles Hutton's *Recreations in Mathematics and Natural Philosophy* (1803) presents a summary of acoustical knowledge at the beginning of the nineteenth century. This work is a translation and enlargement of Jean-Étienne Montucla's 1778 edition of Jacques Ozanam's 1694 work entitled *Recreations Mathématiques et Physiques*. Montucla (1725–1799) and Ozanam (1640–1718) were prominent French mathematicians, while Hutton was an English mathematician and Fellow of the Royal Society. Hutton's edition characterizes sound as "nothing else but the vibration of the particles of the air, occasioned either by some sudden agitation of a certain mass of the atmosphere violently compressed or expanded, or by the communication of the vibration of the minute parts of a hard and elastic body," and he correctly notes that sound is not propagated in a vacuum. Regarding the velocity of sound, he cites numerous experiments that demonstrated that sound travels at a rate of 1172 Parisian feet per second, though he indicates that Gassendus (Pierre Gassendi; French astronomer and physicist, 1592–1655) measured its velocity at 1473 feet per second, while Mersenne found it to be 1474 feet per second, Duhamel (Jean Baptiste Du Hamel; French astronomer and philosopher, 1646–1706) measured it at 1338 feet per second, Isaac Newton at 968 feet per second, while Derham (William Derham; English natural philosopher, 1657–1735), Flamsteed (John Flamsteed; English astronomer, 1646–1719), and Halley (Edmond Halley; English astronomer, 1656–1742) concurred that it was 1142 feet per second, which Hutton acknowledges to be the generally adopted figure in England at the time of his writing (today, the speed of sound in dry air at 20°C is reckoned to be 343.2 m/s or 1,126 feet per second). Hutton correctly disputed Derham's experiment that ostensibly demonstrated that the temperature of a body of air does not affect the speed of sound traveling through it. There are also discussions regarding the general propagation of sound and the phenomenon of echoes, and a short chapter devoted to Ernst Chladni's discovery of vibration patterns formed by sand sprinkled on plates of various shapes that were made to vibrate through the action of a bow, which he published in 1787.

The nineteenth century witnessed important advances in theoretical acoustics with the work of such physicists as Lord Rayleigh (John William Strutt; 1842–1919), author of *The Theory of Sound* (vol. I, 1877; vol. II, 1878) and John Tyndall (1820–1893), author of *Sound* (1867). These treatises introduced rigorous mathematical analyses in the study of the vibrations of strings, membranes, and rigid plates of various shapes, as well as of gases enclosed in open and closed tubes and other vessels, though it is unlikely that instrument makers have ever been influenced by these works as they require facility with algebra, trigonometry, and calculus.

The German physicist Hermann von Helmholtz (1821–1894) studied sound in the laboratory. In his monumental publication *Die Lehre von den Tonempfindungen als physiologische Grundlage für die Theorie der Musik* (1863), he describes how small tuned vessels that resonate at specific frequencies (termed "Helmholtz resonators") can be used to analyze the frequencies of overtones present in musical sounds, and his experiments with a cleverly designed "vibration microscope" revealed the jagged waveform of bowed strings caused by the grip and release of the string by the "sticky" rosin applied to the bow's hair. He also explored the field of psychoacoustics, or the perception of sound. August Kundt succeeded Helmholtz as the director of the Berlin Physical Institute in 1888. Among his achievements was the 1866 invention of the "Kundt's tube," a glass tube containing powdered cork dust or lycopodium (the spores of certain species of moss) that settled at the nodal points of sound waves that were introduced into the tube. Because the spaces between the nodes could be physically measured, the actual wavelengths of sounds could be determined. If the frequency of a sound wave was known, the speed of sound could then be calculated by multiplying the wavelength by the frequency.

Though makers continued to develop and refine their instruments through the nineteenth century, they tended to do so by empirical means rather than by use of the laws of physics and mathematical calculation. For example, though the position of tone holes in a woodwind instrument can be calculated mathematically, these calculations are far more complex than those required to position the frets of a lute or the tangents of a fretted clavichord, for example, and were undoubtedly beyond the capacity of most makers. The noted flute maker Theobald Boehm (1794–1881), who is credited with the development of the cylindrical bore and "parabolic" head joint around 1847, later described how he established the position of the flute's tone holes in *Die Flöte und das Flötenspiel* (1871). While he states that "one must avail himself of the help of theory," he admits that:

> I had a flute made with movable holes, and was thus enabled to adjust all the tones higher or lower at pleasure. In this way I could easily determine the best positions of the upper three small holes, but it was not possible to determine the tuning of the other tones as perfectly as I desired; for in endeavoring to produce an entire true scale in one key, the tones were always thrown out of the proportions of the equal temperament, without which the best possible tuning of wind instruments with tone-holes cannot be obtained.

Boehm continues:

> I made a tube in which all the twelve tone sections could be taken off and again put together, and which was provided with a sliding joint in the upper part of the tube to correct for any defects in tuning. To establish the optimal diameter of the tubing, I constructed many thin, hard-drawn tubes of brass upon which the fundamental tone C, and also higher notes, could be produced