The Invention and Evolution of the Piano

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The piano was invented 300 years ago — and the instrument has changed considerably since then.

Introduction

The piano is a fascinating instrument with an interesting history. The inventor of the piano was Bartolomeo Cristofori, a gifted and creative maker of keyboard instruments, who spent his most productive years in the employ of the Medici family in Florence (Pollens, 1995; Good, 2002). Cristofori lived at essentially the same time as the celebrated luthier, Antonio Stradivari, and both worked in what is now northern Italy (although there is no evidence that they ever met).

A number of Cristofori's instruments can be found in museums around the world, including harpsichords and other string instruments, as well as the three oldest known pianos. These pianos were built in the 1720s and can be seen in the Metropolitan Museum of Art in New York City, the Museo Nationale degli Strumenti Musicali in Rome (which houses the piano in **Figure 1**), and the Musikinstrumenten-Museum in Leipzig. These instruments resemble in a general way the Italian-style harpsichords of that period, but with the incorporation of hammers and what is now known as the piano "action." The action is the mechanical mechanism that links each hammer to a key lever, and it is this mechanism that gives the piano its unique capabilities, setting it apart from its forerunner, the harpsichord. The piano in **Figure 1** has a range of 4 octaves (49 notes), from two octaves below middle C to two octaves above. It is composed almost entirely of wood (except for the strings and a few miscellaneous parts), with each string held at a tension of about 65 N. The Cristofori instruments contrast with the modern grand piano (**Figure 2**), which has nearly twice the range (88 notes covering 7⅓ octaves), with strings held at tensions of more than 600 N and a massive iron plate to allow the case to withstand the much greater force from the strings.

Figure 1*. Piano made by Bartolomeo Cristofori in approximately 1722. This piano is in the Museo Nationale degli Strumenti Musicali in Rome. Image from Wikimedia Commons (wikimedia.org/wikipedia/commons/3/32/Piano_forte_Cristofori_1722.JPG).*

Cristofori called his instrument an *"Arpicembalo del piano e forte"* which translates from Italian roughly as "harp-harpsichord with soft and loud" (Pollens, 1995). Over time the name has been shortened and rearranged to "pianoforte," "fortepi-

Figure 2. Top view of a Steinway model M piano owned by the author. From Giordano (2010) with permission from Oxford University Press.

ano," and (eventually) "piano." The motivation for the name was that the new instrument could play a note either softly or loudly, depending on the intent of the performer. The desire to be able to change the loudness from one note to the next was the prime motivation for the invention of the piano. Such control was not possible with the other main keyboard instruments of the day (the harpsichord and organ) and was quickly exploited by composers such as Mozart in the transition from the baroque to the classical era. This capability was made possible by Cristofori's invention of the piano action.

The history of the piano action and how it was motivated by other non-keyboard instruments has been described in many discussions of the piano (e.g., Pollens, 1995; Good, 2002). In this article I focus on a different part of the piano story that has gotten less attention, namely, how the piano has evolved through various stages from the instrument of three hundred years ago to the modern piano that we have today. We see that this evolution was driven by a combination of factors, including the demands of composers and musicians, advances in the available materials, and the properties of the human auditory system. As acousticians, we know that a sound can convey information that is difficult to describe in words. For that reason, the online version of this article contains sound files with which you can listen to the differences between early pianos and their modern counterparts. The sound files along with a description of the instruments used in the different performances can be found at http://acousticstoday.org/the-invention-and-evolution-of-the-piano/.

General Design of a Piano

In order to appreciate how the piano has changed over time, it is useful to review the general design of the instrument. A schematic drawing showing the components of a single note is given in **Figure 3**. The player presses on a key that is one end of a lever that sets the action into motion. We have not attempted to show the action in any detail in **Figure 3**; it is a complicated system of levers and axles that transmits the motion of the key lever to the hammer (Giordano, 2010). In normal playing, the piano hammer is propelled toward the string at speeds of typically 1-4 m/s, corresponding to notes ranging from pianissimo to fortissimo. The hammer is released from the action just before it collides with the string, traveling freely when it collides and then rebounds from the string. The use of a hammer to excite the string was what differentiated the piano from other keyboard instruments of the era, most notably the harpsichord.

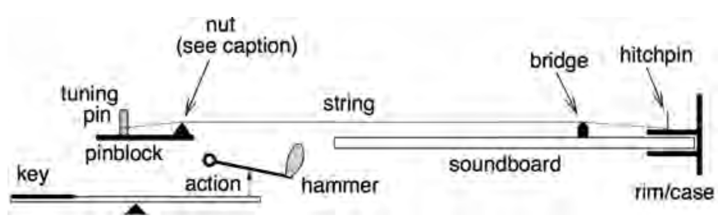


Figure 3. Schematic (and simplified) design of the components that produce a single note. The vibrating length of the string extends from the nut to the bridge. The nut is often replaced by a different structure (the agraffe or capo tastro bar). From Giordano (2010) with permission from Oxford University Press.

The design of the harpsichord is similar to that shown in **Figure 3**, except with the action and hammer replaced by a plucking mechanism. We won't consider that aspect of the harpsichord in any detail here, other than to note that the "amplitude" of the pluck was independent of how rapidly the harpsichord key was depressed (Good, 2002). Hence the player could not change the volume of a tone by pressing gently or forcefully. This *was* possible with the piano, due to the way the action propelled the hammer. Hence, Cristofori's invention of the action was crucial for the success of the piano and was the reason that it soon displaced the harpsichord as the most popular keyboard instrument.

Figure 3 shows several other components of the piano. The string is the vibrating element that determines the frequencies that will be present in the final tone. Most notes involve more than one string, as we will explain shortly. In a modern piano, strings in the midrange and above are composed of steel with a diameter of about 1 mm. The strings in the bass range have a more complicated design that we will describe below. The strings run from a pin (called a hitchpin) at the back of the piano, pass over a bridge glued to the soundboard and over a "nut" or other structure, with the strings's end wound around a tuning pin at the front of the piano (**Figure 3**). The force of the string is transmitted through the bridge to the soundboard, setting the soundboard into motion and producing the sound of the instrument. The tuning pin allows the tension in the string to be adjusted to achieve the desired fundamental frequency for the string. In the next sections I describe how a number of the components in **Figure 3** were constructed in Cristofori's pianos and how they have changed as the instrument evolved into the modern piano.

How Many Notes Should a Piano Have?

The Cristofori piano in **Figure 1** has a 4-octave range, with the fundamental frequencies of the notes varying from about 65 Hz to 1,048 Hz (assuming the now standard pitch of 440 Hz for the A above middle C). However, it did not take long for this range to expand. Much of the baroque keyboard music of composers such as Bach and Scarlatti can fit in 4 octaves, but later composers wanted more. The range expanded to 5 octaves in the late 1700s (Mozart), then to 6 octaves by the very early 1800s (Beethoven), to 7 octaves by about 1840, and the 7⅓ octave range we have today arrived around 1860. The piano's range thus nearly doubled in less than a century, but it has not changed further in the 150 years since then. Technologically, there is no fundamental limit to this range. We also know that human hearing extends over a broader range, which leads to the question: "Why don't we have more notes?"

The lowest note on a modern piano has a fundamental frequency of 27.5 Hz and for the highest note it is 4,186 Hz. (These are the ideal frequencies of these notes. For real pianos these frequencies deviate slightly from these ideal values; Giordano, 2010.) Human hearing is certainly able to detect sounds well beyond these frequencies, both lower and higher. However, the way such tones are perceived is very interesting. Sounds with frequencies much below about 25 Hz are perceived as rapid clicks rather than as a typical musical tone (Plack and Oxenham, 2005). Such clicking sounds are probably of little use musically, so there is no value in extending the piano's range to lower pitches.

Human auditory perception at frequencies above about 5,000 Hz is limited in a different way. The relationship between two or more tones is used often in music, producing musical intervals and chords that are pleasing or provide a particular musical effect. It turns out that humans are not able to perceive such tonal relations at frequencies above about 5,000 Hz (Plack and Oxenham, 2005). That is, while tones with fundamental frequencies of, say, 4,000 Hz and 8,000 Hz can both be heard, and we can tell that the pitch of one tone is higher than the pitch of the other, most people are not able to judge that they are an octave apart. Since tones above about 5,000 Hz cannot be used to form musical intervals, they are not much use to a composer. In this way, human perception has determined the upper limit for the notes of a piano.

Piano Shape and Design of the Strings

All three of the existing Cristofori pianos have been restored multiple times, although much is not certain about their original state. It is believed that they were originally strung with brass wire in the bass and iron wire in the midrange and treble, and that the string diameter increased somewhat in going from the treble to the bass. If we assume for simplicity that all the strings in the piano in **Figure 1** have exactly the same diameter, density, and tension (which would be only a very rough assumption for the string diameters), then the length of the vibrating portion of the string should increase by precisely a factor of two as one moves an octave toward the bass. For the 4-octave piano in **Figure 1** this means that the string length of the lowest bass string would be 16 times longer than the highest treble string. Since the strings must fit inside the case, this variation in length determines the shape of the piano, and with our slightly idealized assumptions, we arrive at the familiar "wing" shape of a grand piano. Indeed, the Cristofori pianos do have this shape and do have string lengths that vary (approximately) by a factor of 2 per octave within a case that is about 2 m from front to back on the bass (left) end.

This simple scaling of the string length is fine for a 4-octave instrument but leads to problems for a modern grand piano. With the lowest note of a modern piano being more than an octave below the lowest note on a Cristofori piano, scaling the string lengths by a factor of 2 per octave would produce a piano more than 5 m long. This is obviously too big to be practical, a problem that was solved by redesigning the strings. The redesign involved two changes, one simple and one not so simple. The first change was to increase the string diameter as one moves from the treble into the bass. For the modern piano in **Figure 2**, the string diameter varies from about 0.8 mm in the extreme treble to 1.0 mm for the strings an octave below middle C. If the tension is held fixed, this allows the strings to be shortened by nearly 50%, which helps but does not solve the problem completely. One might think that simply increasing the diameter by even more could be possible, but such thick strings lead to a different problem.

The vibrational frequencies of an ideal flexible string form a perfectly harmonic relationship, and this relationship leads to a musical tone with components that are harmonic. Real piano strings have a small amount of stiffness that adds a restoring force for the string due to the bending stiffness, causing the vibrational frequencies to deviate from an ideal harmonic series. For this reason the vibrational modes of a stiff string are called "partials" instead of harmonics. It turns out that increasing the diameter of steel string to values greater than about 1.2 mm would make the deviations from harmonicity so large as to result in unpleasing tones. The upshot is that piano designers needed a different way to increase the effective string diameter without causing a significant increase in the stiffness.

The solution to increasing the effective string diameter is to use what are called wound strings (**Figure 4**) in which a copper wire is wound around a central steel core. The diameter of the core is usually about 1 mm, while the diameter of the winding typically varies from about 0.5 mm to more than 1 mm as one moves farther into the bass region (and some pianos have bass strings with two sets of windings). The copper windings add mass to the string without an appreciable increase in stiffness, so much shorter strings can be used in the bass than would otherwise be possible. In this way the length of a modern grand piano is typically around 2 m (**Figure 2**) and is rarely more than the 3 m of a concert grand piano. This also means that the case deviates from the wing shape and is "rounded off" on the bass end (also visible in **Figure 2**).

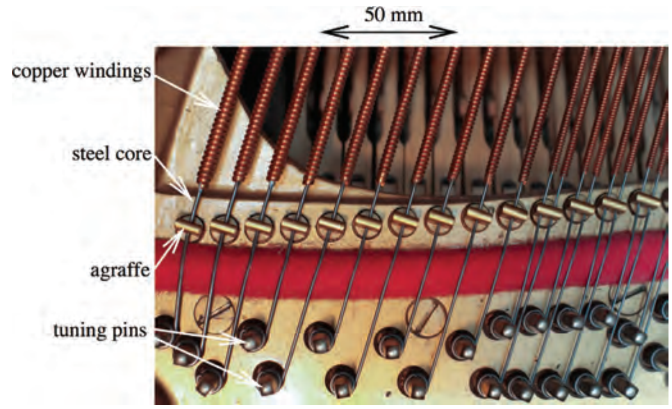


*Figure 4. Expanded view of the lower left corner of **Figure 2**, showing the ends of the first few bass strings. These strings consist of copper wire wound around a central steel core. The agraffe plays the role of the nut in **Figure 3**. From Giordano (2010) with permission from Oxford University Press.*

Stringing the Instrument

Essentially all modern pianos now have 88 notes. While this number is standardized, piano designers still have some flexibility in how many strings they use for each note. Cristofori's pianos all employed two strings per note. This choice was probably copied from Italian-style harpsichords of his time. In Italian harpsichords each note had a pair of strings of essentially the same length that were plucked at slightly different distances from their ends. This caused the strings to produce tones with the same pitch, but with different timbres due to a different balance of the fundamental component and the harmonics. The effect is present for the piano too (even with just a single hammer for each note) but to a much lesser degree than for the harpsichord.

The fact that multiple strings are involved in a single note gives rise to other interesting properties of the piano. For a note involving two strings, there is a strong interaction between the strings since they are tuned to have essentially the same frequency (i.e., they can be thought of as degenerate oscillators). The way in which the two piano strings interact is an interesting problem that was elucidated by Weinreich (1977). He showed how the coupling of two such strings through their connection to the bridge causes their vibrational frequencies to split, in the same way that the interaction of two nominally identical harmonic oscillators results in modes with slightly different frequencies. The slight splitting of the mode frequencies gives a certain richness to the overall tone, in the same way that the sound of two violins simultaneously playing the same note has a very appealing richness. Another reason for using multiple strings for each note is to obtain a greater total volume of sound, an important consideration as concert halls have increased in size since Mozart's time. For these reasons, piano designers have followed Cristofori's lead and employ multiple strings per note for nearly all notes.

For the piano in **Figure 2**, the lowest 10 bass notes are all produced by a single wound string. The next 15 notes employ two wound strings per note, and all of the higher notes are produced by three strings. This general pattern is followed in all modern pianos, although the precise number of notes which employ one, two, or three strings can vary from model to model. Some pianos even have four strings per note in the treble, a feature that has been used occasionally but is not common.

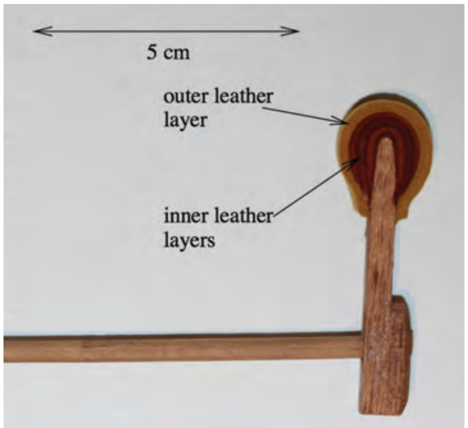
In Cristofori's day, the strings used in harpsichords and pianos were composed of either brass or iron. His brass wire was essentially the same as modern brass wire, but the technology of iron wire-making had very significant changes during the eighteenth and nineteenth centuries. An advantage of iron (as compared to brass) is that iron wire has a greater tensile strength. For a piano, it is desirable for the strings to function at as great a tension as possible (for a given string diameter), as a string at higher tension will have less inharmonicity and can be hit harder by the hammer to produce a louder tone. Increasing the tensile strength of iron wire was of great use in many applications (beyond musical instruments), and metallurgists during the 1700s and early 1800s discovered how to make iron wire with controlled amounts of impurities (mainly carbon) to make ever stronger wire. This wire was adopted quickly by piano makers when it became available, and one finds that the string tension used in pianos increased substantially from about 150 N in 1770 (the pianos Mozart played) to 200 N in the early 1800s (Beethoven), to 400 N in 1840, and then to 600 N in the earliest Steinway pianos built in the late 1850s. These latest pianos employed steel strings that were then just becoming available. Steel had been invented much earlier, but the advent of new fabrication methods made steel wire attractive for application by piano makers. While the tensile strength of steel wire has improved some since the 1860s, the improvement has been modest, and the string tension and other design parameters used in pianos from that era are similar to those in instruments made today.

The improvement in string materials led to instruments that could produce more sound but led to another problem. The earliest pianos had cases made solely of wood, which were strong enough to withstand the tension forces for an instrument with perhaps 6 octaves and strings held at a tension of 200 N. As the number of notes and strings increased, and as the string tension also increased, wood cases were no longer satisfactory. Beginning around 1820, piano makers began incorporating metal rods to reinforce the case, followed by metal plates to strengthen portions of the instrument, usually on the back side of the case (away from the keyboard). Eventually, the full metal plate was invented, which extended from the area of the tuning pins in the front section all the way to the back and sides. This plate is now made of iron, which has excellent strength when placed under tension (so there is no advantage gained by using steel). Interestingly, the full metal plate was the first important contribution to piano design from an American maker, Alphaeus Babcock, who created this invention around 1825. Piano makers initially objected to the metal plate fearing that it would give a "metallic" character to the tone. The fact that the strings were metallic evidently did not matter according to their "logic." These objections stopped for good with the success of pianos made by the Steinway family and a few other makers.

There was one other important change in the overall layout of strings that was introduced around 1850 by the Steinway family makers. Before that time, the strings were aligned straight from the front to the back on the instrument, that is, parallel to the long straight left side of the case. This pattern was used in harpsichords and continued with grand pianos until the Steinway company introduced the idea known as overstringing. For the piano in **Figure 2**, the strings for the notes from an octave below middle C to the extreme treble run are not strung straight from front to back, but slant toward the back left side of the case (the upper left in **Figure 2**). This allows those strings to be slightly longer than if they had been strung straight from front to back. It turns out that all else being equal, longer strings exhibit less inharmonicity than shorter strings, which gives an improved tone, as described previously. The strings for lower notes then slant in the opposite way, toward the upper right in **Figure 2**. These are bass strings, and they lie in a plane above the treble strings. To keep these two string layers separate, there are two bridges, one for the treble strings and another taller one for the bass strings. This layout allows the bass strings to be longer than would otherwise be possible for a case of a given size, which again improves the quality of these notes. This layout of two string planes, one for the bass and another for the treble, with separate bridges, is now standard for both grand and upright pianos.

Redesigning the Hammers

The piano differs from its keyboard ancestor, the harpsichord, in its use of hammers to strike the strings instead of plucking them. The hammers in Cristofori's pianos would thus seem to be a completely new invention. In some ways they were entirely new, but in other ways they were not. Legend has it that the idea of introducing hammers in a keyboard instrument was inspired by an outstanding dulcimer play-



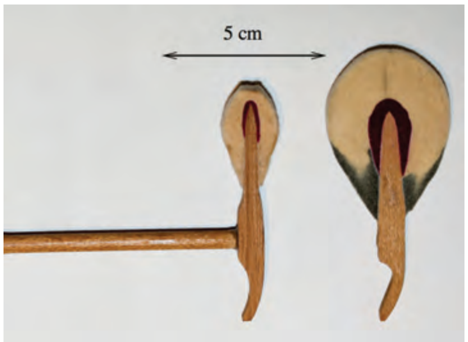


Figure 5. *Top: Hammer like those found in a c. 1800 piano; the wooden hammer head is covered with multiple layers of leather. Bottom: Hammers from a modern piano; these hammers are composed of felt covering a wooden core. The smaller hammer head is from a note in the treble and the larger hammer head from a note in the bass. From Giordano (2010) with permission from Oxford University Press.*

er—a dulcimer is played by hitting the strings with hammers. However, the dulcimer hammers familiar to Cristofori were probably just wooden mallets, and the hammers in Cristofori's known pianos were quite different. Of course, it is possible that Cristofori may have tried using wooden hammers and found them unsatisfactory, but the state of Cristofori's original hammers is not completely clear. In any case, at least some of the hammers designed by Cristofori were very different from those that came later. In one of his pianos he mounted a thin cylinder of parchment on a wooden shaft with a layer of felt on the side facing the strings (Pollens, 1995; Giordano, 2010). These hammers seem quite fragile when compared to the others shown in **Figure 5**. By 1750 until the mid-1800s, piano hammers consisted of one or more layers of leather glued over a wooden core (**Figure 5**). There is some evidence that Cristofori experimented with this design too.

After about 1850 the hammer design changed to using layers of felt instead of leather (**Figure 5**). This change was probably made for two reasons. First, the increase in string tension meant that more durable hammers were needed, and the limit for leather was probably reached. Second, the technology for fabricating felt with a very consistent and reproducible density was only developed in the early to mid-1800s. While felt was available much earlier, this advance in fabrication methods made it then usable for piano hammers. Modern pianos continue to use felt covered hammers, which are very similar to those used in pianos after about 1860.

Action Design

The part of the piano that has probably seen the greatest change is the action. The action designed by Cristofori was incredibly simple, and some of its aspects can be seen in the modern action. Even so, he would probably be amazed to find that the modern action contains dozens of different parts for each note. We will not try to describe or explain the modern action in any detail here but refer the interested reader to the references for information. A nice animation of the workings of the modern piano action can be found on YouTube at www.youtube.com/watch?v=vFXBIFyG4tU, and drawings of the action for pianos from different eras are given by Clinkscale (1999). Here I only mention some general features of the evolution of the action.

By about 1760 there had developed two main schools of piano making, one based in London and another in Vienna. The instruments developed in these two regions evolved in broadly similar ways for the strings, etc., as described in the previous sections. However, the two schools developed two very different action designs that came to be known as the English and Viennese actions. The English action eventually evolved into the design that is now found in virtually all modern grand pianos (and it maintained that name, even though its final form was due to a Frenchman). In the English action, the hammers are all mounted on a rail that is above and not attached to the key lever and the rest of the action. The key lever only pushes on a series of other intermediate levers to set the hammer into motion. The Viennese action was quite different with each hammer on an axel that was mounted on its corresponding key lever. Both action types had their proponents and were favored by different makers, but eventually the Viennese action was phased out by around 1900.

Pianos for the Home: Design of the Upright Piano

Our discussion has so far focused entirely on the grand piano. Early piano makers after Cristofori also developed a more modest instrument intended for the average home. An example of the first "home" instrument is shown in **Figure 6**. These were called "square grand pianos" even though the case was really rectangular. This shape for the case and the layout with the strings running roughly parallel to the keyboard are similar to several types of plucked string in-

Figure 6. *A square grand piano made in 1793. It has a range of five octaves. From Giordano (2010) with permission from Oxford University Press.*

struments, and the resulting piano occupies much less floor space than a grand piano. Square grand pianos underwent an evolution similar to that of grand pianos, and by 1850 they had expanded from 5 octaves (as in **Figure 6**) to 7 octaves or more.

These later instruments were about as massive and nearly as big as a grand piano, which was not a good solution for a home instrument. This motivated a different design in which the soundboard lies in a vertical plane—the upright piano. This is a much more efficient use of space, but the upright piano was slow to be adopted because of difficulties in designing an efficient action. The actions in traditional grand and square grand pianos propel the hammer upward to its collision with the strings and gravity brings the hammer back to its resting position after the collision. For an upright piano, the strings are aligned vertically, and the hammers move horizontally before and after the collision. Thus, gravity cannot help bring the hammer away after the collision, and an entirely new action design is needed. A satisfactory design for such an action (in which springs and carefully placed straps are used to reset the action after hitting the strings) was not developed until about 1820, and it forms the basis for the action in modern upright pianos. For an animation of the upright piano action, please go to https://www.youtube.com/watch?v=2kikWX2yOto.

After that time, the upright piano became popular and completely displaced square grand pianos after about 1860. For those who are interested in that bit of history, square grand pianos can still be found on ebay (!), but they are not recommended for musical use.

Where Will Piano Design Go Next?

The main theme of this article has been the evolution of the piano from the instrument invented by Cristofori to the modern piano of today. There have been substantial changes in nearly all aspects of the instrument, including the strings, string layout, hammers, and case, and these have changed the piano sound in subtle ways. These changes can be heard in the sound files that accompany this article (http://acousticstoday.org/the-invention-and-evolution-of-the-piano/) which contain short segments of familiar pieces by Scarlatti and Mozart that are played on both early and modern instruments. While the tones produced by early and modern pianos certainly can be distinguished, it is evident to most listeners that they come from the "same" instrument. Hence, the "essence" of the piano has been preserved over the three centuries since its invention.

Interestingly, the rate of evolutionary change of the piano slowed greatly in the late 1800s, and a "modern" piano would be very familiar to Johannes Brahms or Theodore Steinway (the patriarch of the famous Steinway family). While there have been small design changes since that time, the piano reached essentially its current form nearly 150 years ago. Why did this evolution stop? We have already seen that the expansion in the number of notes stopped because of limits in the human auditory system. Other factors also contributed, for example, the material used in strings evolved rapidly between 1750 and 1850 as stronger and stronger forms of iron wire were developed, culminating in the availability of steel wire with a tensile strength not far from today's steel wire. However, such technological considerations don't fully explain why the piano has changed so little in the past century. For example, advances in material science have given us the possibility of carbon fiber soundboards and strings that might, at least in theory, lead to an improved instrument (Giordano, 2011). Such possibilities have not been seriously explored yet, perhaps because of a general resistance to change among composers, makers, and performers. It is understandably difficult to convince musicians to make significant changes in an instrument that has been so successful. And this is probably not a bad thing.

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Biosketch

Nicholas Giordano joined Auburn University in 2013 where he is a professor in the Department of Physics and Dean of the College of Sciences and Mathematics. Before going to Auburn he was a member of the faculty at Purdue University where he served as Head of the Department of Physics from 2007–2013. He was an Alfred P. Sloan Foundation Fellow (1979–1983), received a Computational Science Education Award from the U.S. Department of Energy in 1997, and was named Indiana Professor of the Year by the Carnegie Foundation for the Advancement of Teaching in 2004.

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