Nicholas J. Giordano, Sr

# Physics
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*To Pat for all her patience.*

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# Preface

My interest in the piano developed late in life, when I started taking piano lessons about 15 years ago. As I learned to play the instrument, I developed a curiosity about what goes on inside a piano. With my background as an experimental physicist, it was natural to contemplate and then carry out some simple measurements to satisfy this curiosity. At the same time, my lessons drew me to the baroque and early classical piano repertoire, and I soon learned that the keyboard instruments of those eras were quite different from the modern piano. This in turn led me to study how various keyboard instruments, including the harpsichord and early piano, were constructed. Much to my wife's amusement, a small collection of these instruments now occupies our house. I have thus studied the piano from many different angles, all of which have been incorporated in this book.

I am deeply indebted to the people who have guided me in my studies of musical acoustics and the piano. Verna Abe patiently guided me through my early lessons, and also put up with my devotion to (and obsession with) the music of J. S. Bach. Arnold Tubis encouraged my interest in musical acoustics and introduced me to many experts in the field. Thomas Rossing, Anders Askenfelt, Antoine Chaigne, and Gabriel Weinreich have been very gracious with their time in teaching me about musical acoustics. I have learned a great deal about construction (especially harpsichords) from Larry Eckstein, while Tim Hamilton, and Barbara and Debbie Martin have taught me much about restoring historical instruments. It has also been an enormous pleasure working with many students on studies of the acoustics of pianos and other musical instruments. I am indebted to Paul Muzikar, Susan Pashos, Dan Whiteley, and Pat Giordano for their comments on an early draft of this book.

The expert photography of my daughter Lizz has been extremely valuable. Unless noted otherwise, she is responsible for the photographs in this book. Likewise, unless noted, instruments shown in this book are from the author's collection, and most of the measurements of sound spectra and other quantities were carried out with these instruments.

Most of all, I am grateful for the support and encouragement of my wife Pat. While writing this book has taken much of my time, pianos now take up much of our house. And it has all been great fun.

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January 2010

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# Contents

# Introduction

# 1

This book is written for anyone who is interested in understanding how and why the piano came to be invented, how it evolved into the form it has today, and how different parts of the instrument contribute to the tones that it makes. Among the questions we will address are

- *Who invented the piano and why?*
- *Why does a piano have 88 keys and not more or fewer?*
- *How and why is the tone color of a loud note different from that of a soft note, and why is this important?*
- *Why are the bass strings on a piano made by wrapping a coil of wire around a central wire core?*
- *A piano tone is the sum of components that can be described by sine waves. The frequencies of these sine waves deviate a small amount from a simple harmonic series. What is the source of these deviations and why are they important?*
- *What does the bridge do? Why not just connect the strings directly to the soundboard?*
- *What is so special about the pianos made by Steinway and Sons?*
- And the most important question of all (which sums up many of the others), *Why does a piano sound like a piano?*

The answers to all of these questions and more will be discussed in this book, in terms that are understandable by a nonscientist and at the same time satisfying for a physicist.

## 1.1 The goals of this book

Why does a piano sound like a piano? A similar question can be asked of virtually all musical instruments. A particular note, such as middle C, can be produced by a piano, a violin, and a clarinet. Yet, it is easy for even a musically untrained listener to distinguish between these instruments. We would like to understand why the sound of the "same" note depends greatly on the instrument. Moreover, we would like to understand which aspects of an instrument are most critical in producing the musical tones characteristic of the instrument.

Our quest to answer these questions for the piano will lead us to consider the science of acoustics, a well-established area of physics. We could take an approach common in physics, and use the relevant laws of physics (in this case, Newton's laws of mechanics) to write down in great detail the mathematical equations that describe the way different parts of a piano move and vibrate, and the sound waves that are ultimately produced. This can indeed be done, and we can even solve these equations (usually with the help of a computer) to give a precise mathematical description of the sound that reaches a listener. However, would this really give us an *understanding* of the piano and its sound?

This takes us to a different sort of question—what does a scientist mean when he or she uses the word "understand"? In this book, we will take the position that the ability to carry out a mathematical calculation of the sound produced by a piano does necessarily imply a true understanding of the physics that underlies the piano. Our goal is to provide qualitative and intuitive explanations of the key features of the piano sound. We want to understand in a nonmathematical way why the sounds produced by a piano (we will also refer to them as piano tones) are different from those produced by a violin or guitar, and why different pianos can make very different sounds. What are the key components of a piano that are responsible for its unique sound? Why is the sound from a grand piano "better" than the sound produced by an upright piano, and what do we even mean when we say that the sound of one piano is "better" than that of another? We also want to be able to predict, again in a nonmathematical and general way, how a piano's sound would change if a particular component of the piano were changed. This would allow us to understand why, for example, the sound of a large concert grand piano is generally preferred to that produced by a much smaller piano.

So, this book will *not* go deeply into theoretical acoustics. Our explanations are designed to be understandable by readers who do not have an extensive math background (or interest). We will certainly give references to more mathematical discussions for those who are happiest when they see equations, but our focus will be squarely on building a qualitative and intuitive understanding of the piano and its sound.

A second goal in this book will be to explain *why* the piano was invented and how it evolved into the instrument we know today. The invention of the piano is commonly credited to Bartolomeo Cristofori, an instrument maker in Florence, Italy, who made his first pianos around 1700. We will say much about his work throughout this book, and will also consider the musical needs that motivated his invention. Throughout the Baroque era (about 1600 to 1750) the dominant keyboard instrument was the harpsichord.[1] The harpsichord was used as both a solo and accompanist instrument, and was powerful enough to be used in the largest concert halls of the time. However, a major drawback of the harpsichord was that a given note could only be played at essentially one volume level. It was not possible to vary the volume from note to note, and this limited the expressive possibilities of the instrument. Composers and performers both wanted a keyboard instrument with that ability, and this is why the piano was invented. The expressive potential of the piano helped lead to the music of the Classical era (about

[1] Some musical historians may dispute this statement, and suggest that the organ was more "dominant." We base our claim on the fact that organs were limited to a small number of venues (mainly churches) while harpsichords were more numerous.

**Fig. 1.1** A typical grand piano. This particular piano is a Steinway and Sons model M belonging to the author, and was built in 1916. The model M is still manufactured and has changed very little since it was first introduced in 1912. This instrument will serve as our "standard" piano throughout this book. Most of the photographs of particular components were obtained with this piano, and it produced nearly all of the piano tones that are analyzed in this book.

1750 to 1820) and beyond, as is now familiar in the works of Mozart, Beethoven, Liszt, and many others. At the same time, these composers pushed for new capabilities, such as more volume and a keyboard with ever more notes, and thus influenced the evolution of the piano. Understanding this story will help explain why the piano has evolved into its present form.

## 1.2 What exactly is a piano?

Figure 1.1 shows a photo of a typical grand piano. A modern piano[2] is truly a precision machine, with 88 keys, approximately 230 strings (depending on the model), and with approximately 10,000 individual parts. It is amazing to realize that virtually identical instruments were manufactured more than a century ago. While some piano factories, such as those of Yamaha and Kawai, employ the most advanced manufacturing techniques with extensive use of robotic and computer-controlled machines, many factories still rely heavily on more traditional methods of wood and metal working. For this reason, it is sometimes said that the most complicated machine in a Steinway factory is a finished grand piano (Good 2001).

The view of a piano in Fig. 1.1 is probably familiar to most readers. However, to really understand how a piano is put together, it is useful to look at the instrument from many different angles. The photograph on the left in Fig. 1.2 shows a top view of the piano in Fig. 1.1, with the lid removed. In addition to the keys, which are visible at the front of the instrument, this image gives a good view of the strings along with

[2] The evolution of the piano will be discussed in Chapter 9, where we will explain why pianos from the late 1800s onward can be considered as "modern."

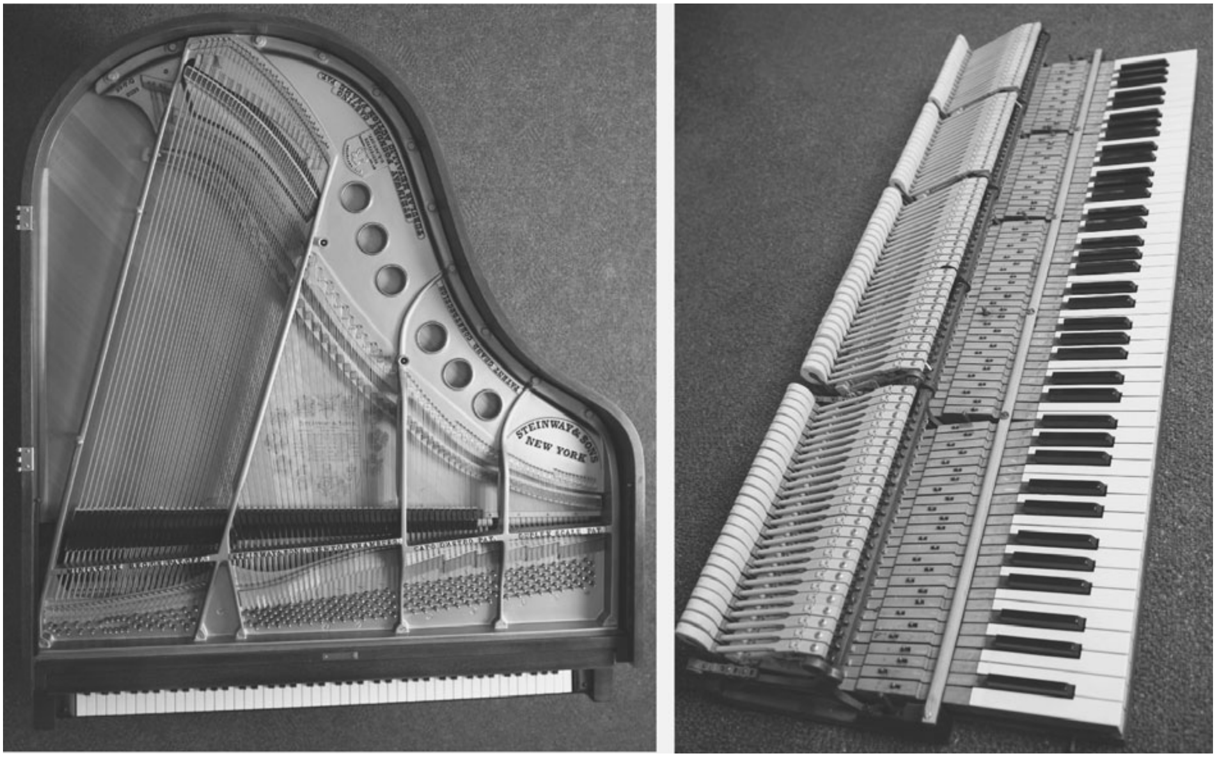

**Fig. 1.2** Additional views of the Steinway model M grand piano from Fig. 1.1. *Left*: Viewed from above with the lid removed. *Right*: Piano action removed from the case.

the metal plate and tuning pins. Beneath the plate one also can see the soundboard.

The keys are visible at the bottom of the photo on the left in Fig. 1.2, but the hammers are obscured. They are most easily seen by taking the piano apart. The photograph on the right in Fig. 1.2 shows the piano "action," the mechanical linkages that connect the keys to the hammers. (A close-up view of the action is given in Chapter 6.) The action slides into the case of the piano and positions the hammers beneath the strings. There are 88 keys in most modern pianos, so there are 88 hammers and 88 separate mechanical linkages. While the earliest actions were relatively simple, the modern action is quite a complicated system of moving parts. This is where most of the 10,000 components of the piano are found.

As we proceed through this book, we'll be discussing all of the components of the piano visible in Figs. 1.1 and 1.2, along with one important "component" that is not visible. That component is the air around the piano. Sound is generated primarily by the vibration of the soundboard, and the resulting sound waves travel through the air to the listener. The general properties of sound will be important to our discussion, so we'll spend Chapter 2 giving a short and nonmathematical introduction to the theory of sound. Another prominent "component" not shown in any of the above photos is the listener. The role played by the human auditory system in how we perceive the tones produced by a piano is also important, and will be discussed in Chapter 10.

## 1.3 The way a physicist thinks

In Section 1.1 we spent some time explaining one meaning of the word *understand*. There is a closely related issue relating to how a physicist describes a complicated system, such as a piano. The approach taken by most physicists is to describe the "essence" of a problem. This means that all the extraneous aspects of the problem are ignored, and only the truly essential parts are described in the simplest possible terms. As an extreme example, a physicist studying piano tones would most likely not worry about the colors of the piano keys. The assumption here is that changing the key colors (e.g., changing all the white keys to black and all the black keys to white) would not affect the piano or its sound in any important way. This seems like a very safe assumption, but other assumptions may not be as obvious.

This quest for simplicity is very much in accord with our use of the word understand in Section 1.1, and is often discussed using the principle known as Ockham's razor. In physics, it sometimes happens that a particular phenomenon can be described equally well by two different theories or explanations. According to Ockham's razor, the simplest theory or explanation is to be preferred, since it gives the most economical description. This preference for simplicity is also expressed in a quote attributed to Albert Einstein (see Fig. 1.3).

> Everything should be made as simple as possible, but no simpler.

This desire for simplicity is very appealing, but how do we know when we have gone too far and made an explanation or theory too simple? The author is a physicist, and has a strong preference for the "simple is better" approach. However, we will see in our studies of the piano that many of the simplifications that are commonly made in physics are *too simple* for describing the piano. As an example, consider the propagation of a wave on a piano string. The problem of a wave on a string is discussed in most elementary physics courses, and the typical physics treatment is to consider an ideal flexible string, ignoring the effect of string stiffness. While no real string achieves this ideal, this is an excellent approximation in nearly all cases. However, we'll see that describing piano strings as ideal flexible strings would cause us to miss an extremely important feature of real piano tones. Making that approximation would, to paraphrase Einstein, make our description too simple.

We will see a number of cases in which the physicist's desire for simplicity and the commonly used physics models are too simple to give

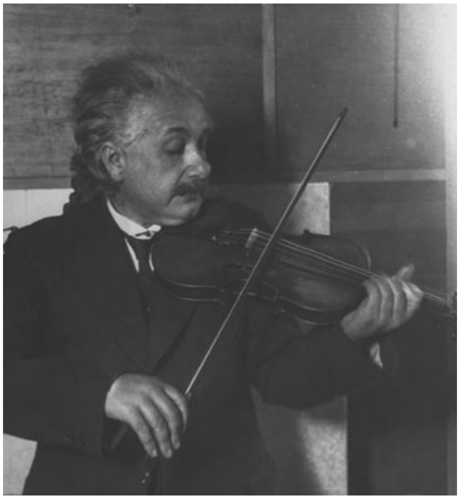

**Fig. 1.3** We have mentioned Einstein's advice on the importance of simplicity in a scientific theory or explanation. It is interesting that Einstein was very devoted to music and was an accomplished violinist. While his ability with the violin was not quite at the professional level, his celebrity gave him opportunities to play with many famous musicians. In one case he was playing with the pianist Artur Schnabel who was evidently not impressed with Einstein's performance, and admonished Einstein by remarking "Albert you can't count." On another occasion, Einstein performed at a public concert and a music critic who was evidently unaware of Einstein's work as a physicist remarked "Einstein plays excellently. However, his world-wide fame is undeserved. There are many violinists who are just as good." (Photograph from *Life Magazine*, 1921.)

an understanding of the piano. In these cases, the details are crucial to gaining a real understanding of the instrument and cannot be ignored. Such details *will* be explained in this book.

## 1.4 Organization of this book

This book is about the musical tones produced by a piano, so in the next chapter we give a quick review of the science of sound and hearing, and follow in Chapter 3 with a discussion of how a collection of tones can be arranged to form a musical scale. We then give a little musical history as we explain (Chapter 4) why the piano was invented. Its invention gave performers and composers new musical possibilities which were put to use by Mozart, Beethoven, and others as the Baroque era was coming to an end and the "new" era of Classical music was beginning. In Chapter 5 we turn our attention the the mechanics of the piano. Figures 1.1 and 1.2 show all the details of a real piano, but in the spirit of simplification suggested by Einstein, it is useful to consider the sketch[3] in Fig. 1.4. Vibrating strings determine the pitch of a piano tone, so we first discuss the behavior of an ideal flexible string (another physics simplification) in Chapter 5, and then describe how real strings differ in a subtle but important way from this ideal. Piano strings are set into motion by a blow from a hammer, and Chapter 6 considers the hammer–string collision along with the mechanical mechanism (the action) that connects the key lever and the hammer. The hammers and action are essential elements of the piano, as they give the instrument its expressive capabilities. Forces produced by vibrating strings set the soundboard into motion, and the soundboard acts as a speaker producing sound

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[3] This sketch is appropriate for a grand piano (like the one in Figs. 1.1 and 1.2), in which the strings run horizontally. Most of our examples and discussions in this book will be in the context of a grand piano. Upright pianos have a different design in which the strings run vertically, that we will describe in later chapters.