# Chapter 1

# Introduction

The work of this thesis has been kindled by the desire for a certain unique product—an electronic keyboard instrument which responds, both in terms of sound and feel, just like an acoustic grand piano. Keyboardists familiar with the piano and the synthesizer have long been dreaming of one instrument with the advantages of both: the response and accompanying expressive potential of the piano and the programmability of the synthesizer. Certainly we are not the first to identify this product need —synthesizer manufacturers have been clamoring for a decade to come up with an electronic version of the piano. Evidently there remain many challenges in the design of such an instrument since by the standards of any pianist, existing electronic pianos are poor substitutes for acoustic pianos.

To produce a device which emulates the behavior of a proven predecessor seems like a simpler task than starting from scratch and without guidelines, especially given the many new technologies available to us which were not available to the designers of that predecessor. To emulate the mechanical and acoustical response of the piano in computer-driven hardware, however, has proven to be a very challenging task.

### Theme for section 2.1

To begin, we are interested in the response of a mechanical system to some rather special driving inputs: those of a human. The responses in turn are to be judged by a human, and thus certain psychophysical factors will enter the discussion. Indeed, for its effectiveness as a musical instrument, the piano depends heavily on certain psychoacoustical and psychophysical phenomena. Simply put, the piano has survived (even flourished) by continually fooling the ears of its listeners and the hands of its players. The sounds it produces are strictly percussive, yet from these our ears somehow construct lyric melodies. The physics of its sound production are separated from its keyboard interface by a very complex system of levers, yet a player's fingers somehow find ways of manipulating all the available sound parameters. The deceptive habits of the piano will become the primary subject of Chapter 2. There I will undertake a thorough discussion of the psychophysics of the piano. My primary aim will be to extract design guidelines for a new digital instrument.

### Roadmap to the document

Aiming to satisfy product desires defines the basic activities of almost every engineer, and thus this thesis touches upon a relatively broad range of engineering topics. Chapter 2 is somewhat self-contained, and should be accessible to all engineers and persons interested in computer music or electronic instrument making. Chapter 2 also introduces the work of the entire thesis. By itself, Chapter 2 is original only in that it is a rather complete collection of thoughts on the subject of keyboard instrument design. The actual results of our work are presented in the remaining chapters. Each of the sections in Chapter 2 introduces the work of a certain following chapter, as shown in Figure 1.1. Effectively, Chapter 2 is a launching pad for the rest of the document.

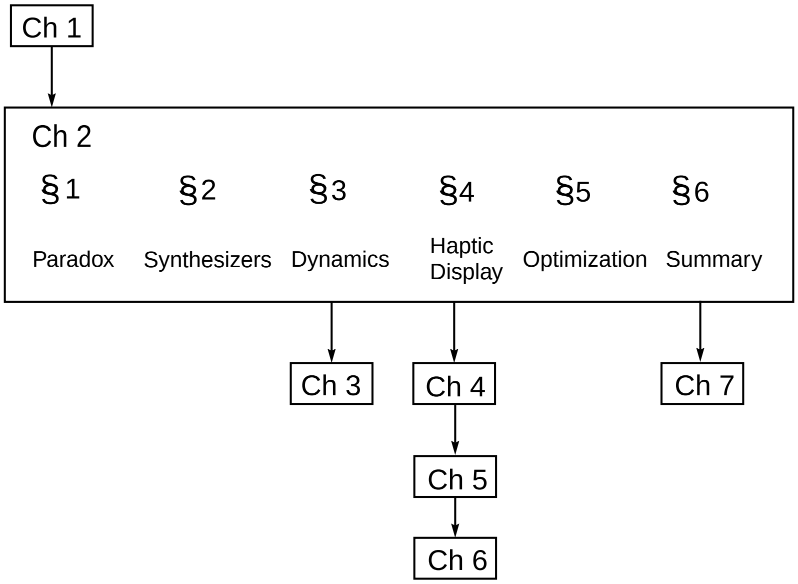

Figure 1.1: *Roadmap to the Document*

### Theme for section 2.1

In section 2.1, the debate over just which sound parameters are actually under the control of a pianist will be taken up and for our purposes resolved. A brief literature review at the end of section 2.1 will establish that this debate has surfaced several times throughout the history of the piano.

### Theme for section 2.2

Behind our interest in creating a digital instrument modeled after the acoustic piano lies the hope of landing one with a career like that which the acoustic piano has enjoyed. We further hope that our process of inventing a prosperous digital instrument will not take as long as the invention of the acoustic piano—which consumed two whole centuries! (approximately 1705-1900). The fact that the piano's design evolved over such a long period of time is due in part to the gradually developing technology to which it was tied, but also, quite undeniably, to its essence as a music-producing 'black box' filled with complex mechanisms whose purposes seem to border on subterfuge as discussed in section 2.1. We trust, however, that our understanding of the psychoacoustics and psychophysics of the piano will allow us to circumvent a few design iterations in our quest to produce a similar instrument. We even expect that a digital instrument will be able to take advantage of psychophysical factors in interesting new ways. In Chapter 2, section 2, I begin an analysis of the black box of the piano by defining its boundaries and the ports through which it interacts with its environment (the pianist and audience). A general definition of a musical instrument, which covers both acoustic and electronic versions, will be presented. Using this definition, the shortcomings of existing electronic pianos with regard to their potential as expressive instruments will be enumerated. Section 2.2 will then conclude with a critical look at the design principles which have been used in present-day commercial synthesizers and digital pianos, leaving the reader with a clear picture of where we, as instrument designers, need to start anew.

### Theme for section 2.3 and Chapter 3

It will become necessary, before embarking on our piano emulator design effort, to study the piano and its dynamical behavior in detail. To this end, the process of modeling the grand piano action will begin in Chapter 2, section 3. We must fully understand the laws and mechanisms which govern the piano's behavior under a player's fingers if we are to duplicate that behavior. In particular, we will be interested in the feel or mechanical impedance of the piano at the key and will develop models of the piano action for the purposes of accounting for observed impedance characteristics. Simplified models will be presented in section 2.3. Section 2.3 will concentrate on the release and catch of the piano hammer by the remaining elements of the action. Our simplified models for this system will be reminiscent of a bouncing ball.

A mechanical system in which bodies may make and break contact with one another shall be called a system subject to *changing kinematic constraints*. The piano action is such a system, and its changing constraints are of particular interest because they give rise to features or mechanical impedance variations which can be felt (and in turn used or manipulated) at the key. Chapter 3 will present models for the piano action in each of its kinematic constraint conditions and further highlight the effects of changing constraints on the observed mechanical impedance at the key. A thorough literature review covering multibody model formulations of systems with changing kinematic constraints will be presented in Chapter 3. Our own model formulation, chosen for computational efficiency, will be compared and contrasted to other formulations.

### Theme for section 2.4 and Chapter 4

In joining the digital piano design effort, we have decided to pay particular attention to the feel or 'touch-response' at the keyboard. Especially with regard to the feel, we believe that present-day digital pianos are gravely deficient. Our proposed method for re-creating, in a synthesizer keyboard, the feel of a grand piano or, for that matter, the feel of another keyboard instrument, is to motorize the keys and place them under computer control. This souped-up synthesizer will thus be touch-programmable—the feel of the keys and the relationship of the feel to the sound production parameters will be customizable or arbitrarily adjustable by the user. In section 4 of Chapter 2, I will discuss our approach to emulating the feel of a mechanical system such as the grand piano action with a motorized key under digital control. I will introduce the manner in which simulations of dynamical models of the piano action may be run in real-time in a human-in-the-loop scheme to re-create the feel of the action.

The portrayal of virtual touchable objects through a motorized device is a lively topic of research at present. Such a device is called a haptic interface or sometimes a haptic display. The word 'haptic' has been appropriated from the medical community, where it is used to refer in one word to the perceptual modalities of taction (senses of the skin), and kinesthesia (senses of the muscles). Our touch-programmable synthesizer keyboard can thus be considered an interface for virtual reality—it renders a virtual piano action or, at the touch of a button, a virtual harpsichord action, or perhaps the action of an altogether new instrument. I will contrast our approach with other possible approaches to mechanical system impedance emulation and briefly review the literature on this topic in section 2.4. Chapter 4 will introduce our unique design of a haptic interface and our techniques for the emulation of keyboard instruments. The manner in which the mechanical design of our haptic interface is related to the mechanical design of the piano action will be highlighted.

### Theme for Chapter 5

A significant challenge which the entire haptic interface research community faces at present is the high-fidelity emulation of changing kinematic constraints. It turns out that even the very simplest of virtual objects containing changing kinematic constraints exhibit non-passive behavior—they tend to introduce energy into the coupled system made up of the device and the human, thereby causing sustained oscillations or 'chatter'. The prototypical simple object whose changing kinematic constraint tends to cause sustained oscillations is the virtual wall, especially a stiff virtual wall displayed with a slow sampling rate. These simulation difficulties are often simply labeled 'numerical problems' and swept under the rug, being relegated to that set of problems which will disappear when computers get faster. In haptic display, however, the challenge is not so easily forgotten. Interactive systems must be run in real-time, and the desire to share computer processing power with other operations such as graphical display will always be present. Therefore, we would like to ensure high-fidelity haptic display despite slow sampling rates.

Chapter 5 will describe the energetics of a haptic interface and its sampled-data controller attempting to emulate a wall, and will present improved controllers which do not exhibit sustained oscillations. These new controllers are immune to the destabilizing effects of two inescapable elements in any sampled-data implementation of a virtual wall: the zero order hold and the asynchrony of wall switching times with sampling times. Controller design techniques, which draw upon predictive simulation, digital domain design tools, and deadbeat control, will be fully developed.

### Theme for Chapter 6

Chapter 6 will analyze the virtual wall controllers presented in Chapter 5. Measures for the energy introduced by the old standard controller designs will be sought so that the costs of implementing the new designs of Chapter 5 may be accurately weighed.

Chapters 5 and 6 treat difficulties which arise in the haptic display of a virtual piano action, namely the real-time rendering of changing kinematic constraints through a sampled data system. The treatment in Chapters 5 and 6, however, is quite narrow in that only a simpler, stand-in virtual system (the virtual wall) is considered. Most notably, dynamical models of the human finger coupled to the haptic interface are used in the improved virtual wall controller designs. Because the time-scale of the chatter problem is short (sustained oscillations run on the order of 10 to 50 Hz), and the need to account for volitional control on the part of the human is thereby obviated, successful virtual wall algorithms may be developed by taking into account the assumed mechanical properties of the human. In part to prepare for extending these results to longer time-scales, but also because there exists much interesting unchartered territory in the area, we will widen our viewpoint again in the remaining sections of Chapter 2.

### Theme for section 2.6

To embark on a project whose primary aim is to improve upon an existing successful human interface design and to generalize that design by making it programmable, raises many interesting research questions. For example, what allows a pianist to maximize his control over the piano, and what role does the mechanical impedance of the piano play in that process? We have begun to address these questions with optimal control theory. Optimization theory allows us to treat the human/piano system in a framework which places each of the participants within this feedback system in an appropriate role. The human is modeled as an optimizing controller, attempting to maximize an output from the piano according to some objective function chosen for its musical significance. Our investigations in optimization will be outlined in section 2.6.

Finally, Chapter 7 will summarize and outline future work.