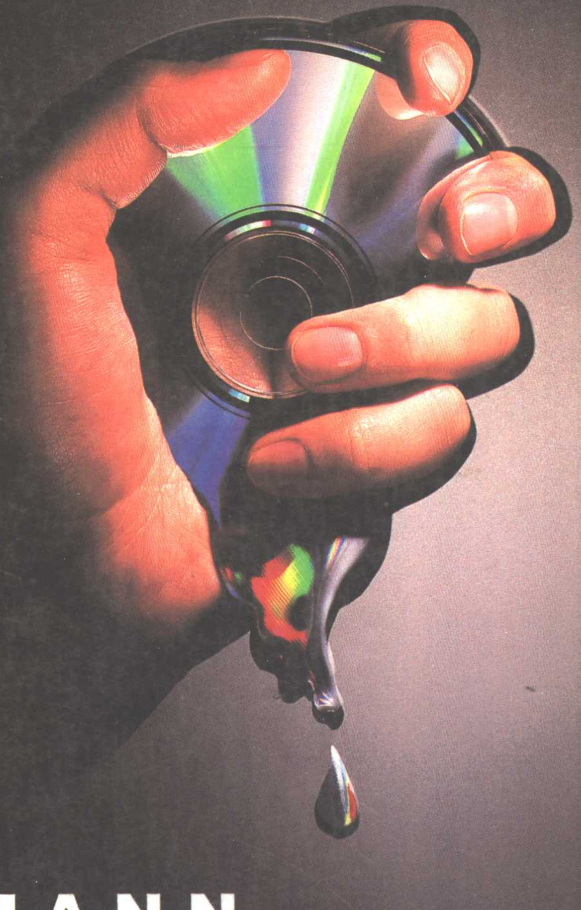
THE COMPACT DISC HANDBOOK

2ND EDITION



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Computer Music and Digital Audio Series

THE COMPACT DISC HANDBOOK

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Preface

There are about a billion reasons that prompted me to prepare a second edition of this book. Specifically, about a billion CDs are sold every year, and the number is still climbing. Exceeding the expectations of even its most ardent supporters (like me), the compact disc has become one of the most successful consumer electronics products ever introduced. The eager worldwide marketplace has encouraged rapid development of CD technology and spawned entirely new applications for the dimpled disc. If you read a magazine article or two on CD a few years back, and you think you're up to speed on the disc, you're sadly mistaken.

It is the aim of this second edition to celebrate the compact disc's tenth birthday and document this decade's swift series of events. Specifically, this edition more fully describes the laboratory origins of the CD and elaborates on the electronic and optical principles underlying the format. It explains technology weaknesses such as converter low-level nonlinearity, exposes placebos such as disc stabilizers, and suggests new testing procedures to measure problems or lack of them. It discusses emerging digital signal processing applications in areas such as low-bit conversion, noise shaping, and data reduction. It also introduces new formats such as Photo CD, CD-I, CD-R, and erasable disc formats including the mini disc. In addition, several structural changes have been incorporated into this edition, rearranging existing material to facilitate access. Furthermore, in an effort to further clarify the presentation, literally every page has seen changes. More obviously, anyone familiar with the first edition will notice that many new pages and figures have been added. Even the references at the end of each chapter and the glossary have been thoroughly updated. In short, this is no minor facelift.

Finally, I should note that I am increasingly encouraged by the conversations I overhear in record stores these days. Hardly anyone still confuses CDs with LPs, partly because consumers are more knowledgeable of digital audio technology and partly because LPs have all but vanished. Of course, I would never take schadenfreude delight in analog technology's quick demise, heh, heh.

Ken C. Pohlmann

Preface to First Edition

A bit of innocent eavesdropping prompted me to write this book. I was browsing through CDs in a record store when I overheard someone explaining the compact disc to his buddy. Knowingly, he told him, "It's the same as an LP, only it's silver."

Although I didn't say so at the time, that remark bothered me considerably. In an unknowing way, his explanation was adequate. The compact disc is indeed a counterpart and successor to the long-playing record, but it's also much more. The sophistication of the technology underlying the CD system should command considerably more understanding and respect than is reflected in a simple comparison to a mechanical groove.

Along those lines, I decided that a book might help illuminate the technological beauty of the CD. My goal was to explain things without generating more confusion. There is enough of that surrounding high technology already. The result, of course, is now in your hands. When you have finished reading, I hope your impression will be that the book was very simple, even though you will have learned a great deal about compact disc technology. A good teacher is just like a good nurse with a hypodermic needle—you never feel the pain.

There is at least one philosophical question that I will not try to answer directly: Is digital audio inherently better than analog? This question is similar to asking whether or not there is life after death. Each of us may ascertain the answer, but not until later.

Meanwhile, I hope this book helps to expand your insight into the CD. And the next time you're in a record store, please try not to embarrass yourself.

Ken C. Pohlmann

Introduction

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First, a word of explanation. From its Dutch and Japanese origins in June 1980, the compact disc system has prospered beyond the wildest dreams of its inventors. The original audio CD was one of the most successful new electronic products ever introduced; everyone was surprised by its rapid acceptance by music lovers. Over the first few years the biggest news concerned shortages, particularly of discs themselves. Then the disc caught the attention of data lovers as well. CD-ROM quickly started its own acceleration into the market of mass storage. As if that wasn't enough, CD-I's future looks similarly promising as an interactive audio-video medium. Of course, while reading data is fun, writing data is even more fun. Thus a standard for write-once CDs was introduced, and erasable CD technology has been developed. Furthermore, CDs with graphics and MIDI information and mini-CDs were also introduced into the marketplace. In short, the compact disc family is a hit and already encompasses more topics than one book could comprehensively cover.

Exactly how important is it to bone up on a new technology such as the compact disc? How significantly will it influence our everyday lives, and for how long? There are a number of factors that determine the lifespan of a technology. Manufacturing cost, product performance, market penetration, user boredom, and innovative competition all move technological evolution forward and heighten expectations. As far as the CD family goes, it is safe to say that the future looks bright indeed. Its market share continues to expand, and new and consequential applications are undoubtedly waiting to be discovered by insightful entrepreneurs. Of course, no technology, except the very primitive kind, lasts forever, and someday (perhaps relatively soon) the CD will be only a curiosity. Fittingly, the discs themselves should long outlast their usefulness.

Meanwhile, this handbook covers all the fundamentals of the CD and should prove useful to anyone delving into this technology, especially for the first time. Hopefully, it will answer all your questions about audio CDs and pave the way to a greater understanding of the derivative CD formats.

This little opus, composed of seven chapters, starts with the basics and proceeds onwards and upwards. Theoretical topics are treated expeditiously, and mathematics have been avoided almost entirely. The emphasis is on practical, understandable, useful information.

Chapter One is an introduction to the fundamentals of digital audio theory. Digital signals are contrasted with the analog variety, and the pros and cons are discussed. Just for fun, a brief history of the events leading to the CD is chronicled. In addition, the compact disc is weighed against its predecessors. The first chapter, like all the chapters, concludes with a list of references for further reading.

Chapter Two begins our technical discussion. Sampling and quantization, the key analytical methods of digitally interpreting analog signals, such as audio waveforms, are presented. Aliasing, a negative attribute of sampling, and dither, a panacea for problems arising from quantization, are examined. Pulse code modulation, a particularly clever method of encoding digital audio data, is presented. Finally, a practical audio digitization system is used to consolidate all the theory.

Chapter Three examines the technical theory underlying the compact disc system. The encoding process leading to the plastic disc is examined. The disc itself is an impressive piece of handiwork, particularly at the microscopic level, so the intricacies of data pits are presented. The use of error correction is unprecedented in audio storage; the methods used to safeguard the CD's data are discussed. The bit stream from the disc is processed just as heavily, and oppositely, to the input bit stream. The signal processing circuitry composing every CD player is examined. The chapter concludes with a look at the non-audio subcode data, which is stored on every CD and used to control playback.

Chapter Four zeros in on CD player design, starting with the laser pickup as it reads data from the disc at a rate of 4.3218 million bits per second. To assist the pickup in its difficult task, electro-mechanical circuits are used for focusing the beam and keeping it on track. Digital filters must be used to process the waveform before it is presented to the ears. Digital filters and digital signal processing in general are carefully introduced. The digital-to-analog converter's job is to transform data back into an audio waveform. These output stages are summarized with a look at a specific chip set. The chapter concludes by examining low-bit D/A conversion and the AES/EBU and SPDIF standards, serial transmission formats used to convey data from one digital audio device to another.

Chapter Five brings the discussion back to the macroscopic level of the consumer. User notes are presented on a variety of topics. Different player designs are examined and critiqued. Specifications provide a means to distinguish good players from the merely mediocre; measurement techniques are examined. Tips are given to assist in purchasing a CD player. Player care is also important, including the dos and don'ts of preventive maintenance. Your disc collection will probably represent a bigger investment than the player; it is wise to take care of your discs and to be able to evaluate any defects that may be present.

Chapter Six carries the discussion to the diverse versions of the compact disc system. The audio CD was only the first of several CD family members. CD-ROM uses the CD's vast storage potential for non-audio applications, such as data bases and software programs. CD-I merges video with audio on CDs. Imagine a new kind of publishing: combined illustrated, printed, and talking books. DVI provides yet another format for interactivity, and the Photo CD format brings high-quality photographic images to the disc. CD-V merges the CD's digital audio format with that of high quality analog video optical storage. The CD-R format offers users the chance to permanently record their own data. Several fully recordable/erasable optical media, including magneto-optics and phase-change technology, allow users to record and erase data. Although incompatible with the CD, the MD format promises to expand optical disc applications. CD + G/M utilizes subcode storage capacity to provide graphics and MIDI output from audio CDs. CD-3 is a mini-sized CD for applications where shorter playing times are sufficient.

Chapter Seven is an examination of the technology of compact disc manufacturing. The discussion concentrates on the foremost production method, injection molding of polycarbonate plastic. Preparation of master tape, the mastering of the glass disc, the production of pressing molds, injection molding, metallization, spin coating, printing, packaging, and quality control are all discussed. Alternative manufacturing methods may simplify the task of making discs; these new methods are explained.

A glossary containing definitions of key technical terms and abbreviations rounds out the presentation.

In summary, this book attempts to cram as much pleasant and useful information into the smallest possible space, rather like the compact disc itself.

Oh, the bits that begin this introduction are from a compact disc recording of Beethoven's *Ninth Symphony*—as we shall see, a work that played an important role in the development of CD technology. It's a little difficult to catch the melody since the bits represent only the first 200 microseconds of the pianissimo opening of the symphony. It gets a little more interesting when the chorus joins in, about five billion bits later.

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4 CD Player Design

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Chapter One

Introduction to the Compact Disc

INTRODUCTION

Let's try a conceptual experiment. From your conceptual seat in your conceptual concert hall, you lean forward in anticipation as the conceptual orchestra begins its conceptual performance of Beethoven's *Tenth Symphony*. (No, I'm not conceptualizing; he really did start a tenth.) Your job is to write down all the information you hear. Ready? Begin!

Whew! After only a few bars, you give up. Even writing down the score in musical notation is overwhelming, much less recording all the timbres, aesthetic considerations, hall acoustics, and so forth.

We have to conclude that music is a surprisingly complex phenomenon; it is filled with information. To store it, we require a system which can deal with incredible amounts of information. It is not surprising that historically the latest and highest technology has always been utilized to make recordings, because only the best technology satisfies our current expectations of what a good recording should sound like. As higher technology was devised and pressed into service, our expectations were redefined. All of which brings us to the topic at hand: digital audio and the compact disc.

ANALOG VERSUS DIGITAL

To understand the nature of analog and digital systems, along with their differences, let's try another conceptual experiment. Suppose that you are stationed in Antarctica. (Since I'm writing this book in Miami in July, this concept has particular appeal to me.) The Audubon Society has charged you with the important mission of noting the effect, if any, of barometric pressure on the mating habits of penguins.

A barometer measures changes in atmospheric pressure. Attached to the barometer is a recording device, a cylinder with graph paper attached to it, and a pen with ink (and anti-freeze). As the atmospheric pressure changes, the pen traces a line on the slowly rotating cylinder. At the end of every day, the cylinder has completed one rotation, and you change paper. You are thus left with a graph of barometric pressure over time.

What you have is an analog recording. It is analog because it is a continuous representation, an analogy or a model of the actual phenomenon. It's very nice, but its accuracy is limited by numerous factors, including the precision of the cylinder's rotation and the flow of ink. Its usefulness is also limited by the fact that its representation is graphical. For example, to communicate your findings to the Audubon Society headquarters, you would have to fax the original graph, and the copy might not be as accurate as the original.

You figure there might be an alternative, and there is. Instead of relying on the graph paper, you decide to document individual readings themselves. You design a device that reads the pressure from the barometer every minute and prints out the number. At the end of a day, there are 1,440 numbers, representing the changing pressure.

What you have is a digital recording. It is digital because the signal is subjected to measurement at discrete points in time, and the information is stored as discrete numbers. It's very nice because the numbers are inherently more robust than the analog graph, and if your digital device is well designed, the numbers are probably more precise. In addition, it is far easier to communicate your findings; simply reading the numbers over the radio would do the job. Moreover, when the scientists at headquarters write down the numbers, they will have an exact copy of your results.

Suppose, however, that the scientists back at headquarters squawk that the numbers are not as good as a graph and complain that there is no record of pressure between each measurement. You could point out that you aren't as stupid as you look. Atmospheric pressure can change only so fast. For example, suppose the barometric pressure was 30.034 inches at 11:01:00 P.M., and 30.036 inches at 11:02:00 P.M. Although you didn't take a reading at 11:01:30 P.M., you can calculate that the pressure was 30.035, and not, say, 29:022. The atmosphere would not work like that. Thus by knowing how fast things change, you can sample often enough to obtain complete information about what's happening.

On the other hand, an event outside the interest of our barometric experiment, such as the overpressure created by a nearby penguin exploding at precisely 11:01:30 P.M., would not be documented. But that doesn't affect our study. By defining how fast things of interest change, we can ignore those events which happen faster.

At any rate, satisfied that the barometric pressure will be accurately documented, you can get down to the primary scientific task of watching the penguins.

Our conceptual experiment illustrates fairly well the relevant differences between analog and digital representations. In fact, barometric pressure is a close analogy to audio signals, since both are simply pressure changes in air. Of course, changes in barometric pressure would produce a very low frequency (about 0.00001 Hz), but if you speeded it up about 100 million times, it might sound musical, or at least like punk rock.

Back to reality. Let's nail down our comparison between analog and digital systems. The principal distinction lies in the way they represent information. Digital information can exist only in pieces, as discrete values, as numbers. This is vastly different from analog information, where one continuous, infinitely indivisible value is recorded.

Analog and digital systems thus differ considerably. There is no doubt about that. Nevertheless, the basic question has still eluded us: Why digital? At first glance, the use of digital technology for audio purposes seems very cumbersome. After all, we must convert sound into a series of numbers, each of which must accurately describe the sound at that instant in time. We must store these billions of numbers and then convert them back into sound to hear what's going on. That's a lot of work. Moreover, since analog audio technology seemed perfectly adequate for a hundred years, is it really necessary to replace analog with digital?

The answer is this: Sure, digital audio is a lot of hassle, but it's worth it. One justification for digital audio lies in the very nature of its signal. Sound is an analog phenomenon, and so is noise. An analog audio device cannot distinguish between them; hence, the noise of an analog signal is the sum total of all the noise introduced in its path. For example, every time an analog tape is copied, its noise increases. The numbers composing a digital signal will carry an error, introduced when they are first selected, but they are impervious to noise; for example, digital copying does not add noise. A digital number cannot become noisy; it is right or wrong.

Analog reproduction is more frail than digital. An analog system introduces distortion as it attempts to convey the exact analog nature of its information. In contrast, a digital system, at least philosophically, has an easy job. It must be able to distinguish only between 1s and 0s to reproduce the signal. The only theoretical limitations are those dictated by the quantity and accuracy of the numbers. In other words, with digital we can more precisely manipulate and process information and thus achieve a more accurate result.

Along similar lines, digital audio is advantageous because its signal is robust. It is a cruel world out there, and under adverse conditions a digital signal suffers less degradation than an analog signal. Moreover, a digital signal suffers no degradation at all until conditions have deteriorated beyond a known level. The design performance of a digital system is designed into its circuits. Performance is thus always a known, defined quantity.

Another justification for digital audio is its consistency of performance. Analog devices can work quite well when they are new, but frequent adjustment and maintenance are necessary to ensure consistent performance. Because digital systems often permit a higher degree of circuit integration, they exhibit greater long-term accuracy, with less performance variation or failure. In fact, when a digital system fails, the problem is often an analog part inside.

Digital circuits are also very efficient because logical functions and operational features can be easily designed and implemented. Moreover, such functions and features can be quickly altered or updated; often the hardware circuit remains unchanged, and a change in programming achieves the new result.

Finally, digital audio's sonic performance is excellent. First-generation digital audio products rivaled the result of a century of analog evolution, and digital's evolution has now surpassed analog's best efforts.

Of course, digital audio isn't perfect—far from it. Its complexity breeds considerable challenges that are not found in analog systems. To use and appreciate such equipment properly, a fair amount of technical understanding is required, as demonstrated in the following pages.

LP VERSUS CD

Many methods of audio storage have evolved since Edison made the first audio recordings in 1877 on a cylinder covered with tin foil. Early acoustical recordings were made on wax cylinder and shellac discs, and many electrical recordings used 78 rpm and long-playing records. Subsequently, numerous magnetic tape formats were developed. However, all of these audio systems shared identical foundations; they recorded and reproduced an analog signal by using a mechanical or electrical pickup in contact with the medium. Overall, this technology is now a mature one and has virtually exhausted the possibilities available within the limitations of analog master tape, phono cartridges, analog circuitry, motors, and mechanical systems.

The difference between analog and digital audio technologies can be illustrated by a close look at a long playing record and a compact disc, illustrated in figure 1.1.

The LP stores its information as an analog groove. Variations in its side-to-side amplitude and depth represent the original audio signal. If someone hit a big drum, the groove would take a big swing. The frequency of the drum sound determines the frequency of the groove's swing, and the amplitude of the drum sound determines the amplitude of the

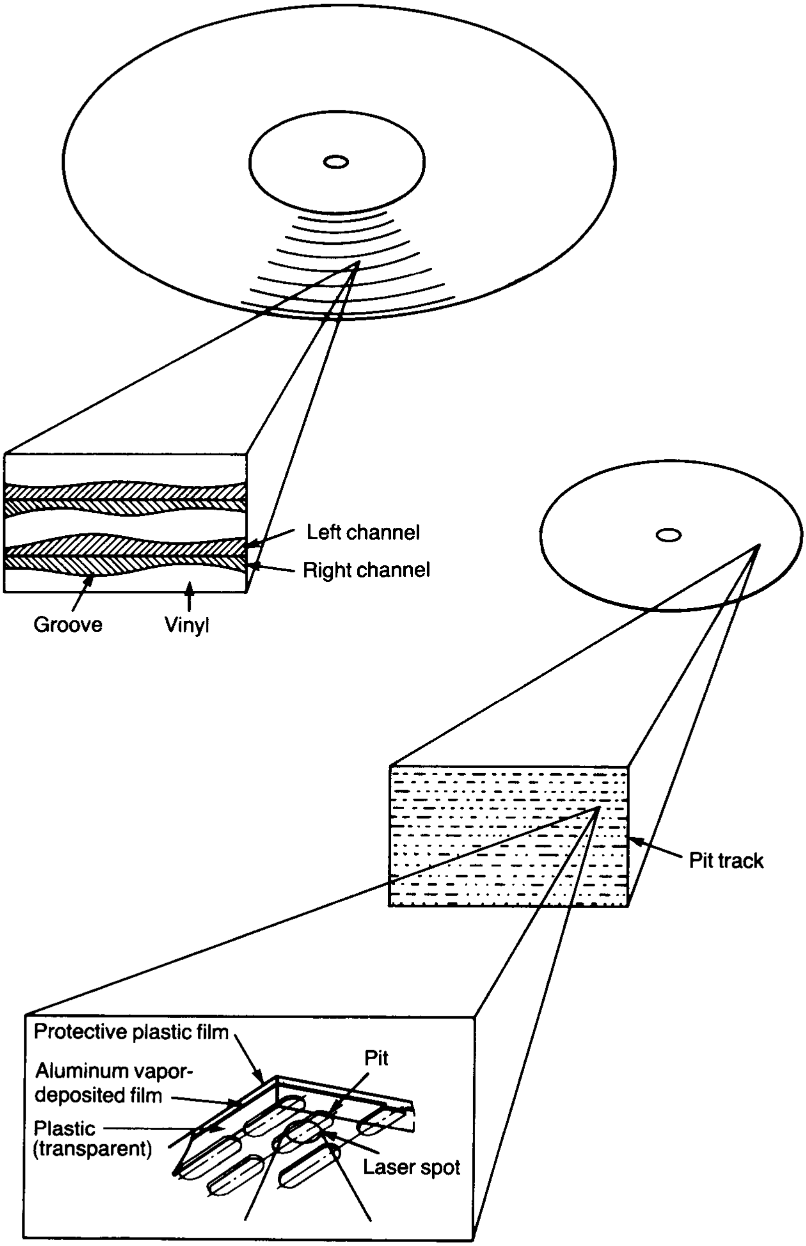

Figure 1.1 *LP grooves, storing analog information, contrasted with CD pits, storing digital information.*

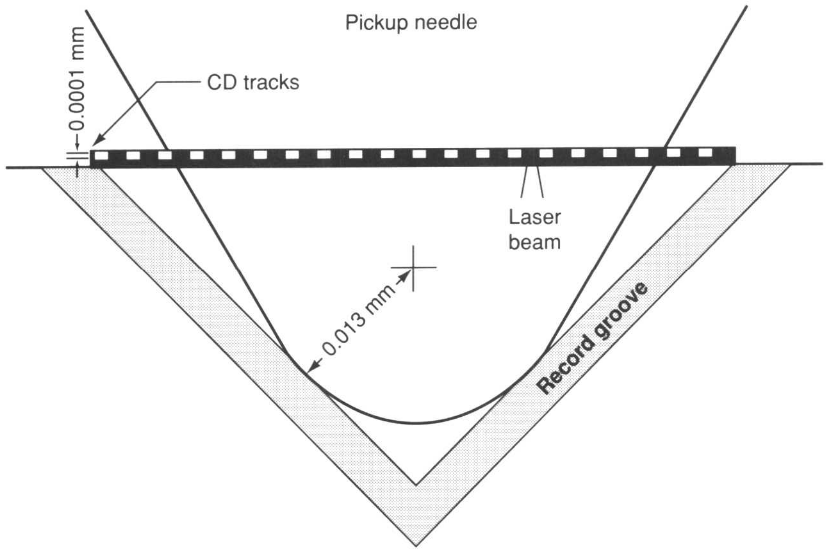

Figure 1.2 *The dimensions of compact disc tracks are small compared to those of an LP microgroove.*

swing. In short, the groove is a physical analogy to the original sound wave. Left and right audio channels are stored on either side of the groove walls. To reproduce the information, a stylus runs through the groove and the phonograph cartridge converts the stylus's mechanical movements into an electrical signal which is amplified. Analog tapes follow the same principles, but, instead of being stored as groove undulations, the analog signal is stored in magnetic orientations of ferrite particles.

The CD stores its information digitally. The length of its data pits represents a series of 1s and 0s—numbers (binary bits, actually) which represent the original audio signal. If someone hit a big drum, the numbers would be different than if there was no drum. Generally, the frequency of the signal is reflected in the rate of change in the numbers, and the amplitude is represented by the magnitude of the numbers. Both audio channels are stored along the same pit track. To read the data, we use a laser beam light source. The numbers are read from the disc as flashes of light and are used to reconstruct the original audio signal. Because nothing (except light) touches the pits, they never wear out.

In practice, the compact disc offers numerous advantages over previously existing audio storage media such as the LP record: The LP must be handled with care to preserve its mechanical groove; groove wear is