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# Principles of Digital Audio

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Fourth Edition

McGraw Hill

Library of Congress Cataloging-in-Publication Data

Pohlmann, Ken C.

Principles of digital audio / Ken C. Pohlmann. — 4th ed.

p. cm.

Includes bibliographical references and index.

ISBN 0-07-134819-0

1. Sound—Recording and reproducing—Digital techniques. I. Title.

TK7881.4 P63 2000

621.389'3—dc21

99-054165

**McGraw-Hill**



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1 2 3 4 5 6 7 8 9 0 AGM/AGM 9 0 5 4 3 2 1 0

ISBN 0-07-134819-0

*The sponsoring editor for this book was Stephen S. Chapman and the production supervisor was Maureen Harper. It was set in Century Schoolbook by Pro-Image Corporation.*

*Printed and bound by Quebecor / Martinsburg.*



*This book was printed on recycled, acid-free paper containing a minimum of 50% recycled, de-inked fiber.*

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## The Compact Disc

The compact disc system is perhaps the most remarkable development in audio technology since the birth of the technology in 1877 with Edison's invention of the tinfoil recorder and the commercial cylinder record. It embodies many revolutionary steps in design, such as digital signal storage, optical scanning, error correction, and new manufacturing processes; altogether it established a new fidelity standard for the consumer. In addition, compact disc music playback is only one aspect of the many CD applications available.

The compact disc system contains several unique technologies original to the audio field; when combined, they form an unprecedented means of storage. A compact disc contains digitally encoded data that is read by a laser beam. Because the laser is focused on a reflective layer embedded within the disc, dust and fingerprints on the reading surface do not normally affect reproduction. The effect of most errors that normally occur can be minimized by error correction circuitry. Because no stylus touches the disc surface, there is no disc wear, no matter how often the disc is played. Thus, digital storage, error correction, and disc longevity result in a robust digital storage medium. Above all, the CD offers high-density data storage. Whereas the (analog) Edison cylinder stored the equivalent of 100 bits/mm<sup>2</sup>, the CD stores about 1 million bits/mm<sup>2</sup>. But as impressive as the CD is, the SACD format surpasses it.

### Invention of the Compact Disc

The chronology of events in the development of the compact disc spans almost a decade from inception to introduction. Even then, the development of optical disc storage predates the CD by several more decades. The compact disc incorporates many technologies pioneered by many individuals and corporations; however, Philips Corporation of the Netherlands and Sony Corporation

inal standard established by these two companies guarantees that discs and players made by different manufacturers are compatible. The CD-Audio or CD-DA format is sometimes called the Red Book standard (after the color of the notebook used to hold the original specification). It is specified in the IEC 908 standard, (International Electrotechnical Commission) available from the American National Standards Institute.

Philips began working on optical disc storage of images in 1969. It first announced the technique of storing audio material optically in 1972. Analog modulation methods used for video storage were deemed unsuitable, and the possibility of digital signal encoding was examined. Furthermore, Philips established laser readout and small disc diameter as a design prerequisite. Sony similarly had explored the possibility of an optical, large-diameter audio disc, and had extensively researched the error processing and channel coding requirements for a practical realization of the system. Other manufacturers such as Mitsubishi, Hitachi, Matsushita, JVC, Sanyo, Toshiba, and Pioneer advanced proposals for a digital audio disc. By 1977, numerous manufacturers had shown prototype optical disc audio players. In 1978, Philips and Sony designated disc characteristics, signal format and error-correction methods, and in 1979 they reached an agreement in principle to collaborate (with design meetings from August 1979 through May 1980), with decisions on signal format and disc material. In June 1980, they jointly proposed the Compact Disc Digital Audio system, which was subsequently adopted by the Digital Audio Disc Committee, a group representing over 25 manufacturers.

Following development of a semiconductor laser pickup and LSI (large-scale integration) circuits for signal processing and D/A conversion, the compact disc system was introduced in October of 1982 in Japan and Europe. In March 1983, the compact disc was made available in the United States. Over 350,000 players and 5.5 million discs were sold worldwide in 1983, and 900,000 players and 17 million discs in 1984, making the CD one of the most successful electronic products ever introduced. Starting with the original CD-DA format, the compact disc family was expanded to include CD-ROM (1984), CD-i (1986), CD-WO (1988), Video-CD (1994) and CD-RW (1996) with a host of applications in data, audio, video, and beyond. Today, well over a billion discs are sold annually. The SACD, introduced in 1999, incorporates aspects of the CD, but is more revolutionary than evolutionary.

### Compact Disc Overview

The compact disc system is a highly efficient information storage system. Each audio disc stores a stereo audio signal comprised of two 16-bit data words sampled at 44.1 kHz; thus 1.41 million bits/second of audio data are output from the player. Other data overhead such as error correction, synchronization, and modulation are required, which triple the number of bits stored on

cm in diameter, and costs a few cents to manufacture. Apart from modulation and error correction overhead, a CD-DA disc holds a maximum of 6.3 billion bits, or 783 million bytes of user information (1.41 million bits per second, for 74 minutes).

A standard compact disc has a maximum playing time of 74 minutes, 33 seconds. By varying the CD standards slightly, playing times of over 80 minutes can be achieved. For example, a track pitch of 1.5  $\mu\text{m}$  and linear velocity of 1.2 m/s would yield about 82 minutes of playing time.

Information is contained in pits impressed into the disc's plastic substrate. That surface is metalized to reflect the laser beam used to read the data from underneath the disc. A pit is about 0.6  $\mu\text{m}$  wide (about the width of 500 hydrogen atoms) and a disc might hold about two billion of them. If a disc were enlarged so that its pits were the size of grains of rice, the disc would be half a mile in diameter. Each pit edge represents a binary 1; flat areas between pits or areas within pits are decoded as binary 0s. Data is read from the disc as a change in intensity of reflected laser light; reading a CD causes no more wear to the recording than your reading causes to the words printed on this page (also conveyed to your eyes via reflected light).

The pits are aligned in a spiral track running from the inside diameter of the disc to the outside. CDs with maximum playing times contain data to within 3 mm of the outer disc edge. CDs with shorter playing times have an unused area at the outer edge. This allows a greater manufacturing yield because errors tend to increase at the outer diameter, and the disc is oblivious to fingerprints on the empty outer diameter. If unwound, a CD track would run for three miles. The pitch (distance between adjacent tracks) of the CD spiral is nominally 1.6  $\mu\text{m}$ . The period at the end of this sentence would cover more than 200 tracks. There are 22,188 revolutions across the disc's signal surface of 35.5 mm.

An optical pickup retrieves data. A laser beam is emitted and is guided through optics to the disc surface. The reflected light is detected by the pickup, and the data from the disc conveyed on the beam is converted to an electrical signal. Because nothing touches the disc except light, light itself and electrical servo circuits are used to keep the laser beam properly focused on the disc surface and properly aligned with the spiral track. The pits are encoded with eight-to-fourteen modulation (EFM) for greater storage density, and Cross-Interleave Reed-Solomon code (CIRC) for error correction; circuits in players provide demodulation and error correction. When the audio data has been properly recovered from the disc and converted into a binary signal, it is input to digital oversampling filters and D/A converters to reconstruct the analog signal.

Music CDs delivers high fidelity sound with outstanding performance specifications. With 16-bit quantization sampled at 44.1 kHz, players typically exhibit a frequency response of 5 Hz to 20 kHz with a deviation of  $\pm 0.2$  dB.

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