OPTICAL CD-ROMs FOR CONSUMER ELECTRONICS

CD-ROMs have become a standard feature of most new personal computers. The acronym CD-ROM stands for compact disc—read-only memory. Because of their large storage capacity and relatively low cost, CD-ROMs have been an extremely successful medium for distributing computer software and information, as well as for storing business records. Compact discs (CDs) were originally developed for the audio music industry as a replacement and improvement over long-playing (LP) records. CDs for music distribution have been phenomenally successful and virtually replaced LP records in less than a decade. Unlike vinyl records and various forms of magnetic data storage, CDs and CD-ROMs have no contact between the read head and the disk itself. With proper handling, CDs and CD-ROMs could last a lifetime.

Figure 1. A CD-ROM disk is 120 mm in diameter and can hold up to 650 Mbytes of information.

CD-ROMs are an excellent example of multimedia. Multimedia computing is usually defined as a blend of media types: audio, text, images, graphics, and video. With CD-ROMs, all these media types can be delivered in one convenient and durable form.

A CD-ROM is, by definition, a read-only storage device. Recordable versions of CDs are also available and are discussed later in the section on recordable CDs. The term CD-ROM correctly refers to the disk itself (see Fig. 1). In order to be read, a CD-ROM disk must be inserted in a CD-ROM drive mechanism or “player” (see Fig. 2). CD-ROM drives are available in both “internal” versions (for incorporation into a computer) and “external” stand-alone versions. An adapter card

Figure 2. A CD-ROM drive (player) is a common component of most new personal computers.

is normally used to connect the CD-ROM drive with the computer.

CD-ROM DISKS

The original CD for music was developed jointly by Philips Electronics of the Netherlands and Sony of Japan. The specifications for this audio CD were included in a guide issued in 1981 by Philips and Sony. This guide is called the Red Book. This Red Book is the foundation upon which all CD and CD-ROM standards have been built. First commercial shipments of audio CD disks and players occurred in 1982. The physical characteristics of CD-ROMs are the same as audio CDs. The basic CD or CD-ROM consists of a molded polycarbonate substrate (120 mm in diameter and 1.2 mm thick), a thin metallic reflective layer (usually aluminum), and a lacquer protective coating on top of the metallic layer. The information is read from the side with the polycarbonate substrate, which is opposite the lacquer protective coating. Labels are printed on the lacquer surface. The data are molded into the polycarbonate substrate as various lengths of pits along a continuous spiral track. The metallic layer produces a reflective surface. A laser head in the drive mechanism detects the differences in reflectivity between areas with pits and areas without pits. These differences in reflectivity provide both tracking information and the data (or audio) stream.

The same data density is used for both audio CDs and CD-ROMs. Sound on an audio CD is digitized by sampling at a rate of 44.1 kHz and converting each sample into 16 bits. Original audio CDs hold up to 74 min of audio in up to 99 tracks (songs). Although the "raw" data capacity of a CD-ROM is as much as 780 Mbytes, a typical CD-ROM will actually hold approximately 650 Mbytes of information. The rest of the capacity is used for formatting, sector identification, and error detection/correction codes.

The basic specifications for CD-ROMs were published by Philips and Sony in 1983 (the Yellow Book). Unlike an audio CD, a CD-ROM is used to store computer data in the form of text, graphics, images, and video, as well as sound. Additional error detection and correction is included in the specifications for CD-ROMs as compared with audio CDs. A series of incorrect bits may not be critical for music but may be very important for data.

A CD-ROM with a silver color is usually considered a "stamped" or "pressed" disk. These disks have been mass produced in a factory that uses injection molding equipment (see the section on CD-ROM disk manufacturing). CD-ROMs with a gold or blue-green color are usually produced one at a time using CD-R disks and recorders (see the section on recordable CDs). Either type of disk will be readable in a standard CD-ROM drive if the drive can recognize the disk's format (see the section on CD-ROM Formats). The major computer manufacturers have exerted considerable effort to ensure compatibility of CD-ROMs across a wide range of platforms.

A CD-ROM disk is designed as a CLV (constant linear velocity) device, as are audio CDs. In contrast, hard disk drives and floppies are CAV (constant angular velocity) devices. Both of these terms refer to the rotational speed of the disk versus the speed of the data passing by the laser read head. In a CLV device, the speed (i.e., transfer rate) of the data is constant at any point on the disk. In order to maintain this constant transfer rate, the rotational speed of the disk must be continuously changed as the head moves across the disk (because the data density is the same at any place on the disk). Therefore, the disk will normally spin more than twice as fast when the head is positioned at the inner diameter than at the outer diameter. However, some of the faster CD-ROM drives may operate in both CLV and CAV modes.

CD-ROM DRIVES (PLAYERS)

The most frequently cited CD-ROM drive specification refers to its transfer rate (and consequently to the rotational speed of the disk). A 2× CD-ROM drive has a transfer rate twice as fast as a standard CD audio drive. Consequently, a 2× drive spindle motor must spin twice as fast as a standard CD audio drive. A standard CD audio drive varies from a rate of 200 rpm at the outer diameter to over 500 rpm at the inner diameter. The standard CD audio drive has a transfer rate of 150 kbyte/s (this could be considered a 1× speed). Therefore, a 2× CD-ROM drive has a transfer rate of 300 kbyte/s and rotates twice as fast at any point on the disk as a 1× drive. A 4× drive has a transfer rate of 600 kbyte/s and so on. Some of the faster CD-ROM drives that have specifications of 16× or higher may refer to the fastest transfer rate available on the disk and not to the transfer rate across the entire disk. These faster transfer rates are particularly important for transferring large files (such as high-resolution graphics) and less important for transferring lots of smaller files. In addition, digitized full-motion video requires not only a tremendous amount of storage space but also fast transfer rates.

Another important specification is access time. CD-ROMs are random access storage devices, as are floppy disks and hard disks. Access time refers to the time required to position the head from one point to another point on the disk. CD-ROM drives tend to be much slower than magnetic hard disk drives. Average access times for a CD-ROM drive range from approximately 100 ms to approximately 300 ms. Hard disk drives normally have average access times of less than 10 ms. One of the reasons for the slower access times of CD-ROM drives is that the rotational speed of the disk (and consequently the spindle motor) must change when the head is moved. Hard disk drives are typically CAV devices, so the rotational speed is always constant.

CD-ROM APPLICATIONS FOR CONSUMERS

CD-ROMs have partially replaced floppy disks as a means of software distribution. The standard 3.5-in. floppy disk at 1.44 Mbytes is very inexpensive, but it is incapable of efficiently distributing large user-friendly software programs that may require tens or hundreds of megabytes. CD-ROMs can be produced inexpensively (less than $0.60 each in large quantities) and are capable of storing as much as 450 standard 3.5-in. floppy disks. The primary drawback of CD-ROMs as compared to floppy disks is that CD-ROMs are a read-only media and consequently are not reusable. However, for many publishers of software programs and other databases, this lack of recordability is actually considered an advantage because it makes software piracy more difficult (but certainly not impossible).

The terms *publishing* and *authoring* are frequently used in conjunction with production and distribution of CD-ROMs. Sometimes the process of preparing CD-ROMs is simply known as optical publishing. CD-ROMs can be compared with other mass-produced media, such as books and newspapers. Books and newspapers are also read-only and are also relatively low-cost on a per-unit basis when produced in large quantities. Some of the first CD-ROMs were used for distribution of large databases, such as telephone directories, census data, and scientific bibliographies. Encyclopedias and dictionaries have also been published on CD-ROMs. Early CD-ROMs primarily consisted of text-based material with appropriate indexing. For example, some of the early CD-ROMs were produced by converting encyclopedias into digital text form and adding retrieval options to help the consumer find information. These CD-ROMs could frequently be produced for less than the cost of *shipping* a multivolume hardbound edition of essentially the same encyclopedia. The primary advantage of these early CD-ROMs versus hard copy or microforms was improved speed of information retrieval. Later versions of CD-ROM reference material added sound and even video capabilities, a huge advantage over hard copy.

The advent of powerful, image-capable personal computers led to a boom in CD-ROM applications. Beginning in 1996, essentially all new personal computers incorporated CD-ROM drives. Approximately 700 million CD-ROM disks shipped in 1996. This boom in popularity was largely due to the demand for high-resolution graphics, video, and high-quality digitized sound for computer programs, games, and even reference material. In addition, these CD-ROMs include improved search and linkage capability, enabling the consumer to explore topics quickly and easily. CD-ROMs proved to be ideal for distributing a wide range of consumer software titles.

Beginning in 1996, the primary competition to CD-ROMs for consumers appeared to be the information available on the Internet, primarily via the *World Wide Web*. The World Wide Web also provides the consumer with access to an enormous amount of information on every conceivable subject. Downloading information from the web, however, can be very time-consuming, whereas accessing information on a CD-ROM can be very quick. Hybrid CD-ROMs that take advantage of the strengths of both technologies have been developed. These hybrid CD-ROMs will normally contain a huge static database (information that does not change, such as historical data) with links to a web site for updated information.

TYPES OF CONSUMER CD-ROMs

Reference Material

Extremely large databases of information, such as encyclopedias, continue to be ideally suited to the capabilities of CD-ROMs. Microsoft's Encarta is an example of an interactive encyclopedia that includes thousands of full color photographs, hours of audio information, video clips, and sophisticated search capabilities. Rather than simply describing musical instruments, for example, these CD-ROM encyclopedias have the capability of providing the actual sound of instruments being played. Or rather than describing a space shuttle launch in words and pictures, these CD-ROM encyclopedias can create a video of an actual launch complete with billowing fire and roaring sound. Other reference CD-ROMs include dictionaries, thesauri, almanacs, and atlases. These CD-ROMs all include interactive search features, enabling the consumer to thoroughly research a subject or simply browse through the massive amounts of information. Other reference CD-ROMs include libraries of classic literature. These libraries will normally include the full text of hundreds of classic books, plays, and poetry.

Business and Productivity

CD-ROMs for businesses include disks that contain regulations, phone directories, and tax information. Interactive financial planning and sales training can be accomplished with CD-ROMs. In addition, salespeople use CD-ROMs for business presentations. Frequently, a CD-ROM containing relevant company information can be left with a customer after the presentation.

Education

A huge amount of course material has been packaged on CD-ROMs. Because of the audio capabilities of CD-ROMs, instruction in foreign languages is one ideal application. Many personal computers include sound cards that enable the student to record his or her own pronunciation to compare with the sample pronunciation. The student is then able to repeat the words or phases until satisfied. Other educational disks include essentially every subject taught in schools and colleges. Instruction in art appreciation will, for example, include color images of nearly every important work of art in existence.

Movies, Music, and Television

The subjects of movies, music, and television are of interest to an extremely large percentage of the population. These subjects are a part of everyone's lives. Therefore, it should come as no surprise that a large number of CD-ROMs cover these topics. In addition to massive databases of information (statistics, reviews, etc.), these CD-ROMs will normally include video and audio clips.

Children's Disks

Some of the most popular CD-ROM titles are designed specifically for children. Children are not intimidated by computers, as are many adults. These CD-ROMs normally include high-resolution color graphics and sound. However, one of the most important elements of a children's CD-ROM is interactivity. The child must respond in order to move forward through the program. In doing so, the child will learn to move through a series of adventures by picking correct answers. Catchy music and tones add to the child's enjoyment.

Games

Games are one of the most profitable CD-ROM products. Games include basic casino-type games as well as fast-moving animated action games. Most of these games have been developed to allow for varying degrees of player skill. Many games also involve puzzles that must be solved before moving to another level. Many, many man-hours of development and testing are required prior to release of any of these games.

Graphics

Many CD-ROMs, which contain thousands of digitized graphic images ("clip art"), are available. The consumer can integrate this clip art into their personal documents. In addition, libraries of photographs are available on CD-ROM. Both professionals and amateurs can develop professional-looking presentations using these images.

General Interest

CD-ROMs continue to be developed for a wide range of interests. Subjects include health care, travel, sports, homes, and essentially any other subject of interest to consumers. Just as books and magazines are available on any conceivable subject, CD-ROMs will be developed for these subjects also.

CD-ROM APPLICATIONS FOR BUSINESS

Whereas consumer-oriented applications may be more glamorous, businesses also use CD-ROMs for archiving, backing up, and distributing computerized information and documentation. All businesses generate information, from accounting data to engineering specifications to marketing correspondence. The larger the company, typically the more information that is generated. Some information is already in computer formats; other information (such as microfilm or printed paper) may need to be scanned and digitized in order to be stored in a computer. A typical company will need to handle various types of computer storage media in developing its strategies for information retrieval systems. The hierarchy of computer storage possibilities ranges from very fast, very expensive (e.g., internal semiconductor memory) to not-so-fast, very inexpensive (e.g., tape cartridges). CD-ROMs and recordable CDs fall into the range of not so fast (but typically faster than tape) and relatively inexpensive.

CD-ROM FORMATS

The primary defining documents for CD-ROM standards have been a series of Books, named according to the color of their binders. As mentioned previously, the foundation for all CD and CD-ROM formats is the Red Book, published by Philips and Sony in 1981. An audio CD compatible with the Red Book is also known as a CD-DA (for Compact Disc-Digital Audio). The Red Book specifies a maximum of 99 "tracks." These tracks could be any length up to the maximum size of the disk. For an audio CD, these tracks would normally be one song. (Do not confuse this definition of *track* with the fact that each disk contains one continuous spiral track that starts at the inner diameter and ends at the outer diameter.) Each track is subdivided into sectors (also called blocks). The length of time for each sector is specified to be 1/75th of a second. Sectors should be considered the fundamental unit of measure for a CD. Each sector will contain 2352 bytes. Each track must have a minimum of 300 sectors. The sector size is identical for both CD audio and CD-ROM disks. However, CD-ROM sectors contain extra layers of error detection and correction, as well as synchronization and header information. The error detection and correction schemes specified in the Red Book comply with Cross Interleaved Reed Solomon codes (CIRC).

The Red Book also specifies a maximum BLER (block error rate) as a measure of the data integrity of a CD. The BLER indicates the number of blocks (or sectors) that contain erroneous bytes during a read from the CD. An average BLER of 220 is considered acceptable, although most manufacturers will set a higher standard.

Because the data on CDs is represented by a series of pits and lands, a modulation system is needed to control the range of pit sizes being written to the disk. The modulation system used for CDs is termed EFM (eight-to-fourteen modulation). Each 8-bit magnetic byte is modulated into a 14-bit optical byte. The bits in an optical byte are known as channel bits. Three more channel bits are added to the optical byte to eliminate transition conflicts between consecutive optical bytes. These 17 bits are then demodulated by the drive electronics to provide the appropriate 8-bit byte to the computer.

Yellow Book

The original CD-ROM physical specifications were included in a document called the Yellow Book published by Philips and Sony in 1983. It is important to note that these specifications defined only the *physical format,* not the *logical format* for CD-ROMs. The physical format defines not only the physical attributes of the disk but also the way in which the data are laid out on the disk (i.e., data modes, error detection and correction, and physical sector addressing). The Yellow Book included a definition of Mode 1 and Mode 2 sectors. Mode 1 sectors contain 2048 bytes of user data in the total sector size of 2352 bytes. The remaining bytes are used for synchronization and header and error detection/correction. The original Mode 2 sectors contained 2336 bytes of user data and less error correction capability. However, this original definition of Mode 2 sectors is rarely used and has been supplanted by Mode 2/XA formats. See Fig. 3 for comparisons of the various sector formats. A CD-ROM will contain approximately 345,000 of these sectors.

Five years after the original publication of the Yellow Book, further extensions were felt necessary and the concepts of Mode 2, *Forms 1 and 2* were introduced. Mode 1 is usually used for computer data because of the extra layers of error correction. Mode 2 sectors provide 14% more capacity than Mode 1 sectors and were originally intended for applications where error correction is not as critical. However, CD-ROM Extended Architecture (CD-ROM/XA) was developed by Sony, Philips, and Microsoft and introduced in 1988. CD-ROM/XA further defined these Mode 2 sectors to allow text, graphics, and audio files to be jointly displayed. This extension to the Yellow Book defined CD-ROM/XA Mode 2, Form 1 for computer data and CD-ROM/XA Mode 2, Form 2 for compressed audio, pictures, and video. CD-ROM/XA allowed interleaving of computer data and compressed audio/video on the same track such that they *appear* to be playing back at the same time.

ISO 9660

ISO 9660 is a basic *logical* format structure that supplements the Yellow Book. The Yellow Book specifications alone did not ensure interchangeability of CD-ROMs if different logical file structures are used in formatting of the disks. Most commercial CD-ROMs today use the ISO 9660 logical structure, which specifies a volume and file structure. This logical struc-

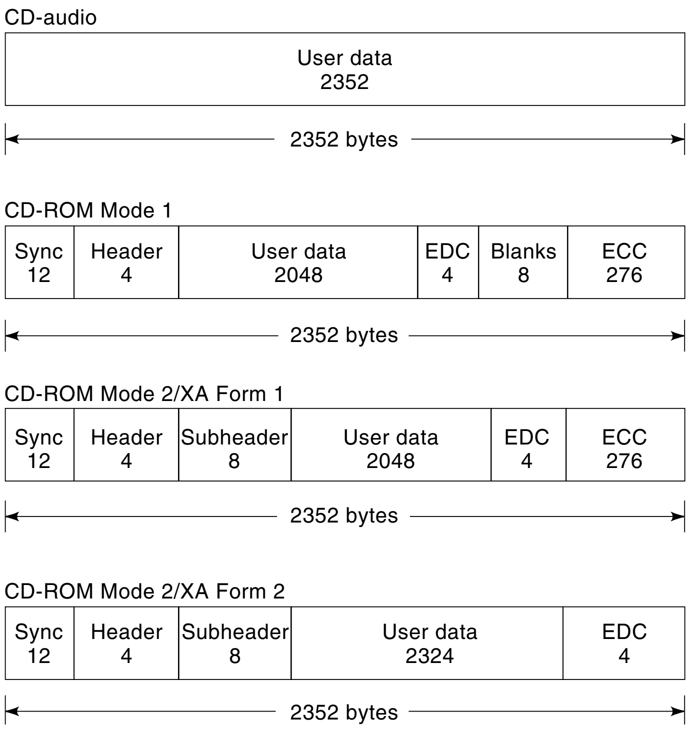

Figure 3. The fundamental unit of measure for all CD-ROM formats is the sector. The sector formats for most types of CD-ROMs are shown and compared with a sector for a CD audio disk. Each sector contains 2352 bytes, but these bytes are used differently depending on the particular format. A CD-ROM will contain approximately 345,000 of these sectors.

ture is defined in a document issued by the International Standards Organization (ISO). The formal title is "ISO 9660: Information Processing—Volume and File Structure of CD-ROM for Information Exchange (1988)." The ISO 9660 format ensures interchangeability of CD-ROMs between various computer platforms and operating systems because essentially all major computer manufacturers have agreed to recognize this format. For example, Microsoft developed an extension to their operating system named mscdex.exe to recognize standard CD-ROM formats. The mscdex.exe program is loaded by autoexec.bat and allows a standard personal computer to designate a CD-ROM drive as a drive letter. Other computer manufacturers developed similar programs to recognize CD-ROMs.

The ISO 9660 document was based on a working paper developed by representatives of major companies in the computer industry. This working paper was called the High Sierra Format (HSF) and was issued in 1986 after a meeting at a hotel (the Del Webb High Sierra Resort and Casino) in Lake Tahoe, Nevada. The ISO 9660 format is essentially the same as the HSF format with a few minor modifications and extensions. The multiplatform nature of the ISO 9660 format has been largely responsible for the worldwide acceptance of CD-ROMs. Furthermore, the logical structure of ISO 9660 has been the basis for many of the enhancements of CD-ROM.

In order to accommodate as many different operating systems as possible, various restrictions had to be applied in development of the ISO 9660 file structure. Some of the primary restrictions are:

1. No directory trees are deeper than eight (8);
2. The file name length must be less than 30 characters, although this is usually limited to 8 characters, followed by a period, plus 3 characters (to be compatible with MS-DOS);
3. There are no extensions for directory names;
4. The alpha-numerical characters are limited to A to Z, 0 to 9, and _ (underscore);
5. Only uppercase characters are allowed.

Extensions to these restrictions were later developed to accommodate the unique features of certain operating systems (see section on Rock Ridge Interchange Protocol).

Green Book

In 1987, Philips and Sony published the Green Book, which set the standards for CD-I (Compact Disc Interactive). CD-I disks require a CD-I player that connects to a television set or computer monitor. CD-I is a format that stores audio, still video pictures, animated graphics, and full motion video. The CD-I format adopted the MPEG 1 (Motion Picture Experts Group 1) standard for representation of video and audio data. In addition, another audio compression scheme called Adaptive Pulse Code Modulation (ADPCM) can be used with CD-I (as well as with CD-ROM/XA) applications. ADPCM produces audio signals that have less than audio CD quality but that require much less capacity. For example, up to 20 h of monaural sound could be recorded on one CD using the lowest level of ADPCM encoding. The sector layouts for CD-I are identical to CD-ROM/XA, but use some of the bytes in a different manner. A CD-I player will also be able to read video CDs, photo CDs, and audio CDs, as well as CD-I disks.

White Book

The White Book was issued by Philips, Matsushita Electric Industrial, Ltd. and Victor Company of Japan (JVC) in 1993. This document defined standards for CDs that could be played in both CD-ROM/XA and CD-I compatible drives. These CDs are sometimes referred to as bridge disks. Types of disks that adhere to this standard include karaoke CDs, video CDs, and Kodak's photo CDs. The photo CD system was developed by Eastman Kodak Company and Philips to transfer images from various types of film (primarily 35 mm) to a CD. The images on these CDs can then be viewed on a standard television monitor using players compatible with the photo CD standard. Photo CD disks are normally write-once disks, which also adhere to another document, the Orange Book.

Video CDs also implemented the MPEG 1 standard (see section on the Green Book). MPEG technology can compress the data down to 1/50 of its original size or smaller. MPEG reduces data by taking out information that does not change between video frames.

Orange Book

The Orange Book differs significantly from the prior Books. All the prior Books defined the specifications for read-only disks, whereas the Orange Book defines specifications for recordable CD disks. Therefore, an Orange Book disk will be "pregrooved" for tracking but will contain no data. Once written, however, an Orange Book disk must adhere to one of the CD-ROM formats in order to be readable in standard players. The Orange Book is divided into two parts. Part I describes a CD-MO (Compact Disc-Magneto Optical) rewritable disk. Part II describes a CD-WO (Write-Once) disk where the data can be written, but not erased. CD-MO disks have never been commercialized. Both CD-R (described in more detail in the section on Recordable CDs) and Kodak's photo CD are in compliance with Part II of the Orange Book.

Single Sessions vs. Multisessions

The subject of single-session versus multisessions tends to be mainly applicable to recordable CDs. However, a prepressed CD-ROM may also be a multisession disk. The original CD audio specification (Red Book) defined only a single-session disk with a "lead-in" area, a program area (where the songs were recorded), and a "lead-out" area. With the emergence of recordable CDs, the concept of multisession CDs was introduced. Each "session" on a multisession CD will have its own lead-in and lead-out area. The table of contents (TOC) for a Red Book disk is defined as being located in the lead-in area. However, a multisession disk has an overall TOC that is written at "closing"—after the last session is recorded. A good example of a multisession CD is the Kodak photo CD onto which additional images can be added until the disk is full. Earlier versions of CD drives would only be able to read the first session. Most current CD-ROM drives are capable of reading multisession disks.

Mixed Mode

CDs containing more than one type of track are termed mixed mode. Each track on a CD must be one and only one of the following: CD-Audio, CD-ROM Mode 1, CD-ROM Mode 2, CD-ROM/XA, or CD-I. The most common type of mixed mode disk contains CD-ROM Mode 1 data in the first track and CD-audio in the remaining tracks. Early CD audio players would attempt to "play" the first track, resulting in harsh static. Newer audio CD players mute this first track.

Blue Book

The Blue Book specifies a standard for CD+ disks (also known as Enhanced CD). These disks are a combination of audio, graphics, and video. As opposed to mixed mode CDs, a CD+ disk contains audio tracks at the beginning (in the first "session"—see section on Single Sessions versus Multisessions). These disks are sometimes referred to as stamped multisession CDs. When played in a standard CD audio player, the audio tracks will be played as normal (because the audio CD player will recognize only the first session). When the disk is inserted in a CD-ROM drive with appropriate software, the graphics and video tracks in the second session can also be accessed.

Rock Ridge Interchange Protocol

The Rock Ridge Interchange Protocol is an extension of the ISO 9660 file structure. This protocol was designed for UNIX and POSIX compliant systems. The protocol allows the disk to appear more like a UNIX File System, but maintains ISO 9660 compatibility. For example, the protocol provides longer filenames than allowed by MS-DOS. The CD-ROM drive must use driver software that understands Rock Ridge protocols in order to take advantage of the UNIX-like features. Otherwise, the disk will appear to be a standard ISO 9660 CD-ROM.

CD+G

A CD plus Graphics (CD+G) disk is a standard audio disk that contains a limited amount of graphics in defined subcode channels. A special CD+G or karaoke player is required to read the graphics portion, but the disk will play as normal in a standard CD audio player.

Other CD-ROM Formats

Other CD-ROM formats are available, such as disks compatible only with Apple's Macintosh operating system (Apple computers will also recognize disks with ISO 9660 file structure). In the case of Apple, these disks have been produced only for Apple computers and maintain the look and feel of the Apple operating system. Disks have also been recorded in a variety of other formats. However, most of these formats tend to be proprietary to individual companies and not intended for interchange.

CD-ROM DISK PHYSICAL CONSTRUCTION

All CDs are 120 mm (approximately 4.75 in.) in diameter and slightly more than 1.2 mm thick. The center hole is 15 mm in diameter. Track spacing is 1.6 μm. The recording area has a minimum diameter of 46 mm and a maximum diameter of 117 mm. The allowed signal area has a minimum diameter of 50 mm and a maximum diameter of 116 mm. A cross section of the disk shows three layers (see Fig. 4). The side nearest the laser head in the drive consists of a 1.2 mm thick polycarbonate substrate. Polycarbonate is the material most manufacturers use for the substrate, although any material with a refraction index of 1.55 would be acceptable. A thin metal layer is deposited on this substrate. This metal layer is typically aluminum, but other metals may be used as long as they have the appropriate reflective characteristics. The final layer (sometimes considered the top layer) is a thin coat of protec-

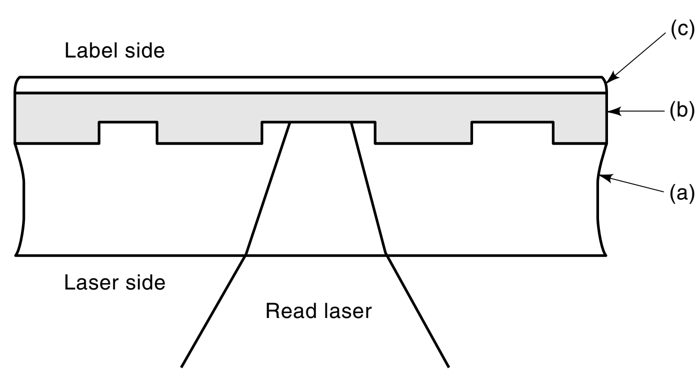

Figure 4. The three layers of a CD-ROM disk are (a) a 1.2 mm injection molded polycarbonate substrate, (b) a metallic (usually aluminum) reflective layer, and (c) a lacquer protective layer. The information is molded into the polycarbonate layer.

tive lacquer or resin. The labels for the CD are printed on the lacquer surface. The laser beam from the head focuses through the polycarbonate substrate to the reflective metal layer. The surface that is most susceptible to damage is the lacquer surface (i.e., the label surface) because it is the closest to the information layer.

The information is injection molded into the polycarbonate substrate as a series of pits along a continuous spiral track. The laser focuses on the reflective metal surface (see Fig. 4). Areas without pits will reflect more light than areas with pits because of the scattering of the light reflected from the pits. The areas without pits have a reflectivity of approximately 70%. The pits have a reflectivity of approximately 30%. These differences in reflectivity are decoded as the data stream from the disk. The reflectivity difference between the track (with pits) and the area between tracks (without pits) is used for servo tracking.

PRODUCTION OF CD-ROM DISKS

Premastering

The first step in developing a CD-ROM is a process called premastering. The information that eventually will be injection molded into the disk must be prepared in accordance with the appropriate CD-ROM data structures, normally ISO 9660. The CD-ROM application is normally developed first on a hard disk, where the correct data structures and indexing are prepared. At this point, the application can be tested (or "simulated") to ensure proper operation of all the functions. This information is then considered to be an "image" of the application. The image is then converted to a premastered file, which is one large ISO 9660 volume file (for example) consisting of a chain of correctly formatted CD-ROM sectors. This premastered file can then be written to a CD-R (CD Recordable) disk. This CD-R should then be equivalent to the final CD-ROM and can then be tested in a standard CD-ROM drive to ensure complete functionality. After thorough testing, the CD-R disk can then be sent to a CD-ROM disk manufacturer for further processing. The CD-ROM image could alternatively be sent to the manufacturer on magnetic tape cartridges or other removable storage media.

CD-ROM Disk Manufacturing

CD-ROM disk manufacturers are normally capable of manufacturing millions of disks every year. The same basic manufacturing equipment used to produce audio CDs can be used to produce CD-ROMs. The investment in mastering and injection-molding equipment is very high, costing millions of dollars. Because tiny dust particles can create enormous problems during creation of a CD, most of the manufacturing process is conducted in very strictly controlled clean rooms. Workers in these clean rooms must wear special clothing and masks in order to prevent contamination of the disk masters or of the disks themselves. Extremely strict clean room disciplines are enforced during any process between the glass substrate preparation stage and the application of the final lacquer coating.

Glass Substrate Preparation and Mastering

Preparation of a glass substrate is the first stage of the mastering process. The glass substrate is a round disk of polished glass. A liquid layer of material called photoresist is spin-coated evenly onto the glass. The glass substrate with photoresist is then baked. After baking, the glass substrate with the photoresist is called a glass master. At this stage, the glass substrate is generic and contains no data.

After the CD manufacturer is assured that the data image (see the section on premastering) is properly formatted, one of the prepared glass masters is placed into a laser beam recorder connected to a computer. The image is then read from the computer and recorded to the photoresist on the spinning glass master by pulsing a high-precision laser. The recording process at this stage is extremely critical. Strict temperature and vibrational controls are employed to ensure an accurate recording. The data are recorded from the center of the glass master in a spiral track that goes toward the outer diameter. All data are recorded continuously in one pass (this process could take up to an hour). After recording, the glass master is developed by spinning on a sodium hydroxide solution. The photoresist is washed away wherever the laser light touched the surface during recording. A small amount of silver or nickel is then evenly deposited onto the surface of the photoresist. The developed glass master coated with silver (now considered a metalized glass master) is then sent to electroforming.

Electroforming and Stamper Preparation

The first step in the electroforming process is to place the metalized glass master into a tank of nickel sulphamate solution for approximately 2 h. During this time a layer of nickel is grown onto the silver surface. When finished, the metalized glass master is removed from the tank, and the nickel is separated from the silver. This sheet of silver is called the father. The father is a reverse image of the data and could be used to stamp (i.e., injection-mold) disks. However, the father is not normally used for stamping because, if it were damaged, the whole process would need to start over. Therefore, at least one "mother" is then produced through the same electroforming process. Stampers are then produced from a mother. The stampers are reverse images of the data like the father and can be used to create CD-ROMs.

Each stamper is finished by punching out the center hole and outer edge. The back side of the stamper is polished to be perfectly smooth. The stamper is now ready to be loaded into an injection-molding machine to make disks.

Injection Molding

The stamper is placed into an injection-molding machine. The injection-molding machine is connected to a continuous supply of polycarbonate. The polycarbonate is heated to a molten state and shot into a mold that contains the stamper. The polycarbonate is compressed against the mold under several tons of pressure. The polycarbonate is then cooled using chilled water, and the clear disk with the information stamped into it is removed. The cooling process is critical because an improperly cooled disk could have unacceptably high birefringence. Birefringence refers to double refractive characteristics of a transparent material. High birefringence could interfere with the read laser path in the finished CD-ROM.

After stamping, a thin layer of metal (normally aluminum) is sputtered onto the side of the disk that contains the pits or information. After the metal is applied, a thin layer of sealant or lacquer is spin-coated onto the metal. This protective coating is dried or cured using ultraviolet light. The CD is now sealed and ready to be printed. The protective lacquer coating not only protects the metallic layer from handling damage but also prevents air from reaching the metal and causing oxidation.

Printing and Packaging

Labels identifying the CD-ROM are printed onto the lacquer surface. Labels are either screen-printed or offset-printed. Most compact discs labels are printed with anywhere from one to five colors.

After printing, the disks are packaged. The most common type of individual package is referred to as a jewel box. These jewel box packages are also commonly used for audio CDs. Information is usually also printed on sheets that can be inserted into the jewel box. Less expensive paper-based packages are also used.

ANATOMY OF CD-ROM DRIVES (PLAYERS)

CD-ROM drives (i.e., players) are used to read the information from the CD-ROM disk. These drives are available in both "external" versions and "internal" versions. An external drive includes a stand-alone chassis with its own power supply. External cables are used to connect the drive to the computer, usually through a host adapter card installed in the computer. The most common interface for external drives is SCSI (Small Computer Systems Interface). Internal drives, on the other hand, are installed in the computer and use the computer's power supply. Internal CD-ROM drives are normally a standard size: 146 mm (5.75 in.) width by 44.4 mm (1.75 in.) height by 199.2 mm (7.75 in.) height. Internal drives may also have an SCSI interface, although many internal drives will have an ATAPI IDE interface (AT Attachment Packet Interface—Intelligent Drive Electronics) interface. These internal drives will be connected to the computer using internal ribbon cables.

Loading of the CD-ROM disk is done through the front panel. The disk is loaded in one of two ways depending on the manufacturer of the drive: either bare disk or in a "caddy." A drive will use one method or the other, but never both methods. If the bare disk is loaded, a tray mechanism will move out of the front panel when a button is pressed. The bare disk is dropped into the tray mechanism. The tray mechanism will move back into the drive when the tray is gently pushed or when the button is pressed again. The alternative manner of loading disks is with a caddy. A caddy is a specially designed holder (or cartridge) for CDs. The CD is inserted into the caddy, and then the entire caddy is inserted into the drive through the front panel. The advantage of caddies is that the disk is less susceptible to damage when handled outside of the drive. A secondary advantage of caddy-based CD-ROM drives is that the drive may be mounted vertically. The main advantage of inserting bare disks into a tray mechanism is user convenience.

After the disk is inserted into the drive, an internal clamping mechanism will clamp the disk to the spindle motor. The spindle motor will spin up the disk. An actuator assembly then will move the laser head to the inner diameter of the disk. The drive will read the information at the beginning of the track to determine what type of disk has been inserted. If the drive recognizes the format on the disk, reading of the disk will continue. Otherwise, the disk will spin down. As indicated previously, the spindle motor will change speeds as the head is moved across the disk (see the section on CD-ROM Drives). The following sections provide more information on three key components of a CD-ROM drive: (1) the head assembly, (2) the actuator assembly, and (3) the electronics.

CD-ROM Head Assembly

A CD-ROM head assembly is made up of four key elements (see Fig. 5). Figure 5 is a *simplified* drawing of the key elements of a CD-ROM head assembly—other elements such as grating plates and additional lenses will be used in an actual head. A low-power infrared laser diode in a CD-ROM head emits light at a wavelength of 780 nm. The laser diode is normally made of gallium arsenide. The light from the laser is transmitted through a beam splitter, reflected off a mirror, and through an objective lens. Numerical aperture is 0.45. The objective lens focuses the light on the reflective surface of the CD (see section on CD-ROM Disk Physical Construction). If the light strikes a land (or nonpit) area, approximately 70% of the light will be reflected. If the lights strikes a pit, approximately 30% of the light will be reflected as a result of light scattering. The reflected light is then directed back through the objective lens and reflected off a mirror. In the beam splitter, the reflected light is directed through another mirror and lens to a photodetector. The photodetector converts the reflected light signals into electrical signals, which are sent to the electronics circuit board. The photodetector is divided into four sections (sometimes known as a quad detector). This quad detector can determine when the light beam begins to move off track and will send the appropriate signals through the servo control circuit (see section on CD-ROM Electronics) to maintain track following.

The objective lens is a key element in the head assembly. The objective lens will move up and down on tiny springs in order to focus on the disk surface. This movement is controlled by the electronics through a tiny voice coil, which ensures that the reflected spot size is at a minimum. In addition, the objective lens can refocus over a small number of

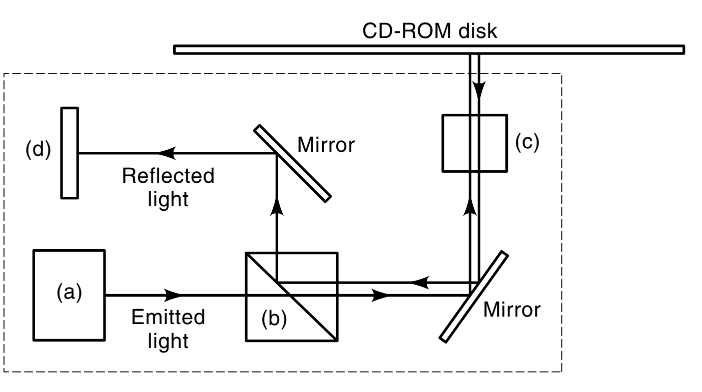

Figure 5. A CD-ROM head assembly is composed of many elements. Some of the basic elements are (a) a 780 nm laser diode, (b) a beam splitter which redirects the reflected light, (c) an objective lens which focuses the laser light onto the reflective surface, and (d) a photodetector to convert the reflected light into electrical signals.

tracks without moving the actuator. This ability of the objective lens to refocus without moving the actuator can result in very fast access times in very narrow bands.

CD-ROM Actuator Assembly

The actuator assembly moves the head assembly over the full range of track positions. A pair of accurately positioned rails guides the actuator assembly. The actuator assembly is attached to these rails by long-life and very smooth bearings. A voice-coil is normally used for positioning, although in some cases a stepper motor will be used. The positioning is controlled by the servo electronics with feedback from the photo detector.

CD-ROM Electronics

The electronics must perform many functions, all of which are essential to proper operation of the CD-ROM drive. One of these functions is decoding the data stream from the photo detector. This decoded data stream is provided to the interface. As stated previously, the interface may be either SCSI or other interfaces. The control of the interface is of course handled by the electronics. Most CD-ROM drives will also include a data cache, which can dramatically improve performance depending on the size of the cache. A typical cache within the drive electronics is usually more than 64 kbyte. Other important functions include servo control circuits for both the spindle motor and for the actuator.

RECORDABLE CD

The subject of CD-R is appropriate for this article on CD-ROM. A CD-R is a write-once disk. The information on a write-once disk cannot be overwritten. Therefore, when a CD-R disk is fully recorded, it becomes a read-only disk and must adhere to CD-ROM standards. Many applications do not require hundreds, thousands, or millions of copies of the same information. For these applications, CD-R is appropriate. A CD-R disk must be recorded in a CD-R drive and *cannot* be recorded in standard CD-ROM player. However, a recorded CD-R disk can be read in a CD-ROM player. The subject of rewritable (i.e., erasable) disks is discussed in the section on Rewritable CDs.

First commercial shipments of CD-R drives and disks occurred in late 1989. CD-R disks are available in 63 min and 74 min versions, although many of the disks are used for storing data rather than sound. The initial drive units were very expensive ($50,000 and up) with media pricing in the $50 per disk range. However, prices have dropped as volumes have risen. Although CD-R drives are not as low in cost as CD-ROM drives, CD-R drives are now very affordable for many businesses and consumers. If hundreds of copies of a CD-ROM disk are required, the most economical method is to "press" the disks as described in the section on CD-ROM Disk Manufacturing. However, if only a few copies are required, the most economical method will be CD-R. The popularity of CD-R is linked to the popularity of CD-ROM. When recorded, a CD-R disk can be read in essentially any of the tens of millions of installed CD-ROM drives in the world.

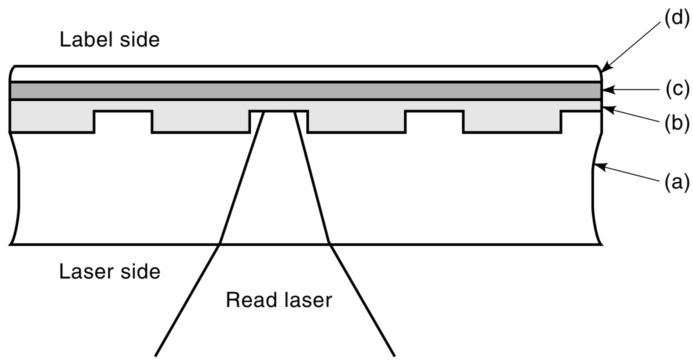

Figure 6. The four layers of a CD-R (recordable CD) disk are (a) a 1.2 mm polycarbonate substrate, (b) an organic dye layer, (c) a gold reflective layer, and (d) a protective lacquer. Recording is accomplished by making changes in the reflectivity of the organic dye layer.

Figure 6 shows the cross section of a CD-R disk. Compare this figure to Fig. 4, which shows the cross section of a CD-ROM disk. CD-R disks have a 1.2 mm substrate, same as CD-ROM disks. However, the CD-R substrate contains a continuous spiral groove, rather than data pits. Track spacing is 1.6 μm, same as CD-ROMs. The groove width is 0.6 μm. Tracking is accomplished using a push–pull tracking error signal generated by the difference in reflectivity between the groove and adjacent land areas. The spiral groove is not perfect; it has a slight 0.03 μm sinusoidal wobble imposed at a frequency of 22.05 kHz and modulated as $\pm$1 kHz. This wobble information is used by the drive's servo motor control to determine the correct rotational speed. In addition, time information is encoded into the wobble. This time information allows the recorder to locate the correct position on the disk to begin recording. A layer of organic dye is deposited on the substrate. A gold reflective layer is applied on top of the organic dye. A final protective layer (similar to CD-ROMs) protects the disk from handling.

Writing of CD-R media is accomplished by focusing laser pulses at the organic dye layer. The physical state of the dye is altered when the laser is pulsed to higher powers. The gold reflective layer brings a written CD-R disk to approximately the same reflective levels as a CD-ROM disk. Consequently, the written CD-R disk is recognized in a standard CD-ROM drive.

The two most common types of CD-R disks use either cyanine or phthalocyanine as the organic dye materials. The cyanine disks have a blue green color, whereas the phthalocyanine disks have a gold color.

Preparation of a CD-R disk is similar to preparation of a CD-ROM disk through the premastering stage. The information must first be formatted according to recognized CD-ROM formats, usually ISO 9660 (see the section on Premastering). After premastering, the disk can be recorded in a CD-R drive rather than being sent to a CD manufacturer. Early CD-R disks all required "disk-at-once" recording (i.e., the data needed to be continuously streamed to the CD-R disk). If the data stream is interrupted during this process, the disk becomes unusable. Interruptions of the data stream usually occurred due to buffer underruns (i.e., no data stream is going to a spinning disk). Blank areas will confuse the CD-ROM reader, and the disk will be useless. Multisession standards (see the section on single session versus multisession) allow information to be added to disks until they are full. However, each session also must not be interrupted during the recording process or the disk will be ruined.

Recording to a CD-R disk is not as simple as recording to a floppy disk or other types of removable media. As stated previously, one concern is ruining a disk as a result of interruptions in the data being streamed to the disk. In addition, a considerable amount of overhead information needs to be added to the beginning and end of each session. This information is required in order to allow the CD-ROM reader to find the data. This overhead information consumes approximately 15 Megabytes per session. Therefore, 20 sessions will require 300 Mbyte of overhead information—nearly half the disk! Whereas the Red Book and Yellow Book specify up to 99 tracks on a CD-ROM, the maximum number of sessions can actually be no more than 45, and that assumes essentially no data per session. Therefore, the most efficient way to record a CD-R is disk-at-once, assuming that the disk will be nearly full after the writing session. In any event, maximizing the size of the recording sessions will always optimize the amount of data that can be stored on the disk.

Another technique for writing to a CD-R disk is called packet writing. This technique allows frequent upgrades without using as much overhead space as multisession. Packet writing allows several writes per track, with only 7 sectors of overhead. The input data are broken into packets of a specified size (e.g., 128 kbyte or 1 Mbyte). Each packet consists of a link sector, four run-in sectors, the data area, and two run-out sectors. Packet writing allows the CD-R drive to be used for general-purpose removable-storage applications, such as back-up. However, the CD-R drive and the software drivers must support packet writing. Also, a standard CD-ROM player cannot read these disks unless special software is also installed with the player.

REWRITABLE CDs

A Rewritable CD (also known as CD-RW) is a CD format disk that can be rewritten. These disks are also sometimes termed 'erasable' CDs, although some of the major manufacturers objected to this term. The concept of an erasable CD might imply that data could be lost. However, magnetic disk drives have been erasable (or rewritable) since their beginnings.

CD-RW disks are based on phase-change technology. Like standard CD-ROMs, phase-change disks operate on the basis of reflectivity changes. Data marks on a phase-change disk can be changed from crystalline states to amorphorous states and back again. A crystalline state has a higher reflectivity than an amorphous state. However, phase-change disks operate at a much lower reflectivity level than a standard CD or CD-ROM. Therefore, earlier CD-ROM readers will not be able to read these disks without modifications. Standard CD-ROM formats (such as ISO 9660) can be used, however, in the recording of these disks.

DVD-ROM

DVD-ROM is expected to be the successor to CD-ROM. Originally, DVD meant digital video disc. However, the term *video* was considered too *limiting.* The acronym DVD was then changed to mean digital versatile disc. This terminology was then considered too *awkward.* Upon agreement of the major manufacturers, DVD now has no meaning other than the initials. A DVD-ROM disk has the same physical dimensions as a CD-ROM disk (i.e., 120 mm in diameter and 1.2 mm thick, consisting of two 0.6 mm substrates bonded together). A DVD-ROM disk contains up to 4.7 Gb on one layer of a single-sided disk in the first generation. These single-sided, single-layer disks are called DVD-5 and consist of a 0.6 mm active substrate with a 0.6 mm blank substrate. Two types of double-layer disks are also available: DVD-9 and DVD-10. DVD-9 consist of two 0.6 mm substrates oriented such that both substrates can be read from the same side of the disk. A semi-transparent layer bonds the two substrates together. Capacity of DVD-9 disks is 8.5 Gb. DVD-10 disks also consist of two 0.6 mm substrates, but the two substrates must be read from opposite sides of the disk. Capacity of DVD-10 disks is 9.4 Gb. The next generation will use two layers per side, achieving a total capacity of 17 Gb. The higher data densities are partially achieved by the use of lower wavelength lasers in the visible red range (635 to 650 nm for DVD-ROM versus 780 nm for a CD-ROM) in order to produce smaller spot sizes. The track pitch for a DVD-ROM disk is 0.74 μm versus 1.6 μm for a CD-ROM. The width of the pits has been reduced to 0.4 μm versus 0.6 μm. The numerical aperture of the laser head is 0.6. All these changes plus more efficient error detection/correction algorithms result in a capacity (on a single layer) of seven times the capacity of a CD-ROM.

Because of the large installed base of CD-ROMs, manufacturers have agreed to provide backward compatibility in DVD-ROM drives. Therefore, a DVD-ROM drive will be able to read both CD-ROM *and* DVD-ROM disks. Future generations of DVD will include DVD-R (write-once) and DVD-RAM (rewritable) disks.

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