Systemized Survey on the Development and Practical Application of Compact Disc (CD) Technology

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Takao Ihashi

■ **Abstract**

Viewing the history of technology as a whole, the latter half of the 1970s had been one hundred years since Edison introduced a sound-reproducing system using a wax cylinder, and the world was awaiting the rise of a new technology. Meanwhile, NHK Science & Technology Research Laboratories had begun their research and development into using digital communication technology for audio broadcasting. After a long period of fundamental research, their first prototype of a digital recording device was presented to the public in 1969, heralding the dawn of digital audio. Heitaro Nakajima, then Director of NHK Broadcasting Science Research Laboratories, was the man responsible for this fundamental research. Nakajima later accepted an offer at Sony Corporation and became responsible for its audio business, developing digital audio and CD, achieving what led to him being called“the father of CD”and“the father of CD-R”and culminating in his name being engraved in a Medal of Honor with Purple Ribbon from the government of Japan. In retrospect, although the time was ripe for digital audio, no manufacturer had developed concrete product ideas. However, in March 1979, Philips, a company in The Netherlands, visited Japan with a prototype of what later became the compact disc. This made a great impact on Sony. It promptly agreed to negotiate directly with Philips and to commercialize the product, then followed this with agile action. The technical details and the product concept for the compact disc were determined by June of the following year. This compact disc system proposed by Sony and Philips was unveiled with ceremony to persons involved with music and recording at Salzburg in April 1981, followed by announcements in New York in June and in Tokyo in October. Commercialization began the following year, in the autumn of 1982, but its widespread adoption was in 1985 and beyond. On the other hand, the fundamental technology for digital audio had been in development for more than ten years, playing a large role in securing and storing master recordings.

The conditions at the dawn of digital audio in this survey report is based on *The Challenge for Next-Generation Audio* and memoranda by Heitaro Nakajima, and the sequence of events leading up to the birth of the compact disc is based on memoranda by Masahiro Mizushima, who was a member of Sony’s negotiation team at the time. Descriptions of optics and digital signal processing technologies forming the core of this technology are based on papers and documentation published by persons in the field. Also described are the CD“family”which followed and continued to grow, how the computer-friendly CD-ROM was born, and how the concepts of“multimedia”and“interactive”were established and came to be put to practical use across a broad scope of applications, including consumer games. Described, too, is how, once the CD-ROM (“read-only”) appeared on the scene, a compatible CD-R (“recordable”) became a necessity in order for consumers to create their own CDs, and, despite concerns about copyright violations, CD-R media production rapidly expanded, with the CD-R becoming the most mass-produced product in human history. Finally, a chapter is spent discussing the cultural revolution thought to have been triggered by the CD, however, this systemized survey is not an academic paper but a record of a valuable industrial technology on the decline.

Today, in which network reigns, CD-DA remains a rare case as it still plays the major role as an audio distribution medium. According to the history of technology, it had been destined to be replaced by new media or systems by the start of the 21st Century. However, the fact remains that, though 35 years have passed since its release, no medium has emerged to supplant the CD. What had the late Karajan, the

one who had valued and supported the CD the most, seen in its future through his keen foresight? On the other hand, CD systems were heroes made by the times which sped fleetingly through the last 20 years of the 20th Century. They grew into the greatest packaged media system of all time as the technology was fortunate to match the market and the times, creating a large group of related industries. It is a fact that the technology which matured on this foundation was passed on to the current world of networks. CD systems have, for the large part, finished serving their purpose, but the brilliant history of its technology—formulating abstract technology to the level of industry—is affirmed to conclude this abstract.

■ Profile

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1967:	Graduated from Saitama University Faculty of Engineering Started working for Sony Corporation Research Laboratory
1974-1988:	Research manager of the Disc Development Division
1988-1994:	Assigned to the Audio Video Business Division
1994-1997:	Manager of the Multimedia Promotion Division
1997-2002:	Head of the Format Center
2002-2006:	President and Representative Director of Start Lab Inc.
2006:	President and Representative Director of Bifröstec Inc.
1989-1998:	Secretary of Orange Forum
1999:	Secretary of CDs21 Solutions
1996-2001:	Director of DVD FLLC Corp

■ Contents

1 | Introduction

The compact disc is the de facto standard by Sony Corporation and Philips Corporation (Netherlands). This appealing system began with the announcement of compact disc digital audio (CD-DA) in 1981 and instantly revolutionized the music industry with the idea of "good music, any time, by anyone". Momentum had been building to create a new world of music using digital audio. In the fall of 1977, a century after Edison's famous phonograph cylinder recording of "Mary Had a Little Lamb", Sony Corporation began proposing technologies and unveiling prototypes, as did other corporate collaborations, such as between Mitsubishi Electric Corporation and TEAC Corporation and between Hitachi Corporation and Nippon Columbia Corporation. This prompted the founding of the "Digital Audio Disc (DAD) Committee" and the commencement of discussions on standardizing digital audio discs. In March 1979, Philips unveiled a prototype compact disc to Japanese manufacturers as a successor to the compact cassette, using basic optical video disc (VLP) technology. While all the other manufacturers took a "wait and see" stance, Sony decided that this was an ideal concept for distributing new music content and promptly signed a joint development contract with Philips. This was due to Nakajima Heitarō, Sony's managing director and general manager of the audio business division, who had previously been the general manager of the NHK Broadcasting Science Research Laboratory. During his time at the NHK, he had worked on research and development of digital audio technology, and Sony was leading development in this area. From August 1979, meetings were held every other month in Eindhoven (Netherlands) and Tokyo to work on the technical details. In the summer of 1980, the two companies reached a basic agreement, signing a famous collaborative development declaration stating that "contribution to modulation as well as error correction from Sony and Philips is equal". The companies set October 21, 1982 as the release date for music software and players. Sony launched the CDP101 together with several dozen music titles, and the compact disc era suddenly began.

The CDP101 was not widely popular due to its high price tag. However, sales soared when the D-50 portable CD player hit the markets in 1984 for a strategically low price of less than ¥50,000. This was accompanied by a huge uptake in music software. Music content production at the time was the domain of the LP record, but LP sales noticeably dropped away from around 1980. Sony and Philips, affiliated with world-leading music content companies CBS/Sony Inc. and PolyGram respectively, keenly felt a sense of crisis and had to undergo a rapid paradigm shift. This became a cause for hastening the popularization of digital audio through technology investment, production equipment and every other area possible. Chapter 2 discusses the dawn of digital audio, describing the sequence of events leading up to the proposal of CD-DA, providing a systematic view of digital audio technology and identifying the process by which CD-DA basic technology was proposed and decided upon. Fig. 1-1 shows data from the Recording Industry Association of Japan on analog record production in Japan. Production volumes of LPs clearly drop away from 1980. Fig. 1-2 is a photograph taken at the official unveiling of the compact disc to the music world in Salzburg in April 1981. This priceless photograph shows Herbert von Karajan of the Vienna Philharmonic Orchestra, a staunch supporter and fountain of knowledge on digital audio, standing in front of the Sony/Philips prototype player and enjoying CD-DA playback with Sony chairman at the time, Morita Akio. The small-scale Sony player shown in the photograph was the result of a design project consigned to the author of the present report.

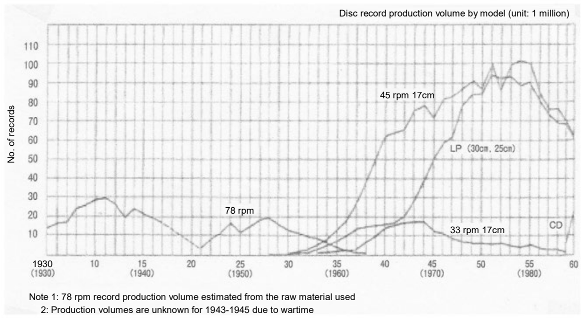


Fig. 1-1 Trends in Analog Record Production Volumes and Production Values (Japan/per year)

Excerpt from RIAJ resources

Fig. 1-2 Unveiling of the CD in Salzburg (Austria, April 15, 1981)

As a means of systematizing CD technology, the book of CD-DA standards, or the “Red Book”, contains characteristic specifications such as external form, digital signal processing and error correction. The main technology items given in this report are based on the process of negotiations between Sony and Philips. Chapter 3 discusses this CD technology in greater detail. Chapter 4 outlines production methods for these discs that held the key to distributing music content.

The CD rapidly grew in scope of application. The computer-friendly CD-ROM standard was announced around 1985. The book of CD-ROM standards was named the “Yellow Book”. The CD-ROM format was actively utilized by Microsoft Corporation for distributing everything from personal computer (PC) user manuals to application software. Other companies adopted the idea and the CD-ROM became the leading form of external storage media for computers. As computers advanced and spread, CD-ROMs were even used for household video game consoles. Hardware devices and distribution media hit the markets in staggering numbers, in turn rapidly driving down the cost of hardware and software, which spread its popularity further.

Other members of the CD family began to appear on the scene from around 1986-1987, just as the CD-ROM had done. This CD family is discussed in Chapter 5. Chapter 6 describes the emergence and scope of CD-related business, including the tabletop CD-DA player business, technology related to the CD Walkman, which made the CD known to the world, and technology related to the CD-ROM, which developed into a huge business.

The most important member of the family was the recordable CD (CD-R), compatible with CD-DA and CD-ROM. This is discussed in Chapter 7, along with the rewritable CD-RW. The CD-R was proposed in 1989 and the standards formulated into the “Orange Book” by Sony Corporation, Philips Corporation and recording film patent holder Taiyo Yuden Co., Ltd. However, the CD standard only defined signal reflectivity of at least 70%, and each company used different characteristics of recording film. Maintaining CD-DA and CD-ROM playback compatibility was a major concern. The only solution was to assign each recording medium an ID code and have the drive read that code to optimize recording. This media identification method system was launched and closely managed. The Orange Forum (a voluntary industry group) was formed in keeping with the Orange Book to provide management and guidance on adhering to this rule, thereby averting the crisis. Even now, the company ID codes are strictly maintained and work in conjunction with the drive system. This was the world’s first test case, but the participants can be proud of their pioneering role, as a similar system was later adopted for DVD/Blu-ray.

The CD-R was easy to use, offering almost 1GB of recording capacity. It was very useful as external media storage for computers, and most computers either came with a CD-R/CD-ROM drive or had one built in. At their peak, CD drives were being produced and shipped at the same volume as computers (around 200 million per year). The CD-R, as the recording media, became the most produced product in human history at around 10 billion per year. The golden age lasted until around 2002, with the CD-R being used for exchanging all kinds of data, storing and sharing photos, educational data and medical data. However, Japanese production only accounted for around 10% of total production, with other countries in Asia accounting for over 50%. This led to price competition and resulted in the market being flooded with “cheap and nasty” unlicensed products and the credibility of recordable optical discs being tarnished. The industry worked hard and in earnest to restore its reputation, banning imports and providing guidance to stores. However, the vitality of illegitimate overseas manufacturers, who, with no concept of the “yield rates” of their own high-performance optical discs, imported second-hand manufacturing equipment from Japan and produced fake CD-Rs, led to serious concerns over the future of the industry. This led to the establishment of ISO standards for estimating the life expectancy of recordable R media, discussed in Chapter 8, and the formation of a stable recordable R disc market. Although increased semiconductor memory density and improved network environments meant that the CD-R/RW had to concede its leading role from around 2005-2006, there is still strong demand for the product and it is still being used in various areas, at around one-third the volume of its golden age.

The compact disc is not just a playback device and a recording device; it is also a uniquely shaped storage medium (120mm diameter, 1.2mm thick) capable of holding almost 1GB of information. It has a recording density similar to that of the semiconductor lithograph of the early 1980s. This required technology capable of etching a semiconductor pattern on a plastic surface, a far cry from anything in the existing recording industry. All manufacturing had to be carried out in a clean room, with production facility specifications at the same level as semiconductor production. Production machinery started out with some trial and error, and it took quite some time to perfect the entire system. Meanwhile, the market expanded from the CD-DA and CD-ROM to the huge CD-R market. The CD-R production line produced around 100 million discs per month and was made up of a vast array of fully-automated production machinery that worked 24 hours a day on pressing, coating depositing, annealing and packaging.

In the end, it is an indisputable fact that over the last 30 years, the compact disc has entered the market and become part of everyday life. Chapter 9 discusses the theory of the cultural revolution triggered by the CD, whereby the interactive culture and the concept of multimedia formed the basis for networking technology and has carried on through to the present day.

Have we angered Karajan?

In the fall of 1977, Maestro Karajan came to Japan with the Berlin Philharmonic Orchestra. During a moment of free time, he decided to visit Sony's chairman, Mr. Morita. Morita wanted to welcome Karajan with something special, so he thought he would play him a digital recording. Morita prepared for the day meticulously. He called on Nakajima Heitarō, head of the research laboratory, to play some music recorded digitally on the PCM1600.

As the music played, the maestro's face turned into a sullen frown. What he was hearing was a recording of a recent lively rehearsal of "Il Trovatore", conducted by himself. It was real and impacting, complete with the occasional reprimand of orchestra members by the maestro and furious tapping of the baton. However, a rehearsal is very private to an artist, which explained the look on Karajan's face. Nakajima recollected profusely apologizing to the maddened Karajan for "slipping into the rehearsal and taking a recording and then playing it back without permission".

The truth was that before the summer break, Sony staff had taken their digital recording system (including the PCM1600) to the recording studio at EMI Records, a well-known record label in London. The EMI engineers were going to be recording an orchestra conducted by Karajan the following week in Salzburg and had asked the Sony staff to run a comparative test using an analog master tape and the PCM1600 connected to the same microphone under the same conditions. However, being angry was only natural, because whatever the reason, the fact remained that they had made a secret audio recording by not asking permission and by recording the digital audio without consent. The maestro accepted their explanation that they only wanted to test the sound quality of the prototyped digital recording equipment and had no other ulterior motive for making the recording and turned his attention to the music once more. As he did, his expression changed to one of surprise.

The sullen-faced Karajan had gone through questions such as "What is digital?" and "What is the rationale behind it?" Now he began to smile and show signs of admiration, with comments like, "This is completely new music. This is the sound of the future." In the end, he even remarked that he would like to set up such a system at his work, to which Morita readily agreed. When the maestro returned home, Nakajima followed him with a letter of thanks. He recalled part of the letter said, "Technology is constantly evolving. Our nature is to conduct research and development in search of good sound anywhere. You are in a different position, but you understand this in the sense of seeking good sound." The maestro later went on to become a backer of digital audio technology, assisting the popularization of the CD as its greatest supporter and evangelist.

2 The Dawn of Digital Audio

2.1 Digital Audio Research

The history of audio in the 20th century is a history of seeking better sound. Broadcasting systems used for broadcasting live music produced and recorded in studios and halls began with medium-wave broadcasting in the 1930s and progressed to FM and FM stereo broadcasting by the 1960s. PCM broadcasting began in the 1990s and we are now in the age of high quality internet broadcasting. Recording began with electrical amplification and transitioned to the age of the tape recorder in the 1960s. Various digital audio tape (DAT) systems began to emerge in the 1980s. Meanwhile, records shifted from phonograph cylinders to disk-type SP records, followed by the emergence of long play (LP) records in the 1950s. These dominated until the CD-DA disc appeared. In that sense, the 1970s were the dawning era of digital audio, while the 1980s were the era in which the technology blossomed. The product that triggered this was undeniably the CD-DA system. Fig. 2-1-1 shows the correlations between recording, broadcasting and records from around 1920 to around 2000. Fig. 2-1-2 shows examples of SP and LP players that were used until the CD appeared. For a detailed report on the systematization of technology before the emergence of digital audio, refer to Anazawa Takeaki "Historical Development of Analog Disc Recording Technology and Artifacts Now in Existence", Survey Report on the Systematization of Technologies, Vol. 21.

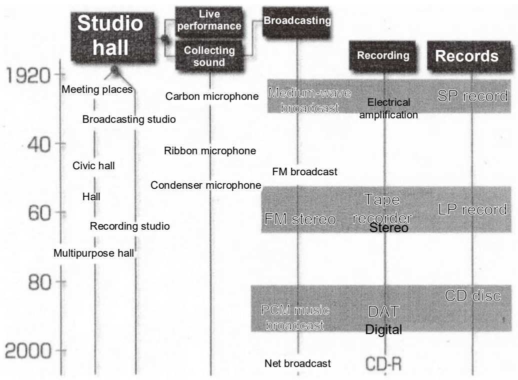


Fig. 2-1-1 Correlation Diagram of Sound Collection, Broadcasting and Records

According to former Sony general manager Nakajima Heitarō in "Jisedai Ōdio ni Idomu [The Challenge for Next-Generation Audio]", records remain of the fresh dawning era of digital audio. Digital audio research was begun by the Acoustic Research Division of the NHK Science & Technology Research Laboratories, where Nakajima was working.

SP record player

30cm φ SP record

Stereo LP player

30cm φ vinyl record

Fig. 2-1-2 SP and LP Record Players

Nakajima was taking great efforts to improve the quality of FM broadcasting. On November 23, 1963, shocking news came through the Japan-USA satellite relay (the assassination of President Kennedy). What left an impression on Nakajima was that this relay came through on digital communication technology. This prompted him to start studying how digitization could be applied to sound broadcasting. He identified the tape recorders that were being used as one cause for the deterioration in FM broadcasting quality. Consequently, with the opinion that a key technology innovation was needed, he set out to see if the tape recorder system could be digitized. At the time, digitization meant converting the signal to pulse code modulation (PCM). This was front-running technology in the world of communications. Given that the frequency band used for PCM recording is 1-2MHz, the under-resourced digital audio project got under way with the assumption that a video recorder could be used. However, the prevailing view regarding research on the digital audio tape recorder for improving FM broadcasting quality was that digital technology was used for space communication and telephones and had nothing to do with high-quality audio technology. This research was nothing more than a side current in the Science & Technology Research Laboratories. Nevertheless, Hayashi Kenji, who had first proposed the project, and the other researchers worked tirelessly and finally produced a barracks-model prototype in 1966. It was not perfect, but it was capable of playing back digital audio. Fig. 2-1-3 shows photographs of the improved stereo-specification PCM prototype No. 2 produced by the NHK Science & Technology Research Laboratories.

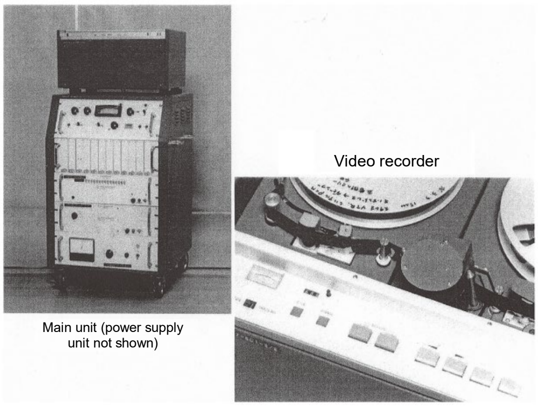


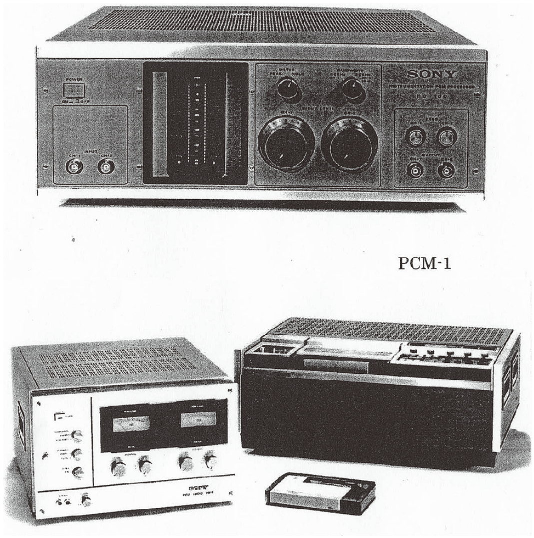
Fig. 2-1-3 NHK PCM Prototype (Stereo)

In May 1969, the NHK Science & Technology Research Laboratories unveiled the PCM prototype No. 2 on its opening day. The music played was from the Rimsky-Korsakov opera "The Golden Cockerel". The researchers had been up all night making adjustments and were deeply moved when the sound of the Cockerel played. The quality of the sound mesmerized the listeners and was a great success. This "world's first digital sound" was thought to be a premonition of the dawn of digital audio and the world of digital audio to come. However, Nakajima later transferred to the NHK Broadcasting Science Research Laboratories. With the focus shifting from acoustic technology to color image technology, the Science & Technology Research Laboratories' digital audio technology development mission came to an end and the researchers involved had to seek out new areas of activity. The PCM technology that had been cultivated went to the private sector along with the researchers. From around 1972, efforts began to be made in the field of music recording to produce a practical digital audio tape recorder. Around a decade before the launch of CD-DA, technological developments in digital audio recording were steadily building up, improving and being put to use in recording, well on the way to practical implementation. It is admirable how suited the Japanese character is to this type of technology development. Nippon Columbia took the world by storm with the release of "Denon PCM digital records", high-quality digitally-recorded LP records. This is discussed in detail in Anazawa Takeaki "Historical Development of Analog Disc Recording Technology and Artifacts Now in Existence", mentioned previously.

Meanwhile, Nakajima Heitarō had gone on to become the general manager of the NHK Broadcasting Science Research Laboratories, and then was headhunted for a position at Sony Corporation in 1971, serving as the head of the newly established Audio Technology Center. Since he also served as the head of the Audio Business Group, everything about audio at Sony, from development to business, came under Nakajima's domain. However, in those days Sony was concentrating its investment into the professional U-Matic and the household VTR, with digital technology not even getting a glimpse. Around 1973, Nakajima began suggesting digital audio development to Sony's technical laboratory, based on research from his time at the NHK. Nakajima initially proposed a system comprising a 2″ tape recorder unit that had 56 fixed magnetic heads, a tape speed of 76cm/s and weighed around 300kg, with a separate PCM digital audio adapter.

Analog tape recorders for directly recording continuous sound waveforms usually have a frequency band as close to 0.2MHz as possible. High-end digital audio requires several million bits per second, which equates to several MHz per second. As irony would have it, this issue was resolved by the professional U-Matic and household Betamax video recorders that Sony was commercializing at the time. Since these systems were handling video signals, recording pulse codes of several megabits was well within their specifications. Mechanical parts were a high investment cost, but a reliable supply could be obtained by adapting the video cassette recorder (VCR) that was coming onto the market. This meant that development only had to concentrate on the PCM digital audio adapter processing unit, which made achievement all the more likely. The VCR was usually used for recording and playing television programs. By adding a processor, it could be functionally upgraded into a digital audio tape recorder. The idea was that this could rouse consumer interest as an attractive feature of the household VCR that was rapidly gaining popularity. Thus, two PCM digital audio adapter systems came into being: the PCM-1, designed to integrate with the Betamax household VCR, and the PCM-1600, designed to integrate with the U-Matic professional VCR. Fig. 2-1-4 shows the PCM-1 and the full professional U-Matic system with the PCM-1600.

PCM adapters, especially the PCM-1600, are extremely historically valuable. In an age where there was only analog recording equipment and hardware, Sony's release of the PCM-1600 digital audio recording system for professional applications was truly impacting. This made it possible to record digital master tapes and was the forerunner of integrated systems in which the entire process from recording to editing and cutting could be done digitally.



PCM-1

U-Matic and PCM-1600

Fig. 2-1-4 Sony PCM-1 and PCM1600

Vast amounts of analog tapes began to be converted to digital at a rapid pace. The new added value was beneficial when it came to introducing digital systems. Further developments were made to the PCM-1600, and the 1610, 1620 and 1630 were released on the market. This was a major supporting factor for the production of CD-DA.

2.2 The Start of Digital Audio

The basis for the PCM adapter is the sampling frequency. This also played a significant role in the CD-DA sampling frequency and in the quantization bit number. The sampling frequency is 44.1kHz, the optimum value calculated from analog VCR. This was brought over into the standards for studio digital recording and developed into the sampling frequency for CD-DA, as shall be discussed later. It was also used in the multichannel recorders that followed and became the basic sampling frequency for digital studios. Another frequency, 47.25kHz, also reached implementation stage, but 44.1kHz processing is used for almost everything in the area of audio mastering, including recording, editing and master production.

Although a major controversy later arose regarding whether the quantization bit number for commercial CD-DA products should be 14 or 16 bits, in the early days of digital audio recorders until around 1971, a 12-bit non-linear system was used. Nippon Columbia achieved PCM digital recording around 1972 using 13 bits. A 14-bit system was also investigated. Eventually, around 1979, the 16-bit format was adopted, as it was technologically possible in terms of professional application, plus the engineers wanted to “give end users the same high sound quality as professionals”. In that sense, the conditions for digital audio were laid out a decade before the CD-DA, and the emergence of the CD-DA was the best choice as far as timing of introduction was concerned. Records indicate that the first digital recording was in April 1972 was a performance at Aoyama Tower Hall of two Mozart string quartets, String Quartet No. 15 in D Minor (K. 421) and “The Hunt”, String Quartet No. 17 in B-flat Major (K. 458), by the noted Czech Smetana Quartet, which happened to be in Japan at the time. The performers later asked to redo the recording, and so another version partially re-recorded in Prague was released with the first CDs in 1982. By strange coincidence, the first digitally-recorded CD released also featured a Mozart string quartet.

Another major role played by the PCM adapter is its significant contribution to the practical implementation of digital discs for optical audio, that is, compact discs. Around the mid-1970s, the household VCR (VHS, Betamax) started gaining more attention as a medium for video distribution rather than just serving as a time shift option for recording TV programs. Of course, there was demand from content holders in Hollywood and elsewhere for video discs as a distribution medium, just like the record. In response, household electronics manufacturers around the world began proposing technological possibilities. Table 2-2-1 shows the first video disc ideas proposed in 1977. These futuristic technologies came in a variety of formats, such as the optical video disc proposed by Philips and introduced on the market as the Video Long Play (VLP), the electrostatic CED developed by juggernaut RCA and the mechanical TED proposed by Telefunken.

Table 2-2-1 Comparison of Video Disc Formats (1977)

Signal Detection Method		Optical	Electrostatic	Mechanical
Developer: Product Name		Phillips: VLP	RCA: CED	Telefunken: TED
Cutting		Photoresistor (using laser)	Photoresistor (using laser)	Mechanical (same as the LP)
Disc	Material	Transparent plastic (deposition process required)	Conductive plastic (yield?)	Plastic (same as the LP)
	Signal surface	1mm depth from surface (caddy not needed)	Surface (caddy needed)	Surface (caddy needed)
Signal Reading	Sensor	Laser reflected light	Playback needle with electrode	Playback needle → piezoelectric element
	Relationship between sensor and disc	No contact	Contact	Contact
Cost Push Factors		Optical pickup?	Disc?	None

The optical video disc format stood out from the other technologies as it could read a signal without making physical contact. The signal from the PCM adapter was recorded in FM modulation on the principle that it would be recorded by VCR. However, experiments by Sony revealed that digital sound files simply would not play. Although error correction had been identified, it was not yet at an adequate level of completion. Sony learned two things from these experiments: the signal from the PCM adapter had to be recorded directly; and a signal processing format had to be developed with improved error correction for the unchartered field of digital audio discs. This direct recording was the only format using optical video disc technology and later led to the CD-DA.

Around 1977, when the PCM-1 was launched, was also when RCA, the world’s largest electronics manufacturer, began fighting for a share of the household VCR market and set its sights on developing a video disc. This was the eve before the dawn of the video media business, and most manufacturers had faith in the video disc market as a medium for video distribution. Everyone was focusing on standards and commercial products for video discs and digital audio discs alike. There were no manufacturers dedicated to digital discs only for audio. The cutting-edge technology exhibited at the All-Japan Audio Fair in the fall of 1977 included prototype digital audio disc players by Sony, a Hitachi/Nippon Columbia group and a Mitsubishi Electric/TEAC/Tokyo Denca group. The direction of technology trends at the time was evident in that Sony exhibited a dedicated digital audio player, while the other two groups presented prototypes that were compatible with video discs.

The atmosphere at the time clearly indicated that the new digital audio technology was in the air and that new technologies were beginning to blossom profusely. The following year, in 1978, 15 companies established the Digital Audio Disc (DAD) Committee for discussing the standardization of digital audio discs. After two and a half years, 50 companies had become members and over 100 meetings had been held. Eventually, the committee dissolved after proposing the CD as a digital audio disc format, along with several other formats. As a result, the DAD Committee had no part in the specifications for the CD or its manufacturing. Although it had not made any recommendations on unifying digital audio specifications, the activities of the DAD Committee were the first movements in standardization led by the private sector.

2.3 CD Concept Proposed

At that time, Sony’s technical laboratory under Nakajima was focused on getting better direct recordings of audio signals and improving other technologies such as error correction. They were also making rapid advances in recording density and working on getting longer recording times on smaller forms of recording medium. The prototype system exhibited at the 1978 Audio Fair had a two-hour digital sound recording on a 30cm disc. The following year, in 1979, the team had achieved a recording density that could record over 13 hours on the same sized disc. These advances in recording density were the result of research at the time. Fig. 2-3-1 shows the progress in basic technology for improving recording density from 1976 to 1979. The 30cm disc, which could only hold 30 minutes of FM recording in 1976, could hold 13 hours of direct recording three years later. This was entirely due to bright ideas and hard work by engineers. Fig. 2-3-2 shows a 30cm optical DAD prototype (13 hour playback) released by Sony in 1978. However, many were of the opinion that while recording more than ten hours was feasible for business purposes, it was not a reality for household use. Of course, there were no clear answers on how a 30cm product could become a commercially viable commodity.

	Rotation	Modulation	Playback time	Waveform/code
1976	1800 rpm	FM modulation video format	30 min (single sided)	1 0 1
Sep 1977	900 rpm	Direct recording Delay Modulation	1 hour (single sided)	1 0 0 1 1 0
Oct 1978	450 rpm	Direct recording Run Length Limited Code	2 hours 30 min (single sided)	1 0 0 1 1 0 0 1 0
Jun 1979	64 rpm	Direct recording HDM-1	13 hours 20 min (single sided)	0 1 0 1 0

Fig. 2-3-1 Advances in Sony PCM Audio Disc Recording Density

Fig. 2-3-2 Sony 30cm Optical DAD Prototype

The year 1979 is one of the most important years in CD development history. World renowned Dutch electronics manufacturer Philips brought a prototype CD player to Japan to demonstrate it. The team from the Netherlands included Lou Ottens, technical director of the Philips Audio Industry Group, Joop Sinjou, also from the Audio Industry Group, and chief engineer Jacques Heemskerk. They visited each of the major manufacturers in turn. The intention was clear: Philips was thinking about proposing a new global standard and Japan, brimming with prominent electronic manufacturers, was the first target. The prototype had a huge impact on Sony. Nakajima recalls, “We hadn’t even thought as far as a commercial product, but our eyes were opened and we were very impressed by Philips’ approach”. As mentioned previously, the reaction from most manufacturers other than Sony was to take a “wait and see” stance. This was because most Japanese manufacturers at the time were caught up in the appeal of the video disc and had disregarded the idea of commercializing an audio-only disc. Another reason for this reaction is that most manufacturers were developing contact-type signal reading technology and had little confidence in a contactless optical system.

Meanwhile, Sony had improved digital recording and error correction technology to achieve higher density recording and longer playing time and was now at the stage of having to define a specific product image. The question was how to market several hours of music software. At that point, the surprisingly good proposal came from Philips, and Sony leapt on board to resolve its own issues. With its “eyes opened” to Philips’ idea of a small scale, dedicated audio disc, Sony worked with Philips on standardization based on the Philips prototype. The company was quick to reach a consensus, and the Philips/Sony joint task force was formed in August 1979.

At the same time, Sony’s senior management was moving quickly. In April 1979, a month after Philips’ demonstration in Japan, Sony Vice President Ōga Norio met with W. Zaiss, Philips VLP division manager. Sony chairman Morita Akio met with Philips vice president Cor van der Klugt in May, while Sony president Iwama Kazuo visited PolyGram in Eindhoven and Hanover. This rapid succession of moves by senior executives was keen and agile, and deepening these bonds between business is thought to have been the greatest factor in the success of the CD.

The Philips prototype had the following specifications.

Demonstration model description

- Disc diameter: 115mm
- Disc thickness: 1.5mm
- Sampling frequency: 44.3kHz
- Quantization: 14 bit
- Rotation: 500-215 rpm, starting from center

Development concept

- Replacement for LP records
- Dedicated audio
- Wider scope of application by downsizing
- Uses a semiconductor laser

Other details, such as the recording density and error correction, are still under investigation and have not yet been published. Fig. 2-3-3 shows the Philips demonstration prototype. There was a considerable amount of digital circuitry under the table, but as advances were made in LSI, this all was made to fit inside the small sized player. Philips and Sony had been unable to negotiate to an agreement over household video cassette recorders and both had experience bitter failure. Now faced with shrinking music production, this made the bond between the two companies stronger and probably became the driving force behind the new-concept product, the CD-DA.

Fig. 2-3-3 Philips Concept Model

2.4 Sony/Philips Discussion Memorandum

With “eyes opened” by the compact disc product proposal from Philips, Sony had a rapid succession of questions and suggestions for Philips, confident in its decade of experience in digital audio technology. Despite the fact that it had its own music company, CBS Sony (with the power to resist a new format), it was less than a month after the demonstration that the company reached a consensus to base its technology on the optical format compact disc. This was the first time in the company's history that a basic agreement on how to proceed had resulted from urgent meetings between senior managers. Based on that agreement, relevant staff from the two companies held a series of six meetings in Eindhoven (Netherlands) and Tokyo between August 1979 and June 1980 to establish specifications. Discussions between the companies began in Eindhoven and resulted in a basic agreement within six months. Within a year, a provision standards book, the so-called "Red Book", had been put together. The negotiated outcomes between Sony and Philips were added into the detailed report (memorandum) by Mizushima Masahiro (Sony R & D manager). Mizushima was the only Sony representative present at all of the meetings. Since the senior managers of the companies had already agreed on the product concept, the necessary items to be discussed regarding digital audio disc specifications included: (1) the outer diameter, inner diameter, thickness and other physical characteristics of the disc; (2) playback length; (3) sampling frequency and quantization bit number; (4) modulation method; (5) error correction method; (6) standard laser frequency (780nm semiconductor laser).

- First meeting (August 27-28, 1979, Eindhoven)

The attendees were Nakajima Heitarō, Miyaoka Senri (manager of the Disc Development Division), Doi Toshitada (deputy director of the technical laboratory) and Mizushima Masahiro from Sony, and Pieter Bögels, Marino Carraso (manager of the Optical Disc Research Division, Research Center), Joop Sinjou and Jacques Heemskerk from Philips. It was agreed to aim to release new products in 1982-1983 and to finalize a summary of specifications by the end of the year. The details of the discussion are given below.

(1) Disc Outer Diameter

The demonstration disc Philips brought to Japan had a diameter of 115mm. This diameter matched the diagonal length of the compact cassettes that were the main audio system at the time.

Philips was conscious of the car audio industry and wanted to maintain company consistency with a size that matched that of the compact cassette. The shared development task of the developers was to go "from compact cassette to compact disc". However, this did not mean Philips was fixated on 115mm. The requirement was to have the player fit within the DIN standards, which meant any disc diameter between 105mm and 125mm was possible.

(2) Playback Length

Both companies were of the same opinion regarding playback duration. Philips proposed a playback duration of 45-60 minutes, to which Sony agreed. The echoes of four-channel audio were still present throughout the audio industry at the time. Sony insisted on the importance of a four-channel system that was bi-directionally compatible with two-channel systems. Frequency division and time division were also discussed, but there were questions about both. There were also doubts about the marketability of a four-channel system, so the discussion did not go into depth. However, it was standardized in the Red Book that one bit would be allocated to four-channel and if there was market demand, this could be achieved by halving the playback time. Unfortunately, no four-channel audio has emerged to date.

(3) Sampling Frequency and Quantization Bit Number

Sony believed that the strongest candidate was 50.4kHz, as discussed by the Digital Audio Standards Committee of the Audio Engineering Society, and advocated for a sampling frequency of 50.4kHz and 16-bit quantization.

However, Philips argued that this was too much, since 20kHz was adequate for audio bandwidth. Regarding the quantization bit number, Philips spoke on behalf of its subsidiary music company, PolyGram, with the view that "since 16-bit is used for professional mastering, 14-bit is enough for consumer use". Either way, both companies agreed that "one level down from professional use is adequate for consumer use".

(4) Modulation Method

At this meeting, Philips explained that the demonstration model had used modified Miller modulation, the so-called M2 method, for its modulation. Philips also discussed the effect of the molding precision of the pit (the shape the signal forms on the disc) on jitter and highlighted the importance of controlling the low frequency component of the modulation signal.

Sony agreed that jitter depends on molding precision. Regarding the effect of the low frequency component, Sony asserted that the emphasis should be on having the minimum inversion intervals during high density recording, and promised to present data on the verified four to twelve modulation (FTM) at the next meeting.

(5) Error Correction Method

Philips showed the huge amount of data it had compiled on disc errors and claimed that most of it was random error using 3 bits or less. Sony insisted on the importance of countermeasures for burst error as well as random error and the importance of error signal correction with long interleave length. The two companies had very different opinions. As the debate went on, Philips admitted the importance of burst error countermeasures, but insisted that burst error is caused by hardware mistracking or defocusing and that a method to completely prevent the cause from occurring would be sufficient. Sony repeatedly advocated the idea that if long burst error is presumed to occur, then a suitably capable error correction method should be built into the system from the outset.

The companies also discussed the concept of control and display, the forerunner to subcode, and how to implement it.

- Second meeting (October 3-5, 1979, Tokyo)

The two companies first presented and explained their modulation and error correction methods. These were at odds, with Sony favoring (1) FT modulation and (2) cross-interleaved error correction and Philips favoring (1) M2 modulation and (2) convolution error correction (2,3). They agreed to technically compare, measure and verify both claims and to reciprocally send engineers to work on trial disc manufacturing. Laying the groundwork for proceeding with discussions based on data made for significant progress in that it was the first step towards joint development.

It has become something of a legend that the team sent to Philips were true engineers with very little English. Dr. Heemskerk, chief engineer at Philips, shared the following recollection. "Those engineers were very brave. Fluent English is not always necessary to have a discussion about technology, and they were able to fully enter the discussion using the universal language of technology. In the end, we became a single team, regardless of nationality or management." As a success story for future generations, this proves that no matter what the situation, the determining factor is "having the courage to take the plunge". It has long been said of many events that "it was easier than we thought".

At the meeting, Sony insisted that if it was possible to have a disc diameter of less than 125mm while still ensuring more than 45 minutes of playback time, then the standard sampling frequency should be 50.4kHz with 16-bit quantization. Philips commented that if the disc was less than 115mm, it had no issue with Sony's proposal.

However, despite understanding that the basic concept for the CD was a dedicated audio system, Sony unusually proposed that it should have some components in common with video disc players. The situation at the time was probably affected by the introduction of video disc systems on the market, and so this came up for discussion. Specifically, this included making factors such as disc thickness, center hole diameter and signal area start diameter the same as video discs. The conclusion was that it would not be possible to implement, given the significant difference between the concepts, and Sony agreed. This resolved the first question of compatibility with video discs and the matter was settled that the CD would be a dedicated digital audio disc. The CD continued to be developed as a dedicated digital audio system for another decade until around 1990, with the emergence of the video CD, a digital video disc using MPEG1 video signal processing technology.

- Third meeting (December 17-19, 1979, Eindhoven)

The test results of the jointly developed experimental discs agreed on at the previous meeting were reported.

In terms of modulation method, the FT method proposed by Sony resulted in three times more bit errors than the M2 method proposed by Philips. It was also reported as being less adequate in terms of dropout, fingerprints and sensitivity to asymmetrical pit shape. Sony had predicted this situation and had developed 3PM modulation, a new and improved method to replace FT modulation. Consequently, Sony agreed to abandon FT modulation immediately and propose a new "ASAP" method as soon as possible. The improved 3PM modulation method was later named eight to fourteen modulation (EFM) and became the mainstay of basic CD technology.

In terms of error correction, the proposals by both Sony and Philips were reported as having no issues for ordinary discs, although Sony's method proved to be better in the low-error range and Philips' method proved to be better in the high-error range. However, from a technical point of view, the reports indicated that there was room for improvement in error correction capabilities for scratches and fingerprints on the disc surface and where signal reading tracking or focus was out.

Despite the tireless efforts of the engineers, time went marching on. The directive from management to gather measurement data in 1979 and reach a final agreement in March 1980 was impossible to achieve. However, the engineers at Sony and Philips admirably did all they could to put together the main specifications in time for the DAD Committee scheduled in March.

To achieve this, they did anything they could and used any resource they could find. For error correction in particular, they separated the factors causing random error and the factors for burst error caused by physical anomalies in the disc and implemented a very thorough computer simulation. At this time, Sony only had one IBM 1340 and it was shared by the business division. Commandeering this IBM, used to calculate the payroll, to run simulations overnight meant that the payroll could not be calculated, resulting in delayed salary payments and angry scolding from the managers in general affairs. At the beginning of March, an ASAP modulation method was proposed to Philips, with this muddled month having widened the window margin. The error correction method proposed by Sony was cross interleaved Reed-Solomon code (CIRC) error correction, developed by converting adjoining code into Reed-Solomon code with the idea that it would make the hardware configuration easier.

- Fourth meeting (March 17-19, 1980, Tokyo)

The objective of this meeting was to have a summary of basic CD technology ready in time for the DAD Committee meeting scheduled for the end of March 1980. The main specifications agreed on were: (1) a sampling frequency of 44.1kHz; (2) 16-bit quantization; (3) Sony's proposed error correction method of converting adjacent code into Reed-Solomon code; (4) disc diameter and playback time. Although Philips insisted on 115mm/60 min and Sony insisted on 127mm/75 min, they agreed that this was a question of marketing and better left to the judgment of senior company executives in both companies. Unfortunately, the modulation method was still being experimented with and was left out of the discussion.

(1) Sampling frequency

The standards for professional and consumer digital audio at the time included several standard frequencies. One was 50Hz, set as the studio standard in 1978 by the Audio Engineering Society. Another was 44.1kHz, used by Sony in the PCM-1 and PCM-1600 (derived from (525-30)×3×30 NTSC video signal), and its integral multiple (8/7) 50.4kHz. A third was 48kHz, an integer multiple of the 8kHz frequency used for digital telephone communication being considered for use by broadcasters and record companies in Europe. Amidst all this, Sony withdrew its initial insistence on 50.4kHz in favor of 44.1kHz, as this was the frequency it used in the PCM-1600 master recorder released in March 1978. Sony had decided that this sampling frequency was still theoretically able to produce audio playback at 20kHz. At the same time, the greatest advantage to digital audio was no loss of sound quality by having the same sampling frequency from recording to editing, cutting and disc production. This was necessary to be able to easily use the many master sources already recorded on the PCM-1600. This revolutionary decision meant that the same sampling frequency would be used for professional use and consumer use alike.

(2) Quantization bit number

Philips had pegged the CD as an easy listening medium for in-car audio and insisted that a quantization bit number of 14 could theoretically produce a dynamic range of 86db and would be adequate for consumer use. In fact, most analog cassette tapes and LP records to date have been around 70db, so the 86db achieved with 14-bit quantization would have provided far superior sound quality. It is also a fact that many of the key 16-bit devices at the time were only used for military or measuring equipment. Using these for consumer use would have added two extra digits to the cost, which actually was a preposterous proposal. Despite this, Sony continued to insist on the importance of 16-bit audio even for consumer use, as it would ensure digital audio discs were a high quality sound system capable of classical or jazz.

This situation did not sit well with the claim that "the mission of the CD is to provide households with a far superior recorded sound than existing LP records and cassette tapes". At the time, Sony had its sights on the forthcoming development of a 1-chip 16-bit computer. Most computers processed in 8-bit units, but the technology for integral multiple processing was soon to emerge. In his book "CD Ōdio Dangi [Discussion of CD Audio]", Nakajima is of the opinion that "as a system for the 21st century to come, improving by a mere 10db was not enough; we had to ensure a dynamic range of over 90db for the future – we had to do 16-bit."

The 14-bit/16-bit debate dragged on with no focal point. As part of the debate, the task force compared recordings of the sound of a triangle, the last test carried out by the engineers. Heemskerk (Philips chief engineer) recalled that as they all listened to the metallic clang reverberate, he thought, “There seems to be no difference, but maybe there is”. However, the Philips team were also engineers and had no objection to making the sound quality as high as the technology would allow. After this experiment, the decision was finally made to have a quantization bit number of 16.

(3) Error correction method

The task force had differences of opinion regarding burst error. Generally speaking, it is impossible to reduce optical disc defects to zero, regardless of what process is used to manufacture it. Discs can also be scratched or get fingerprints or dust on them. As this can cause abnormal reading, it was clear that steps had to be taken to somehow detect errors and restore the signal back to normal. Most disc defects are errors called random bursts (short bursts) that last for around 1-2 bits. As these can occur as much as several dozen time per second, Philips proposed an efficient error correction system using an experiment-based, mathematical approach. Meanwhile, Sony proposed a design with a practical simulation that effectively corrected long burst errors, which do not occur frequently, but can last for dozens of bits as a result of mistracking, or from scratches or fingerprints on the surface. The differences between these two underlying approaches to error correction were preventing the companies from reaching an agreement.

As a final step, the task force decided to test error correction performance by open experiment. The first round was a comparison of ordinary high quality discs. The second round was a comparison of discs covered in dust and smeared with gunk. There was no difference between the two methods for these two rounds. The third round was a comparison of discs that had deliberately been scratched with sand on a tabletop, and this time Sony’s method was clearly better. In response, Philips confused the meeting by offering to add improvements to its own method to make it perform as well as Sony’s method, such as by having a longer interleaving length.

However, Philips noted that the improved version suggested by Sony improved redundancy by up to 17% and cooperated in making changes, including making simulation estimates for the LSI proposed by Sony to prevent concerns about rising costs. The two companies finally came to a basic agreement to use Sony’s new proposed method. They also agreed on converting adjacent code to Reed-Solomon code, and Sony agreed to present the final version of the error correction to Philips at the next meeting. The method was named cross interleaved Reed-Solomon code (CIRC) and performed as well as they had hoped. As luck would have it, having error correction in byte units, and later having signal modulation in byte units as well, made the CD more compatible with computers, which led to the rapid development of the CD-ROM.

(4) Modulation method

No agreement was reached on modulation method at this meeting. There was discussion comparing the Philips M3 method proposed at the third meeting with the new method proposed by Sony. Sony’s method was suited to a higher density than Philips’ method, but there were still questions about its stability in relation to fingerprints, scratches and other noise. At this meeting, the parties agreed that if Sony could increase the density by a further 20% and confirm that the impact of bit asymmetry was within a tolerable range, they would proceed with Sony’s proposed method, otherwise they would use the M3 method. However, after the meeting, Philips started developing a modulation method similar to the one proposed by Sony. This method, with further efforts to reduce the low frequency components, was the BES method that formed the prototype for the EFM method that would become the modulation method used in the CD.

Up until the fourth meeting, the Sony/Philips specification negotiations had been reaching basic agreements and getting basic conditions prepared in time for the DAD Committee submission deadline. However, none of the DAD Committee members knew that Sony and Philips were developing jointly. Of course, there was no issue with Sony or Philips making proposals independently, but it must be explained why Sony kept the DAD Committee in the dark about going into partnership with Philips when the two companies started working on joint development. Although there is no problem at all with having an agreement or alliance with a particular company as a management strategy, in Japanese society it was unthinkable. Nakajima later recollected having to weather a storm of anger from most of the members. Members Watanabe Shū (Hitachi) and Kamio Kenzō (Matsushita Electric) recollected that “although everyone at the time hated it that Sony had teamed up with Philips to develop the CD, it is normal to do it now. Looking at the fuss over the DVD after that, we have to say that Sony’s ability to take action on the CD at that time was remarkable” (JAS Journal Proceedings).

- Fifth meeting (May 13-15, 1980, Eindhoven)

Based on the agreement from the previous meeting, Sony's amended error correction was agreed upon and the official name designated as cross interleaved Reed-Solomon code (CIRC).

At the previous meeting, the decision on disc diameter and thickness had been left to senior management. A diameter of 120mm and thickness of 1.2mm were confirmed, according to the specifications agreed on in early April between Sony vice president Ōga Norio and Philips audio division general manager Joop van Tilburg. Philips had previously proposed 115mm with a playback time of 60 minutes. This proposal had been strongly underpinned by Philips' subsidiary PolyGram, asserting that the cost of the disc was not the cost of manufacturing the disc, but the cost of the software on the disc. By this rationale, the longer the playing time, the greater the cost of the disc. It claimed that around 90% of all music, including classical but not opera, was no longer than 60 minutes. Sony's vice president invoked the famous argument: the Japanese love Beethoven's 9th Symphony. Being able to fit that piece of music on one disc would give meaning to the new media. Ōga insisted that 75 minutes would allow enough room for the piece to be conducted at any tempo. van Tilburg reluctantly agreed on the condition that PolyGram would not be further aggravated. (The published CD standard playback time remains "60 minutes", not the maximum 75 minutes.)

Disc diameter, as previously mentioned, had started out with a product plan for in-car players, in keeping with the DIN standards. Sony engineers had concluded that the maximum possible diameter was 130mm. van Tilburg responded that he "wouldn't concede 130mm, but 120mm would be OK". Ōga said that would be fine, and the diameter was promptly set at 120mm. Incidentally, the 15mm inner bore diameter of the disc was the size of the Dutch 10 cent coin. By adjusting the drive motor and the optical pickup in the design, the playback start position was set at 25mm. Calculated from this, 10mm or so was a suitable inner diameter. This coin, playfully nicknamed by the Dutch as the "dubbeltje", is an unforgettable symbol as the only coin in the world that can fit through the center hole in a CD. The later DVD and Blu-ray discs also had 15mm center holes. While this is partially for compatibility, allowing different types of discs to record and play back on the same player or recorder, in another sense it is a "fun fact" that the "DNA" of this ten cent coin, the smallest in the world, has been successively passed down to other types of optical discs after the CD.

- Modulation method

The main topic at the fifth meeting was the modulation method, the most pivotal point in the negotiation.

The M3 (modified Miller modulation) method proposed by Philips was DC free, but lacked in recording density. The method proposed by Sony had around 10db greater low frequency component, but lacked in system reliability, leading to concerns over the recording density level that could be achieved practically. Accordingly, Sony proposed an amendment that reduced the low frequency component, while Philips proposed a new modulation method suited to high density recording. There was no great difference between the two proposals in terms of performance. Philips pointed out that Sony's method would transmit errors, but Sony insisted that error transmission was not highly important. The method proposed by Philips had the issue of hardware cost. The debate continued in two parallel lines with no signs of convergence. The suggestion came up of discarding the agreed-upon CIRC error correction method, and the Japanese team started preparing to go back to Japan. At this point, the two companies had lost all the achievements they had built up together, and the decision was left to management. Bögels suggested extending the meeting for one more day and arranged a friendly dinner party. He affirmed his appreciation for the negotiations between the two companies and his respect for technology. In the end, Nakajima accepted Bögels' proposal and a de facto agreement was reached on the modulation method. The details of the agreement were that Philips would further investigate the servo circuit synchronization recovery time and the effects of bit asymmetry on the BES method, while Sony would agree to the BES method if the scale of hardware could be brought within a reasonable range. As if to soften the antagonism between the two companies, the following well-known memo was appended.

Philips and Sony agreed that contribution to modulation as well as error correction from Sony and Philips is equal.

H. Nakajima, Tr. P. W. Bögels

The patents for the agreed technologies were filed in the names of engineers from both companies. In that sense, both companies contributed equally to the CD.

- Sixth meeting (June 17-18, 1980, Tokyo)

The BES method was adopted as the modulation method, but the official name was up for review. It was later changed to eight to fourteen modulation (EFM).

The official name of the system was designated as Digital Compact Disc at this meeting, although the official name was changed to Compact Disc Digital Audio due to trademark concerns. It was also confirmed at the time that a Sony/Philips alliance would present the CD system to the DAD Committee.

With the above final agreement in place, the Sony/Philips CD standardization task, begun in August 1979, reached the first stage of completion in June 1980 and could finally be revealed to the world. At this point, with much still to decide on, Sony and Philips continued on into the second stage of negotiations. Fig. 2-4-1 shows a commemorative photograph taken at the end of the sixth meeting.

Fig. 2-4-1 Sixth Meeting with Sony and Philips (Tokyo, June 1980)

A year later, in April 1981, Sony and Philips held a grand CD demonstration in Salzburg, backed by Karajan, for the music and record industry. This kicked off a world debut, with an official announcement was made in New York on June 27 and an exhibit at the All-Japan Audio Fair in the fall. Fig. 2-4-2 shows a photograph of the presentation in Japan. However, at this point there were as yet no prospects for any of the key devices, such as semiconductor lasers, optical pickups or signal processing LSI.

Fig. 2-4-2 CD Presentation in Japan (Palace Hotel, October 1981)

The following is a summary of the CD-DA specifications agreed by Sony and Philips.

- Performance time: 74 minutes 42 seconds
- Disc diameter: 120mm
- Sampling frequency: 44.1kHz
- Quantization number: 16bit
- Error correction code: CIRC
- Modulation method: EFM

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3) “Sony/Philips Discussion Memorandum” Mizushima Masahiro
4) “Dejitaru Ōdio no Genjō to Shōrai no Yume [Current State and Future Dreams of Digital Audio]” Nakajima Heitarō, JAS Journal (Mar 1988)

Human-Powered Fan

Finally, a demonstration CD player was unveiled in April 1981. The venue was a presentation in Salzburg, Austria, where Karajan lived. Karajan, who in Morita's home three years earlier had first been angered by the secret recording, then delighted by the sound quality, wrote in a letter that "when it is finally possible to have a CD demo, I am ready to invite the members of the recording industry, journalists and music aficionados from around the world to a trial exhibition". On that basis, a presentation was held, hosted by Philips, Sony and of course Karajan. The maestro himself pressed the button on the player. In that moment, the magnificent sound of CD digital audio was officially released to the world. It was introduced to the eager crowd present as "a gift to music lovers". The members of the Berlin Philharmonic present were played a recording of themselves on CD. They were all thrilled and agreed they had never heard their own performance sound so beautifully as it did on the CD. Nakajima recollects that even the maestro admitted, "There's nothing better than this."

However, although things had come this far, the unveiling party was still one of cold sweat and close calls. The demonstration CD player at the unveiling was a working machine that met most of the specifications, but it was hand built. Under the table, covered with a white sheet, was a huge digital signal processor circuit on a rack. They had not been able to use LSI integration, so there were several thousand integrated circuits, memory circuits, resistors and capacitors arranged on circuit boards. These circuit boards generated an incredible amount of heat. This was no problem in a well-ventilated area, but not covered up under a table for a lengthy demonstration. As the temperature rose, so did the risk of phase lock loop (PLL) occurring and the entire machine shutting down.

Initially, the team tested an electric fan, but there was a risk that electromagnetic interference from the fan motor would cause major trouble with the large-scale electronic circuits. Concluding that there would be no solution without sacrifice, the team decided on a "human-powered fan", using a hand fan to cool the circuits. However, the difficulty was how to hide somebody under the table during the demonstration to keep fanning the circuits. By chance, Sony had sent an engineer who was of a small build. He took on this important mission and spent a full hour under the table fanning the circuits for the demonstration. Although it was the engineer that was drenched in sweat, Nakajima could not help breaking out in a cold sweat himself. The unveiling was a true balancing act, but, like a baby's first cry, the CD had now been heard. After Salzburg, major events were held at the Hilton Hotel in New York and the Palace Hotel in Japan. Ultimately, the "cold sweat" demonstration ended in success.

3 | CD Technology

3.1 Optical System

The world of 12cm optical discs began with the CD (around 0.7GB). As developments were made in higher density, optical discs progressed forward to the DVD (around 5GB, or just less than 10GB on two layers) and then the Blu-ray (around 25GB, or 50GB on two layers) from around the year 2000. These discs have become very diverse in application, going beyond music to storing photographs and films, and from there to storing archive data. Advances in optical disc recording density alone in 25 years (1980 to 2005) enabled discs to hold around 25 times more (not including layering technology) than they did before. The most important piece of technology that started this all is the optical disc using contactless signal detection. This chapter provides details on the underlying technologies in the optical system that allow it to read signals from the physical form of the CD optical disc. Fundamentally, the underlying technology that was perfected in the CD continued on unchanged in the DVD and Blu-ray, only with higher recording density. It is at the heart of all 12cm optical disc technology and is still being developed into practical everyday technologies today. Fig. 3-1-1 shows a schematic overview of the world of 12cm optical discs that began with the CD.

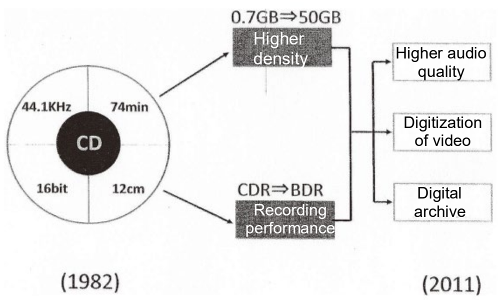


Fig. 3-1-1 The World of Optical Discs

3.1.1 Optical Disc Physical Appearance

As shown in Fig. 3-1-2, the CD has a diameter of 120mm, a center hole of 15mm and a thickness of 1.2mm. The programmable area that content can be written to starts at a diameter of 50mm (25mm radius) and extends out to a diameter of 116mm (58mm radius). There are the lead-in (46-50mm) and lead-out (116-117mm) areas. The optical disc reads and controls this signal. There is also a defined clamping area from 26mm to 33mm, which holds the disc in its rotation. The outer 2mm beyond the outer edge of the content area at 116mm cannot be used, but it is important for ensuring the reliability of the disc, especially in terms of preventing moisture from penetrating into the disc. If the content is shorter and does not reach all the way to the edge, a lead-out area is placed at the end of the recorded area. Since the CD was designed to be a total optical system, including disc thickness, it is important to consider the optical properties of the disc material (such as the refractive index and complex refractive index). Most of the material used is optical polycarbonate, a high-performance plastic with the optimal molecular weight for pit molding. Incidentally, the optical discs that followed the CD used the same basic parameters to maintain compatibility with the CD. The only difference is the depth of the light transmissive layer (0.6mm for DVD, 0.1mm for Blu-ray). Since the CD was designed to hold 74 minutes of Beethoven's 9th Symphony, as mentioned in the previous chapter, it has a recording capacity of 0.783GB ($44100 \times ((16\times2)/8) \times 60 \times 74 \times 10^{-9}$).

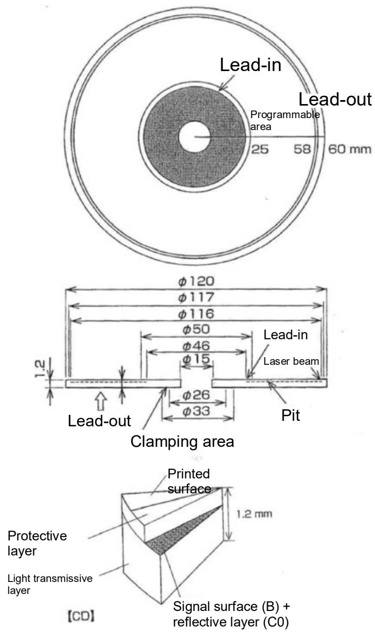


Fig. 3-1-2 Compact Disc (CD) External View and Cross-Section

Fig. 3-1-3 shows a schematic diagram of the basic optical disc principle. For CDs, the most distinguishing characteristic is that the signal is not read from the surface of the disc, but from within the disc. It is essentially made up of three layers. These comprise the laser penetrating substrate layer, the signal data + reflective layer and the protective layer. For recording and playback, the laser beam (a 782nm semiconductor laser for CDs) shines from underneath, as shown in Fig. 3-1-3, and is concentrated on the signal surface. The light that is reflected off the reflective surface, shown at the top of the signal layer in the image, is altered in intensity according to the physical changes in the signal layer. This is picked up by the light sensor and converted into an electrical signal, which is processed and then output as a music or video signal. Fig. 3-1-4 shows a diagram of the signal surface. The grooves, called pits, appear to be arranged at random. Each pit is around 0.9-3.3μm in length (for EFM modulation), 0.5μm wide and has a track pitch of 1.6μm. The pit depth is related to the servo signal. Fundamentally, it is around ¼ of the laser wavelength λ. Taking the refractive index of the polycarbonate substrate of around 1.5 into account, this results in a depth of around 100nm. These pits are recorded on the entire surface of the CD. Since each specification has a margin of error, the key to developing the CD was how to rectify those errors and produce an accurate signal. Fig. 3-1-5 shows the physical error (deviation) that occurs towards the outer edge of the disc. The largest value is the vertical deviation of the disc due to the flexibility of the plastic substrate, which allows for ±6°. This means that a disc on a planar surface can bend by around 1mm. There is also eccentricity of around 70μm, including rotation axis error, as well as a focus error tolerance of ±0.5mm. To achieve a flawless servo system at the time would have been almost impossible. Fortunately, disc molding precision steadily improved, eventually making it possible to detect signals on tabletop hardware. However, the portable players that came out two years later in 1984 required drastic measures to prevent skipping, and so the hard work and trial and error continued.

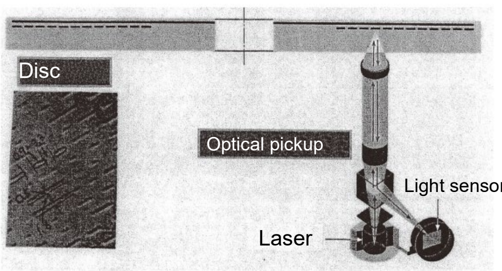


Fig. 3-1-3 Disc Principle

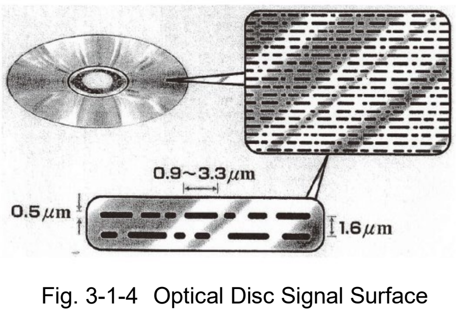


Fig. 3-1-4 Optical Disc Signal Surface

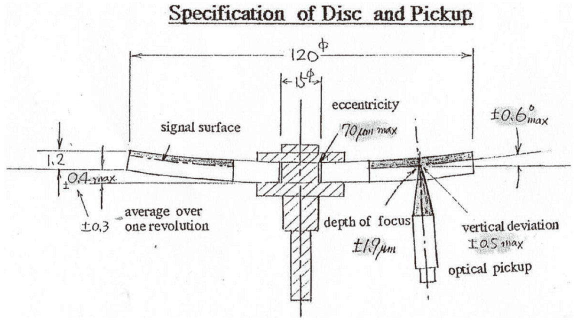


Fig. 3-1-5 Error Occurring on an Optical Disc

The CD has a system called constant linear velocity (CLV), which maintains a constant linear velocity along the diameter. Essentially, this technology improves the recording density. The linear velocity of a CD is 1.2-1.4m/s (the model value is 1.25m/s), with a revolution speed of around 200rpm (outer diameter) to 600rpm (inner diameter). The conventional LP records had a constant angular velocity (CAV) instead of the CLV, with fixed rotation speeds such as 33⅓rpm. In terms of recording density, if the outer perimeter ratio is n, then the value for CLV is (n+1)/2× higher than CAV. For a CD, n=2.4, so the recording density is 1.7× higher, thus making it possible to fit Beethoven's 9th Symphony on a single 74-minute disc. Incidentally, the CD single was specified with an outer diameter of 80mm to fit one or two songs on it. This grew in popularity, especially in the Japanese music market. Other than the outer diameter, the specifications were all the same as for the 120mm CD, including the inner hole diameter, music start diameter, etc. This made the two disc sizes fully compatible.

3.1.2 Contactless Signal Detecting Technology

The most distinctive of the main CD technologies is the "contactless signal detection" using light. While the physical form of the optical disc is as previously discussed, an important part of the technology is how the embedded signal is detected. The light used for this must meet the following conditions.

(1) The light must have good coherence properties and be able to be condensed into a spot the size of the signal pits on the disc using a condensing optical system
(2) The light must come from a tiny illumination source to be incorporated into a small pickup
(3) The light must have sufficient quantity to read and write signals with good signal to noise (S/N) ratio

In other words, the optical system focuses the light down to a small point and then reads the signal produced by the light diffracted from the pits etched into the disc. The term coherence is also used to describe another property of light.

Spatial coherence is important when light is converged. If light with good coherence and a good wavefront is converged through a lens, it can be focused down to a very small point. Light with poor coherence cannot be focused down to a small point, because the wavefronts are overlapping in different directions. This is a major factor in light source selection. For example, an LED is an incoherent light source and cannot be condensed to any size smaller than the light source. However, a semiconductor laser (light amplification by stimulated emission of radiation) literally produces light by stimulated emission and is an extremely coherent light source and thus satisfies condition (1) as an ideal light source for optical discs. Since semiconductor laser crystals are very small, they also fully satisfy condition (2). In terms of the S/N ratio of condition (3), the S/N ratio requirements are determined by the playback system. Generally, optical disc noise includes laser noise, disc noise and sensor and preamplifier noise, which means care must be taken with design. The semiconductor laser used for optical discs will be discussed in more detail in the following section (Optical Pickup (OP) Technology).

Light is a wave and can be condensed down to an infinitesimally small point with geometric optics. However, from a wave optics perspective, the diameter of the condensed beam has a finite value by the effects of lens diffraction. If two parallel beams with identical intensity distribution are incident to a lens, the condensed beam is known to form an airy disk. This is illustrated in Fig. 3-1-6. Around 84% of the total energy converges in the center spot. The diameter of this circle can be expressed as $1.22 \times \lambda/NA$, where NA is the numerical aperture value, represented as $NA = n \times \sin\theta$, λ is the light wavelength, and n is the refractive index of the transmission medium. For CDs, λ = 780nm and NA = 0.45, producing an airy disk diameter of $1.22 \times 0.78/0.45 = 2.1\mu m$. This formula indicates that to condense the light down to a small spot, it is better to have a shorter wavelength and a higher NA.

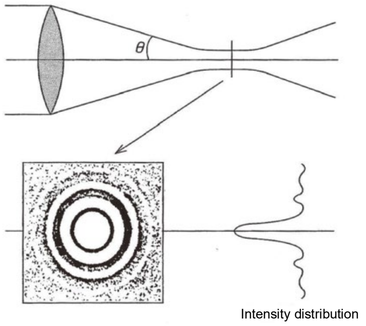


Fig. 3-1-6 Intensity Distribution of Condensed Light

In 1982, a semiconductor laser light wavelength λ of 780nm had just been achieved. A prototype could not be procured due to the prohibitive cost. Eventually, mass production level technology was achieved, and the capability was there to produce 10,000 units per month. The Sharp Corporation plant in Tenri was the only manufacturing site. Later, from around 1985, as CD player production started growing exponentially, production of this key device in the pickup also started to increase. Production levels reached over 100 million per year, and Sony started producing its own. Semiconductor lasers developed further, achieving a red-light wavelength λ of 650nm for DVDs in 1996 and a blue-light wavelength of around 400nm for Blu-ray in 2003. The semiconductor laser remains a key device in optical discs today and is still produced in high quantities.

In terms of lens NA, the lenses used at the time were the ones that could be mass produced, the same as for the semiconductor lasers. The NA determined the beam spot diameter as well as important factors for optical discs. Optical disc signal detection requires various error corrections, as shown in Fig. 3-1-5. Factors relating to the NA include: (1) focal depth = λ/NA^2; (2) tolerance for disc tilt $\propto \lambda/NA$; (3) tolerance for uneven thickness of disc light transmissive layer $\propto \lambda/NA^4$. In terms of optical system design, the lower the NA, the better. (1) Assuming λ=0.78 and NA=0.45 provides a focal depth of around ±1.9μm, thus providing an optimal residual error value for the focus servo. (2) In terms of disc tilt, the optical axis between the disc signal surface and the optical pickup is not straight due to disc curvature and other factors. This causes various aberrations in the optical system, including coma aberration and spherical aberration. Fig. 3-1-7 shows typical examples of these aberrations. Light condensed into a small point has a comet-like appearance under coma aberration and a surrounding halo under spherical aberration, as shown in the image on the right. This produces a soft focus. The principle of focusing down light as much as possible and using a physical phenomenon of interference from pits to read a signal requires aberration to either be rectified or suppressed in the design to within acceptable limits for recording and playback. The CD optical system is designed to incorporate light being transmitted through the plastic substrate. The fundamental signal detection principle is as follows. A laser (for CD, wavelength λ=780nm) is condensed through a lens and passes through a disc, where it is diffracted by the pits on the signal surface of the disc. The diffracted light does not reflect back, while the light that hits the physically unaltered surface between the pits is reflected back. A signal is detected from the changes in reflected light. Fig. 3-1-8 shows a schematic diagram of optical disc signal detection.

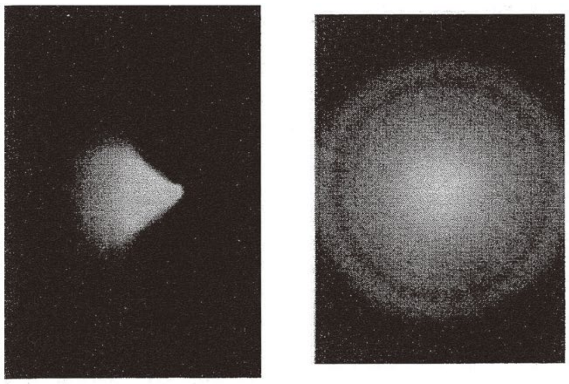


Fig. 3-1-7 Optical System Coma Aberration and Spherical Aberration

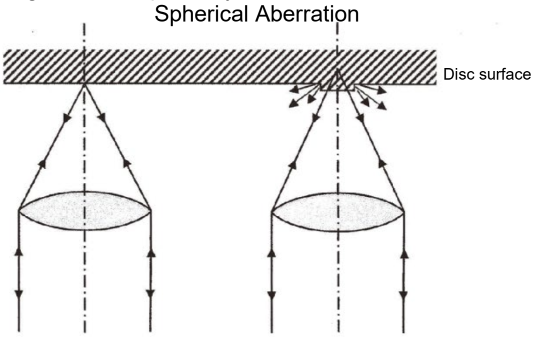


Fig. 3-1-8 Optical Disc Signal Detection Principle

Another important parameter is the frequency characteristic of the optical system. Like a camera, this is essentially achieved by optical transfer function (OTF) and generally expressed as a complex number. The absolute value of the OTF is the modulation transfer function (MTF), which represents the amplitude transfer function. The non-real part of the OTF is phase transfer function (PTF), which represents the phase properties. Fig. 3-1-9 shows the general concept of OTF. In a CD optical system, the light is condensed through a single lens, reflected off the signal surface of the disc and returns through the same lens modulated by the pits, so the OFT only needs to find the autocorrelation between the two circular apertures. Generally, spatial frequency or optical system cutoff (x) is represented as 2NA/λ. For CDs, λ=0.78μm and NA=0.45, which means $x = 1.154\times10^6$. In other words, there is a spatial frequency readout limit of 1154 per mm. Given that the smallest pit on a CD is 0.87μm, the basic spatial frequency of a row of these pits is $1/(1.87\mu m\times2)=0.581\times10^6$. Given a density of 581 per mm, 1154/581 ≈ 2, meaning that the signal is read out at 2× the frequency band. Entering the same values for DVD, the spatial frequency readout limit is 1846 per mm, which gives a basic spatial frequency of a row of pits (smallest size 0.4μm) of 1250 per mm. Since 1846/1250 ≈ 1.48, the signal is read out at 1.5× the frequency band.

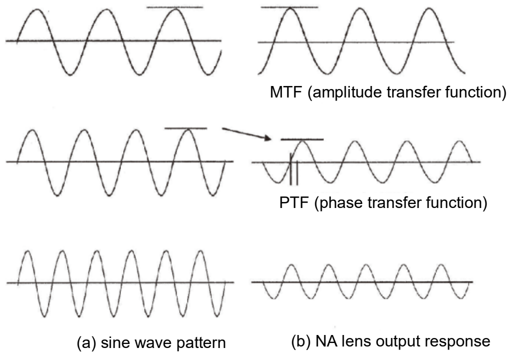


Fig. 3-1-9 Optical Disc Transfer Functions

Of course, the MTF, PTF and other factors break down in actual optical systems due to various factors, as opposed to theoretical optical systems. The main causes are: (1) aberration in the lens system itself; (2) spherical aberration due to uneven disc thickness; (3) coma aberration due to the signal surface of the disc tilting off the optical axis; (4) imperfections in the signal surface that cannot be handled by the focus servo. These factors need to be addressed, either by designing to ensure certain margins or by actively adding correction mechanisms. This is the key to hardware stability.

3.1.3 Servo Technology for Signal Detection

Servo technology for optical disc signal detection can be broadly categorized as relating to the focus servo and the tracking servo. The former follows the vertical movement of the disc in order to maintain focus on the signal surface. The latter maintains the light focus on a particular signal track as the disc rotates, within a certain error margin from a perfect circle, to ensure continuous signal reading. Servos are a core technology for optical pickups and there are several types of them that operate depending on how an error signal is detected. A brief description is given here, to avoid overlapping excessively with "Historical Development of Laser Disc (LD) Technology with Respect to Efforts to Hasten Its Technological Development and Practical Application" (Vol. 21).

A) Focus Error Signal Detection Method

Focus servos can be broadly categorized into three types, according to the signal error detection method. The most commonly used technology is an astigmatic error signal detection mechanism. Fig. 3-1-10 shows a diagram of this. The light beam reflected back from the disc is divided by a beam splitter, and a four-way photosensor is placed on the surface where the focal points connect. By placing a cylindrical lens between the beam splitter and the photosensor, the light beam on the photosensor forms a circle at the point shown by j in the figure if the signal is in focus, otherwise the spot on the photosensor forms an elliptical shape. The four output differences from the four-way photosensor are calculated as {((1) + (3)) - ((2) + (4))} to give a result of 0. The calculation result is translated to a focus error signal. The closer the disc comes to the lens, the farther away the image plane shifts and the image on the four-way photosensor at point j becomes elongated, giving a negative focus error signal value. The farther the disc moves from the lens, the wider the ellipse, giving a positive focus error signal value. This allows two opposite error signals. Other methods include spot size detection (SSD) and the Foucault method. Since these essentially treat changes in disc focal point as changes in the shape of the spot on the photosensor, which is amplified and converted into an error signal, the technology is the same.

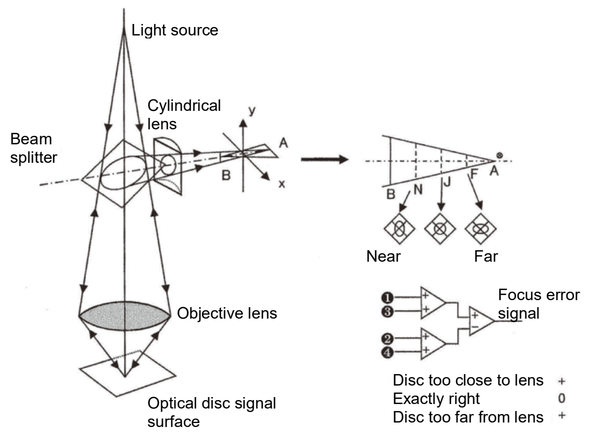


Fig. 3-1-10 Focus Servo Principle

B) Tracking Error Signal Detection Method

The technology to rectify errors in track orientation is very important for optical discs to detect signal. The main methods used in CDs are the three-spot method and the push-pull method. Improved tracking error detection methods using the push-pull method can be categorized as differential push-pull or directional phase detection. The former is used in recording media systems that have grooves without pits, such as the CD-R, while the latter is used in playback systems, such as CD-DA and CD-ROM.

I) Three-Spot Method

Optical disc systems read a signal from pits or grooves in the disc as the disc rotates, as mentioned previously. Naturally, the accuracy depends on several factors. With a track pitch of around 1.6μm and center hole measurement accuracy of 15mm ± 0.1, a disc can have around 70 tracks that the concentrated beam must traverse, at the maximum size of 100μm. With pit molding error and deviation from a perfect circle also factored in, the error potential increases further. Fig. 3-1-11 shows a diagram of tracking correction. The three-spot method is essentially the same as the method used for optical video discs. Two auxiliary beams are placed in front of and behind the signal reading beam in the center. The auxiliary beams A and B go slightly over the edge of the track, while the main beam spot sits directly on the track. If the track moves up or down, the signal to auxiliary spots A and B changes due to diffraction, resulting in opposite error signals. In other words, the system provides information as to which side the track is misaligned towards and how much the signal is misaligned by. While this is the most commonly used method of CD tracking error correction, it does have several drawbacks, including needing a diffraction grating for the auxiliary spots and poor efficiency of the main beam. For CD-R recordable media, which requires the main beam to be utilized as efficiently as possible, there has been a transition to DPP and other methods.

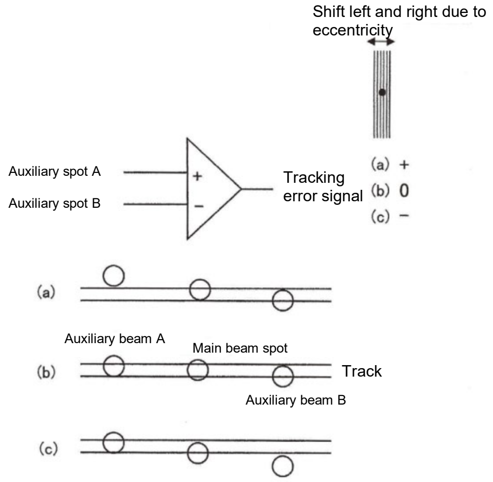


Fig. 3-1-11 Tracking Correction Diagram

II) DPP and DPD Methods

Both methods are excellent in their capability to detect an error signal with a single beam. This utilizes the change in light intensity as the light is diffracted from the pits and reflected back into the objective lens. The change of intensity is due to the relative difference in location between the pit and the spot. Since the diffracted pattern is also observable in places other than the objective lens, the light intensity distribution can be picked up by two-way photodetectors (PD) along the track direction, making it possible to detect a tracking error signal. Fig. 3-1-12 shows a diagram of push-pull track error signal detection. Various technologies have been devised to detect tracking error signals reliably. As the RF signal increases, the detected signal decreases with a pit or groove depth of λ/4. Accordingly, the pit depth can be set between λ/4 and λ/8 to produce an error signal and limit offset. In addition, if the light is reflected back to the laser it was emitted from, noise increases. Offset limiting technology and noise cancelling technology are therefore very important in ensuring an accurate RF signal.

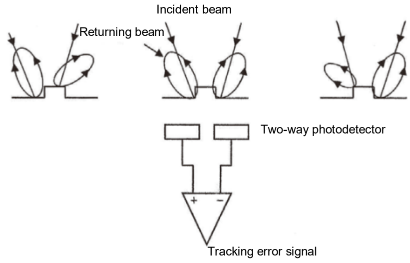


Fig. 3-1-12 Push-Pull Method Tracking Error Correction

The DPP method is a technology that eliminates offset using three beams. Fig. 3-1-13 shows a diagram of DPP tracking error signal detection. The light from the laser is divided three ways using a diffraction grating. The strong beam in the center enters the recording channel, while the two side beams move the diffraction grating to ensure it stays between the channels. There are also three photodetectors, one for each beam, arranged along the tracking direction and subtracting respectively to calculate the push-pull of the center beam and the push-pull of the side beams. Next, the side push-pull gain is adjusted and the groove and land offsets are reverse phased to produce a push-pull signal with no offset. This is mainly used in CD-R and DVD-R recording systems. For CD-R/RW, recording is done with an address signal in a groove that is made in a special way with a wobble so that it cannot be read by playback systems. This is discussed in Chapter 7 and the emergence of recordable CDs.

The DPD method is an excellent improved push-pull method. Fig. 3-1-14 shows a diagram of this method. The main advantages are (1) it is hardly affected by pit depth and (2) it is hardly affected by movement of the beam on the photodetector. Accordingly, it is suited for an optical pickup tracking method that is not housed in one structure. The DPD method essentially takes the light distribution from the relative change in position between the beam and pits, detects and calculates a signal using a four-way photodetector, and uses this as a tracking error signal. In the sense that the HF signal is represented as the sum of the four-way photodetector (a + b + c + d), it is a modulated signal with a band limited by the wave properties of the light in the player. The diagonal error signal is represented as {(a + c) – (b + d)}. When the track is in the center of the beam, the diagonal error signal is zero. If the disc misaligns in the direction of the arrow in the figure as it rotates, it outputs a sine wave, but the phase is out by ±90° from the HF signal. If a diagonal error signal phase is detected based on the HF signal, opposite tracking error signals can be produced. In practice, heterodyne detection and phase contrast are used as error signal detection methods. The DPD method requires optical discs to have pits, and is mainly used for CD-DA and CD-ROM. In many cases, the DPP method is used for tracking error signals in CD-R recordable media.

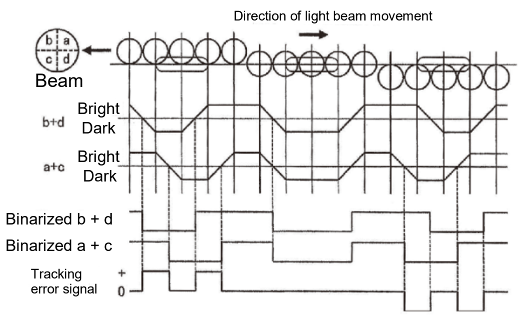


Fig. 3-1-14 DPD Tracking Error Signal Detection

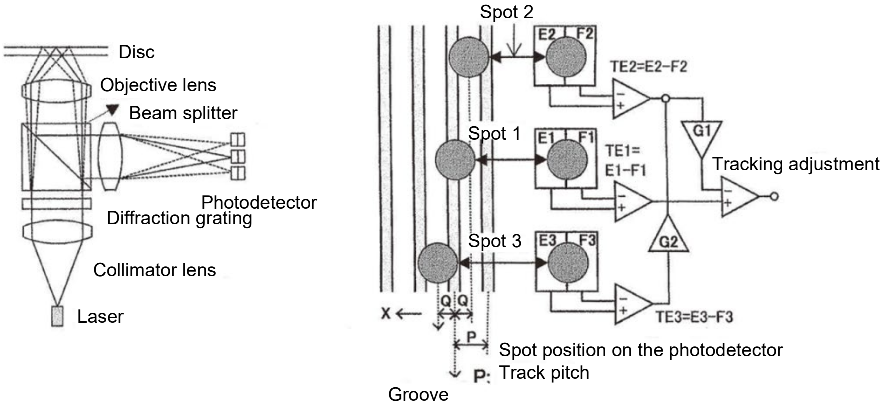


Fig. 3-1-13 DPP Tracking Error Signal Detection

3.2 Optical Pickup (OP) Technology

One of the most important technology devices for CDs is the signal detection system, called the optical pickup. The main components include the semiconductor laser or laser diode, the objective lens, the photo diode and various optical elements. Details of the semiconductor laser are given in 3-2-1. In order to read the signal recorded on the optical disc, the light source must be condensed to a diameter smaller than the pits in which the signal is recorded. The light emitting part of an LED chip has a finite size and cannot be made infinitely small. Consequently, the light cannot be condensed small enough to be the same size as the pits on an optical disc. The optical disc signal reading principle requires a certain degree of coherence, as it is produced by interference between the light from the surface of the pit and the light from the bottom of the pit. In that sense, a semiconductor laser is ideal.

The objective lens is also an important device. In the early stage of CD development, the only lens that met the technical specifications was a microscope objective lens. Like a microscope, the lens is made up of several layers of glass lenses. These were used for laser discs at the time and were very highly priced, as they were unable to be mass produced. Unless this prominent objective lens could be developed into something smaller, cheaper and able to be mass produced, then “the CD could not be developed”. Developers spared no effort with their trial and error attempts to achieve this crucial mission. The result was a single layer aspherical lens. While it was largely dependent on advances in machining centers to be able to produce the aspherical molds, the practical implementation of the ideal objective lens was an overall success, in terms of both costs and mass production capability. The development of the aspherical plastic lens with a diameter of just over 7mm is a story of hardship. The details of this are given in 3-2-2, with great respect to the engineers who worked on this development. Fig. 3-2-1 shows the advances in CD objective lenses. Technology is now being adopted that will reduce the size and weight even further to achieve an ultra-small aspherical plastic objective lens around 3mm in diameter. In terms of future compatibility between DVD and CD, the technology is being developed to produce a lens for two laser wavelengths, 780nm and 680nm, whereby a hologram is produced on the aspherical plastic surface to produce zero-order and first-order diffracted light, making it compatible with both.

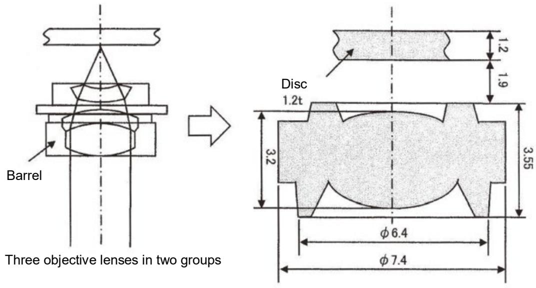
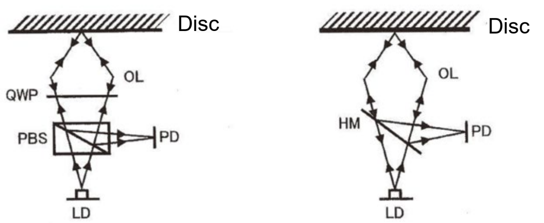


Fig. 3-2-1 CD Objective Lens Development

Optical pickups can be broadly categorized as either polarized light systems or non-polarizing light systems. Fig. 3-2-2 shows the structure of optical pickups. Figure (a) shows a polarized light system, the earliest type of optical pickup. This is still used today for recording where the disc signal surface requires laser power. Since the polarization direction of a semiconductor laser is a straight line, a polarizing beam splitter is positioned in the path of the light in that direction. The light from the semiconductor laser passes through a quarter wave plate to produce circularly polarized light, which is focused on the disc surface. The light reflected from the disc passes back through the quarter wave plate to produce linearly polarized light. As the polarized light is travelling in a different direction, the polarizing beam splitter bends it 90° to direct it to the photodiode photodetector. The issue with this system is that the use of polarized light means that any polarization defects in the disc will be detected as being larger than they actually are. For example, if some foreign matter was mixed in with the disc when it was molded, altering the refractive index of the surrounding material, it would be detected as being several times larger than the actual defect and lead to servo instability. Since polarized light optical pickups have this issue, they are largely not used for CD playback, although they are still the main type of pickup used for recording CD-R, as the recording surface requires power.



(a) Polarized light system (b) Non-polarized light system

Fig. 3-2-2 Optical Pickup Structure

The non-polarized light system (b) has a half mirror in place of the polarized beam splitter and no quarter wave plate. There are issues with this structure in that the light reflected from the disc returns to the laser and causes interference noise. Semiconductors generally oscillate at several wavelengths. Each spectrum is considered as a group of wavelengths that oscillate easily. If the power is increased, the vertical mode changes to single mode. However, changing the vertical mode to multi-mode has been demonstrated to be less affected by noise from the reflected light. In recent years, semiconductor lasers have been developed that are less susceptible to this reflected light. As a result, this type of non-polarized light system is the most commonly used for optical pickups in playback systems.

There are two other categories of optical pickup: finite and infinite. Generally, infinite refers to a system in which the light enters the objective lens in parallel beams. This was widely used in early optical pickup systems. However, one drawback was the high cost of the optical components in the pickup. To resolve this, the finite system was developed, using the smallest possible number of components. The finite system is difficult to use, due to its susceptibility to spherical aberration with the vertical movement of the focal servo and other types of aberration with the radial movement of the tracking servo. Despite this, most commercial optical pickups today are finite systems.

Sony, the leading manufacturer and seller of optical disc systems, mostly made its own optical pickups. The following is a list of optical pickup technologies by Sony. Table 3-2-1 categorizes Sony optical pickups for CD. The most highly sold pickups are the finite KSS-210 and KSS-213, which peaked at over five million units produced overseas per month. This was the ultimate discrete optical pickup, with the minimal component design, the aspherical plastic lens and the photodetector integrated in an IC. Fig. 3-2-3 shows a design diagram. This model is still the main model being manufactured and is marketed under various brands.

Table 3-2-1 CD Pickup Categories

	For normal devices	For mid-range devices	For high-end devices
Infinite optical system PDIC Type (511 optical pickup unit)	KSS-150	KSS-151	KSS-190 (base diecast)
Finite optical system PDIC Type (CD model mentioned above)	KSS-210		
Finite optical system OPS IC Type (RF Amp 3 VR Type)	KSS-240		
Infinite optical system OPS IC Type (RF Amp 3 VR Type)		KSS-270 KSS-272 (acoustic noise countermeasures)	KSS-280 (base diecast)
Finite optical system KSS-240 compatible LC Moving Mg Type	KSS-390		
Finite optical system KSS-210 CD model unadjusted	KSS-213		

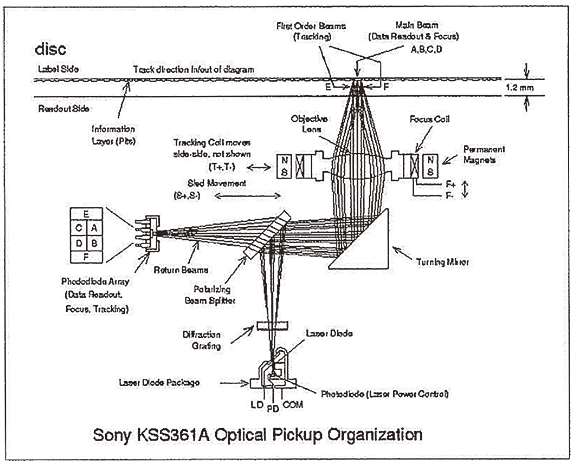


Fig. 3-2-3 Finite Optical System (KSS-210, 213)

An examination of what this type of optical pickup was known for and what kind of hardware it was used in revealed the following. While there is only one example from Sony, the systematic development of the technology is clearly seen. Fig. 3-2-4 ((1) to (3)) shows some of the optical pickups and hardware developed between 1980 in the prototype era to 1993 in the golden age. The optical pickup used in the CDP-101, marketed in 1982, was the infinite KSS-100 optical system with its huge objective lens. The specifications of the KSS-150were almost identical, and the derived models KSS-151 and KSS-190 were used in all CD players at the time. The finite optical pickup with its minimal number of parts emerged around 1990. This reduced costs dramatically, and the CD player business grew rapidly as a result. Later, with the development of the CD-ROM and CD-R, CD players gained an unshakeable hold as computer terminal devices, accompanied by a dramatic rise in the demand for and production of optical pickups. It became a major industry, with global production peaking at over 200 million units per year. Unfortunately, the only optical pickups produced in Japan today are specialized business products with high reliability and high recording density specifications. In that sense, Japan may be suited to added-value, low-quantity, high-variety production, but the booming technology industry has come to a quiet close, with nothing passed on but the glory of a former era.

3.2.1 CD Semiconductor Laser

The term semiconductor laser is literally made up of the words “semiconductor” and “laser”. Laser is an abbreviation for “light amplification by stimulated emission of radiation”. Before the emergence of semiconductor lasers (1970s to early 1980s), small gas lasers were used.

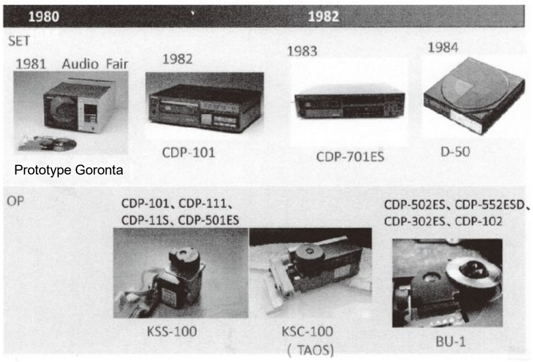


Fig. 3-2-4 Evolution of CD Pickups (1)

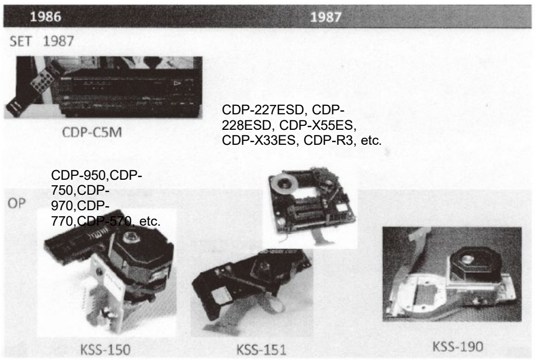


Fig. 3-2-4 Evolution of CD Pickups (2)

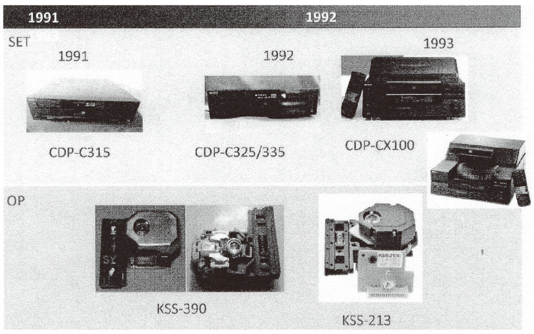


Fig. 3-2-4 Evolution of CD Pickups (3)

The most commonly used of these was the He-Ne laser, a red-light laser with a wavelength of 632nm, used in consumer laser discs. However, with dimensions of around 300×30mm and requiring a special power source, these did not make it into small consumer CD players. In the 1980s, an infrared semiconductor laser was developed based on gallium arsenide (GaAs), but Sharp was the only manufacturer that managed to commercially mass produce it.

Since many books have been published on the principle of semiconductor laser light emission, details are omitted here. According to the Sharp Technical Journal, research and development on semiconductor lasers can be traced back to the early 1960s. By the time of its practical implementation into the Sony CDP-101 in 1982, the foundational development of semiconductor lasers had already been going on for 20 years. The technological outcome was no accidental product, but point-blank proof of the earnest and hardworking endeavors of dedicated engineers to make it happen. This is truly admirable.

Sharp developed a V-channeled substrate inner stripe (VSIS) using its own P-type GaAs substrate. The company successfully managed to resolve the problematic lifespan issue, extending it to 40,000 hours, and thus successfully achieving the industry's first mass-produced infrared semiconductor laser for CD players. The VSIS structure is a system for effectively emitting laser light by creating a V-shaped channel in a crystal and narrowing down an area for an electric current to pass through. Fig. 3-2-5 shows the VSIS structure developed by Sharp (taken from Sharp Technical Journal).

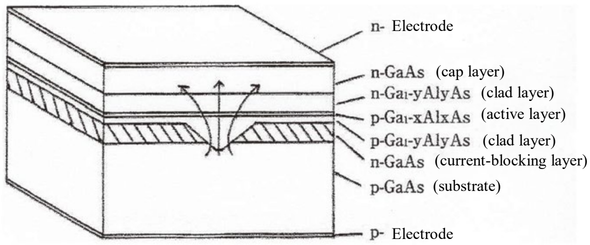


Fig. 3-2-5 Sharp VSIS Structure

The CD is designed with a system based on a 780nm wavelength semiconductor laser. This light is tentatively categorized as visible light, although in practice it is only visible if illuminating a white piece of paper in a dark room. For CD playback, only 0.5mW is needed to reach the disc surface, while 3-5mW is enough for effective use of the optical pickup. However, the growing popularity of the CD-ROM drive from the end of the 1980s and the CD-R/RW drive from around 1995 triggered a competition over high-speed playback and recording. With CD-R/RW recording speed increasing, the semiconductor laser output also had to increase. For recording, the highest speed of the CD-R was 16× that of its base speed. Recording with an optimal waveform required a peak value of around 30mW. This also depended on the efficiency of the optical system and the recording waveform (write strategy). In the 2000s, advances in high-powered semiconductor lasers saw the emergence of systems with 200mW lasers. Sharp even achieved a high-powered infrared laser capable of 48× CD-R recording. The infrared semiconductor laser was destined to trigger further competition over higher power, faster recording speed, smaller size, lighter weight and lower cost. To remain competitive, manufacturers improved their operational efficiency and picked up their development speed. This endurance-building resulted in new DVD and Blu-ray products.

In 1985, Sony started producing infrared semiconductor lasers for CD, using a metal organic chemical deposition (MOCVD) technology it was developing. Organic refers to carbon. A gas such as gallium is converted into organic metal trimethyl gallium (CH3)3GA, gasified using a carrier gas and passed into a reaction chamber with a substrate of highly heated GaN or GaAs, and a thin layer is deposited onto the substrate. Indium (In) or aluminum (Al) can also be added into the gas, as well as the necessary impurities for N and P type semiconductors, thus producing multiple layers of high-quality thin film. Different companies explored different methods, such as liquid phase epitaxy (LPE) and molecular beam epitaxy (MBE), but MOCVD became the industry standard as it was good for mass production. The method was also later used for the 650nm infrared semiconductor lasers used for reading DVD and the 450nm blue-violet semiconductor lasers used for reading Blu-ray. Since the early laser products used a lot of electricity, a large 9mm diameter package was used to ensure waste heat dissipation. As lower power consuming systems were developed, the optical pickups and other hardware grew smaller. Today, the package for reading Blu-ray and other discs has a 5.6mm diameter. The highest-produced semiconductor laser for CD by Sony is the SLD104U-A, with a colossal 700 million produced between 1989 and 2007. Sony is still producing semiconductor lasers for CDs, and production now totals over 3 billion, including double wavelength semiconductor lasers that can read both CDs and DVDs (780nm and 660nm in one package). Fig. 3-2-6 shows a Sony semiconductor laser for CD.

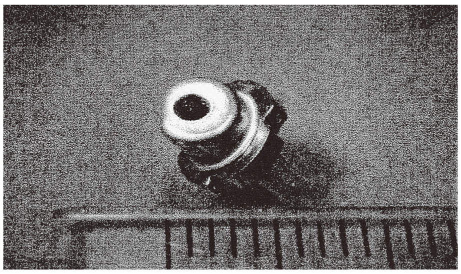


Fig. 3-2-6 Sony Semiconductor Laser for CD

3.2.2 Aspherical Plastic Objective Lens

As previously mentioned, the first objective lenses used for CD pickups were microscope objective lenses made of optical glass and comprising two groups and three layers. These were a very expensive component, costing around ¥3000 at the time. While this was a fair price for microscope manufacturers, electronics manufacturers commercializing CD players needed to drop that figure into double or even single digits. The physics and applied physics specialists from the electrical manufacturers came together to try to design a lens that would resolve this. This was just after the emergence of the portable CD player around 1984. Through successive meetings, the study group was able to calculate the coma aberration and spherical aberration and virtually created an optical lens by trial and error. They worked on the possibility of an aspherical lens and reached a point where they could design it themselves. The wavelength used in CDs is a single 780nm laser wavelength and does not require an achromatic lens. Introducing an aspherical lens into the design made it possible to achieve with a single lens. This conclusion was simply conjecture. The curved design was completed but manufacturing the mold for the lens took a series of trial and error. By a stroke of luck, they tried casting an aspherical lens using inorganic glass and it met the requirements. However, when it came to pilot plant production, it was clear that they needed to improve the poor yield rate and reduce costs. To resolve this, if the lens could be made from acrylic resin or similar, this would be optimal for reducing cost. However, this was no easy task at all.

The Philips optical laboratory in Eindhoven is said to have had shelves full of failed plastic objective lenses. An engineer at Philips made the following comment to a visiting Japanese engineer. “We’ve tried so hard and haven’t been able to get it right, there’s no point in the Japanese trying. For your own good, stop wasting your efforts trying to make plastic pickup lenses.” CD pickup lenses required submicron accuracy, beyond the specifications of plastic lenses for glasses or viewfinders. Everything down to ambient humidity was a major factor. There were an incalculable number of failures. Many companies gave up trying to produce a plastic pickup lens. The only one that did not was Sony. Sony, perhaps as a safeguard while working on its own developments, provided funds to Konica, which had a long wealth of technical experience in lens design, and handed over the project to the Kojima Tadashi Group, which had spearheaded the design of the zoom lens for the single-lens reflex camera. The Kojima Group had been looking for a change of direction from single-lens reflex cameras and leapt to the task. Through a tremendous amount of trial and error, the efforts finally paid off with the successful development of an aspherical plastic objective lens for CD. This success was underpinned by research and prototypes in aspherical lenses by Yoshida Shōtarō in the late 1950s and early 1960s (Bulletin of the Research Institute for Scientific Measurements, Tohoku

University). The Kojima Group quickly took note of Yoshida's research and proved it was possible to produce an aspherical plastic objective lens by developing a lens with a similar shape to Yoshida's aspherical aplanatic lens (a lens for correcting spherical aberration and coma aberration). Yoshida's aplanatic lens suddenly came under the spotlight, opening up a fierce patent dispute after three decades. However, thanks to Konica's perseverance, the patents were established in Japan and the United States, with Konica securing a monopoly share over aspherical plastic objective lenses for CD.

Eventually, all of Sony's globally-booming CD drives were fitted with the aspherical plastic objective lenses developed by Konica. Production went from 1 to 2 million per month to a colossal 10 million per month. As production increased, the unit cost of the lens dropped dramatically, from ¥300 to ¥100 and then to ¥50, while Konica continued to hold the monopoly. However, Sony began to see that Konica's hold on this key device (the principle of having a key device procured by two companies) would cause future problems in business. Sony again began developing its own technology and also began to consider the possibility of manufacturing its own.

Kojima Tadashi, who originally designed the single-lens reflex camera zoom lens, was awarded the Medal with Blue Ribbon in recognition for the development of the aspherical plastic objective lens for compact disc. The number of aspherical plastic objective lenses for CD produced by Konica totaled to well over 500 million. In that sense, without Konica's objective lens, there would have been no hope of the CD becoming as widespread as it is today. Fig. 3-2-7 shows a Konica aspherical plastic objective lens for CD.

Meanwhile, Sony was having a difficult time developing its own aspherical plastic objective lens. The final deposition stage of the process was proving particularly impossible. The company built a new dedicated plant in Singapore and continued the race against time. The most important and technically demanding step in the manufacturing process for aspherical plastic lenses was the deposition of the anti-reflective coating. The Konica team had found that applying a coating with grooves to allow vapor in and out of the plastic lens surface made it possible for the lens to have a refractive index distribution with an onion-like appearance that maintained the imaging performance. With no knowledge of this research and development, the team at Sony found that the refractive index distribution of the aspherical plastic lens was always distorted and could not achieve the specified imaging performance. The Sony engineers worked day and night to develop this deposition method with multiple grooves, and the Singapore plant somehow managed to achieve mass production. In that sense, Konica's greatest technical knowledge of the aspherical plastic objective lens was this vapor respiration mechanism.

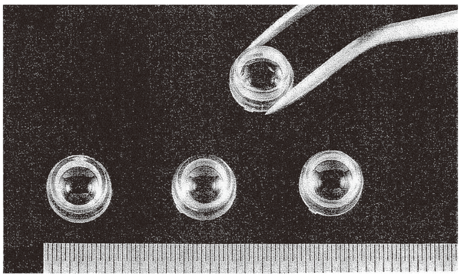


Fig. 3-2-7 Konica Aspherical Plastic Lens for CD

3.3 Deciding on a Digital Signal Processing Method

Fundamentally, audio digitization began in 1982 with the sale of the CD-DA disc. According to the Kōjien Japanese dictionary, digitization means expressing a certain quantity or data as a finite numeric string (e.g. binary). Analog is given as expressing a certain quantity or data as a physical quantity that can change in continuum (e.g. voltage or current). Naturally occurring physical quantities such as temperature, humidity, length and mass are all continuous analog quantities. By contrast, digital uses a number to express the nearest value to the analog quantity within a certain range of accuracy. Since values that are represented digitally can be processed by computer, it is possible to record and store those values and they do not change. Using digital methods to record, transmit, distribute and play back images and sounds means the data remains constantly unchanged regardless of how many times the content is viewed or heard. This is a major advantage over analog, in which the data is susceptible to change through deterioration or noise. In the process of audio playback, there are a number of processes between recording at the concert hall or studio and hearing by the user, including editing, duplicating and playback. With conventional analog audio, each of these processes was accompanied by a very slight deterioration in sound quality. However, with the emergence of the CD and digital audio, for the first time it was possible to have no deterioration at all in these processes, other than errors in the initial digitization.

Fig. 3-3-1 shows the general configuration of digital audio recording and playback equipment. The analog signal enters the recording system, passes through the line amp and low pass filter (LPF), and is converted to a digital signal by the sampling circuit (sample-and-hold circuit) and quantization circuit (A/D converter). An error-correcting code is then added to the signal, it undergoes modulation or other digital signal processing and is then recorded on optical disc or other recording medium. For playback, the signal is read from the recording medium and undergoes demodulation, error correction, digital filtering and other digital signal processing before being converted to an analog signal by the D/A converter.

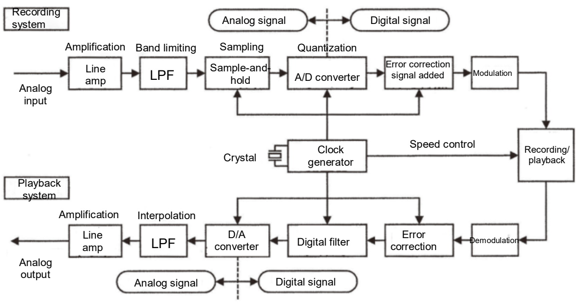


Fig. 3-3-1 Digital Audio Recording/Playback System Configuration

Essentially, sound comprises subtle changes in atmospheric pressure. It is an analog signal with an amplitude that changes continuously with time. In actual analog recording, factors such as the S/N ratio of the recording medium, frequency characteristics and non-linear distortion have a direct impact. Other issues include wow and flutter and modulation noise caused by uneven rotation of the rotary or drive system, as well as noise from mechanical scratches on the recording medium. By contrast, digital recording converts the audio signal into discrete numerical values, which not only does away with the issues given above, but also has other inherent advantages, such as essentially no deterioration when making digital copies and the ability to correct the few errors that occur.

The outline of this chapter is as follows. 3.3.1 discusses the basic mechanisms of digital audio (PCM), quantization and sampling frequency. 3.3.2 outlines the eight to fourteen modulation (EFM) CD modulation method. 3.3.3 provides an overview of the cross interleaved Reed-Solomon code (CIRC) error correction method.

3.3.1 Digital Audio (PCM) Mechanisms

A) Quantization

Pulse code modulation (PCM), the cornerstone of digital audio, is a digital signal format used in CDs. CDs use 16-bit quantization, which comprises 16 digits of binary values, either 1 or 0. The highest value is 1111111111111111, which equates to 65535 in base 10. The word "digital" comes from the Latin word "digitus", meaning "finger". Generally, binary digits are called "bits". Using the fingers on both hands gives 10 bits in binary, which equates to 1023 in base 10 (1 + 2 + 4 + 8 + 16 + 32 + 64 + 128 + 256 + 512). Table 3-3-1 shows a comparison between binary, base 16 hexadecimal and base 10. In hexadecimal, letters of the alphabet are used to represent the values from 10 to 15, since these must be represented as single digits. Accordingly, 10 in base 10 is represented as A in hex, 11 as B, 12 as C, 13 as D, 14 as E and 15 as F. Two-digit hex values go up as high as FF, which equates to 255 in base 10. Each additional digit adds a new place and indicates the number of times by which the digit has been increased by the base number. Binary is used in digital devices and is highly compatible with hexadecimal. This is apparent in the timing by which new digits are added. For example, the highest single-digit number in hex is F, which is represented in binary as the four digits (bits) 1111. The highest two-digit number in hex is FF, which is represented in binary as the eight digits (bits) 11111111. For each digit added to a hex number, four digits (bits) are added in binary. Table 3-3-1 shows a comparison between binary, base 16 hexadecimal and base 10.

Table 3-3-1 Binary, Base 10 and Hexadecimal

Base 10	Binary	Hexadecimal
0	0	0
1	1	1
2	10	2
3	11	3
4	100	4
5	101	5
6	110	6
7	111	7
8	1000	8
9	1001	9
10	1010	A
11	1011	B
12	1100	C
13	1101	D
14	1110	E
15	1111	F
16	10000	10
17	10001	11
18	10010	12
19	10011	13
20	10100	14
21	10101	15
22	10110	16
23	10111	17
24	11000	18
25	11001	19
26	11010	1A
27	11011	1B
28	11100	1C
29	11101	1D
30	11110	1E
31	11111	1F
32	100000	20
33	100001	21
63	111111	3F
64	1000000	40
127	1111111	7F
128	10000000	80
255	11111111	FF
256	100000000	100
1023	1111111111	3FF
1024	10000000000	400
4095	111111111111	FFF
4096	1000000000000	1000
65535	1111111111111111	FFFF
65536	10000000000000000	10000

Electronic devices operating digitally use binary, as they can only have two values, “on (1)” and “off (0)”. By processing these values at high speed, they can represent large numbers, character information, graphics, images and even sound. Sound is originally a wave that oscillates in objects and the air. As the wave increases, it moves up and down from a zero point. The portion above zero can be expressed as a plus value, while the portion below zero can be expressed as a minus value. To represent minus values in binary, a notation system called “two’s complement” is used. This way to calculate negative numbers in binary is achieved by “inverting all the original bits and adding 1”. The highest positive number in two’s complement representation is not 111111111111, but 011111111111, which equates to 32767 in base 10. The lowest negative number is 100000000000, which equates to -32768 in base 10. The PCM used in CDs operates with 16-bit (16-digit) binary, which allows for digital data with a range of 65536 values from 32767 to -32768.

The size of the original analog signal of a sound can be represented as the amount of voltage after it is picked up by a microphone and converted into an electrical signal. This is converted to digital data by analog to digital (AD) conversion. The analog sound (amount of voltage) is converted to the nearest values in the 16-bit range outlined above. This process of digitizing the sound is called quantization.

Although the voltage value of the (analog) sound at AD conversion varies depending on the components and circuit configuration used, it generally uses 5V or 3.3V values. These are divided out by 65535, so that each step has a value of 5/65535 = 0.076mv (76μv). The signal is converted to the nearest digital values with 76μv accuracy.

B) Sampling Frequency (Sampling)

Taking a signal that changes continuously with time and representing it with values at fixed intervals is called sampling. Sampling makes it possible to turn a continuous signal into discontinuous, discrete signals. Turning these discrete signals into a continuous signal again is called interpolation. This is done by sending a sample sequence through a low pass filter (LPF). Generally, the audible range (bandwidth) of the human ear is around 20-20,000Hz. Sound below 20Hz is called ultra low frequency, while sound above 20,000Hz is called ultrasonic frequency or ultrasound. The well-known Shannon’s Theorem sets out the conditions for signal reproduction in the sampling interpolation process. If the signal bandwidth is represented as B and the sampling frequency is represented as f, then provided B (Hz) ≤ f/2 (Hz), playback can be achieved without distortion. This means that provided a signal is captured at a frequency more than two times greater than the highest frequency of the original signal, digitization can be achieved without any loss of original signal information. However, in practice, frequencies are chosen to allow for a further 10% margin. Based on this principle, the sampling frequency could be any frequency higher than 40,000Hz, since the highest frequency audible to the human ear is 20,000Hz. The frequency used in PCM for CDs is 44,100Hz, as mentioned above, to maintain compatibility with VTR. This means signals are captured at a frequency of 44,100 times per second. This process is called sampling, and the frequency used is called the sampling frequency. Fig. 3-3-2 shows a diagram of quantization and sampling. The size of the increments on the vertical axis is determined by the quantization (bit number), while the size of the increments on the horizontal axis is determined by the sampling frequency. Essentially, the greater and more precise the values on both axes, the more precise the representation will be. The 16-bit, 44.1kHz specifications for CD allow a precision of 65,536 steps on the vertical axis and 44,100 steps per second on the horizontal axis.

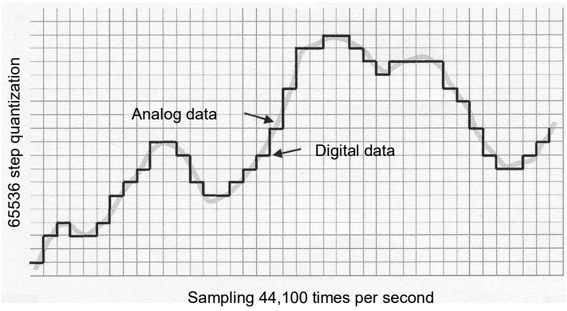


Fig. 3-3-2 Diagram of Quantization and Sampling

The quantized sample values are converted to discrete numerical values in reference to amplitude. The dynamic range that represents the quantization of n bits can be expressed as D (dB) = $20\text{Log}2^{n}$ + 1.76 (dB). For CDs, n = 16, which gives a theoretical dynamic range of D = 97.8 (dB). It is also important for digital signal processing technology to deal with quantization error noise, aliasing and other issues. Accordingly, careful attention has been paid to LPF design. Technically, the LPF is not set to not rapidly drop from 20kHz. An oversampling LPF carries oversampling out at eight times higher than 44.1kHz, then gently curves to half that frequency, 176kHz. This prevents aliasing and delays in the 20kHz region, thereby minimizing any changes in sound quality.

3.3.2 Eight to Fourteen Modulation (EFM) Method

Modulation is converting given information at a given frequency band to record and play back reliably, that is, matching frequency band to signal. Specifically, when a CD player reads data, a technology called eight to fourteen modulation (EFM) ensures that the track with the data recorded is kept in sight.

A compact disc has data etched onto it in a spiral shape. Since it is binary digital data, a pit with data is read as 1 and a land with no data is read as 0. Automatic tracking control (servo) is used to maintain track position as the CD player reads the pits to prevent the same effect as a needle jumping to a neighboring track in an analog player. This can be controlled automatically based on the pits where pits are etched onto a compact disc, but if there are areas with no pits, it can be difficult to track the signal. Simply, EFM technology was developed to prevent this from happening.

Data recorded on compact disc is essentially in units of eight bits. Eight-bit data has 256 values, ranging from 00000000 to 11111111. For example, if a signal of 00000000 continues for a while, this equates to a section that is all land and no pits. To resolve this, the 256 values are temporarily converted to 14-bit values containing moderate amounts of 1 and 0, and then recorded onto the disc. Since the 256 values of 8-bit data are a selection from the 163,384 values of 14-bit data, it is possible to use only data that includes moderate amounts of 1 and 0. This is handled as per the EFM lookup table shown in Table 3-3-2. One 8-bit symbol is converted to a specific pattern in 14-bit representation. Eight-bit 00000000 is converted to 14-bit 01001000100000 and then recorded. Even if this data signal continues for some time, 1 continues to appear at a moderate rate. The CD player then reads 14-bit 01001000100000 and converts it back from the lookup table to 8-bit 00000000.

EFM modulated digital data is read by a system with frequency characteristics such as an optical pickup. When 8-bit (256) is converted to 14-bit (16,384), the channel bit “1” is inverted and “0” is not inverted so that the pits on the disc form a certain shaped interval. The number of 0s between 1 and 1 can be between 2 and 10, giving a total of 257 values.

Table 3-3-2 EFM Lookup Table Example

Data (base 10)	8-bit data (binary)	Data converted to 14-bit
0	00000000	01001000100000
1	00000001	10000100000000
2	00000010	10010000100000
3	00000011	10001000100000
4	00000100	01000100000000
5	00000101	00000100010000
6	00000110	00010000100000
7	00000111	00100100000000
8	00001000	01001001000000
9	00001001	10000001000000
10	00001010	10010001000000
11	00001011	10001001000000
12	00001100	01000001000000
13	00001101	00000001000000
14	00001110	00010001000000
15	00001111	00100001000000
16	00010000	10000000100000
17	00010001	10000010000000

Forms a pulse signal between a minimum 3T and maximum 11T, where T is the channel bit cycle. The length of the pit is represented as T min and T max. In terms of a standard clock sensor, the longer the T min the better and the shorter the T max the more stable the system. The actual CD pit length after EFM modulation can have nine values at a speed of 1.25 m/s: 0.87µm, 1.16µm, 1.45µm, 1.74µm, 2.02µm, 2.31µm, 2.60µm, 2.89µm and 3.18µm.

The EFM signal then has a 1B (8-bit) non-audio control code called a subcode added and a frame cycle signal added to produce the CD recording signal. One frame is made up of 588 channel bits. A three bit guard is positioned between each symbol converted to 14-bit to prevent “1” bits running together. This is processed in real time during data creation. The number of channel bits in a frame is $14 \times 33 + 24 = 588$ (bit/FRAME). The channel bit frequency is 7.35kHz × 588 = 4.3218MHz. This is the read clock frequency generated by the CD player.

3.3.3 Error Correction Method (CIRC)

Cross interleaved Reed-Solomon code (CIRC) is an error correction method first adopted in the Red Book. It combines two methods: cross interleaved and Reed-Solomon. Error correction is based on advanced mathematical theory. A brief summary is given here, as this is best left to a specialized book. The Reed-Solomon (encoding) method is a system of error correction using a combination of data words (code words) and parity words (redundant words or check words). This system allows powerful error correction for short, frequent errors (random error). Interleaved correction is more effective for correcting long errors (burst error) that occur easily on disc media. Interleaved refers to the process of breaking up the data and dispersing the error. Those data blocks are then combined with Reed-Solomon encoding. Fig. 3-3-3 shows an interleaved example.

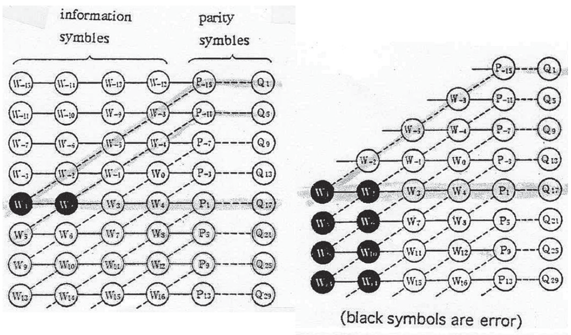


Fig. 3-3-3 4 Interleaved Words

The concept of error correction can be described using a supermarket receipt as an example.

A receipt from the supermarket might total ¥1000 of shopping, where A = ¥200, B = ¥100, C = ¥400 and D = ¥300. If the receipt gets dirty or torn so that it can no longer be read, the following ways could be used to restore it to its original condition.

(1) If the unreadable area can be identified

If one row cannot be read (one word missing), e.g. ¥200 + [?] + ¥400 + ¥300 = ¥1000, the missing word can be calculated from the total, in this case [?] can be calculated to be ¥100 and the sequence can be fully restored (error correction is possible). However, if "1" is read as "2" (one word error), it cannot be determined where the abnormality lies (error detection possible). If there are errors in two or more rows, error detection is not possible. The receipt data comprises four code words and one check word. The following system applies.

i) With one word missing, correction is possible

ii) With one word in error, detection is possible but not correction

iii) With two words in error, detection is not possible

With a two check word configuration, the check words are the total P and a newly added weighted sum Q, where P = A + B + C + D, and Q = A + 2B + 3C + 4D.

(2) If an error is read (error area cannot be identified)

(a) ¥200 + [¥200] + ¥400 + ¥300 = ¥1100 (P)

(originally ¥1000; difference of ¥100)

(b) ¥200 × 1 + [200] × 2 + ¥400 × 3 + ¥300 × 4 = ¥3000 (Q)

(originally B = 100 × 2, Q = ¥2800; difference of ¥200)

From this, (b) ÷ (a) = 2, (b) – (a) = ¥100, thus it can be determined that the correct value for the second code word is ¥100. Adding the check word Q improves the error correction capability as follows.

i) With two words missing, error correction is possible

ii) With one word in error, error correction is possible

iii) With two words in error, error detection is possible

P and Q are called parity words. This code structure is called Reed-Solomon encoding.

The following is a summary of interleaved and cross interleaved encoding. Data loss due to optical disc dropout can occur for longer than two words, making error correction impossible using the methods described above. Consequently, if the signal is recorded with the word sequence temporarily rearranged so that no two of the same block words occur beside each other, it is possible to reduce the chance of two word errors. This rearrangement of word sequence is called interleaving. The following are the main causes of error in CDs.

(1) Errors occurring during the disc manufacturing process

(2) Scratches or soiling on the disc surface

(3) Servo or sync misalignment

In the case of (1), errors occur frequently in the form of random error (short gaps), while for (2) and (3), errors tend to occur less frequently, but in the form of burst error (long gaps). The error correction method used is cross interleaved Reed-Solomon code (CIRC), a combination of Reed-Solomon code, which is good for correcting random error, and the cross interleaved method, which is good for correcting burst error.

The occurrence likelihood of bit errors correctable by CIRC is around "once per disc". Of course, the error correction sets to work to produce a correct signal. Even if the disc is scratched beyond the scope of error correction, it is possible to correct scratches on the disc up to 2.4mm in length with erasure correction. CD-DA output is a continuous analog signal with high correlation between adjacent samples. It is therefore possible to interpolate the signal by inferring from the correct data before and after. The interpolated signal is hardly noticeable to the listener.

However, it was very clear when the Red Book was standardized that the CD is not just a digital audio disc (DAD), but also a digital data disc (DDD). Standardized production began immediately for use as high capacity computer memory storage. The standard book for CD-ROM used in computers is called the Yellow Book, as shall be mentioned later. If a user tries to use an audio disc for computer memory storage, the greatest issue will be error correction. Computer data will not allow even one bit of “error” and requires a more powerful method of error detection and correction. In addition to CIRC, the Yellow Book includes an error detection code (EDC) and an error correction code (ECC). The EDC checks for the presence of errors using a check sum. Any errors detected are corrected using a correction code in the ECC. The two systems are so effective that the random error bit error rate is around 1000 times lower than using CIRC alone. This is the level of performance required by the Yellow Book for computers CD-ROMs. Accordingly, all PC CD-R/RW drives now sold include EDC and ECC systems as well as CIRC. When producing CD-R and CD-RW content (storing data), powerful error correction is automatically included in that data.

In terms of data flow through encoders, the CIRC configuration is as follows. The data from the A/D has a 12 word input (6 samples left and right; 1 sample = 2 words, 1 word = 16 bits). First, the word is divided into two symbols (1 symbol = 8 bits), upper (A) and lower (B), and converted to 24 symbols. A two symbol delay is applied, and then the signal is scrambled and sent to encoder C2. Parity generates 4 symbols, making a total of 28 symbols. The 28 symbols are interleaved and sent to encoder C1, where parity generates another 4 symbols to a total of 32 symbols. A one symbol delay is applied to every other symbol; the two symbols are output as 1 frame of data. The 8-bit data output undergoes EFM modulation and recorded to the CD (the frame actually has cycle signal and subcode added). Fig. 3-3-4 shows an outline of CIRC encoding. When the signal is decoded, this configuration is reversed.

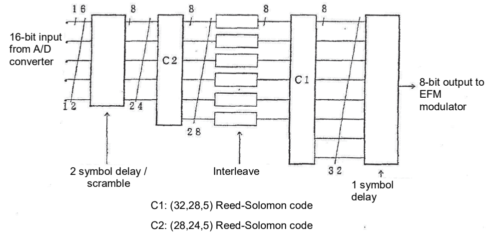


Fig. 3-3-4 CIRC Encoder Overview

3.4 CD Media Physical (Logical) Format

In order to utilize a recording medium as an actual versatile medium, various conventions must be met. For example, if a sheet of white paper is designated as A4 size and 0.1mm thick, its physical specifications are clear. This is its “physical format”. When data is being recorded on to CD media (CD ROM), unless a physical format and logical format (file system) are specified, nothing can be recorded to the disc. The following discusses aspects from the basic CD media subcode and file structure to the file system. The file system used in actual writing technology is discussed in Chapter 7 “Emergence of Recordable CDs”. Fig. 3-4-1 shows a diagram of the track structure and block structure of the CD family.

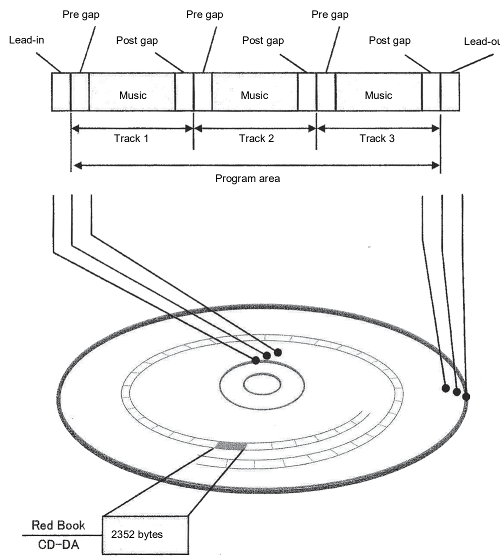


Fig. 3-4-1 Track Structure and Block Structure of the CD Family

3.4.1 CD-DA Subcode

Music is recorded on CD-DA discs in song units called "tracks". This has the same recorded subcode control information as CD media. The smallest unit needed for recording this subcode is called the frame (subcode frame). In other words, a CD-DA music track is a collection of multiple frames. The information necessary information for CD media playback and control is designated as subcode. For CD-DA, the FFM modulated digital music data is managed as a collection of 98 EFM frames. These are the subcode frames. While Fig. 3-4-2 is quite detailed, it shows the relationship between the EFM frame and the sub code frame. One EFM frame is made up of 24 bytes of recorded audio data with C2 and C1 error correction parity added to every 12 bytes of data. This set comprises 98 EFM frames. Thus, EFM frame × 98 = 1 subcode; subcode frame recording capacity = 24 bytes × 98 = 2352 bytes. Music tracks are made up of multiple subcode frames, although the total subcode varies depending on the length of the music. Subcode information is 8-bit and plays back continuously when the disc is played. It is managed in units called channels. There are eight subcode channels, P-W. The P and Q channels are used for CD-DA media. The R-W channels are not used elsewhere in the CD family except for subcode CDs.

The P channel records the lead-in area indicating the start of recording, the lead-out area indicating the end of recording, and the interval between music tracks. The Q channel records the table of contents (ToC) indicating the songs recorded on the CD, the music track numbers, index numbers, track duration, disc length and other information. Fig. 3-4-3 shows a diagram of the P and Q channels. The main control signals in CD-DA players are held in these channels and they are used as the basis for all system controls. These channels are also used for recording the international standard recording code (ISRC).

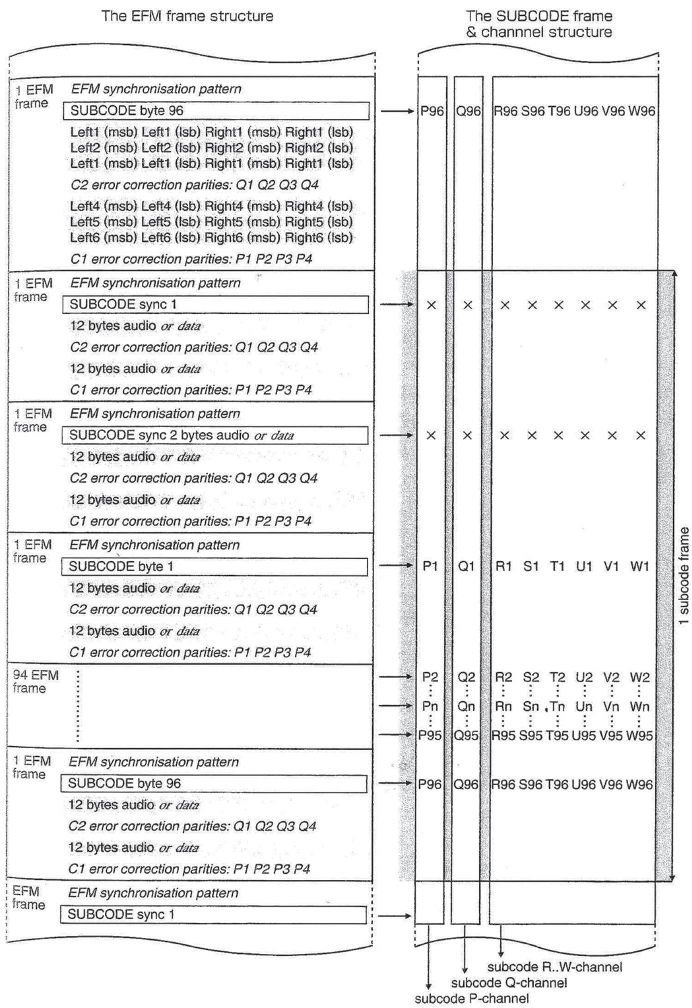


Fig. 3-4-2 Relationship Between EFM Frame and Subcode Frame

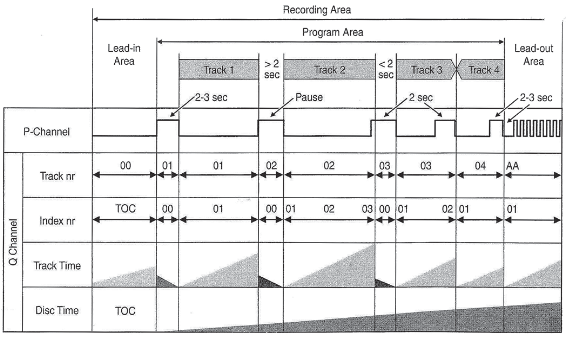


Fig. 3-4-3 Relationship Between CD-DA Subcode P and Q Channels

Meanwhile, the R-W channels are designated for subcode CDs and used for applications such as CD-G (CD graphic still images), CD text (text information) and CD-MIDI (MIDI signals). A typical CD-G plays back music like a CD-DA, but can also play karaoke videos with images synchronized to the music. These were very popular in the karaoke industry. CD text records information such as album title, track names, artist names and messages on CD-DA discs. Although these added value to the CD-DA, they were not highly popular, as the difficulty in authoring could not be reflected in the price. The CD-MIDI records data in MIDI format, the standard interface for electronic musical instruments. Although these could be used for ensembles of MIDI connected electronic instruments, in practice they have been used to control musical equipment and venue lighting and have not been overly popular.

3.4.2 CD-ROM Technology Development

The most popular CD media, the CD-ROM, has the data on disc controlled by subcode. The following provides a simple outline of CD-ROM sector formatting. Generally, a CD-DA transmits 75 frames of data per second. On CD-ROM, the frames are called sectors. CD-ROMs also physically record in minimum units of 2352 bytes per frame. The data recorded in each frame is structured in two modes.

(1) Mode 1 records the necessary data for error correction in some sectors. This mode is used for recording files, programs and other general data. One frame of user data has a recording capacity of 2048 bytes. This figure is calculated by 2048 = 2352 – 12 (sync) – 4 (header) – 288 (auxiliary, including ECC). Accordingly, a 74 minute disc CD-ROM has a recording capacity of around 650 megabytes. Most CD-ROMs are structured with Mode 1.

(2) Mode 2 has no error correction data and is suited to video or audio signals where read errors have little impact. The benefits of Mode 2 is that the area used for error correction in Mode 1 can be used for user data. This increases the recording capacity by 15% to 2336. This figure is calculated by 2336 = 2352 – 12 (sync) – 4 (header).

The physical format specifies that general data and audio/video data cannot coexist on the same track. This means the disc cannot be used for multimedia content. One proposal was to divide Mode 2 into Form 1 and Form 2, making it possible to have a mix of general data and audio/video data. Specifically, a subheader is designated to specify the form, as shown in Fig. 3-4-4. A major feature of subheaders is the ability to play back audio and images in sync. The Mode 2 Form 2 structure is unique, culminating in the CD-I (CD-Interactive), specifying the CPU (Motorola MC68000) and OS (real time OS, OS-9). This standard is generally called the Green Book. This technology was undergirded by an era in which computer technology had to be incorporated into consumer electronics. Household appliances had to start with a single switch, and media had to be compatible. Specifying the latest CPU and OS was written into the standard to achieve a superior position. The system had the latest real time OS and the fastest consumer CPU, the Motorola MC68000, capable of multitasking. Unfortunately, the high price and the lack of infrastructure for software production meant this did not grow into a major business and the technology was eventually engulfed by the Microsoft stronghold. However, in industries with various computers (CPU and OS), specifying the CPU and OS is not done generically. A new standard called CD-ROMXA (CD-ROM extended architecture) was formulated to remove that limitation and has been widely used in the field of PCs.

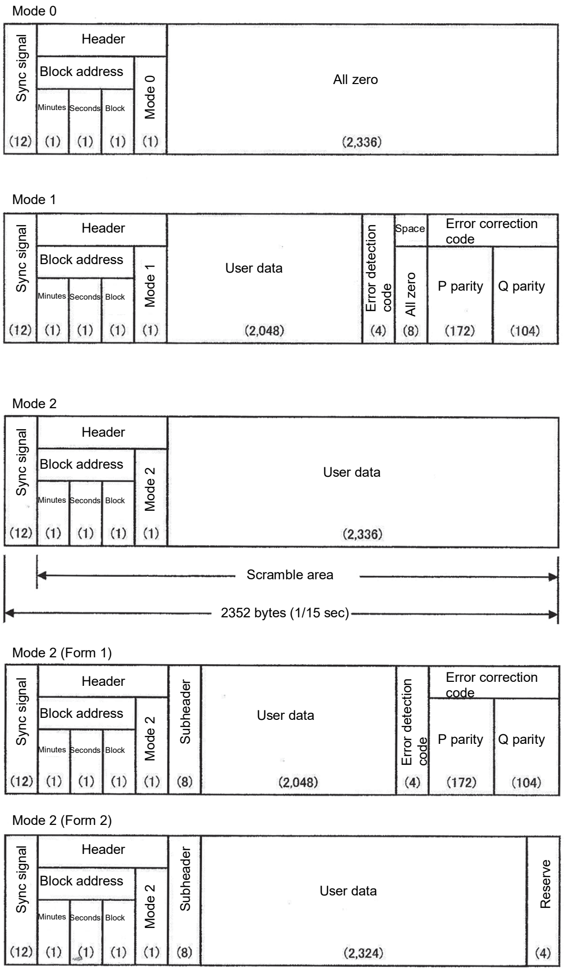


Fig. 3-4-4 CD-ROM Mode Structure

The development of CD-ROM technology, which records digital data instead of CD media audio information, began directly after the launch of the CD-DA. The personal computer originated with the microcomputer LSI chip 4004 in 1971. This was followed by the emergence of the 8-bit CPU 8008 in 1972, but it was never used for anything beyond a high-end calculator part. An improved version, the 8-bit CPU 8080, was launched in 1974. This was a major turning point in the course of history. In 1975, the first microcomputer kit, the "Altair 8800", was commercialized using the 8080 chip. This triggered a worldwide boom in home-built microcomputers. "BASIC", the programming language used in the Altair 8800, was developed by a college student venture led by Bill Gates. This venture business was later significantly impacted by the development of CD media, growing into global giant Microsoft. In the early 1980s, the microcomputer system was fitted with a keyboard input device and output results to a display. With a built-in hard disk operated by BASIC programming, it was steadily progressing into what would become known as the personal computer. However, the personal computer of this era was still an expensive system. The main reason for the high price was the cost of the internal memory (RAM) and the hard disk. This was a time when 1MB of hard disk came with a price tag of ¥10,000. There was indeed demand for a high-capacity, low-priced memory device.

PC recording media consisted of floppy disks. In 1976, the 8-inch floppy gave way to the 5.25-inch floppy, but these were still small in capacity and expensive in price. It was not a convenient form of media. PCs were loaded with graphic display functions and audio functions, while more reasonable floppy disks were produced. While the large external devices were being built in internally, what the PC needed to become cheaper and more widely accessible was an inexpensive, high-capacity media to replace the hard disk. In 1984, Sony and Philips formulated the CD-ROM standard. Microsoft immediately started up a CD-ROM business. In 1985, a publication was produced called "CD-ROM, the New Papyrus" (ASCII, Japan). The CD-ROM had a clear strategy forward.

The CD-ROM standard only stipulates the physical format, as the stipulations for recording general data are included in the CD-DA audio data standard. Since the CD-ROM was to function as a practical media device, it obviously had to have various logical formats stipulated. Since whoever first gained control of the logical format would gain control of the market, Microsoft actively worked on the logical format. In that sense, Microsoft and the CD-ROM were in a were in a highly reciprocal relationship. The CD-ROM played a major role in the company developing into a global player.

3.4.3 CD-ROM Logical Format

With the CD-ROM standard formulated, the way was finally open for it to be used as a recording medium for general digital data. However, for the CD-ROM system to be used as an external recording device, the logical format or "file system" had to be worked out. Generally, computer data is handled in file chunks. The file system manages these files. The issue was that the file system specifications were different for each operating system (OS). Even if generic files were recorded on a CD-ROM, if the file system on the CD-ROM differed from that of the computer, the recorded data could not be read from the disc. This was a serious situation. When CD-ROMs were first put into use, the level to which the software would be developed to fit the file system was left to the discretion of the software developers. As a result, manufacturers produced their own software with almost no thought to compatibility.

There were high hopes that the long-awaited, precious, high-capacity, low-price CD-ROM media would open up new markets that had not previously existed, such as database publications and multimedia software. The challenge of somehow ensuring PC compatibility crossed the border between the media industry and the computer industry. There was a strong push to standardize the logical format at the necessary file system level in order to use the CD-ROM as a medium for exchanging general data. In an unprecedented move for in the highly self-reliant computer industry, rival companies came together to establish a system to commercialize the CD-ROM as soon as possible with industry-wide support. Such was the appeal of the CD-ROM.

The first step towards compatibility was to adopt the physical format of the CD-ROM as an international standard. The International Standards Organization (ISO) and International Electrotechnical Commission (IEC) formulated ISO/IE 10149:1989 as a basis. The European Computer Manufacturers Association (ECMA) adopted ECMA-130, based on ISO 10149, while the Japan Industrial Standards (JIS) did the same with JISX6281:1992. Similar industrial standards were adopted by many countries around the world. The CD-ROM standard may have started out at consumer level, but its official adoption by the ISO in the form of ISO 10149 elevated the CD-ROM physical format to international standard status.

The second step towards compatibility was unification of logical formats. In May 1986, Philips and Sony, together with prominent computer manufacturers including Microsoft, DEC and Apple Computer, proposed a logical format named High Sierra Format, after Del Webb's High Sierra Hotel and Casino in Lake Tahoe, California, where the first meeting was held. This specified a common file system structure for press-type optical discs that was not dependent on any specific hardware or OS.

Technologically, by introducing the idea of a file set called a volume, it was possible to have multiple volumes on one title or, conversely, have a single volume spanning multiple CD-ROM titles (multi-volume). The ISO 9660 file structure, ordered as "root directory → directory → file", was managed by a "structure containing descriptive information relating to the file system", known as a volume descriptor. Taking the characteristics of the CD-ROM drive into account, the pointers to the directories and files in the file system were created in advance using a path table. This allowed file access with as little seeking as possible by the optical pickup. Improvements were made to the High Sierra Format and it was standardized in 1988 as ISO 9660. The format has since been widely used as the standard logical format for CD media. Fig. 3-4-5 shows the basic ISO 9660 structure.

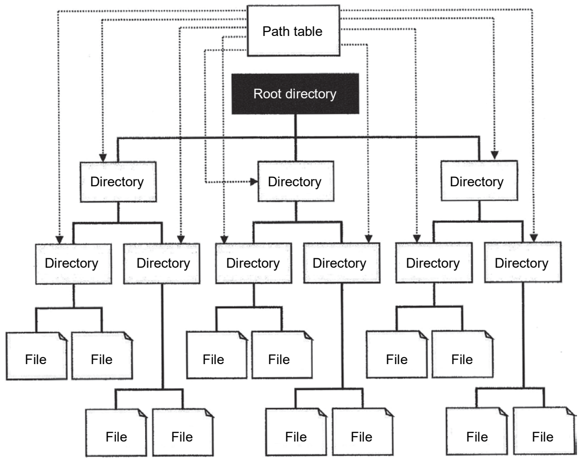


Fig. 3-4-5 ISO 9660 Basic File Structure

With ISO 9660 formulated as the international standard logical format for CD-ROM, file sharing by CD-ROM was immediately possible. However, there were later issues with long file names. The standard originally allowed for file names with a maximum of 32 characters, although the early CD-ROMs gained popularity as PC peripheral devices in the MS-DOS environment, which generally used the MS-DOS 8.3 format for file names (8-character file name + 3-character extension). To resolve this issue, various logical formats were proposed with extended specifications added. One format proposed by Microsoft was the extended logical format "Joliet" used in the Windows environment. Joliet made it possible to record file names up to 64 characters long on CD-

ROM, while maintaining compatibility with ISO 9660 as a logical format. It also extended the directory structure from 8 layers to unlimited. However, while the CD-R and CD-ROM read function was standardized in the Windows 95 CD file system (CDFS) and worked without any problem in the Windows environment, there were compatibility issues in non-Windows environments. Accordingly, this was unsupported by Apple Computer, and even the Ministry of Land, Infrastructure, Transport and Tourism and other government agencies endorsed ISO9660 or JIS 0606 and did not recognize Joliet-compatible logical formats for the public electronic application system under the e-Japan strategy. The unfortunate reality was that while the CD-ROM (CD-R/RW) optical disc industry had to maintain compatibility, it was being drawn into disputes in the computer industry.

In 1995, the Optical Storage Technology Association (OSTA) in the United States proposed Universal Disc Format (UDF) Ver1.0, an optical disc file system developed based on ISO 9660 as a Magneto-Optical disc (MO) file system. This was adopted as the file system for DVDs and has made a significant contribution to maintaining compatibility with CD-R/RW/CD-ROM.

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4 Establishing Disc Production Methods

The CD-DA production process generally requires the following six working steps.

(1) Premastering

(2) Mastering

(3) Substrate molding

(4) Depositing

(5) Protective coating

(6) Printing

When the CD-DA went on sale in October 1982, there was a rush to prepare software titles. Most of the production equipment had been designed experimentally, a complete change from the existing LP record production environment. Early compact disc production was also still largely experimental. Recording density was around the same as the semiconductor lithographs at the time. Production had to be carried out in a clean environment. Processing was mostly done offline, a far cry from the online processing carried out in the integrated production systems of today. However, the aim was for CD media to have the same recording density as the semiconductors of the day. The industry grew by absorbing all the available expertise from semiconductor production. Producing CD media, required to distribute high volumes of digital information, was a large-scale equipment industry requiring the ultimate in production efficiency with a product turnaround time of several seconds per disc. This challenge in improving efficiency took production technology to breaking point. As a result, most of today's production facilities were updated in the 1980s and 1990s and production continues on the latest production equipment. The investment into cutting-edge facilities capable of producing tens of millions of discs per month has lasted 30 years to the present day. In that sense, unfortunately, very few of the past facilities that would usually be examined for a technology systematization report are still in existence. Fig. 4-1 shows an example of the latest production facilities still used to produce CD media at Sony DADC Japan (Shizuoka).

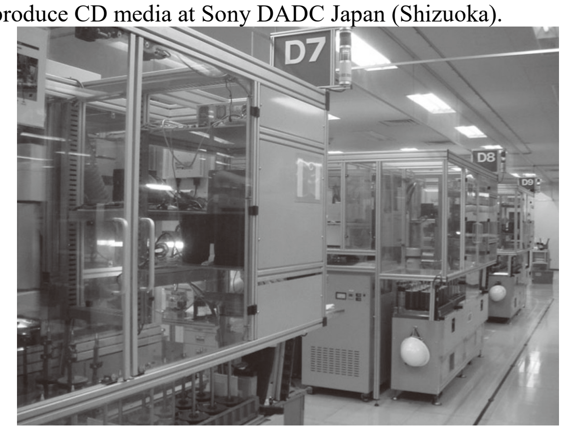

Fig. 4-1 DADC (J) Production Facilities

4.1 Premastering

The premastering process is the process of preparing the original master for CD-DA or CD-ROM. From the early days of the CD until around 2000, most original masters were U-matic. U-matic is an analog video cassette with a ¾ inch tape, originally mainly for business use. Around 1980, when the CD standard was being considered, the only media that could hold large volumes of data similar to a CD were these kinds of analog videos. Since they would record the digital signal 1 and 0 as a video signal, a PCM processor was used to convert the 1 and 0 digital signal into a video signal, which was then recorded by the VTR as digital data. As mentioned previously, the CD sampling frequency of 44.1kHz (3×254×60=44100) had to be determined by the video signal, as the U-matic video recorder was used to produce the master tape. In pursuit of good sound, every studio in the CD recording industry used the U-matic for a mastering machine. In 1982, the U-matic BVU-800 was paired with the PCM-1600 processor.

Later, computer-based equipment was introduced into master production. The emergence of the writable CD-R, playback compatible with the CD, saw the adoption of the premastered CD (PMCD), using CD-R as the master, from the early 1990s. In addition to the usual information recorded in CD-DA format, the CD-R also recorded master information (such as track start and end information) in the area after the lead-out in CD-ROM format. Having the important information written in CD-ROM format with high error correction reduced the read failure rate during pressing. Although the PMCD required a special CD-R drive and writing software, it steadily took hold as it used the inexpensive CD-R as its media. However, the CD-DA industry began to notice issues with the difference in sound quality between the master PMCD and the pressed CDs. There are inherent differences in the physical structures of pressed CDs and CD-Rs, meaning that the playback conditions are not entirely the same. There was a major debate over the constant called sound quality, which cannot be evaluated quantitively, regardless of digital signal processing. The master is the "container" by which the original recording from the studio is transported to the pressing plant. Ground-breaking efficiency in master production was achieved using a computer produced by American venture Sonic Solutions, with software to correct various noise generated on the PMCD master. This had the advantage of being able to check that the master disc was complete before being recorded to CD-R. PMCD is still used for CD production today. A CD-R master disc such as a PMCD is necessary for CD-ROMs, which have a lot of data. The software from Sonic Solutions has been very useful for creating masters for applications (such as games) where content on separate, compatible data discs is repeatedly checked. This software has played a major role in the spread of CD-ROM titles. Fig. 4-1-1 shows a photograph of the Sonic system using a Macintosh, released by START Lab (a joint venture between Sony and Taiyo Yuden).

Fig. 4-1-1 PMCD Sold by Sonic Solutions

Advances in PCs in the 2000s made it possible for computer-based mastering systems to save master data as files on computer. The main format used for this was Disc Protection Protocol (DPP). This master format developed by American company Doug Carson & Associates, Inc. was originally designed for equipment used at pressing plants. As studio mastering systems gradually became compatible with DPP output, it became the de facto standard. Since DPP comprised files managed by computer, the data could be saved to hard disk, server or CD-R in CD-ROM format. Master data could also be sent long distance or overseas via the internet. This has become the main current means of producing master data. Unlike the PMCD, the DPP format cannot be played directly on an ordinary CD player. There are few disputes over the sound quality of the DPP master itself. As a computer file, it is also easy to use and can be expected to remain the main master format used for the foreseeable future. Fig. 4-1-2 shows a photograph of a basic signal transmitter at a production plant, with the aforementioned U-matic master signal system in the center.

Fig. 4-1-2 Signal Transmitter

4.2 Mastering

The mastering process is the most important process up to producing the original recording. It involves the following procedures.

i) Resist coating of the glass disc

ii) Cutting

iii) Developing and adhering

iv) Creating a metal disc (electroplating)

v) Stamping / cleaning

Fig. 4-2-1 shows an overview of CD production processes.

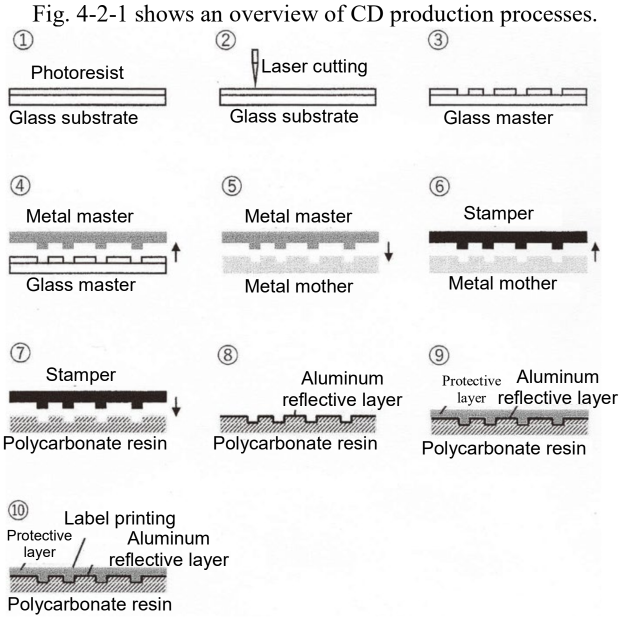

Fig. 4-2-1 CD Production Processes

The first procedure is i) resist coating of the glass disc. The disc used is made from highly polished glass. Macro flatness and microscopic surface roughness are carefully controlled according to the compact disc format. The disc is uniformly coated with photoresist that is sensitive to different lights. This is achieved by spin coating, an old technology. The disc is rotated while the photoresist solution is applied from the circumference ad shaken off by the high-speed rotation. The thickness of the photoresist layer is approximately the depth of the pits. Since this is analog technology, consistently producing a film coating with a thickness of wavelength $\lambda/4 = 0.1\mu m \pm 0.01\mu m$ requires detailed attention to photoresist concentration, solvent concentration, rotation speed control, temperature and humidity management and other factors. This must be carried out in a strictly controlled clean room to prevent physical defects from foreign matter or scratches. The disc is transferred to cutting. Everything from transportation to laser beam recording (LBR) is done by automation in the clean room, as there is a risk of contamination from dust or other foreign matter with humans present. Fig. 4-2-2 shows a photograph of an automated transportation robot and laser beam recorder used in modern CD production. Fig. 4-2-3 shows a structural diagram of laser beam recording.

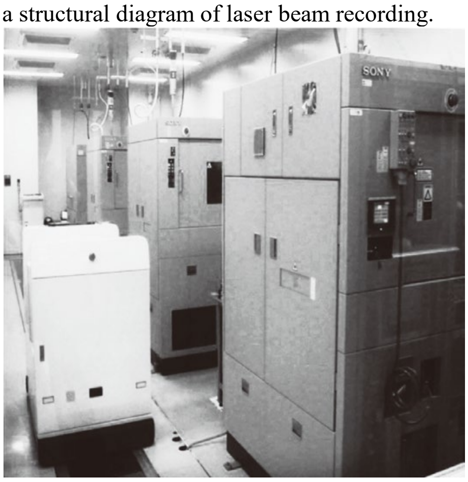

Fig. 4-2-2 Laser Beam Recording (using automated transportation robot)

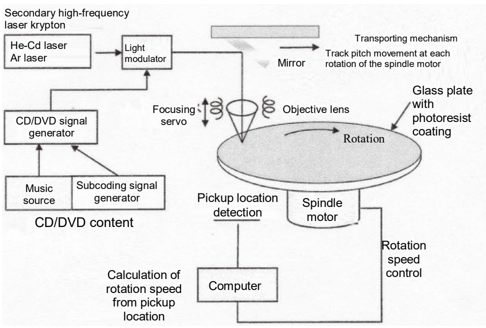

Fig. 4-2-3 Laser Beam Recording Diagram

ii) The cutting process involves exposing the photoresist to light. The light sources used for the CD family are Ar lasers (wavelength 457.9nm) and He-Cd lasers (wavelength 441.6nm). As the lasers converge on the disc, the photoresist is exposed to the light at that point. Switching the lasers on and off exposes only the areas that the light hits, making it possible to record a signal. As gas lasers are used for CD laser beam recording, a component called a light modulator is required to turn the light on and off. In principle, acoustic optical modulators (AOM) are used for ultrasonic waves and electro-optical modulators (EOM) are used for electro-optical effects. However, these require high voltage and special care is needed for safe operation. The laser beam recording objective lens also has a high numerical aperture of around 0.9 to converge the light. Essentially, etching elliptical pits with a track pitch of 1.6μm in blanks areas requires a circumference precision of 1.6μm ± 10%, or ± 0.16μm. At the time, there were no bearings that could support the creation of a perfect circle at submicron level. The emergence of ferrofluid bearings and subsequent trial and error has added another decimal place of accuracy, used in DVD and Blu-ray masters. Since all of the CD family are recorded at a constant linear velocity (CLV), the location of the beam is detected from the center of the spindle shaft during mastering and the revolution speed changes according to master diameter. This technology accumulated in the form of expertise contributing to the design of the laser beam recorder, which came into being by pairing computers with highly precise mechanisms and highly accurate location sensors. Japan was the only country to achieve this ultra-precision laser beam recording system. While it formed the basis for the development of the Japanese optical disc industry, in reality a boomerang phenomenon was occurring, in which changes in industry structure saw used laser beam recorders being offered to overseas markets.

As this technology developed, a new technology called phase transition mastering (PTM) was introduced in the Blu-ray-era laser beam recorders in the 2000s. This system was a clever combination of optical recording and thermal recording. This technology used a thin thermally reactive inorganic resist layer evenly sputtered over a silicon wafer to create a master disc, which was then cut using a laser beam recording system with a 400nm wavelength blue semiconductor laser. The introduction of PTM made a major contribution to simplifying the disc production process. The system was even used to achieve pits with a 0.32μm track pitch on Blu-ray, previously not thought possible. Even higher density is being developed for use as Blu-ray archive media. The technology is characterized by the ultra-precision of the mechanism. Since it uses a semiconductor laser, recording can be achieved by modulating the semiconductor laser itself, thus eliminating the potentially hazardous AOM and EOM and making the system simpler overall. Although it may be travelling upstream in technology, attempts are being made to apply this technology to CD mastering in the insatiable pursuit of increased productivity. Practical implementation is probably not too far off. PTM technology is a Japanese technology that has made a significant contribution to higher density optical discs. Kashiwagi Toshiyuki of Sony was one of the engineers awarded a Medal of Honor with Purple Ribbon for this achievement in 2016. The laser beam recorder that made this technology possible is an ultra-precision device that could have only been produced in Japan. It is now being exported overseas.

The remaining procedures iii) developing and adhering, iv) creating a metal disc (electroplating) and v) stamping / cleaning are carried out as part of the same sequence. The details of these are omitted here, as they are essentially the same as for laser discs, discussed in Survey Report on the Systemization of Technologies Vol. 21 “Historical Development of Laser Disc (LD) Technology with Respect to Efforts to Hasten Its Technological Development and Practical Application”. However, mention will be made of some differences due to differences in diameter. The developing and adhering procedure involves development processing of the 0 and 1 signal created by the laser beam recorder turning off and on. In the areas touched by the laser light, the photosensitive material begins to dissolve, exposing the glass plate below. The areas no touched by the laser remain hard. This is called the glass master. Controlling the development conditions that affect pit precision is of course an important parameter. After developing, the glass master is baked and the shape of the pits becomes permanent. A metal master is produced from the glass master through an electroplating process (electroforming). The glass plate is covered with silver conductive film and immersed in electroforming fluid. A current is passed through, causing nickel to precipitate on the surface of the glass, thereby transcribing the shape of the pits onto a nickel disc. This is called the metal master, which is finished off by washing away the remaining photoresist and removing the silver electrodes. The quality of the metal master is of course significantly affected by the composition of the electrolytic solution. It is important to control the quality of the nickel sulfamate and other component ingredients.

The metal master is used to produce a similarly electroplated metal mother. Since the metal mother has mirrored pit shapes from the metal master, the same technology is then used to produce the stamper from the metal mother. The number of stampers is determined by the number of CDs to be produced. If several hundred thousand CDs are to be produced within a short time, several stampers are made. As the stamper is used as the metal mold for the resin, it has its inner and outer diameters machined and reverse side polished. Polishing the reverse side is particularly important, as any unevenness on the rear surface will transfer through as unevenness on the signal surface after molding. It is polished to a mirror finish.

The completed stamper undergoes inspection of its physical, electrical and other properties, with strict criteria for good and inferior products. Successful stampers move on to the substrate press molding process. Fig. 4-2-4 shows automated metal master production equipment. Fig. 4-2-5 shows the inner and outer diameters of a stamper being bored out. Fig. 4-2-6 shows the stamper manufacturing process, from glass master to stamper. Of course, the stamper produced undergoes strict inspection before moving on to substrate molding. Fig. 4-2-7 shows a stamper inspector.

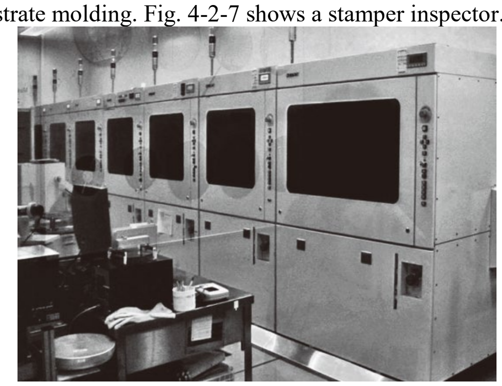

Fig. 4-2-4 Automated Metal Master Production

Fig. 4-2-5 Boring Out Inner and Outer Diameters

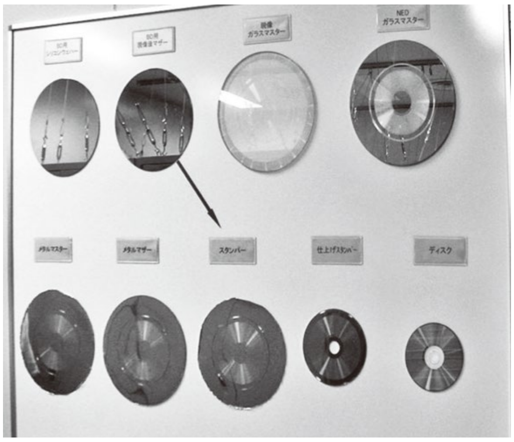

Fig. 4-2-6 Stamper Production

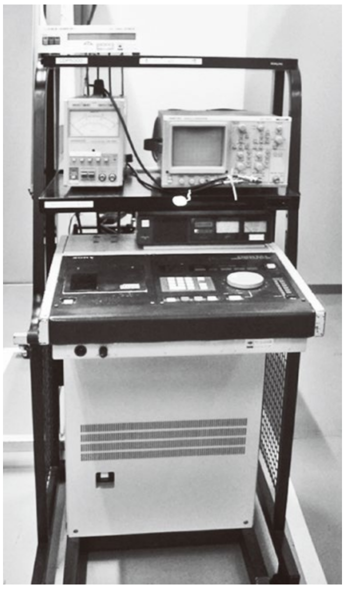

Fig. 4-2-7 Stamper Inspector

4.3 Plastic Substrate Molding

Plastic substrate molding involves (3) substrate molding, (4) depositing, (5) protective coating and (6) pressing. When optical discs are produced, many replicas are molded from a single stamper. As technology improved over the years, this has become a valuable field of technology capable of mass production. The most important process is (3) substrate molding. For CD media, the substate material used is usually polycarbonate resin, a high-performance plastic. The special characteristics of optical disc grade polycarbonate resin include (1) refractive index of 1.58, (2) optical transmittance of over 87%, (3) birefringence of less than 20% of the phase contrast, (4) heat deformation temperature of 130-140°C, and (5) moisture absorption of less than 0.15%. Optical disc grade refers to a grade of resin developed to have fewer foreign contaminants at submicron level and to inhibit deterioration or deformation of the aluminum reflective film, making it more reliable for longer and increasing transfer precision. Melt fluidity during molding is also an important parameter relating to pit formation and orientation. A melt flow index (MFI) of 20 or higher is recommended. This polycarbonate was difficult to develop. Only a few manufacturers in Japan to develop and produce it, including Teijin Chemicals and Mitsubishi Chemical Engineering. To prevent contamination of the polycarbonate resin, it was taken directly from the factory in pellet form and carefully put in silos. Recent attempts to improve CD-DA sound quality have meant a search for a higher molecular weight polycarbonate resin. Some discs have been marketed under brand names such as HPCD, but this has been a marketing tactic with no actual quantitative improvement in sound quality.

Substrate molding machines for CD media are usually screw type injection molding machines. Fig. 4-3-1 shows a diagram of an injection molding machine. Injection molding machines operate in a sequence of four processes: 1) mold clamping, 2) injecting, 3) dwelling, 4) cooling and 5) mold releasing. The machines currently used for CD media are 50-ton electric injection molding machines. The transition from hydraulic machines to electric machines came after many years of trial and error. This has made the production system easier to maintain and led to greater CD productivity and higher mass production. Fig. 4-3-2 shows an injection molding machine currently used by Sony DADC Japan. The main conditions for molding include (1) cycle time, (2) metal temperature, (3) clamping pressure, (4) cooling time, (5) cylinder temperature, (6) injection rate and (7) injection pressure. The cycle time is directly related to productivity and is set to a target value, while the other molding conditions are determined by repeated operation to find the optimal parameters. Only the skill and experience of the engineer can achieve this. Of course, the shape and size of the metal disc mold have to be accurate, with high molding efficiency and durability. Cycle time and disc performance are determined by mold performance. Mold structure, dimension accuracy and surface treatment are important factors that come with experience.

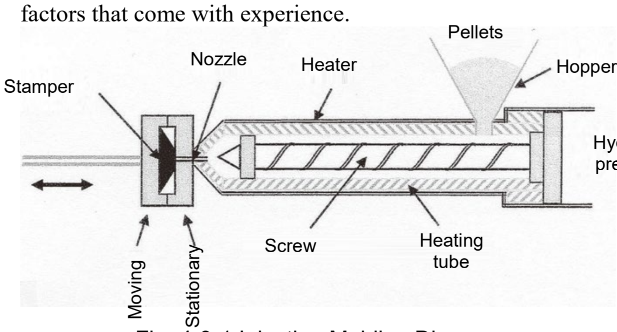

Fig. 4-3-1 Injection Molding Diagram

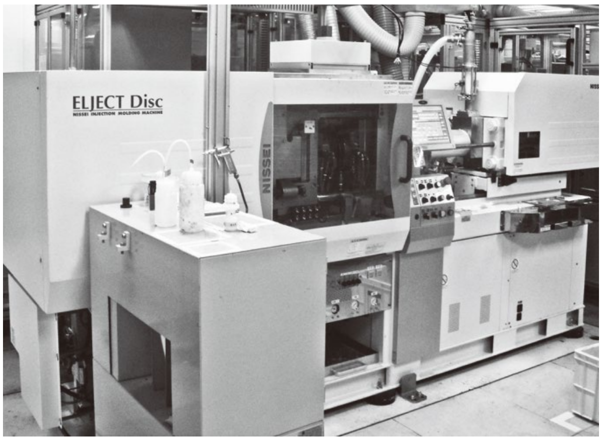

Fig. 4-3-2 Electric Injection Molding Machine

Depositing refers to the depositing of an aluminum reflective coating onto the signal surface of the disc. The disc standard specifies 70% reflectance. The coating is deposited in a layer around 100nm thick using a sputtering method. In-line sputtering is now possible as part of a series of processes, which has markedly improved production efficiency. Fig. 4-3-3 shows an in-line sputter coating machine used today. The process after this is applying a protective coating. This is achieved by applying a UV-curable resin (several microns thick) by spinning or spraying, and then hardening it under UV light. Extra care must be taken when handling the edges of a disc with protective coating. Any moisture penetrating from the edge can affect the aluminum reflective coating and impact the reliability of the disc. The final process is printing the label on. For CD-DA in particular, a label that matches the music is a valuable piece of art. Special printing is carried out with consideration given to color scheme and shading. Printing will make users want to buy and keep a disc. Printing is often carried out by multicolor screen printing or offset printing. A lot of work goes into finishing off the completed product, and no perfect solution has yet been found for this step.

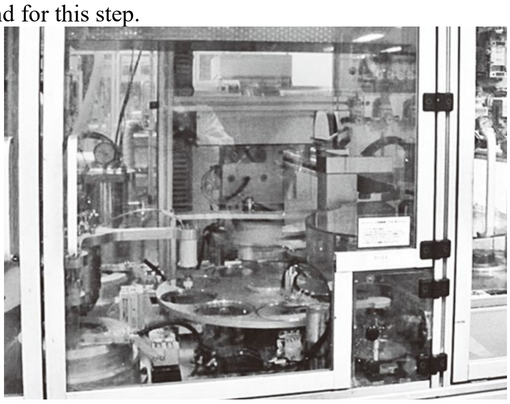

Fig. 4-3-3 In-Line Sputter Coating Machine

Optimizing the shape of the signal (pits) when the disc is molded is strongly linked to disc performance. The ideal pit shape is rectangular with a depth of $\lambda/4$ to maximize the reflectance. Calculating using λ = 780nm and the polycarbonate refractive index of 1.5 gives a figure of around 100nm. However, since the stamper is electroplated and has to be transcribed, the pits actually have a sloping edge like a football stadium. For CDs, there are nine types of pit length, described above, due to EFM modulation (0.87-3.18μm/linear velocity 1.25m/s), with a pit width of 0.8μm (1.6μm track pitch). Due to the analog process of developing the photoresist, the pit lengths on the stamper are longer and shorter in the track direction when viewed under microscope. This means that the read signal varies in accuracy and requires technology to correct the asymmetric variation. A technical solution has been found is currently being worked on that involves intentionally lengthening the pits (around 1.4×).

The finished CD-DA disc is shipped out after being inspected by an inspecting machine. At Sony DADC Japan, all original master discs produced to date are stored and strictly managed in a dedicated building with earthquake and fire protection measures in place. This not only provides an ultimate data archive, but also ensures that there is a system for dealing with repeat orders at any time. Fig. 4-3-6 shows the first CD-DA disc to be sold in Japan in October 1982. It is a Japanese music title called “A Long Vacation”, produced by DADC Japan’s predecessor CBS Sony Records at its plant in Shizuoka. Its product number 35DH1 is made up of 35, representing the price of ¥3500, D referring to digital, H referring to Japanese music (hōgaku in Japanese), and 1 referring to the catalog serial number. This title made a name for itself at the start of Japanese CD history, 35 years ago.

Fig. 4-3-4 Inside the Master Storage Building

Fig. 4-3-5 Master Storage

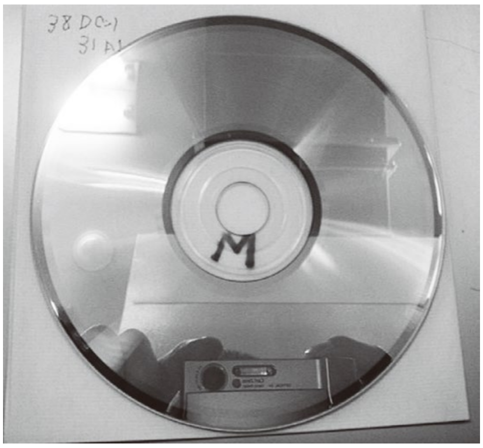

Fig. 4-3-6 Japan’s First CD-DA Disc

References
1) “Zukai Konpakuto Disuku Dokuhon [An Illustrated Compact Disc Reader]” Nakajima Heitarō and Ogawa Hiroshi, Ohmsha (1996)
2) “CD Famirī [The CD Family]” Nakajima Heitarō, Ihashi Takao and Ogawa Hiroshi, Ohmsha (1996)

5 Overview of the CD Family

The CD-DA is the origin of all CD media. Tracing along a hypothetical technology road map, the CD family has grown with the formulation of the various CD media standard "books". There are generally quite a few twists and turns from the emergence of a new technology until its acceptance as a standard part of the CD family. The development of the books for the CD family was not through systematic technology planning, but instead was in many cases decided on in a more fluid manner, affected by market principles and the power balance between manufacturers. Even with the books or standards in place, in some cases the product has never been seen on the market. Despite the trouble taken to formulate the book, the product was not well received on the market. Not uncommonly, in some cases the product is no longer sold or the service no longer provided. There is a saying that "after the tiger dies, its skin remains". In the same way, a discontinued CD product leaves its name in history: "after the CD media product comes to an end, the CD family book remains".

While "book" is a simple word, there has been a huge range of factors in the process and background leading up to formulation and it can be a little difficult to understand the purpose why these were formulated. In other words, in order to understand the history of the CD family, you need to understand not only the technical "book" itself, but also the political aspects behind the book.

The CD family standards are entitled "___ Book", but there is no clear definition of the basis for the colors of the books, except for the Red Book standard for CD-DA. When Sony and Philips held their technical meetings to discuss CD specifications, the folders containing the handouts happened to have red covers. At some point, they happened to start referring to the "Red Book". The CD book color may have started out by accident, but the subsequent Yellow Book and Green Book were "chosen because they were obvious colors that were not red". These names are simply practical. Fig. 5-1 shows the main standards related to CDs.

5.1 CD Book Categories

There are three main groups of books in the CD family.

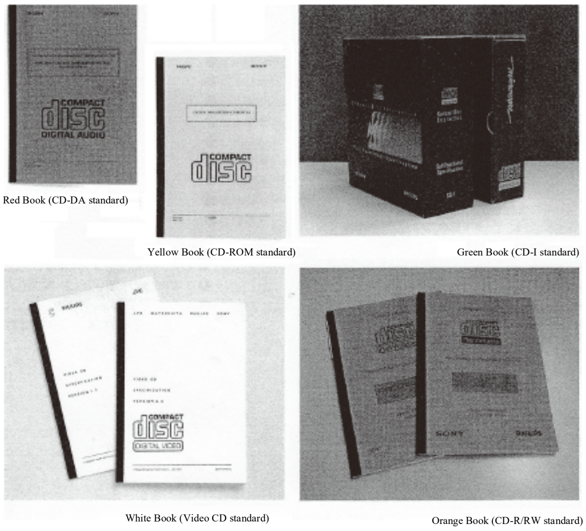

Fig. 5.1 Main Standard Books Related to CDs

(1) Foundational technology books. This category includes the Red Book (CD-DA), the Yellow Book (CD-ROM), the Green Book (CD-I), the Scarlet Book (SACD) and the Purple Book (DDCD). This group is distinguished by being relatively organized due to pre-existing standards.

(2) Books for organizing/combining specifications. These were formulated to organize/combine technological developments by multiple companies. Books in this group include the White Book (Video CD), the Orange Book (CD-R) and the Blue Book (CD-Extra). This group is distinguished by dealing with the relationships between several CD media standards.

(3) Books for combining the CD family. This group was formulated to integrate and unify previously developed new products and services into the existing CD family system. Accordingly, these standards often take the form of extensions to books. This group includes the Super Video CD, Photo CD and CD-BGM parts of the White Book. This group is distinguished by later additions to books of existing products and services out of consideration for the market. As a result, this group is also characterized by having standards that remain in the CD family even though the actual product or service has been discontinued from the market.

There is also a "bridge format", the first derived group. The bridge format is an extended format designed to maintain compatibility between several existing "books" to allow new technology to gain popularity. These include CD-ROM XA and CD-I Ready. This group is distinguished by strategic additions to books from product seeds rather than existing products or services. As a result, the boundary lines become blurred between the CD media originally designated by the book and that designated by other standards. This is not often understood clearly. Fig. 5-1-1 shows a diagram of the CD family.

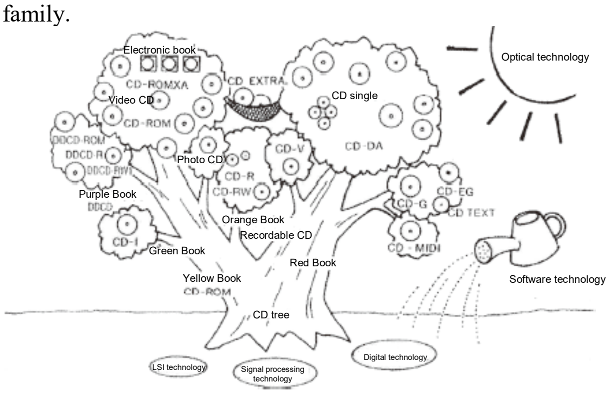

Fig. 5-1-1 CD Family Diagram

5.1.1 Phase Contrast Microscopy

The CD family is a concept first mentioned by Philips. It refers to different standards discussed and formulated by Sony, Philips and other licensers to designate how CD media is used. Specifically, it is used to refer to all CD formats, such as CD-DA, CD-ROM, CD-I and video CD. “Book” is the popular name for the specification documents that designate the standards for the CD family. A system logo, discussed later, and the specification documents are provided based on a license agreement. However, multiple CD standards may sometimes be designated to a single user. For example, the Red Book (CD-DA) prescribes other members of the CD family, including CD-G and CD Text. Currently, with CD media more generalized, essential book content provided for in ISO and JIS standards and licenser patents expiring, it is becoming possible to obtain technical information for parts of books without a license agreement.

Meanwhile, when a specific group proposes a concept, it can be difficult to understand. The “multimedia CD” concept was proposed by the multimedia CD consortium (CD media promotion association). “Multimedia CD” was a general term used for CD-I, Video CD, Photo CD and CD-G, but there was no multimedia CD standard or book. The same was true for the “Subcode CD”. Subcode does not refer to any particular member of the CD family, but is used as a general term for the members of the CD family that use a subcode area (CD-G, CD-EG, CD-MIDI, CD Text). However, the subcode standard is provided for in the Red Book.

There are two main types of CD formats, with standards determined independently by different manufacturers.

(1) Those fundamentally based on the “CD family” standards, with additional extensions added. Specifically, this refers to CD-ROMs for gaming machines. To protect business profitability with exclusive software distribution rights, CD-ROMs for gaming machines have a warning message on the CD-DA track on the inner perimeter to prevent misuse in an audio CD player. The game program is placed on disc beyond that point, with copy protection in place. This unique section is designed to prevent duplication. This technology is based on the CD-ROM specifications, but has an independently developed technology element. Sony has a separate license agreement for this business.

(2) Those physically based on CD media but with independent specifications. From a strict CD family perspective, these are not CD formats, but have been proposed for market reasons. Hardware manufacturers can make no guarantee regarding compatibility. This category includes copy controlled CDs and enhanced CDs, or CD-DA discs with a CD-ROM area on them.

Thus, there are some CDs outside the CD family (books). The development of the game market over the past two decades has made this a valuable area of CD production that has supported CD factories as CD-DA production has dropped worldwide. Fig. 5-1-2 shows the correlation in the CD family as seen by the correlation between discs and players.

5.1.2 CD Family System

Looking at how various CD standards were formulated and how the CD family has been structured over time reveals that like all products, the CD family has a life cycle.

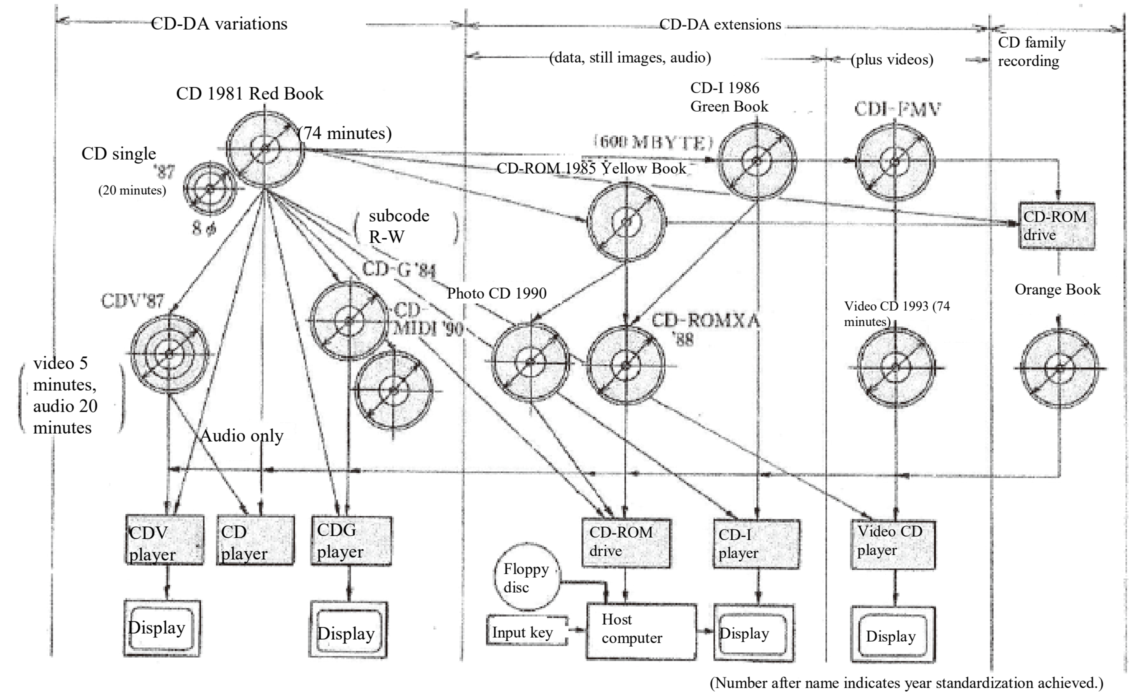

Fig. 5-1-2 CD Family Correlation Diagram

(1) CD Family Introduction Period

The CD family introduction period began in 1980 with the formulation of the book that would later become the foundation for CD media and lasted through to 1985. The Red Book in 1980 determined the basic specifications for CD media. The Yellow Book in 1982 determined the basic specifications for data recording. The Green Book in 1985 identified the concept of multimedia “interactive”, making CD media easier to work with. The common characteristic here is that the standards were formulated before the product was developed. In making these CD family products, the infrastructure was first laid out in the standards and then product development moved forward accordingly.

(2) CD Family Growth Period

The period called the “growth period” began in 1985 and continued through to around 1990. In this period, various CD family products emerged and diversified based on the basic books formulated in the introduction period. This period is characterized by standards being added to by extending the existing books. Extensions to the Red Book include CD-G in 1985, CD-EG in 1991, CD-V in 1987 and CD singles and CD-MIDI in 1990. Extensions to the Yellow Book include CD-ROMXA in 1989. Extensions to the Green Book include CD-IDV and CD-BGM in 1992. The common characteristics between these is that developing the applicable product resulted in the emergence of new products not covered by the existing books. Specifications were added in accordance with the products. In many cases, there were initial compatibility issues because the products and standards were developed at the same time, and it took a lot of labor and costs to set right. (The later Orange Book had the same issue, and a promotion group was formed to implement a solution.)

(3) CD Family Maturity Period

From 1990 onwards, CD media were developed with various specifications. These were consolidated and follow up books were formulated to maintain compatibility. This period is called the maturity period.

Since the technological foundation for CD media had already been laid, companies worked on their own developments based on the foundation. These products appeared to have the same functions and external appearance, but in reality these products were incompatible and created discord in the market. To resolve this, books were formulated to act as a mediator.

Books formulated during this period include the Orange Book (CD-R) in 1990, the White Book (video CD, CD-IDV) in 1993 and the Blue Book (CD-EXTRA) in 1996.

Although it took some time, the CD family has become variously diverse. The next-generation audio system SA-CD (super audio CD, Scarlet Book) was formulated in 1999 in response to demand for improved quality in recorded music. Essentially derived from the Red Book, this improved system adopted a new audio encoding format called direct stream digital (DSD), as well as a sampling frequency of 2822.4kHz and a playback frequency range of DC to above 100kHz. With the DVD standard formulated around 1996, the two businesses were starting out at the same time, resulting in opposition to DVD audio. A standard emerged for a disc with two layers, a CD layer and an SACD layer (both 0.6mm thick, with a total thickness of 1.2mm). The greatest feature of an SACD player was that it could handle both CD-DA and high quality super audio CD. There are still users today who prefer high quality audio, and software titles are still being sold in this format.

CD media recording capacity was considered to be high volume (around 0.65GB) in 1982. As multimedia data later became more widespread, it was noted that the capacity would not be enough. To address this need for high volume media, the double density CD (DDCD) standard was formulated, approximately doubling the capacity of CD media to 1.3GB. The standard enacted in 2000 was called the Purple Book, and licenses began to be issued for it. Although the DDCD standard belongs in the CD family, playing it required a special DDCD drive and there were also issues with the cost of the media and the half-finished state of the media capacity. Sony and Yamaha brought out DDCD products, but these were overtaken by the higher capacity DVD drives and media and the DDCD did not take hold. Fig. 5-1-3 shows the correlation between the CD-ROM standards. From a technological perspective, these can be categorized as either various application specifications built on from the Red Book, or completely different technology, represented by the Orange and Scarlet Books.

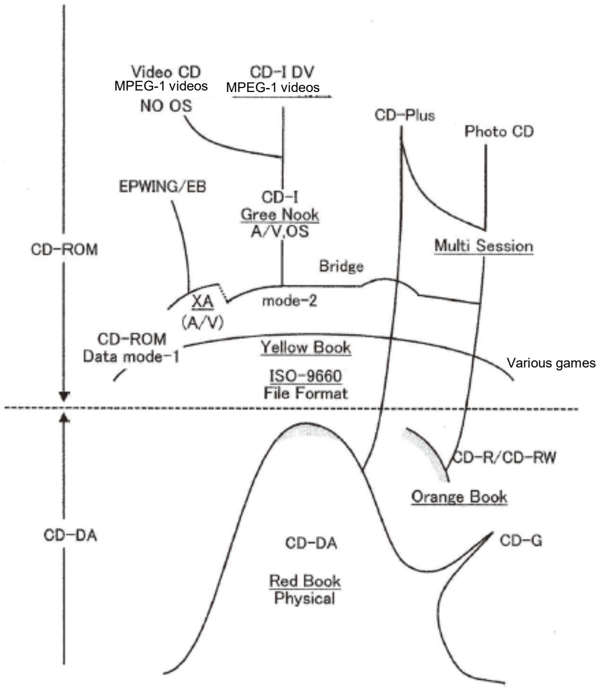

Fig. 5-1-3 Correlation between CD-ROM Standards

5.1.3 CD Family and Logos

As mentioned above, many diverse formats have been produced in the CD family, starting with CD-DA. For each CD related product, a "system logo" has been produced to show that the product has been based on the respective CD standard. These system logos represent all CD-relate products. In granting a license for essential patents related to CDs, Sony/Philips grant access to the "three sacred treasures" of CD technology: the consent agreement, the written standards, and the system logo. As well as administering these, the companies also provide standard test discs, updates to the written standards and compatibility verification of CD-related products. These efforts in maintaining and preserving standards ensure the compatibility of CD family products. Accordingly, the system logo on CD related products proves that an official license agreement has been signed. Fig. 5-1-4 shows the main system logos and marketing logos. Essentially, each logo comprises the words "compact disc" in the center with a name underneath to indicate the intended use, for example "digital audio" or "digital video".

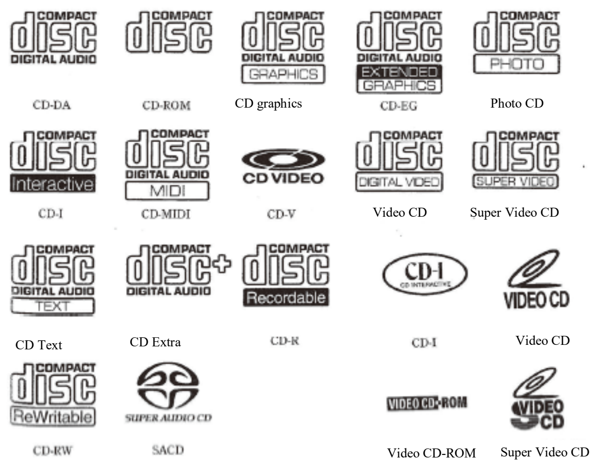

Fig. 5-1-4 CD-Related System Logos and Marketing Logos

The marketing logo is present alongside the system logo. The marketing logo is a logo established by relevant industry groups in collaboration with the licenser with the aim of promoting the business in the industry. A good example is the CD-I marketing logo, the first instance of a marketing logo, proposed in 1992 by the market promotion committee of the CD-I Consortium Japan. The video CD marketing logo was established in 1994 as a logo to be used on video CD players and video CD software titles based on the video CD standard 2.0. Initially, these logos were only used in Japan, but as the video CD business expanded into China, India, Taiwan, Singapore and into the Middle East, the familiar video CD "seashell logo" began to be used around the world. Marketing logos were also established for Super Video CD and video CD-ROM, although these had limited use as these businesses did not expand as widely.

5.2 Organization of the Main Books (Standard Books)

From the perspective of historical CD development, there are three main books (standard books): the Red Book (CD-DA), the Yellow Book (CD-ROM) and the Orange Book (CD-R). These three standard books have made a major contribution to the development of the CD family, bringing in a very significant amount of business and dramatically reforming the world.

5.2.1 Red Book (CD-DA)

The Red Book is generally referred to as the CD-DA standard book, although it stipulates two main categories of information related to CD specifications.

The first is determining the characteristic specifications for music CDs. This is the CD-DA standard book aspect. As well as specifying the music sampling frequency, channel number, recordable frequency band and other necessary system specifications for digital audio discs, the book also specifies the cross interleaved Reed-Solomon code (CIRC) error correction method for data recorded on the disc and the EFM modulation format. It also specifies the maximum number of songs that can be recorded on a disc (99 songs) and the interval between tracks. By stipulating these standards in such detail, the Red Book ensures CD-DA product compatibility between manufacturers. This laid the foundation for the widespread of use of CD media seen today.

The second is determining the specifications shared by CD media. This is the CD media standard aspect. The standard specifies physical disc characteristics, such as thickness and possible material used, as well as stipulating the disc signal recording format with each frame (block) comprising 2353B and that the data is written from the inside to the outside. These specifications are not limited to CD-DA but shared by all CD media and form the basis for compatibility. For example, the required specifications for disc material are mentioned but the material is not specified, nor is the disc production method. As a result, manufacturers have competed to improve disc material and innovate their manufacturing equipment, which has led to reduced CD media manufacturing costs and invigorated the CD market to the point that it is a major industry.

5.2.2 Yellow Book (CD-ROM)

The Yellow Book determines matters relating to CD-ROM, which has general data recorded on it in information tracks in place of the audio information recorded on CD-DA. The Yellow Book only stipulates the physical format of the CD-ROM, not the logical format. Accordingly, for the CD-ROM to be useful as a media device, it was necessary to determine various logical formats over and above the Yellow Book. The CD-ROM data format stipulated in the Yellow Book includes the mechanical and physical properties of the disc, disc size and material quality, disc recording characteristics, data track format, error detection and correction characteristics, information coding and optical characteristics for playing back information.

Original user data recorded on CD-ROM has a CD-ROM error correction code added and is then scrambled. The data then has an audio error correction code added. This two-stage process makes it possible for CD-ROM and CD-DA to be compatible, as well as ensuring the high reliability needed for data recording. The CD-ROM physical format based on the specifications in the Yellow Book was later adopted as the international standard for the “120mm playback optical disc (CD-ROM)”. As mentioned previously, as the international standard, it has achieved industrial standard status in many countries.

5.2.3 Orange Book (CD-R)

Strictly speaking, the Orange Book is divided into Part 1 and Part 2.

Part 1 deals with CD-MO (magneto-optical recording media not compatible with CD). Part 2 deals with CD-R (recordable media compatible with CD). The CD-MO standard formed the basis for the MiniDisc (MD) system released by Sony in 1992. Part 2 is the standard for CD-R, mutually compatible with CD. Since the technical details of CD-R are covered in Chapter 7, only an outline of how the book was formulated is given here.

Following the basic agreement between Sony and Philips regarding CD-WO, electronic component manufacturer Taiyo Yuden asked Sony to include the organic dye recordable media it was developing into the CD-WO standard. Sony had connections with Taiyo Yuden through digital audio pioneer Nakajima Heitarō, who was then the president of Aiwa.

Acknowledging Nakajima's request to give priority to CD-compatible development, young Taiyo Yuden engineers Ishiguro Takashi and Hamada Emiko developed an organic dye recording layer that somehow met the 70% reflectance requirement and the technology to directly attach the new gold reflective film. They also optimized the organic dye for the recording film and successfully solved the difficult challenge of reducing the jitter component due to the steep rising edges of the signal pits, thereby achieving CD compatibility.

CD-compatible media is the double-edged sword of the soft content industry. For those who favor preventing illegal copying, it is despised as "the media from hell". However, CD-ROM businesses that experienced rapid growth would never have been able to produce soft content with CD-compatible CD-R media. This is all due to Sony deciding in August 1988 to develop a recording drive and working with Philips on standardization. The company shared its technology with Philips, carried out verification testing and officially released the new specification document Orange Book Part 2 in May 1989. The CD-R became a business. After many twists and turns, Sony and Taiyo Yuden established the joint venture Start Lab (Sony Taiyo Yuden Advanced Recording Laboratory) in June 1989 with Nakajima Heitarō as president, and began providing media and hardware sales and services. Ironically, the CD-R "media from hell" has been most commonly used by manufacturers of games and published software titles in the soft content industry. The problem of illegal copying cannot be stopped, and while some point out the harm caused to the soft content industry, the CD-R has demonstrated its "ill repute" well. Start Lab engaged in exclusive sales of Taiyo Yuden's high quality R-media (made in Japan) and special services for R-media. The venture's 26-year mission came to an end in March 2016 with the rapid transition to a networked society.

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2) "CD Famirī [The CD Family]" Nakajima Heitarō, Ihashi Takao and Ogawa Hiroshi, Ohmsha (1996)
3) "Onkyō Gijutsu-shi [History of Sound Recording]" Mori, Kamekawa and Kimizuka, Geidai Press (2011)
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6 Emergence and Scope of CD-Related Business

While Fig. 6-1 shows the general trends in optical disc systems, it is difficult to determine the extent of CD-related business. The optical disc system started with the laser disc (LD) in the early 1980s. CD-related business began in the fall of 1982 with the launch of the CD-DA player by Sony and went on to form a major market. The CD offered high computer compatibility, with factors such as good random accessibility. It also answered the demand for an inexpensive recording medium. As a result, the CD-ROM took center stage as an external memory device for computers, storing digital data in place of audio data. This led to a dramatic increase in hardware and software. The CD-ROM recording capacity of around 0.65GB was equivalent in character count to around one and half years' worth of newspapers. A major feature was the ability to duplicate this vast amount of data in several seconds. This "printing revolution" formed a major industry, with the greatest impact on the printing and publishing industry since Gutenberg. CDs were also used in the field of gaming. CD-ROM use by consumers began in 1994 with the launch of PlayStation by Sony Computer Entertainment. The CD-ROM business expanded dramatically, extending from games and electronic publications to GPS vehicle navigation systems.

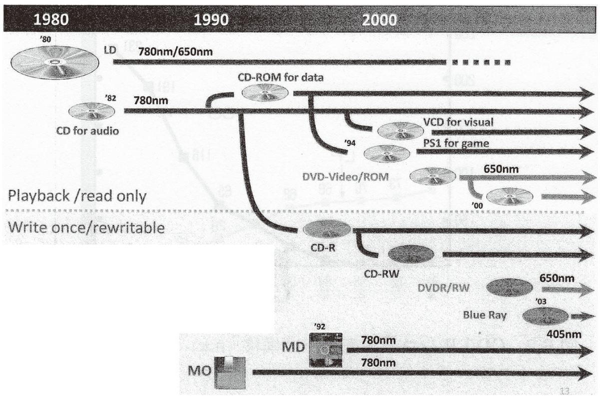


Fig. 6-1 Trends in Optical Discs

Section 6.1 below discusses the major trends in consumer optical disc hardware and the related business. Section 6.2 describes the portable CD players that brought CDs to the world. Section 6.3 outlines the emergence of CD-related businesses, while 6.4 provides an overview of other businesses that emerged as a result of the CD-ROM.

6.1 Trends in Optical Disc Systems (Hardware)

In the early 1980s, optical discs suddenly became the center of attention. This was the point in time when there was a demand from Hollywood and others in the film industry for disc-based (non-copiable) film distribution to replace VTR-based film distribution. The 30cm diameter laser disc (LD) appeared on the market, known in the early days as the "record with pictures". However, despite efforts by Pioneer, Philips and other companies, there was never a huge market for the LD, due to the difficulty of the video software business and the fact that it was in competition with the VTR. A specialized professional market did emerge for the LD, however, and it was used for various applications, including the karaoke industry and education industry, due to its high computer compatibility because of its good random accessibility. This business continued through to the early 2000s. Around the mid-1990s, LD players were given the ability to play CDs, which allowed the consumer business of LD / CD-DA compatible players to continue.

6.1.1 Trends in Tabletop Players

Under the circumstances described above, Sony launched the CDP101 tabletop player in October 1982, six months after the CD-DA standard was published, signaling the beginning of the CD-DA business. The high price of ¥168,000 and the shortage of software titles meant that only a limited number of users could purchase it, but the first lot of several thousand were somehow accepted by the market, an indicator for later manufacturers. The CDP101 was a highly perfected machine with the following technical features.

(1) Stable playback function using a shaft-sliding optical pickup
(2) Slide-loading disc transport mechanism
(3) Highly sophisticated 3-chip LSI circuit design
(4) The world's first 780nm semiconductor laser
(5) Small mini-component size

This model had a major impact. It was recognized by all companies as the standard model, with most tabletop players sold after that incorporating features such as a slide-loading mechanism. The main components of the optical element and digital LSI also had a significant impact on other companies. Although production volumes were not high, this commemorative piece of technology was a “milestone model” in CD player mass production.

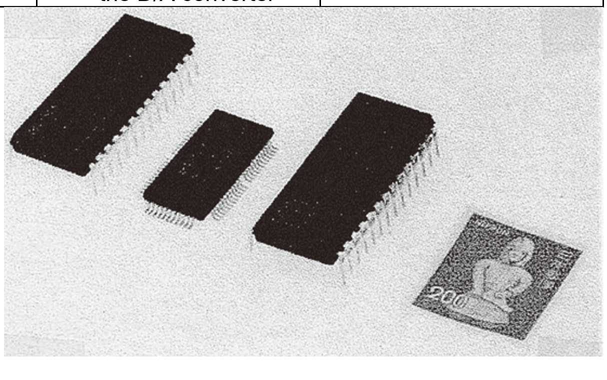
The signal processing LSI used in this model was a three-chip configuration. The CX-7933 chip was used for the EFM demodulation circuit, the CX-7934 was used for controlling and interpolating the exchange between RAM and data. The CX-7935 was used for CIRC error correction. At the time, Fujitsu was the only cutting-edge enterprise capable of producing LSI with around 10,000 gates using the MOS process. The N-MOS process made it possible to reduce the chip size to around 4×6mm for a 20-70 pin DIP plastic package. The issue with the large, unstable circuit board used in the prototype was resolved with this chip size. This remarkable feat was a clear demonstration of the level of Fujitsu’s technological prowess at the time. Another key part in the player was the DA converter. The 16-bit consumer DA required nine levels of LPF, which was difficult to design and cost more than $1000. However, from around 1986, as players became more generic, digital filtering technology was incorporated into the DA converter. LSI also underwent successive generations of technology revolutions, making it possible to hold around 30,000 gates on a single chip. This also rapidly reduced the cost, making it possible to incorporated into portable CD players and causing the market to boom. The successful mass production of semiconductor lasers and three-chip LSI signal processors were key innovations to the mass production of CD players. In that sense, the completion and launch of the CDP-101 was the fruit of Japanese technological prowess, not just Sony. It was a glowing landmark achievement in the history of CD technology development. Table 6-1-1 shows the specifications for the DAD three-chip LSI.

All CD player production technology starts here. For example, the technology for attaching the optical pickup needs to be accurate enough to account for any measurement error due to adhesive shrinkage. This requires a vast amount of accumulated experience, and only Japanese companies have the ability to produce optical components with such high precision. Production of optical pickups has increased since 2000, and more are being produced overseas.

However, it is difficult to pass on the experience needed for the precise adhesion technology in this field, and it remains as a field of expertise for Japanese companies.

Table 6-1-1 DAD Three-Chip LSI Specifications and Photographs

Name	CX-7933	CX-7934	CX-7935
Use	DAD player demodulation circuit	DAD player data control & interpolation	DAD player error correction
Process	N-MOS	N-MOS	N-MOS
Chip size	4.0mm x 4.2mm	6.0mm x 5.3mm	5.8mm x 5.7mm
Package	28-pin DIP plastic mold	70-pin FP plastic mold	28-pin DIP plastic mold
Operating speed	4.32 MHz	2.16 MHz (original oscillation 8.64 MHz)	2.16 MHz
Power supply voltage	5V single power supply	5V single power supply	5V single power supply
Power consumption	350 mW	550 mW	720 mW
Output level	TTL compatible	TTL compatible	TTL compatible
Functions	• EFM data demodulation • Subcode signal demodulation • Frame sync detection, dropout protection and interpolation • Interface signal generation	• Interface with RAM • Control of writing data to RAM and reading data from RAM • Mean interpolation • CLV reference signal generation • Interface signal to the D/A converter	• Super strategy CIRC signal (error detection and correction)



Although production is carried out overseas, it is done with technical guidance from Japan. In 1983, Yamaha launched a tabletop CD player (CD-X1) for under ¥100,000, thus heightening market expectations. Other companies followed suit with tabletop CD players of their own. This overlapped with the launch of portable CD players, discussed later. CDs were initially targeted at middle-aged adults, but with the price band now successfully halved, CDs began to attract younger audiences and female users, previously the mainstay of the record market.

As a leading company in this field, Sony played a major role in expanding into new markets. Consequently, the company significantly expanded the scope of its product planning. The company launched the CDP-5000S professional CD player in 1983 (¥1.8 million), followed by the CDP-701ES (¥260,000) and the CDP-501ES (¥168,000) in the high-end ES series. After these came the successor tabletop players, the CDP-111 (¥145,000) and the CDP-11S (¥115,000). The CDP-102 (¥89,800) and CDP-103 (¥84,800) were added to the lineup in 1984, followed by the launch of the CDP-33 (¥54,800) in 1985. In a short space of just over three years, the player price dropped to a third, invigorating the CD market, with increasing numbers of companies joining in.

Having previously established the concept of a small, easily portable music player product with its Walkman cassette tape player, Sony turned its attention to the most important idea for the 120mm compact disc: a portable CD player that would allow anyone to enjoy CD music anywhere. Although there was much anticipation for such a product, the level of technology at the time meant that portable CD players were beyond anyone's wildest dreams. Despite this, engineers began to resolve each challenging issue with novel ideas.

Specifically, the following challenging issues had to be solved.

(1) Ultra-downsizing the optical pickup
(2) Developing a PWM drive system to reduce electricity consumption
(3) Developing the technology to prevent servo disturbance and skipping while the player is being carried around
(4) Developing smaller and more energy efficient second-generation LSI
(5) Developing a special battery for the power supply

In making the commercial product, Ōsone Kōzō, head of Sony's audio division at the time, encouraged his engineers to develop the technology so thoroughly and with such high density and integration that if a prototype were to be submerged in a tank of water, no bubbles would come out. This resulted in a major project that took three years to complete, incorporating development and design. The tireless efforts of engineers paid off and the product took shape. However, the costs were calculated to be far in excess of the target price. Everyone on the technology team was at their wits' end.

Sony had invested heavily in development since launching the CD player. This project was the highest priority in the CD business, and it had to succeed no matter what. Company president Morita Akio gave strict orders. "We can't stop now. The price will come down when we mass produce it. Set the sale price under ¥50,000 and we'll spread the initial loss across all of Sony." Morita was finely attuned to the market, and experience had taught that consumer products sold extremely well when the price was under ¥50,000. In the fall of 1984, the portable CD player D-50 Discman (¥49,800) was released to the world. As Morita had expected, the D-50 did sell extremely well. The hardware cost dropped rapidly, accompanied by a rapid increase in CD software titles. This product should be commemorated for creating a space in the world for the CD-DA business. The portable CD player was known as the Discman. There was rapid growth in model numbers, accompanied by further downsizing of batteries and power-saving technologies, resulting in its being essentially the same size as the CD casings. This led to the world's first 100-hour playback capable devices. Today, the D-50, like the CDP-101, is carefully stored and displayed at the Sony museum. Fig. 6-1-1 shows the CDP-101, launched by Sony in 1982, and the D-50, launched in 1984.

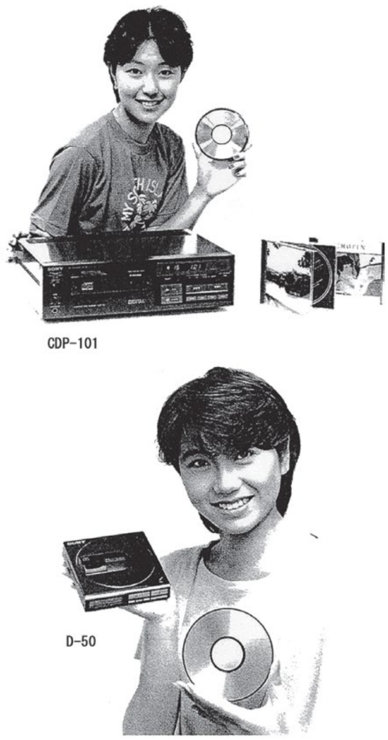


Fig. 6-1-1 CDP-101 and D-50

CD title production in the introductory period began with only four companies, in 1982 (CBS Sony, Polydor, Nippon Columbia and Toshiba EMI). Two years later, in 1984, there were 22 companies. When they were first released, CD titles sold for ¥3800 for digital recordings and ¥3500 for digitized analog recordings. Imported discs were ¥4000-4200. CD titles, too, were highly priced. Since most record companies were subsidiaries of electrical manufacturers, they were quick to note the digitization trend and actively invested into this revolutionary new product called the CD, acquiring technology and further refining the production of titles. As a result, by the end of 1984, production capacity had increased and there were around 4000 CD titles available on the market. At the same time, various policies were put in place to encourage the spread of CD titles. Famous recordings by conductors such as Bruno Walter and Wilhelm Furtwängler were remastered on CD and were well received. In November 1984, the retail price was lowered for these "retail adapted products". This resulted in a turning of the tide for analog LP sales in the classical music market as it truly became a CD market. According to statistics from the Recording Industry Association of Japan, 6.36 million CDs were produced in 1984 for a total sum of ¥14.4 billion. In terms of total sales revenue, analog LPs still outsold CDs by 88.6 to 11.4. There was rapid growth in the CD market from 1985, with CD production in Japan reaching more than 20 million discs, three times higher than the previous year. In 1986, this figure grew to over 45 million, rivalling LP records. In 1987, CD production reached 65 million, more than double that of LP records. CDs had gained a firm foothold in the market. Fig. 6-1-2 shows the trends in CD and LP sales, taken from documents by the Recording Industry Association of Japan.

million units

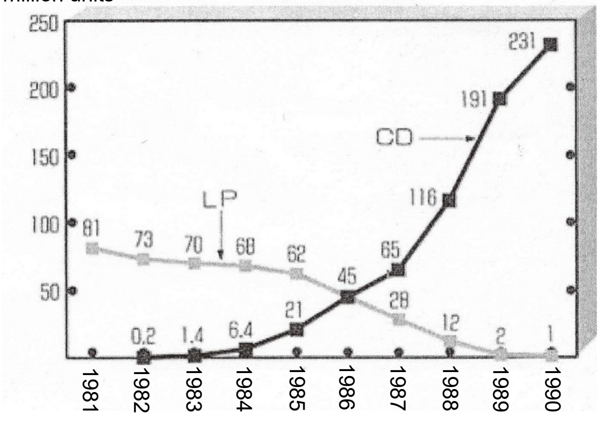


Fig. 6-1-2 Trends in CD/LP Record Sales
(from RIAJ data)

The global leaders in Japanese CD production technology began to shift their production bases overseas. Nippon Columbia and JVC expanded into the United States, while CBS Sony went global, including the United States. Toshiba EMI supported a CD production plant in the United Kingdom. Such was the superiority of Japanese CD production technology.

As mentioned previously, companies were actively investing into portable CD players. This had a significant impact on the tabletop player business. Perhaps because it was the golden age of the audio market, around five to ten tabletop CD player models were being designed each year. However, there was difficulty in reducing costs. From around 1985, when the benefits of LSI mass production began to take effect as a result of the D-50, Sony was able to design products for prices in the vicinity of ¥50,000. The subsequent launch of the CDP-33, mentioned above, and the CDP-510 aided the popularity of the product. In 1986, competition between companies grew more intense. Players such as the CDP-M30 started being sold for around ¥30,000. As price competition intensified further, the market grew. The release of CD single titles in 1988 drove further expansion in the youth and female user markets. According to RIAJ, production of 8cm CD singles reached 110 million in 1992, five years later. Production peaked in 1997 at around 168 million. This phenomenon was made possible by the low cost and ease of use of CD players. The players had made a huge transition from conventional tabletop machines into the realm of general audio products. These were personal user devices, such as the CD radio cassette player. CD software was also rapidly expanding into a large-scale market. Album production reached around 210 million, securing a central position for CDs in the music industry.

However, Sony was also developing products such as the ES series, mentioned earlier, for the high-end audio arena and a specialized market was taking shape. High-end audio players, starting with the CDP-701ES in 1983, were designed for the best possible sound quality. These models were very highly priced at over ¥100,000. When the higher sound quality super audio CD (SACD) was released in 1999, the SACD compatible players SCD-1 (¥500,000) and SCD-777ES (¥350,000) were put to market, followed by the DVP-S9000ES (¥200,000) and SCD-555ES (¥180,000) the following year. Specialized manufacturers overseas later modeled their ¥100,000 to ¥1 million CD players on these machines. SACD discs used two-layer technology with two 0.6mm discs attached together. These were positioned firmly in the CD family under the Scarlet Book, although they differed from the CD standards in the strictest sense. They required special players and could not be played on existing CD players and so were limited to certain areas. As a result, these high-quality CDs unfortunately never achieved widespread popularity. However, the underlying 1-bit sampling direct stream digital (DSD) technology was recognized as prior art when it came to later high-quality music distribution online.

6.1.2 The Emergence of Players with Changers

CD changers first appeared in late 1986, due to the abundance and widespread popularity of CD software titles. Sony's first CD changer model was the CDP-C10 (¥110,000), designed to play 10 consecutive CDs. The five-disc CDP-C50 (¥44,800) was also launched on the market. This model was especially popular in North America, and a new market was formed.

CD changers can be broadly categorized into three types: (1) the magazine type, (2) the roulette type and (3) the storage type.

(1) Magazine type CD changers hold 5-12 CDs in a magazine and are noted for easy disc handling. These were first built into tabletop players. The technology reached its pinnacle in 1988, with the CDP-C100 (¥79,800), CDP-C900 (¥49,800) and CDP-C910 (¥49,800). Later devices for car audio had additional features, such as anti-vibration technology and built-in memory to aid against skipping. These significantly expanded the high-quality car audio market. Even today, there are still in-car CD players with magazine type CD changers, although they now have evolved further in various ways, such as integrating navigation into the audio server. Fig. 6-1-3 shows a magazine type CD player and a magazine type car CD player.

Fig. 6-1-3 Magazine Type CD Player and Car CD Player

(2) Roulette type CD changers hold 3-5 CDs on a roulette disc that makes the changer function possible. Due to the simple method of disc change is simple and the advantage of the discs being visible, this system became the main one used in tabletop players. The design was first introduced to the market in the CDP-C5M (¥54,800) in 1987 and was used in a number of models until the CDP-C535 (¥49,800) in 1993. Marketed as a tabletop player, there are still a few being produced today. This features some examples of unique Japanese technology, including the fixed disc chuck mechanism that allows stable playback of multiple discs, the dust-proof shutter mechanism to protect the optical pickup from dust and dirt and the disc peeling mechanism, environmental countermeasures for deserts and other special climate areas overseas. Fig. 6-1-4 shows a five-disc roulette player. Fig. 6-1-5 shows examples of a disc peeling mechanism and a dust-proof shutter mechanism.

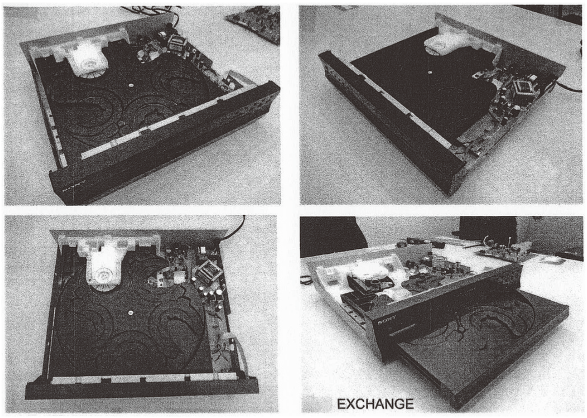


Fig. 6-1-4 Five-Disc Roulette Type Player

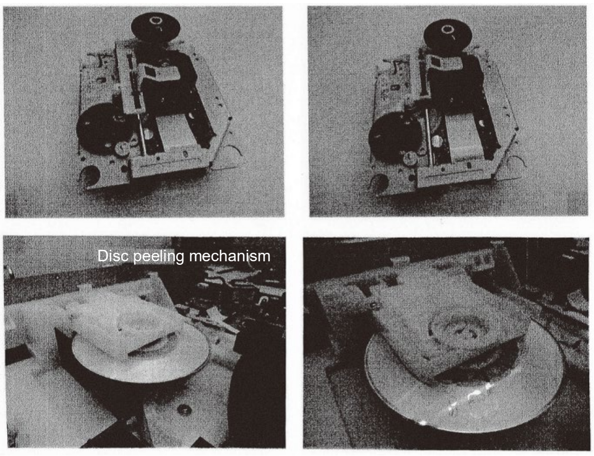


Fig. 6-1-5 Dust-Proof Shutter Mechanism and Disc Peeling Mechanism

(3) Storage type changers were introduced around 1993 and were designed to hold around 100-400 CDs. The discs are stored one by one in a circular storage area,

with a number of devices used to minimize the storage space. This was the culmination of unique Japanese technologies. The CDP-CX100 (¥100,000) was brought out with a 100-disc changer and was well received in the North American market in particular. Later, in 1995, the improved CDP-CX100F was launched. The CDP-CX200F (¥59,800) was launched in 1996, making it possible to store and change between 200 CDs. The ultimate CDM62 was capable of storing and changing 400 CDs and became a major talking point.

This changer type mechanism was uniquely developed in Japan. Pioneer also released products in this field. These changers had extremely high precision mechanical design, with a dual deck able to store up to 400 CDs and play the selected CD in an instant. Fig. 6-1-6 shows a 400 CD changer.

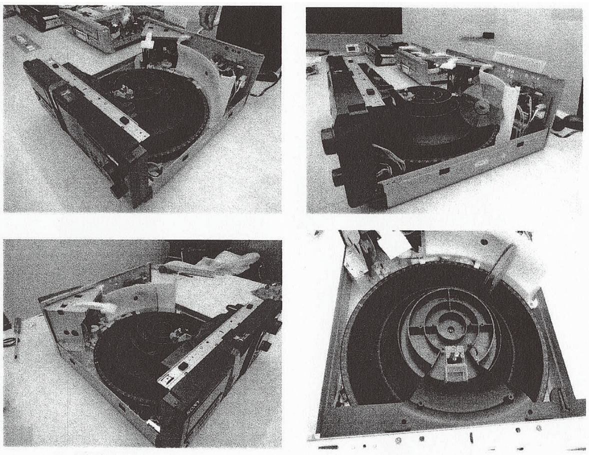


Fig. 6-1-6 400 CD Changer

Japan has the technological monopoly in this field, with patents including Patent No. 3541515 and Patent No. 3951500. These are quite complex mechanisms and difficult to explain. Essentially, the patents are for a mechanism in which a robotic arm takes out one of the 400 discs and puts it in the CD drive chuck to play it. Fig. 6-1-7 shows a diagram from Patent No. 3951500, used as a reference for later systematized technology.

6.2 The CD Walkman that Made the CD Famous

In 1984, two years after the emergence of the compact disc, the CD player itself was limited to being a luxury item. A portable player then emerged that was surprisingly as thin as four CD cases, yet had high sound quality.

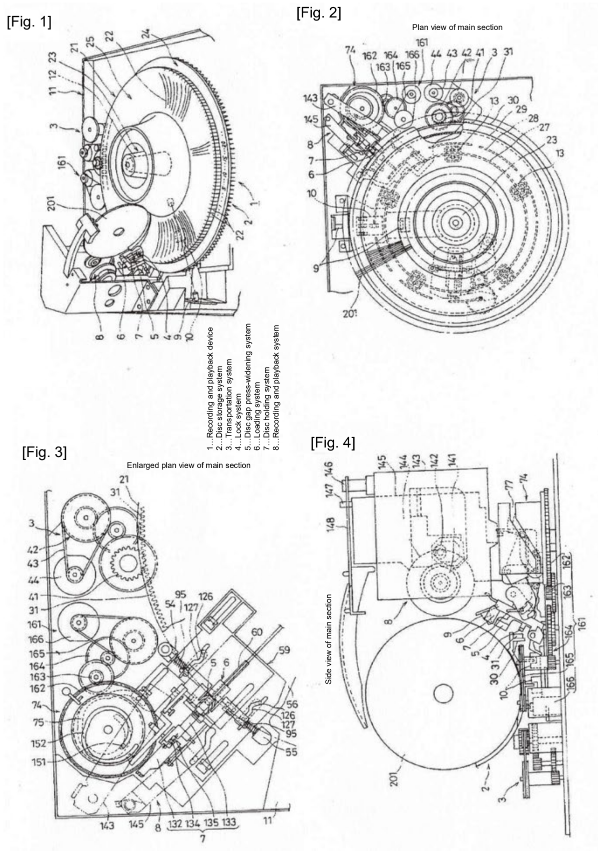


Fig. 6-1-7 Patent No. 3951500 400 CD Changer Mechanism

This was the Sony D-50 and it created a sensation. Sony had experience in implementing high density technology, having produced the cassette tape Walkman. This small, lightweight player had sound quality to rival that of the tabletop CD players. With functionality including an LCD panel to display the current track number and playing time, this device not only offered a real sense of the unique user-friendliness of CDs, it also offered specifications from a user's perspective, such as being able to connect to an amplifier or radio cassette player as an audio output.

Besides this high functionality, what took people aback was the extraordinary price of ¥49,800. Making full use of integrated circuits, low power consumption, fewer parts and other gradually acquired technologies had resulted in a product that was even attractive to those who had given up hope of affording a CD player. The small size and user friendliness combined with a high quality design that would go on to attract many followers. The level of completion of the product meant that a broad range of music lovers, not just the hi-fi enthusiasts, could easily enjoy digital sound. These factors together triggered a new CD media boom around the world. This chapter outlines the lineup of technology that led to the "CD Walkman". Since the main target for development was the optical pickup, it goes without saying that the history of the CD Walkman is the history of microminiaturization and ultra-lightweight development of the optical pickup. Fig. 6-2-1 shows the development of the optical pickup, from the historical He-Ne gas laser pickup, designed and developed for the CD player before the emergence of the semiconductor laser around 1980, to the miniaturized optical pickups of the early 1990s.

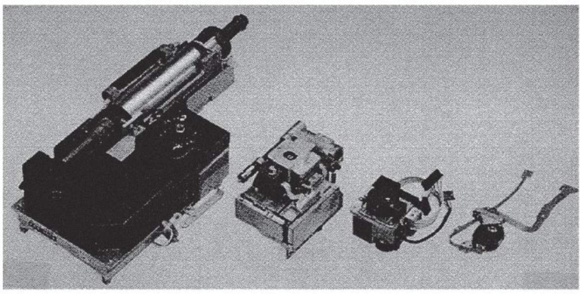


Fig. 6-2-1 Optical Pickup Progress

6.2.1 Development of Optical Pickups for Portable CD Players

The emergence of the D-50 resulted in the price of CD players dropping across all companies. Software titles also went on sale in large numbers. The CD business was fully developed across the entire industry. However, the D-50 required a large adaptor when carried around and was also quite heavy. It was still a long way from being a fully portable, easily carried product.

The optical pickup in the D-50 was a so-called generic product, designed with specifications that could be applicable to various different applications. To make it smaller and lighter, it had to be optimized for the CD Walkman. A special design task force was put together to work on creating a dedicated CD Walkman pickup. The team tried to develop the technology by simply testing things out. It took three years to complete. On top of this, there were a few challenges to be resolved before mass production was possible. The team ended up having to prototype five or six optical pickup models. Eventually, the team completed the first-generation optical pickup unit, weighing 8 grams. Although the most important devices in the optical pickup are the semiconductor laser and the objective lens (from glass lens to aspherical plastic lens), these fell to different divisions of the company to industrialize. The main goal for this development was to make the optical pickup unit smaller and lighter. This began with testing whether the zinc diecast slide base for the generic optical pickup could be replaced with a resin version. Using resin instead of metal not only made the part lighter, but also more moldable, which reduced the amount of secondary processing, thereby reducing the cost. As a result, glass-reinforced polycarbonate was selected for the slide base in the first-generation optical pickup. There were many benefits to using resin, including better responsive and power conservation. These benefits made the use of resin indispensable. The actuator bobbin generated heat, requiring a highly heat-resistant resin. “Fortron” was used for its high precision moldability, necessary for making components smaller and lighter. The new material improved the resonance characteristics of the bobbin and made it possible to reduce the number of parts in biaxial actuators. “Fortron” has excellent heat, flame and chemical resistance, as well as having low ionic impurities and superior solder heat resistance. Because of this, it is being used more frequently in a variety of applications, particularly for electronic components used in severe conditions. Fig. 6-2-2 shows a first-generation pickup and its components. The central component is the mechanical unit, made up of the disc rotation motor, the resin optical pickup unit and the optical pickup slide base.

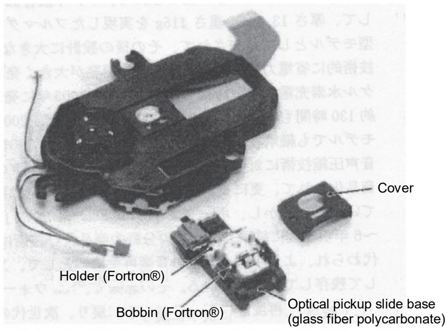


Fig. 6-2-2 First-Generation Pickup Components

The second-generation pickup was a continued development of the first-generation pickup to make it smaller, lighter and more functional. The performance aims were greater stamina (lower power consumption), faster reading and lower susceptibility to skipping. To achieve these aims, the second-generation pickup (1) had two models of optical pickup slide base, one made from the existing glass reinforced polycarbonate and the other made from a metal “Vectra alloy”. (2) The bobbin material changed from Fortron® to Vectra®, with superior mechanical and vibration absorption properties, while the holder continued to be made from Fortron®. This resulted in a more lightweight optical unit that weighed around 8 grams with the metal slide base and around 4.5 grams with the Vectra material. Since the bobbin was made of Vectra, it had a high Young’s modulus. While other resin materials (such as PPS resin) had a high Young’s modulus, they had little internal loss, which meant they had poor vibration properties. Only Vectra performed well in this regard. The two models of second-generation optical pickup, one with a thin metallic optical pickup slide base and one with a thicker resin slide base, were used variously for different types and models of CD Walkman. To be able to read faster than the first-generation pickups, they had to have a higher resonance frequency for each component. The higher revolution of the disc rotation motor meant greater vibration. To minimize the effects of this, each part had to be made a higher grade. The main reason for using Vectra alloy for the optical pickup slide base was its extremely high hardness, heat resistance and chemical resistance. The resin itself was flame retardant, with all grades having V-0 level properties. It also had very high thin moldability with little burring. It took a lot of effort and ongoing trial and error to reach this point in material selection, with a lot of technical support. It was not a matter of individual component characteristics, but of finding an optimum solution for the pickup as a whole, combined with other parts and also taking part adhesion properties into account to produce superior vibration properties. Fig. 6-2-3 shows a CD Walkman with a second-generation pickup, as well as the optical pickup slide base, holder (Fortron) and bobbin (Vectra) that make up the optical pickup unit.

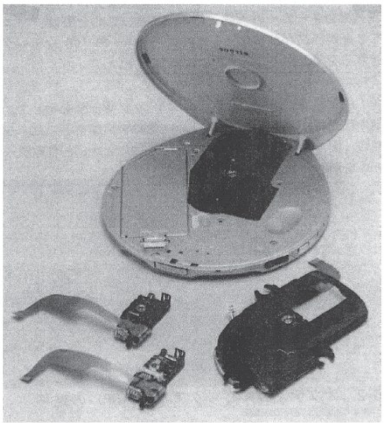


Fig. 6-2-3 CD Walkman with Second-Generation Optical Pickup

The third-generation pickup emerged in the summer of 2001. It was the complete optical pickup for the CD Walkman, both in performance and in cost. This pickup made it possible to take the CD Walkman from 15.5mm to 13.4mm thin. The pickup also only weighed 3 grams. Following thorough analysis of vibration properties, the material used for the bobbin was special grade Vectra® with low anisotropic vibration properties, thus improving performance. A lightweight Vectra alloy material with good vibration properties was used for the optical slide base. For the second-generation pickup, the only consideration for optical slide base material selection was the vibration and strength of the individual component. For the third generation, consideration was also given to compatibility with adhesives and layout balance with other parts. As a result, the third-generation optical pickup was successfully made thinner, smaller and lighter, as well as offering better vibration properties and costing less. With the ultimate ideal type now achieved, all slide bases were transitioned to the Vectra alloy and are still produced in this form today. Progress was also made in areas other than pickup development. The CD Walkman was being thoroughly investigated in all aspects, including size, electricity consumption (stamina) and skipping. The issue of skipping was an essential feature that spelled life or death for the CD Walkman. Technological development in this area continued, resulting in a "G-Protection" skip guard function. Today, the system is complete, with music able to be enjoyed with little concern for skipping even with vibration from being carried about or jogging. This technology is characterized by having a buffer memory of several seconds for CD-DA playback. Even if the system skips, the music data is played back from the buffer memory until the optical pickup returns to the original track. Although the system servo had the gain enhanced to prevent skipping, it was still possible for the track or focus to jump for some reason, losing the original signal. The buffer memory system was developed as a means to combat this. While this could be considered to be audio delay-line technology, it is the ultimate degree of perfection in playback technology, playing back with the user unaware of the skipping, as if nothing had happened. Fig. 6-2-4 shows a CD Walkman with a third-generation pickup. Fig. 6-2-5 shows the parts that make up a third-generation optical pickup.

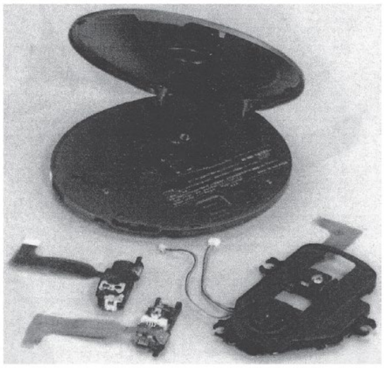


Fig. 6-2-4 CD Walkman with Third-Generation Optical Pickup

6.2.2 Development of the CD Walkman

The history of the "Discman" portable CD player began in the fall of 1984 with the release of the D-50. In that sense, the history of the portable CD player is the history of the Sony CD Walkman itself. Examining the technology systems has shown that the development process can be broadly divided into four stages. This is the case for Sony, who pioneered in this field, and the same is true of many Japanese household appliance manufacturers. These stages largely align with the generations of optical pickup. The period from 1985, when the Discman was first commercialized using the generic pickup described previously, through to the early 1990s was the “dawn era” of the Discman. The period from the early 1990s, when the first-generation optical pickup was successfully developed and commercialized, through to around 1996 was the “growth era” of the Discman. The period from 1996, when the second-generation pickup was introduced, through to the early 2000s was the “maturity era”, when the name changed from Discman to CD Walkman. Finally, the period from around 2000, when the third-generation ultimate optical pickup was introduced and conversion to other media was considered, through to 2005-2006 was the “conversion era”. Through these four stages, which span 20 years in time, portable music playback devices have fulfilled their mission and transitioned to second-generation media (IC memory, internet, etc.). Even now, portable CD players are being produced overseas more or less as toys, sold for $10-20. This simply shows how things inevitably change with time.

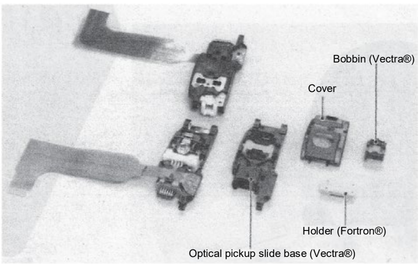


Fig. 6-2-5 Third-Generation Pickup Components

(1) The portable player of the dawn era was essentially a model derived from the D-50. There were many models with different color variations and increasingly longer playback durations. The D-50 MK-II in 1985 had a change in design to make it smaller and more lightweight. The D-30 released in 1987 and the D-20 and D-40 in 1988 were popular-priced models, coming in at under ¥30,000. These also offered over six hours of playback. The use of CD players in cars was spreading, with a focus on sound quality. Sony launched the high sound performance D-600 model for in-vehicle use in 1987. Designed for in-car performance and operability, this was an unprecedented new design, powered from the cigarette lighter socket. The high-end D-2001 model featured a built-in 50W amplifier. With the favorable reception of the 8cm CD, particularly in Japan, the D-88 portable CD player was launched in 1988 as a specialized 8cm CD player. The design emphasized a unique shape and operability. When playing a 12cm disc, the disc would jut out from the player as it rotated. At the same time, CD-DA disc production surpassed LP record production in 1987. On top of this, CD players ranged from popular-priced models to 8cm CD models and high-performance models. There were even high sound quality models featuring digital sound processing (DSP) and low-frequency sound playback models with TV/FM/AM tuners. All these different models began to emerge in the dawn era.

(2) The Discmans of the growth era were the models launched from around 1990 to around 1996, distinguished by the second-generation optical pickup. The D-J50, launched in 1991, featured the newly developed, significantly smaller and lighter optical pickup. This made it possible to achieve a thickness of 14.8mm, only slightly thicker than a CD case (10mm). Regardless, this jacket-sized CD player had a form that felt more rigid than any player before it. However, although the design attempted to come as close as possible to the outer edge of the CD itself, this could not be achieved with the technology of the time. This era is characterized by many models having a mixed design that was rounded at the front, like a CD, and rectangular at the back. The D-111 in 1992, the D-321 in 1993 and the D-777 in 1995 had the same external design, using carbon fiber to make it lighter. These models were 18.5mm thick, weighed 175g and used sports-specification 10-second electronic shock protection (ESP) to prevent skipping. This era is also characterized by issues with power consumption. Power conserving technology continued to develop and by 1996 had reached a level where 10 hours of playback was possible with AA alkali batteries. However, power conserving technology is a continual challenge for portable devices and developments can be expected to continue in future. Another feature of this era was the MD Link function that made it possible to connect to the MiniDisc launched in 1992. The function to connect with other devices was an attempt to further extend the world of portable CD players. The D-848K “CAR Discman” launched in 1995 was the definitive in-car model, featuring electrical opening and closing of the tray, 15 types of digital signal processing (DSP), anti-skipping protection and a substantial repository of accessories. The growth era was further supported by the launch of the popular-priced D-131, selling for around ¥13,000

in 1995, followed by the D-140, D-153, D-155, D-330, D-340 and D-365 in succession.

(3) The portable CD players of the maturity era underwent a change in name from the existing term “Discman” to “CD Walkman” in 1997. These CD players featured second-generation optical pickups and the newly developed ESP2 anti-skipping system. This was a new era of renewed function and design.
The early D-E500 CD Walkman was capable of around 40 hours of continuous playback using four AA batteries and was also compatible with MD Link. The design remained the same round-fronted, rectangular-backed shape, although it had aluminum alloy panels and at 24.8mm thick, it was the size of two CD jewel cases. The D-E700 and D-E800 were later developed from this model and served as the pattern type for promoting the CD Walkman brand. A new brand, the WIDDIT series, was proposed in 1998. Expansion into new fields continued with the release of the D-5WD, a new model devoted to being carried around. Meanwhile, the D-E900 achieved new levels of holdability at 20.1mm thick and weighing 175g. An adapted multifunctional model, the D-V8000 was launched in 1998, allowing playback of both music and video CDs and adding a touch of color to the lineup of the maturity era.

(4) The conversion era began with the D-E01, launched in 1999 to commemorate the 20th anniversary of the Walkman (from the cassette tape era). This model achieved the idea of a CD Walkman finally having the same round shape as a CD. It was packed with features that were carried over to later models, such as the newly developed G-Protection skipping prevention, slide-in disc loading and a round design. The optical pickup was the small, lightweight third-generation design. The overall player had a beautiful shaped-up design that was only 19mm thick, weighed 167.5g and was 130mm in diameter. This design was taken to further extremes in the D-EJ2000, released in 2002. Launched as an ultrathin model, it had a seamless casing and full magnesium body that was only 13.4mm thick and weighed only 115g. This model had a significant impact on later designs. Significant developments had also been made in power conservation and battery technology. The D-NE800 was launched in 2003 with the new gumstick nickel metal hydride battery (NH-10WM) capable of around 130 hours of continuous playback. This technology was carried over into the D-EJ720 high sound quality model launched in 2005. A number of models emerged at this time that were capable of intelligent and convenient playback of high-quality sound, implementing specifications for compatibility with ATRAC3 or MP-3 audio compression technology and specifications for CD-R/RW playback. However, the mission of the portable CD Walkman started coming to a close in 2005-2006. Products and technology in this field have been replaced by IC memory and continue on in the form of smaller, lighter music playback devices or as a function on mobile phones. In that sense, the “CD” has been dropped from “CD Walkman”, returning simply to “Walkman” with the inevitable transition to the next generation of media.

Although a survey report on the systematization of technology ought to collect all Japanese resources impartially, it has not been possible to collect materials in this field from anywhere but Sony, due to the reorganization and dissolution of Japanese electrical goods manufacturers. Unfortunately, the report has had to focus unilaterally on the Sony CD Walkman.

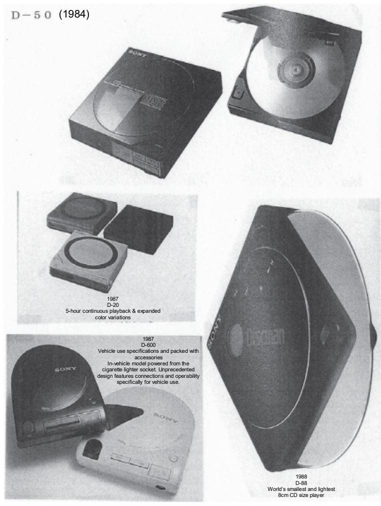


Fig. 6-2-6 Portable CD Players of the Dawn Era

Fig. 6-2-6 shows representative portable CD players of the dawn era. Fig. 6-2-7 shows representative portable CD players of the growth era. Similarly, Fig. 6-2-8 and Fig. 6-2-9 show representative CD Walkmans of the maturity era and conversion era, respectively.

Fig. 6-2-7 Portable CD Players of the Growth Era

Fig. 6-2-8 CD Walkmans of the Maturity Era

Fig. 6-2-9 CD Walkmans of the Conversion Era

6.3 Emergence of the CD-ROM

The emergence of the CD-ROM as a new form of recording media was a major event, akin to the arrival of the black ships for software developers and a kind of Renaissance for the software industry. As software developers agonized over how to store their programs, FM audio data and graphics data on the existing floppy disks that only held 1-1.4MB, the arrival of the CD-ROM with around 540 times the storage capacity of a floppy disk must have bewildered them no end. They were now faced with the previously unimaginable problem of what to store on something with such huge capacity and what kind of programs they would have to develop to satisfy users. A request came at the time to develop multimedia titles for the FM Towns, a computer produced by Fujitsu with a built-in CD-ROM drive. For the software industry, still finding its way forward, even the idea of multimedia came as a major shock. Fujitsu had confidence in the potential for the CD-ROM and established a "Hypermedia Center" in Tokyo and in San Francisco to provide information on CD-ROM title development and to support the production of CD-ROM titles. While CD-ROM titles can now be produced easily at home, at that time this required specialized equipment that cost over ¥10 million. These Hypermedia Centers had a huge role to play in this and were the greatest contributor to encouraging the production of CD-ROM titles. Besides games, a great variety of titles were developed, one of which was called Hyper Planet, a planetarium simulator combining a vast amount of star data, photographs and background music. This outstanding work is still talked about today. The title won the Minister of International Trade and Industry Award at the first Digital Content Grand Prix and has been used as a teaching tool in a great number of schools.

Thus, the emergence of the new high-capacity CD-ROM recording media introduced people to the first multimedia titles, incorporating audio data, graphics, photographs and videos. A different style of development (much like movie production) was introduced to the software industry and used in many markets, including PCs, games, vehicle navigation, film, education and electronic publishing. Huge numbers of titles were produced in the early 1990s and introduced to the market, causing a so-called CD-ROM Renaissance that carried on into the 21st century.

6.3.1 Multimedia PC Application

At one time, PCs were not at all good with audio, still images, videos and other so-called multimedia information. This was due to the following reasons.

(1) Slow CPU processing speed

(2) Low internal memory capacity

(3) No established format for multimedia data

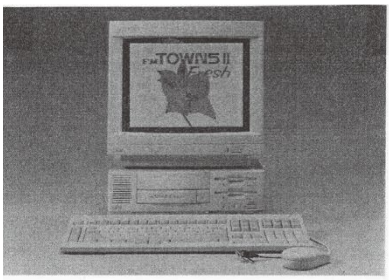
(4) No OS with a standard multimedia function

Another major factor was that multimedia data was sizeable and there was no suitable recording media for PC handling, even from a cost perspective. By using the CD-ROM as a delivery media, it was finally possible to achieve "multimedia title" software products. CD-ROM title distribution provided favorable conditions for electronic publishing businesses to enlarge and spread. PC multimedia titles led to the growth of the CD-ROM market and the spread of the "multimedia PC" in a positive way.

The first multimedia PC with a CD-ROM drive as standard was the FM Towns launched by Fujitsu in February 1989, followed by others in 1991, including the PC-98 Multi by NEC and Quadra 900 by Apple Computer. Many other companies later followed suit with multimedia PCs of their own, such as the PS/V series by IBM Japan in 1994, and the market suddenly boomed.

Another factor behind the spread of multimedia CD-ROM titles was the fact that PC manufacturers were hedging various risks for manufacturers of CD-ROM software titles, establishing multimedia production studios and renting these out at low cost. As a result, CD-ROM titles rapidly increased and grew more diverse. Fig. 6-3-1 shows various multimedia PCs with CD-ROM drives built in. Fig. 6-3-2 shows a multimedia studio established by NEC.

While multimedia PCs were simply an extension of conventional PCs, just with a built-in CD-ROM drive, there was also another type of hardware called the player PC, which also had an internal CD-ROM drive. These were operated by a game pad instead of a keyboard and connected to a household TV rather than a monitor for a display screen. These were also known as TV computers. These existed overseas, such as the Commodore Dynamic Total Vision (CDTV), launched by Commodore in 1991, and the Video Information System (VIS) by Tandy in 1992, but were not very widespread and the market faded away within a few years. In Japan, the most representative TV computer is the Towns-Marty, launched by Fujitsu in 1993. While basically compatible with the FM Towns multimedia PC, there were limited titles available. Fig. 6-3-3 shows the Towns-Marty, which bore a striking resemblance to the CD-ROM gaming machines at the time. Later, Fujitsu Ten also commercialized the Car Marty, a Marty-compatible vehicle navigation device.



FM-Towns (Fujitsu)

PC-98 Multi (NEC)

Quadra 840AV (Apple Computer)

PS/V Vision (IBM Japan)

Fig. 6-3-1 Multimedia PCs (with CD-ROM) from Various Companies

Fig. 6-3-2 NEC Multimedia Studio

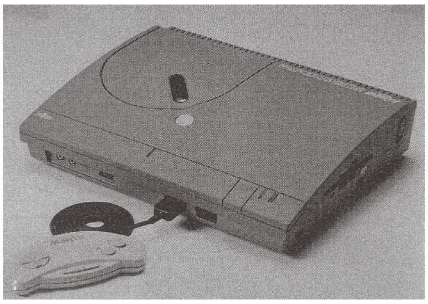


Fig. 6-3-3 Towns-Marty (Fujitsu)

CD-ROM drives came down in price and were increasingly fitted into PCs as standard. As CPU speeds increased and hardware with AV functions emerged, the PC itself rapidly evolved into a multimedia machine in the late 1990s. However, PC manufacturers each used their own multimedia designs and the issue arose of CD-ROM software compatibility not being maintained. To resolve this situation, the multimedia PC (MPC) specification was created as a PC standard specification to ensure multimedia software would operate in the Windows environment and to ensure CD-ROM software compatibility. The MPC specification provided the necessary guidelines for IBM AT compatible machines to operate multimedia software. The MPC Marketing Council (MPCMC) was established as an MPC promoting organization led by Microsoft to facilitate the spread of MPC.

Microsoft published the MPC specifications in 1990. The MPCMC published an expanded version, Level 2, in 1993. The specifications were as follows.

(1) CPU: 80486SX (25MHz) or higher
(2) Memory: 4MB or higher
(3) Hard disk: 160MB or higher
(4) Audio: 16-bit digital sound / MIDI
(5) Graphics: 640×480 dot, 65,536 colors
(6) Interface terminals: Serial, parallel and joystick

In 1995, the MPC Level 3 was published for MPEG-1 movie playback compatibility. As a result of the strong promotion of the MPC specifications, the multimedia CD-ROMs requiring independent hardware to operate had been eliminated. The CD-ROM drive became a standard feature on PCs, and multimedia became so well established that the term “multimedia” was no longer needed. With recordable and rewritable CD media superseding floppy disks, CDs secured the perfect position as everyday PC media.

Multimedia PCs came in desktop and laptop form. In the golden age of the early 2000s, around 200 million were being produced each year. Almost all of them had CD-ROM drives (CD-R/RW drives), which were smaller in size and offered faster signal reading speeds during playback. The competition for speed began with user demand for 4× faster and culminated in the emergence of products 48× faster in 2005. Drive control technology had reached its highest peak.

The ordinary CD standards stipulated that the outermost edge of the disc should rotate at around 200rpm due to constant linear velocity (CLV). For instance, if a disc with a 50mm radius is read at 48×, the rotation speed is around 9600rpm, which equates to $2 \times \pi \times 50 \times 9600 \times 60 \approx$ 180km/hour. This would require tracking the pits at the average speed of a bullet train, which would have a very high level of technical difficulty. To resolve this, the CD standards stipulated an average data reading speed of around 1.2Mbps for 1× and around 60Mbps for 48×. While the signal would not be unreadable using today’s technology, it was difficult to achieve with the level of technology at the time. Ideas were devised to resolve non-reading issues, such as adding a safeguard circuit to automatically slow down the rotation speed to enable reading. The competition over speed also took place for CD-R/RW drives, sometimes resulting in insufficient recording power and optimal write strategy design failures. Speeds of over 24× in particular had stable writing technology, but the writing did not meet the product specifications. Realistically, 16× was the highest stable writing speed. Mass production was achieved by adding a recording film to CD-R/RWs that allowed stable writing in this range (around 30Mbps). The CD-ROM/CR-R/CD-RW drive speed competition had become detached from reality. On top of that, PC manufacturer cost requirements were very tight. The competition came to an end once drive manufacturers overstretched and then lost motivation to continue developing, perhaps because the cost competition was all that remained. There were many drive manufacturers at that time. The main companies were widespread, from

Sony (Optiarc, a joint venture with NEC), NEC, Pioneer, Matsushita (Sanyo), Mitsumi and Teac in Japan, to Toshiba Samsung and Hitachi LG in Korea and Lite-On in Taiwan. However, only two companies, Pioneer (for business) and Lite-On, remain active in this business today. This is an indicator of how severe the "cost pressure" has been in this area. Fig. 6-3-4 shows a CD-ROM drive unit and block, the main proponent of business at the time. As can be seen, it is structured with the rotation motor at the center, along with the optical pickup and its powertrain and control IC. As these were fitted internally (or externally) to every PC, production was huge, reaching around 200 million units a year at its peak. However, technology moved on and data recording media changed, and businesses that were unable to keep with the times had no choice but to consolidate. More recently, the rapid spread of the internet and broadband has meant that even quite large software can be distributed over the internet rather than packaged media. In that sense, technology is increasingly being used as appropriate for the situation and it is a matter of exploring the potential for coexistence alongside areas where the use of CD-ROMs has been well established.

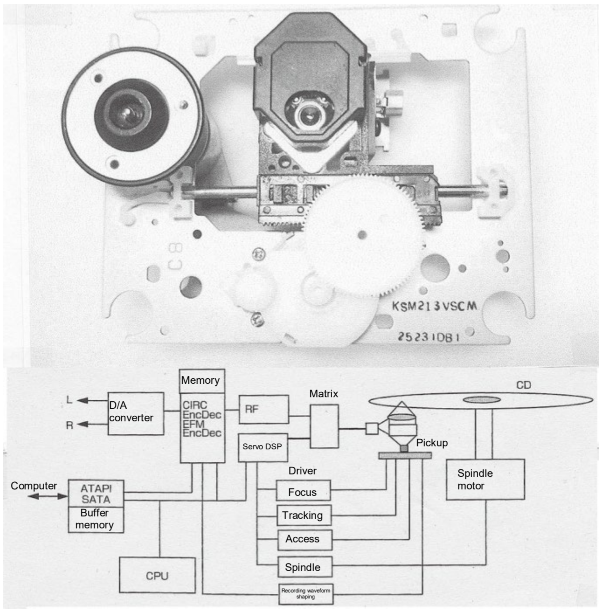


Fig. 6-3-4 CD-ROM Drive Unit (provided by Sony)

6.3.2 Household Game Machines that Support CD-ROM

The household game machine market began in the United States with the Atari VCS in the 8-bit CPU era. Later, a global market was established for the Nintendo Famicom through a brilliant market strategy. A market also formed for PC game software in the field of entertainment. PC games could be freely developed and marketed, leading to successive new genres in game software. As story content became more complex, software developers found they lacked sufficient memory to store the data.

The first household game machine distributed on CD-ROM was the PC Engine CD-ROM developed by NEC Home Electronics in 1988. With the PC Engine CD-ROM, NEC took the strategy of making a product to rival game machines and game PCs for a market dominated at the time by the Famicom and the MSX computer. Using CD-ROM had the following advantages.

(1) Substantial increase in recordable program and data size, allowing the game to effectively utilize sound, photographs and animated video
(2) CD-ROM was lower in cost than the conventional semiconductor ROM
(3) CD-ROM could be mass produced in a short time
(4) CD-ROM is more suited to smaller scale production than semiconductor ROM

However, there were some candid observations from game users, particularly that the data transmission rate was slow. Based on the prediction that (1) the CD-ROM drive would be able to handle this as technology progressed, there would be (2) a dramatic decrease in the cost of internal RAM that would allow for a large read buffer to be implemented. If (3) audio compression and video playback circuits could be implemented on a chip, these could be played back easily as the game went along. In addition, (4) the rapid development of the PC would result in a better development environment, which would allow more complex games to be developed more easily. As a result, the game machine market made a sudden switch to CD-ROM software. The CD-ROM overcame its drawbacks to become the main delivery media for household game machines. Fig. 6-3-5 shows the PC Engine CD-ROM system (NEC Home Electronics).

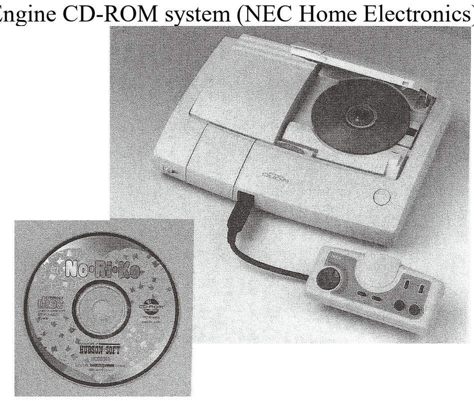


Fig. 6-3-5 PC Engine CD-ROM^2 System

Before the CD-ROM arrived, the main household game machine delivery media was semiconductor cartridges that stored several megabytes. In the unique game industry business model, these were the greatest revenue setback for game manufacturers. Production of ROM software cartridges was controlled by the game manufacturers with license agreements. Nothing from production numbers to inventory could be actioned without approval from the game manufacturers, who held control of all information. Some game manufacturing companies achieved huge profits under this system. Given such circumstances, an alternative delivery media to the ROM cartridge naturally gained attention, and external CD-ROM drives were commercialized for household game machines. CD-ROMs also benefited game manufacturers in various ways. They could be produced quickly, and their small size reduced transportation and storage costs. Not only that, the ability to produce in smaller numbers meant companies could be flexible to the needs of the market and produce more as needed. With agreement on both sides, the household game machine delivery media rapidly transitioned from ROM cartridge to CD-ROM.

A movement began of leveraging CD media compatibility and multimedia capabilities to turn household game machines into generic home entertainment players. One such platform was the Sega Saturn, launched by Sega in November 1994. Sega partnered with several third-party consumer electronics manufacturers under production and marketing licenses. Hitachi oversaw production of the CPU, while JVC and Yamaha oversaw the mega drive. The idea was for an all-inclusive home entertainment system. A similar situation was happening overseas. Commodore in the United States launched the CD-32 (using the Amiga multimedia computer), compatible with various kinds of CD media. This gained a high share of the market, especially in Europe. The multimedia, all-inclusive multi-player was established in the United States in 1990 with the launch of the 3DO Interactive Multiplayer by the 3DO Company. It was marketed in Japan in 1994 by Matsushita Electric as the 3DO Real, and again by Sanyo as the 3DO Try. These household multi-player CD-ROM game machines were impeded by conflicts between various hardware standards and no main platform was established. Fig. 6-3-6 shows the 3DO Real integrated CD-ROM household game machine (Matsushita Electric).

Fig. 6-3-6 3DO Real (Matsushita Electric)

Multimedia computers with inbuilt CD-ROM drives started gaining popularity around the same time as household CD game machines. The secret to popularity was having the killer content sought after in the game industry while securing multimedia titles for household game machines. As a result, hardware platforms lost their uniqueness, as the software could be used on either system. There was another key factor that made it difficult to distinguish between hardware platforms. Game software manufacturers were in a hurry to recoup their production costs, which had increased as a result of adapting to multimedia, and were offering their new software to multiple hardware manufacturers. The turning point came with the emergence of the so-called next-generation game machine. The appearance of the PlayStation, released in December 1994 by Sony Computer Entertainment (SCE), and the Dreamcast, released in 1998 by Sega, quickly drew the household game market to these hardware devices. These platforms successfully secured a stable group of users by essentially encapsulating the game software and having exclusive games that were not available on other hardware systems. The release of the PlayStation 2 in March 2000 and the Xbox by Microsoft in 2001 signaled a transition to platforms with higher capacity DVD-ROMs. The delivery media began to transition from CD-ROM to DVD-ROM. However, since the ROM drives are backwards compatible, CD-ROM games remain popular, especially in overseas markets, and CD-ROM game titles are still in full production at disc factories. Fig. 6-3-7 shows the PlayStation 2 (SCE).

Fig. 6-3-7 PlayStation 2 (Sony Computer Entertainment)

6.3.3 CD-ROMs and Electronic Publishing

Electronic publishing on CD media was made possible by the digitization of the publication and printing process. Previously, publication involved producing block copies for a printing manuscript using a typesetting machine and photographs from the manuscript. The block copies were then used to produce a plate-making film, which in turn was used to produce printing plates for printing. A computer typesetting system (CTS) was developed to computerize the block copy production and revision process, making it more efficient. As Japanese-language word processors and computers had already begun to be used for editing, these manuscripts in electronic data could be converted to CTS data, making printing and publishing much faster. Although there were compatibility issues, as publisher and printing companies built up their CTS data, it was the natural next step for them to process this data and reuse it for electronic publishing. At the same time, there were high hopes for transitioning to CD media, which was easy to duplicate and effective to mass produce. However, the reality was that there were several technological hurdles, with the following challenges proving difficult to resolve.

(1) Slow CR-ROM drive speed meant data reading took time
(2) There was no established logical format for CD publications and separate reading software was required
(3) It was unclear how to handle intellectual property rights for electronic publications

Prompted by the standardization of the CD-ROM Yellow Book, the Japan Electronic Publication Association (JEPA) was established in 1986, mainly consisting of publishers. The "Wadōkaichin" (Japanese language compatible CD-ROM logical writing format, named after Japan's first minted copper coins) was established as the standard format for electronic publication on CD-ROM, and efforts were made to introduce CD-ROM publications. In July 1987, a CD-ROM edition of the Japanese dictionary Kōjien, jointly developed by Iwanami Shoten, Sony and Fujitsu, was released to the market, triggering greater interest in CD-ROM publications. The Kōjien CD edition was made up of a Sony CD-ROM drive fitted externally to a Fujitsu Oasys Japanese language word processor, allowing access to dictionary data. This dictionary is highly regarded as the technology that laid the foundation for later CD-ROM publications. Fig. 6-3-8 shows the Wadōkaichin and Mohan Roppō CD-ROM editions (Iwanami Shoten).

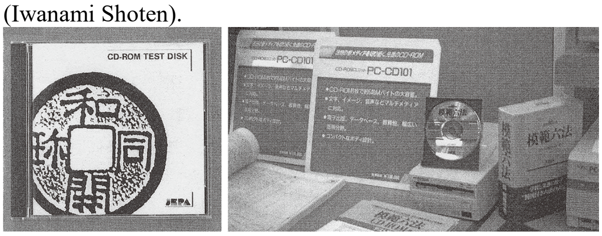


Fig. 6-3-8 Wadōkaichin and Mohan Roppō CD-ROM Editions for PC-98 (Iwanami Shoten)

Since CD-ROM drives were slow at the time, a special logical format was required for CD media. This was called the WING format. Based on this format, two types of logical format were established to form the basis of later CD-ROM publications. These were the electronic book (EB) format and the EPWING format. The EB format was an electronic publication format proposed by Sony, using encased 8cm CD-ROMs and a specialized portable player with a built in LCD screen. The format introduced EB electronic books containing characters and images, EBXA with ADPCM audio compression compatibility and S-EBXA with expanded display for color images. Fig. 6-3-9 shows a Sony EB player being used with XA audio to play example English sentences for travelling. There was a steadily growing playback environment for EB compatible players, with Matsushita Electric and other household electronics companies bringing out special viewers for EB. Software was also released that could be played on the FM Towns and Japanese word processors. However, increasing capacity and decreasing prices for IC memory triggered a technological revolution in the early 2000s, spelling the end for the portable CD-ROM dictionary.

Fig. 6-3-9 EB Player "Pelala" (Sony)

The EPWING format was a standard electronic dictionary format proposed by the EPWING Consortium. The EPWING Standard Version 1 was published in 1991 as the industry standard for using 12cm CD-ROM electronic dictionaries on PC, word processor, workstation and other hardware. In July 1996, the standard was registered as JISX4081 “Retrieval Data Structure for Japanese Electronic Publication”. EPWING was originally intended to be used on PC with EPWING compatible retrieval software. The specifications have been expanded to include support for audio and video data in addition to characters and images, and the content can also be copied to hard disk. The format is still used today.

Thus, growth in the CD-ROM electronic publication market has revolved around reference publications such as dictionaries and yearbooks, as well as photograph collections. Above all, a major factor for this expansion in playback environment was the multimedia PC with its standard built-in CD-ROM drive. With this growth in playback environment, major changes began to happen, such as the Ministry of Posts and Telecommunications including a CD-ROM with its White Paper Information and Communications in Japan in 1993. At the same time, there was also a rapid increase in CD publications for hobbies and practical applications. Where previous CD-ROM publications had mainly consisted of converting existing publications to CD-ROM, these titles made use of the multimedia aspects of sound and video. CD-ROM production costs were also decreasing, allowing them to be used for supplementary content in journals and periodicals. All at once, CD-ROM publications became an everyday item. They are still used today to provide supplementary content for various publications. The digital content made possible through electronic publishing has shifted to downloadable electronic publications and on-demand publications since around 2000. A new deposit copy system established on March 31, 2000 means that copies of CD-ROMs and other package-type electronic publications must be provided to the National Diet Library.

6.4 Interactive Title Pages for CD Media (Video-CD/CD-I/GPS Imaging Market)

Video recording on optical disc was first achieved with analog discs. The main video disc was the laser disc (LD), brought out by Pioneer in 1981. The video content business expanded, with commercial software produced for enthusiasts of movies, anime and music. Professional use of the system included karaoke and museum exhibits. However, since the LD was an analog system, the disc size was very large at 30cm in diameter and there was limited scope for reducing the size of the machines. This prompted the move to commercialize video recording on the smaller diameter CD media.

The first to emerge was the CD-V, standardized in 1987. The CD-V is a standard in the CD family, an extension of CD-DA to allow analog video recording. Essentially, it was a hybrid CD, with the area towards the inner diameter containing CD-DA audio data and the area towards the outer diameter containing analog video data (of around five minutes). CD-V players were also compatible with LDs. Pioneer launched a so-called CLD player that played both LD and CD-V. Although CD-Vs were used to sell music software together with videos promoting the artist, the medium did not achieve widespread popularity. The CD-V music format formed the basis for the 20-minute audio CD single.

Quite separate from this, progress was being made on developing digital video recording. An early digital video compression/decompression technology was Digital Video Interactive (DVI). Research and development for DVI began around 1984 at the RCA David Sarnoff Research Center. The technology was announced at the second international conference on CD-ROM (hosted by Microsoft). The division was acquired by GE, and then again by Intel in 1988. DVI and CD-ROM became a combined product. Unlike MPEG, the video compression technology had variable compression with two compression algorithms, PLV and RTV. PLV had a high image quality with a compression ratio of 160:1 and could display a 718×480 pixel JPEG image. DVI technology had the advantage of not limiting the OS and CPU. There were no limitations on the function or storage medium in any environment, including MS-DOS, Windows 3.0 and OS/2. DVI became known around the world as the technology that made it possible to record 72 minutes of natural images and audio on CD-ROM. In the CD family, DVI is a standard CD-ROM that complies with the Yellow Book with no special extension to the logical format, although playback required a special decoding board. The format featured full-frame, full color video playback at 30 frames per second.

DVI production required the use of Intel equipment or equipment licensed from Intel due to the proprietary compression technology used. In September 1989, an Intel DVI studio was opened in Japan in the former Marunouchi Building in Tokyo. The studio was used for software production. The DVI technology promotion association

DAVIS was established, and in October 1991, a standard specifications book was published for DVI playback machines. This equipment was most widely used for karaoke. In 1992, Nippon Columbia launched "DVI Karaoke". Development continued on MPEG-2 and other image compression technology, although DVI was the cutting-edge, all-purpose technology of the day. In 1992, it was combined with the INDEO image compression format. At that time, each company was developing and announcing its own digital image compression format. In 1991, Apple Computer developed QuickTime 1.0. The following year in 1992, Microsoft launched Video for Windows. Although this made it possible for computers to display digital videos, there were hardware limitations. This was an "only just" level, with display made possible by dropping partial frames. Fig. 6-4-1 shows a DVI exhibit (at the 1990 international multimedia convention). This chapter mainly discusses the application of CD media in the field of video, including Video-CD (6-4-1), CD-Interactive (CD-I), business technology with an interactive function (6-4-2), and CD media and GPS (6-4-3).

Fig. 6-4-1 DVI Exhibit

6.4.1 Emergence of Video-CD (MPEG1)

Needless to say, the history of the CD is "a history of compatibility", or perhaps "a history of proper pedigree". The CD business has always been carried forward according to a "system". In the 1990s, the CD-Interactive (CD-I) business reached a major turning point, and a new lineage came into being, with CD-I as the junction point. This was the video CD (VCD). VCD is characterized in that it is a MPEG-1 digital video disc that shares the same logical format as CD-I, but with limited highly interactive functions. At this time, all the focus was on developing the next-generation digital video distribution (DVD) media. Developers were aware of the situation and that it would be some time before DVD became widespread. The Video-CD (VCD) was developed on the idea that there would be scope for such a business to develop in the meantime. There were four VCD licensers, known as the 4C: Sony, Philips, Matsushita Electric and JVC. The first three were the manufacturers and promoters of CD-I, while JVC had developed the karaoke system that combined CD and MPEG-1 and earned a position in the 4C through this technology. The VCD was clearly positioned in the "proper pedigree".

The competition over digital video standards came to a close with the formulation of the international MPEG standard. MPEG is an acronym for Motion Picture Expert Group, the standardization committee formed by the ISO and IEC. The digital video standard put forward by this group became known in turn as the MPEG. There are different MPEG standards according to resolution and encoding rate, including MPEG-1, MPEG-2, MPEG-4 and MPEG-7. The final draft for the MPEG-1 format was completed in March 1993 and decided on as the format for recording digital video to CD media. However, MPEG-1 is purely a digital video compression encoding system and nothing is stipulated as to how to actually make it into a product. As a result, there were conflicting proposals over various incompatible CD-ROM products. To settle the confusion, the White Book standard was formulated, officially incorporating the Video-CD into the CD family.

The first MPEG-1 compatible CD-ROM product was a professional karaoke system. With the formulation of the White Book, VCD had become the main form of digital video in the karaoke industry. Later, with the growing popularity of karaoke on demand, VCD simply became the media for providing background images. Meanwhile, VCD was gaining popularity in the consumer electronics market as the delivery media for digital video content. To begin with, VCD had issues with poor encoding technology, poor image quality and block-noise caused by frames dropping out (due to the 1.2Mbps signal speed). This was unsuited to the Japanese market, which was accustomed to high image resolution. Video content distribution in Japan transitioned to DVD and broadband internet.

However, in countries in Asia and the Middle East, there are many areas where the vast territory and lack of communication and broadcasting infrastructure means that packaged media is the only available video content. Accordingly, the video CD has become more popular than the VTR, as its smaller size and low cost has made it better suited to physical transportation and delivery. Large markets formed in China and India, making the VCD the main video distribution media. It has proven particularly popular in China, where there was previously no video market. As the economy grew, it showed promising signs of becoming a new form of entertainment. The advance into China was accompanied by efforts to make the Chinese government and local manufacturers aware of the ideas and rules around licensing, patents and royalties, which were not strictly observed for CD-DA, and to understand the mechanisms of "legal compliance". From 1997 to 1999, ten rounds of negotiations were held with the available points of contact with the Chinese government, which were the National Research Institute and the Ministry of Industry and Information Technology. One member of the negotiation at the time recalled making the following appeal. "China unmistakably has enough of a role to play as one of the world's leading manufacturing bases. To get its own brands out into the world market, the Chinese government needs to carefully guide its manufacturers to take licenses and patents seriously. If not, Chinese manufacturers will always remain domestic manufacturers, never able to join the WTO and never able to shake off the stigma of markets rampant with piracy and imitations." These "wasted effort" negotiations and marketing tactics were successful, and the VCD player market grew rapidly in China. Sales of around 5 million units in 1996 tripled to around 15 million in 1997. However, successive domestic de facto standards began to appear in China, based on the VCD, and the market grew more convoluted. To resolve the mayhem, the Chinese government came up with the "Chaoji Video CD" (October 1998) and proposed it as an IEC standard.

The Chaoji VCD standard that enabled recording video and audio data on CD media compressed in MPEG-2 format to achieve a higher image resolution and sound quality than VCD. Unlike the CD standards, this standard included specific Chinese guidelines, which left the 4C concerned about compatibility. However, the 4C combined the Chaoji VCD standard with the Super VCD standard Version 0.9 (4C/SVCD) in December 1998 and began consulting with the Chinese government about IEC standardization. Approval was given at the meeting of the IEC in Beijing in December 1998, and Super VCD (IEC/SVCD) became an international standard. The IEC/SVCD standard is in the same subset as Chaoji VCD and 4C/SVCD. Unfortunately, Chaoji VCD standard software titles had issues with licensing when they were exported out of China. Accordingly, they were officially incorporated into the CD family with the Super Video CD extension to the White Book in 2000. The Video CD 2.0, based on the SVCD, was designed to play on a CD-ROM drive, so its data transmission speed was limited to around 1.5Mbps (the maximum transmission speed under the CD standard). This meant the image quality was around the same as that of a VHS video. By contrast, the SVCD used MPEG-2 compression and had a transmission rate of 2.6Mbps, almost double that of the CD. Although this limited playback time to around 35 minutes, it was cheaper than DVD and consequently served as a bridging format. However, it was never brought into production by the 4C. In that sense, the Super VCD was only a final draft format and lacked the specifications for a video content distribution media. As the DVD rapidly dropped in price, the SVCD lost its only advantage and came to an end. Delegations to the negotiations have recalled experiencing how difficult it was negotiating with the Chinese government. Fig. 6-4-2 shows a VCD capable mini component system (Matsushita Electric) used for VCD household use.

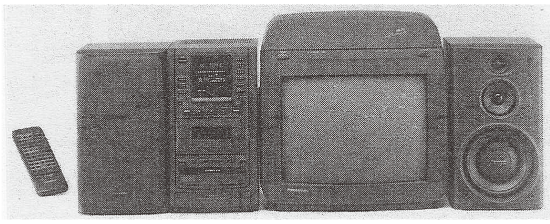


Fig. 6-4-2 Video CD Mini Component System (Matsushita Electric)

6.4.2 Professional Interactive Applications (CD-I etc.)

CD media completely changed the face of professional karaoke. "Karaoke with pictures" using LD and VHD analog video discs rapidly grew in use from around 1982, as this new technology made it possible to play the music and lyrics together. However, the video discs were around 30cm in diameter and required a lot of storage space, which meant they were not highly popular with smaller businesses. Accordingly, there was much anticipation over the emergence of a compact karaoke system that used CD media.

The first professional karaoke system using CD media used the CD-Graphic (CD-G), introduced around 1986. CD-G karaoke displayed computer graphic (CG) still images and lyrics in sync with the music.

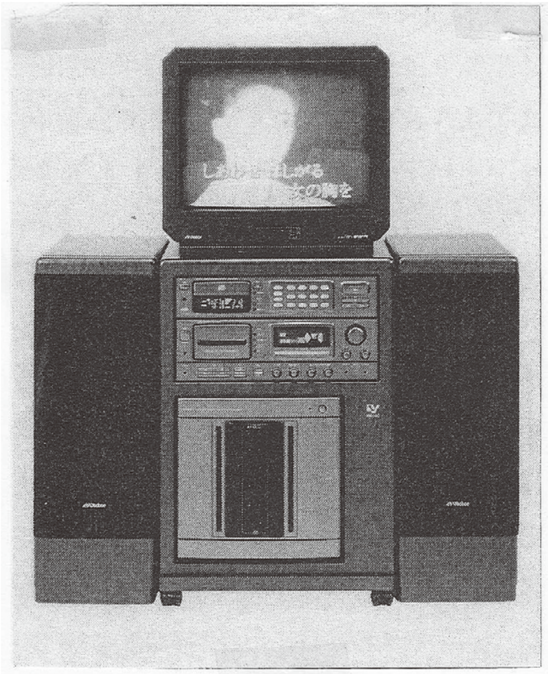


Fig. 6-4-3 VCD Karaoke System (JVC KX-DV100)

Fig. 6-4-4 Portable CD-I (Sony IVO-V10)

This was very popular with smaller businesses, and a new market came into being. However, as karaoke culture became more well established, there was a demand for systems that could play videos. The CD-I system was completed in 1992, capable of storing several thousand karaoke tracks. Companies began announcing their own “CD video karaoke systems” using the MPEG-1 standard that had finally been standardized. These commercialized systems had large-scale automatic changers and central control systems, but the detailed specifications varied slightly from company to company, making the software titles incompatible. With concerns that incompatible new releases would cause confusion, the White Book was formulated in 1993 to ensure compatibility between CD-I extensions, CD-ROXMA and VCD. The karaoke format VCD eventually became the industry-wide standard, and business expanded. The VCD was developed at the same time as the automatic disc changing system. Around 1995, karaoke on demand emerged, with the background images provided on VCD and the music and lyrics distributed by telecommunications (ISDN). This system rapidly grew in use. As networks became faster, and with broadband connections now available, it became commonplace for karaoke systems to be 100% distributed by telecommunications, thus bringing the role of interactive CD media to an end. Fig. 6-4-3 shows a professional VCD karaoke system.

Meanwhile, attempts have long been made in sales promotion to provide information using video. In 1979, American automotive companies led the way in sales promotion with an LD system with improved random access and capable of playing videos. In Japan, search terminals using computers and LDs emerged around 1984 and began to be used as electronic catalogs and various kinds of guides. This system that combined PCs with VDs was known as the interactive video disc (IVD). Later, CD media began to be used in this field. The emergence of CD-I, DVI and other multimedia CDs made it possible to provide information interactively. As an example, in 1989 Fiat, Renault, Peugeot and other automotive companies in Europe started using CD-I to provide vehicle maintenance training software with multilingual functions. This is a good example of meeting the need for interactive multilingual training with a view towards EU integration in 1992. Many countries have made similar efforts for information services such as travel guides.

In Japan, Philips launched the professional tabletop CD-I player in August 1991. The following year, Sony released the IVO-V10 portable CD-I player, while Kyocera brought out the CD-I200. Professional CD-I players had RS-232C ports and specifications capable of connecting with touch panels, card readers, printers, communication networks and other systems. In October 1991, NEC launched the MM-P1, which supported its own NID video, while JVC brought out the multimedia presenter DM-P10, which supported MPEG-1 video. These were widely used in promotion areas. Thus, at a time when notebook PCs were still highly priced and not widely used, interactive multimedia CD players were being widely used for presentations and other areas of business due to their high maneuverability and ease of operation. Fig. 6-4-4 shows the Sony IVO-V10 portable CD-I player.

The CD-Interactive (CD-I) began with the publication of the Green Book CD-I standard, announced at the international CD-ROM convention in 1986. As previously mentioned, the Green Book standard stipulated the details on how to store and manage information (digital content) on CD-ROM, what system to use and how to control (operate) it. With the CD-I operating as an information device using a 16-bit PC, this was the household electronics manufacturers' approach towards a CD-ROM. As a household appliance, it had to be simple to operate without freezing up as PCs did. Accordingly, the standards contained very detailed specifications. Unfortunately, these strict specifications limited the production environment and consequently inhibited the progress of the CD-I, as can be imagined. However, the CD-I managed to achieve a glimpse of the world of multimedia. Many people still hold the CD-I as the forerunner of multimedia. One pioneer who promoted the growth of multimedia made the following assertion. "I think most of what we call multimedia and IT concepts today started with the CD-I. What is different between then and now is that the processing speed has become faster as the CPU has progressed, which has markedly increased storage capacity. Most of the other concepts were achieved in the CD-I, and what we have today is an extension of that." The following statement was also made on multimedia software titles. "Deduction only makes up about 20% of what essentially should be the 'selling point'. The other 80% is the man-machine interface, or interactive design." The dispute over multimedia that came out in the late 1980s was strongly linked to CD media, which was transitioning out of its infancy into a growth period. Today, there are countless excellent software titles lying dormant, overshadowed by the internet and IT. The hope is that this outstanding multimedia content pioneered in the CD-I will eventually be put to use in various areas.

The CD-I was also a challenge against the PC faction's iron grip on the OS by electronics manufacturers (such as Sony, Philips and Matsushita), who predicted the advent of a multimedia era. They valiantly aspired to create a system that operated and functioned without the complexity of a PC system, based on the cutting edge, real-time, multitasking-capable OS-9 used in consumer electronics at the time. Consumer software titles were designed for that purpose, and Philips launched the CD-I505 consumer use player. However, it ultimately lost out to Microsoft and other PC manufacturers (the US government PC strategy), and the business came to an end.

6.4.3 CD-ROM and GPS (Vehicle Navigation Market)

The vehicle navigation market came into bloom with CD media and GPS. GPS stands for "global positioning system" and is the cornerstone technology of vehicle navigation systems. The system receives signals from four or more American military satellites orbiting at 21,000km and then calculates the longitude and latitude of the vehicle by triangulation. The navigation system takes the vehicle location information provided by the GPS, collates it with a digital map and displays it on a monitor to guide the driver to the destination.

Digital map data is essential for vehicle navigation systems, and the CD-ROM provided the optimal low-cost, small-sized, high-capacity recordable and distributable media. Another reason for adopting CD-ROM media vehicle navigation systems was to add value in the automotive market. In other words, there was a need to stimulate demand for vehicle navigation systems that worked with the newly developed car CDs as soon as they came on the market. Development on vehicle navigations systems was driven forward by automotive manufacturers and car audio manufacturers. As such, the digital map data CD-ROM media was also in the format decided on by the automotive manufacturers and car audio manufacturers. This led to compatibility issues between map data formats. To resolve this, Sony, Kenwood and other car audio manufacturers joined with Zenrin and other map data providers to establish a navigation system association. The unified CD-ROM map format (integrated navigation standard) formulated by the association became the industry standard format approved by the majority of members. However, other members, including Toyota, Nissan and Shobunsha, proposed the CD and CRT applied format (CD CRAFT), while Pioneer proposed its own Carrozzeria format and continued to commercialize its own products.

As better gyro sensor performance reduced location discrepancies and as mass production began to lower the price, vehicle navigation systems began to be more widely used. Another factor for this widespread usage was the growth of the “aftermarket” and ongoing standardization of road map data. Combined with this, some CD-ROM road map formats had been released and various platforms were emerging that were compatible with CD media. If a platform with a CD-ROM drive could run vehicle navigation software, it could run a vehicle navigation system using CD-ROM road maps. The main platform manufacturers developed vehicle navigation system functions to add further value.

As an example, the CD-I vehicle navigation system was announced by Fujitsu Ten at the Tokyo Motor Show in August 1989. The system was commercialized by Maspro in October 1993. When the CD-I was standardized in 1986, nobody was working with interactive material. Since CD-I technology characteristically enabled the interactive handling of various data and content on consumer devices, Fujitsu Ten resolved to work towards a next-generation vehicle navigation system using CD-I technology.

For a vehicle navigation computer that would operate CD-ROM, Fujitsu Ten and Fujitsu customized the Fujitsu FM-Towns-compatible Marty into the Car Marty, a specialized vehicle navigation computer. The system went on sale in 1994. There were also car navigation systems on VCD. The Delu:ga Mini portable VCD player by Funai Electric could be used for navigation by means of a special GPS antenna and electronic maps. The platforms grew for CD vehicle navigation, and systems began to offer other applications in addition to road maps. Simply providing location information was the basic feature for navigation systems. Voice guidance was added to this, followed by a range of content with information from sightseeing to fine dining and every kind of store. Based on the idea of added-value map information, the multimedia capabilities of the CD platform made it possible to diversify into a wide range of in-car entertainment, including karaoke and games. As a result, the amount of data inevitably increased. From around 2005, when CD media storage capacity reached its limits, the natural progression was to gradually transition to higher capacity DVD media. Vehicle navigation systems also began connecting with real time information sources (VICS in Japan) for up to date information on delays and traffic restrictions. As it became possible to access traffic information in real time, map information had to be updated to the latest data. CD and DVD media are naturally limited in information updates, as the map information has to be delivered by packaged media. Because of this, cheaper navigation systems were released with built in hard disks. A further advantage with the spread of the internet has been the continuing integration between vehicle navigation and the internet, making it possible to download the latest map information online and check the latest traffic information there. However, this has not spelled the end for the CD-based vehicle navigation systems that breathed life into CD media, and the industry has continued to this day.

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7 Emergence of Recordable CDs

Around 1983, when CD-DA related businesses began to be established, debate arose over how to place the following objectives. One objective was formulating specifications for using CD media, with its then ground-breaking high capacity of 650MB, as a special form of computer-readable memory (CD-ROM). Quantization was 16-bit, an integral multiple of 8-bit, rather than 14-bit, which meant that data was read in 8-bit units. This made it more suitable as a computer memory.

The other objective was research on recordable CD discs. Developers had hopes and dreams pinned on recording their own music and digital content a small disc, as implied by the name CD. Nakajima Heitarō, the lead CD developer, recalled the following. “When we were developing CDs at Sony and finally getting it out to the world, I saw the ‘next dream’ for the CD. The CD system we first developed recorded professional software onto disc and we sold these together with the players. That was how the business was, and we were able to provide users with fairly high quality sound. But I had growing doubt as to whether ‘audio’ simply meant being able to listen to professionally performed music. People who really want to enjoy audio probably also want to try making their own music and want the very best they can get. I thought it would be good if we could make a system that let people put together an album of songs by their favorite artist or their favorite performances, or let people in a music club record their own music on CD just for themselves, just like they would on a normal tape recorder.” (from “Jisedai Ōdio ni Idomu [The Challenge for Next-Generation Audio]” Nakajima Heitarō, Fuun-sha)

Various companies began developing recordable discs from the early 1980s. There were three broad categories of these. The first and most widely used was called direct cutting, which involved perforating a low-melt-point metal film with a laser. The second was called DRAW, which involved illuminating an amorphous recording film (GeTeSb material) with a laser. The areas illuminated with the laser would change from crystal to amorphous. An optical head would detect the difference in reflection due to the change in phase. Although it could not achieve high reflectance, this system was very good for its signal stability. The third was called magneto optical, which involved a combination of heat from a laser and magnetic properties for recording on a ferrimagnetic layer. TeFeCo material was used for the recording film. This could be categorized further into modulation and magnetic modulation. Practical implementation was achieved with magnetic modulation. A constant-intensity laser was used to heat up a prepared recording film (vertically magnetized film) to the point where the direction of magnetism could be altered. The magnetic field was then altered in the direction of the current flowing through the magnetic head. Signal reading was achieved by illuminating the recording surface with a less intense laser. The polarization plane of the reflected light would alter in the direction of magnetization due to the Kerr effect. The altering intensity of the reflected light could then be detected as a signal.

Incidentally, the development of recording film has been mainly achieved by engineers specializing in physics, applied physics, chemistry and chemical engineering. Engineers with expertise in metal film are often employed by electrical and mechanical manufacturers, as these fields are essential to semiconductor manufacturing. Engineers with expertise in amorphous materials and organic dyes are often employed by chemical companies or parts manufacturers. A major determining factor in the development direction taken by different companies in developing recording film was the “philosophy” of the engineers or researchers. Since Sony had researchers with expertise in sputtering and deposition and a long history of magnetic recording technology, the company tended towards magneto-optical recording and developed products from the 5.25″ and 3.5″ MO through to the MiniDisc (MD) using magneto-optical technology. At the same time, chemical/parts manufacturers such as Mitsubishi Chemicals and Taiyo Yuden had experience in organic dyes, and developed the CD-R technology discussed below, which formed a major market. This is a rare case of engineering expertise at different companies successfully forming different markets.

7.1 Organic Dye and CD-R (CD-Recordable)

Various attempts have been made to record digital data onto optical disc. To begin with, the main method used was to use a metal recording layer and perforate pits in this metal layer with a laser. This method had a huge advantage in that it did not require a development process and could be played back immediately after recording. The recording film was generally made of a metal layer with a high melting point and high thermal conductivity. In 1977, Philips achieved the direct read after write (DRAW) system using a recording film made from tellurium (Te) with a low melting point and low thermal conductivity. Significantly, the Philips DRAW system was not only a professional digital data recording system, it was also a forerunner of consumer “low-level laser and optical disc” systems. This predicted the emergence of semiconductor lasers for CDs and set the direction for Philips in its development of recordable optical discs.

With the Philips DRAW system, the recording film shifted from high melting point metal to low melting point metal. Moving on from this, the focus fell on replacing the metal recording film with organic dyes, which is the main system used today. The development of organic dye DRAW discs accompanied an increased demand for optical document filing (although this never became a major market). Basic research had been done by computer manufacturers, media manufacturers and chemical manufacturers before the CD-R was developed. In 1988, Taiyo Yuden completed a means of CD-R media using cyanine organic dye. The only reason media manufacturers and chemical manufacturers were able to dive straight into the CD-R market is that these companies had already been researching the use of organic dyes as a recording film for DRAW discs. There were several historic breakthroughs in CD-R media. For example, instead of the laser perforating the recording layer as it had done previously, the organic dye recording layer used some completely different concepts. These included using organic dye for the recording film, using a gold reflecting layer (initially) and having a non-air sandwich structure (discussed later). With this major technology change, the system then met the 70% signal reflectance requirement for CD-DA compatibility, which had seemed unattainable.

To begin with, CD-R was a “surprise technology” with no official roadmap by Sony or Philips. Before that, the two licensers Sony and Philips had been searching along a completely different path for recordable CDs. Philips, which had come up with the DRAW system, had been working on the CD-WO (brand name CD-PROM, CD Program ROM), a DRAW CD with a metal recording film, designed to be used like a CD-ROM, while Sony had been working on the CD-MO, a magneto-optical writable CD, and its extension product, the MD. The direction of development taken by the two companies were completely at odds, but a more serious issue was that it would be highly technically difficult, perhaps impossible, to make the CD-WO, CD-PROM and CD-MO compatible with the CD. A further issue was that if recordable CDs were CD-compatible, there was a risk of violating the copyrights of artists and record companies (and CD-ROM content holders). Recordable CDs were intended to “fulfill new dreams beyond the CD”, but their development and standardization was by no means straightforward. The creation of the CD-R not only presented a technological challenge, but also a mountain of other issues, including political challenges, rights issues, cultural hurdles and market challenges.

7.1.1 Recordable CD Standardization Process

Sony proposed a recordable CD technology conference. Following the commercialization of the CD, many companies were working on researching, developing and implementing recordable optical discs. This had resulted in rapid improvement in recording bit density and performance and increased the feasibility of practical implementation. In June 1986, Sony and Philips held a meeting on recordable CDs at the Philips headquarters in Eindhoven. The aim of the meeting was to share the companies’ respective development progress, although at this point in time the two companies had very different objectives for developing recordable CDs.

Philips’ main aim was to develop a recorder for Yellow Book standard CD-ROM media. To ensure better ROM drive compatibility, Philips put forward the idea of write-once phase change media (CD-WO). Meanwhile, Sony had two research and development groups within the company. One group, the pro audio group, was developing a recorder for creating CD and CD-ROM proof discs and a recorder for professional archive discs. The other group was developing a magneto-optical technology (CD-MO) recorder as a commercially viable consumer audio disc recorder.

Given the different expectations of the two companies, the items discussed at the first meeting included (1) how to include disc speed and position information on the disc, (2) whether the information should be written on the land or the groove, and (3) what form of media was suitable. However, this was simply an avenue for exchanging ideas and speculating on each other’s intentions by reading their expressions.

The second meeting was held in Tokyo the same year on September 30 and October 1. This time Sony shared its data on the rapidly developing CD-MO and proposed an “embossed” method for recording rotation speed and position information by forming pits on the land, having considered CD-MO media to be unsuited to groove recording. In return, Philips proposed a “wobble” method that detected disc rotation speed by making the track deviate slightly on its course. The wobble method is also known as absolute time in pregroove (ATIP). The track deviates at a maximum amplitude of 60μm and a frequency of 22.05kHz, while the absolute time digital information used in CDs is recorded in FM modulation with 1kHz deviation. On comparing the two discs, the companies agreed that the land and wobble signal were good ideas. The companies also agreed that recordable CDs should be rewritable rather than simply writable. However, Sony favored the strategy of going ahead and commercializing the CD-MO, while Philips favored compatibility with existing CDs for the time being and presented a road map that involved promoting the CD-WO and then releasing rewritable phase change media as the technology developed. In any case, Philips viewed phase change discs as a core technology in recordable CDs.

Phase change discs can be categorized as (1) “L to H” media, in which the reflectance of the recorded area is higher than the unrecorded area, and (2) “H to L” media, in which the reflectance of the recorded area is lower than the unrecorded area. The two companies agreed that (1) L to H was better for groove recording and (2) H to L was better for land recording. Philips was strongly in favor of the CD-WO, which combined L to H media and groove/wobble recording, for greater CD player compatibility. However, the group at Sony who had been developing the CD-MO consumer recorder did not agree with Philips’ proposal. At the time, magneto-optical media was very promising, both in terms of marketability and future prospects, and the CD-MO was a direct descendant of that technology. CD-MO technology had characteristics to rival CDs in recording density, number of overwrites, media lifespan and other factors. A comparison of the wobble and embossed address methods revealed the following.

(1) The wobble method required fewer drive changes, but the groove shape, recording signal and servo needed to be optimized
(2) The embossed method allowed greater distinction between the address area and recorded area, but the drive was more complex and differed from the CD format.

The discussion had thus far had established that the wobble method was the method to use to ensure the legitimacy of the technology as far as the standardization of the CD-WO was concerned. Sony was not agreeable to this, having envisaged a rewritable format.

However, Philips’ intention was for “anyone to be able to play their own music easily on a CD player”, and this was Nakajima’s line of thinking as well. If music was easy to record but not easy to play back on the increasingly widespread CD player, then recordable CDs would be of little value as a recording media format. The “CD of the future” envisaged by Nakajima would be CD compatible. The CD-WO was not yet entirely compatible with existing CDs, but it played a very significant role in demonstrating the idea that “writable CDs should be CD compatible”.

Sony and Philips took very different approaches to recordable CDs, especially the CD-WO, both in terms of technology and direction. This difference began to be bridged as the two companies used their expertise to improve the technology, such as optimizing the shape of the groove and the shape of the writing spot. This led them to a point where they could agree on the wobble method for CD-WO address position. The main specifications were established at a meeting in February 1987. The rest of the year was spent running verification testing on the main specifications. The companies reached a basic agreement in November 1987 and sent out the specifications to licensers the following February. At this stage, Philips branded the CD-WO as the CD-PROM and started on computer-related sales. Sony decided to stop developing the CD-WO due to development resource constraints, although it continued to develop its basic CD-MO technology. The MiniDisc (MD) was launched in 1992 with ATRAC audio compression technology.

7.1.2 Recordable Discs Before CD-R

Around four years before the creation of the CD-R, Yamaha started developing the programmable disc system (PDS), a CD-compatible recording system. In 1984, most recording systems were still analog and digital recording systems were yet to emerge. The key technologies for CD-compatible systems were (1) CD-compatible recording discs, (2) optical pickups for recording, and (3) LSI. Yamaha had recording pickup technology and LSI technology, and approached Fuji Photo Film with the idea of developing the most important technology: CD-compatible discs. Although it was very difficult to achieve both the high reflectance needed for CD compatibility and recording at a linear velocity of 1.2m/s, within about three years it was looking promising. Fundamentally, this was a direct cutting type of write once disc, achieved by directing a laser onto the recording film to form the pits. However, there was no standard for CD-compatible recording standard. To ensure the disc was CD compatible, the developers had to buy up CD-ROM drives and CD players and then spend time running as many compatibility tests as possible. For example, the first generation had a protective sheet on the recording surface to prevent scratches and dust, but this meant that the air pressure characteristics could not be checked. Since the companies lacked the appropriate testing facilities, the developers had to go to the trouble of taking the PDS device up to the 5th Station on Mt Fuji to carry out recording tests.

The main uses for the PDS were for debugging CD-ROM and CD-DA and small quantity electronic publishing of a variety of works. It was even considered for an on-demand map writing service for vehicle navigation. The PDS was first announced as a CD-compatible recording system at the first electronic publishing system exhibition in April 1987. The announcement of the world's first CD-compatible system had a major impact on the CD industry. The first PDS was released in 1988, around six months after it was announced, at a price of ¥2.3 million for the system and ¥7000 per disc. It was made up of a drive unit and an encoder unit. Multiple drive units could be connected to one encoder unit, making it possible to create multiple copies of the same disc at the same time. However, including the PCM recorder, encoder and other peripheral equipment, the system cost more than ¥10 million, which meant it was a recording system more aimed at publishers than everyday users.

The launch of the PDS radically shortened the debugging time in electronic publication and made a significant contribution to the development of the CD-ROM. The CD-ROM discs made at the factory had to be debugged. The cost of debugging could be calculated based on how many improvements were made and how much it cost. With each prototype costing around ¥500,000 and debugging taking an average of five times, this could total up to ¥2.5 million. Each prototype cycle could take from two weeks to two and a half months. By contrast, the PDS system could produce a CD-compatible disc in about an hour at a price of ¥7000. This was revolutionary tool was warmly welcomed by the CD-ROM software industry. The PDS system was used most actively in the development of the CD-IA500 CD-I karaoke player and CD-I karaoke software series, launched by Nikkodo (now BMB) in December 1991. The CD-I karaoke player was capable of continuously playing both music and images. Depending on distribution factors, this revolutionary system could hold up to 50 songs and around 7200 still images on a disc. Around 70 discs were completed for this series in the short space of one year. This would have been impossible to accomplish without the PDS, whose CD compatibility remains a talking point to this day. A studio facility with six PDS writers was actively producing various CD-ROM, VCD and CD-I titles until around 2002. The contribution made by this technology has been immeasurable. The system developed to be more user friendly, with a double speed PDS recorder announced in 1992 and an SCSI compatible interface added, eventually becoming used as a professional audio recorder as well.

The PDS was a CD-compatible system developed before the CD-R. As a specialized business machine, it was never commonplace. However, it was such a valuable optical disc system that it is no overstatement to say that the CD-R only came into being because of it. Fig. 7-1-1 shows the Yamaha programmable disc system (PDS), a piece of industrial heritage.

Fig. 7-1-1 Yamaha Programmable Disc System (PDS)

7.1.3 The Emergence of CD-R

Following the announcement of the basic agreement between Sony and Philips on the CD-WO, Sony received a proposal from electronic device manufacturer Taiyo Yuden to see if the organic dye writable media the company was developing could be used in the CD-WO. The link between Taiyo Yuden and Sony was Nakajima, then president of Aiwa. Taking a gamble on the possibility and prospects of recordable CDs becoming the next CDs, Nakajima approached companies that were prototyping recordable discs to provide CD-compatible resources (from "Jisedai Ōdio ni Idomu [The Challenge for Next-Generation Audio]"). However, the responses from the companies were not what

Nakajima had hoped. There were many negative responses, as companies prototyping recordable discs were unable to get past the 70% reflectance requirement for CD compatibility, or found it an absurd goal to begin with, as light passing through the recording layer was absorbed. Other companies would not associate with newcomers to optical technology. Most companies were not willing to work together, although Taiyo Yuden aimed to achieve CD compatibility

Despite the circumstances, Taiyo Yuden was committed to developing a write-once, read many (WORM) disc using organic dye, and was the only company aiming towards CD compatibility. The company had developed CD-R around 1985 and was focused on developing a CD-compatible writable CD in accordance with Nakajima's wishes. Successful development has always come about as a "product of chance". The product usually goes unseen and unnoticed. At the time, the Aiwa office was located in Ikenohata, Taito, about a five-minute walk away from some of Taiyo Yuden's research facilities in Kuromonchō. Nakajima made good use of any spare moments he had as a busy company president and would often visit the laboratory in Kuromonchō, where he enjoyed talking to the engineers, checking development progress and giving advice where appropriate. The "product of chance" in the close proximity of the two locations led to the success of the project. As mentioned previously, the recordable optical discs at the time used the same direct cutting method as the CD-WO, in which the recording film itself had grooves etched in it by the laser. This method of perforating the recording layer is called the air sandwich method. Under the laser, the recording layer would undergo rupture, dissolving, expanding, contracting and other physical changes that generated air. The disc had to have a special structure designed to let this air escape. It was very difficult to develop this type of disc while maintaining the CD compatibility specifications of 70% or higher reflectance and 1.2mm disc thickness. However, Ishiguro Takashi and Hamada Emiko, the young engineers at Taiyo Yuden, kept experimenting at the laboratory in Kuromonchō in pursuit of "Nakajima's dream".

What made Taiyo Yuden revolutionary was simply breaking through the "common sense barrier". They removed the air space thought to be crucial to recordable optical discs and directly attached an organic dye recording layer to a new gold (later silver alloy) reflective layer. This was a simple idea, but it caused a breakthrough unlike any existing technology. In technical details, the laser directed at the disc raised the temperature in the area it contacted, causing the organic dye to dissolve and disappear. Rather than simply melting, this caused an instant "implosion" that altered the shape of the polycarbonate substrate. In other words, this design not only altered the physical properties of the organic dye, but also the shape of the substrate, and achieved the required CD reflectance of 70% or higher (degree of modulation). This most important point in the principle of CD-R playback, occurred unexpectedly in this "product of chance" by altering the shape of the substrate. The phase contrast (contrast in reflected signal intensity) made possible by this change in shape in turn made it possible to achieve higher reflectance. This was nothing short of a Columbus' egg.

The shape of the written pits affected the sound quality of the signal recorded on the disc. Usually, the optical clarity of the rising and falling of the pits affects the S/N and jitter of the signal being read. Since recording was done by a small semiconductor laser, lack of edge clarity could be a challenge. Using an organic dye with a high refractive index worked well to make the pit edges optically appear to rise and fall more sharply than they actually did. While the signal recorded on CD-R was digital, it relied on a high number of analog factors, including the characteristics and thickness of the organic dye and the accuracy of the pregroove on the polycarbonate substrate. This method of disc recording was very good for mass production. As facilities developed, the price of media rapidly dropped from \$100 in 1990 to around \$1 in 2000. Production volumes rose rapidly, and the industry grew. The write-once (WO) function was more effective the cheaper the disc cost. Unlike paper, there was no need to erase and reuse. Because of this, and because of the short recording time, these discs became the main form of recordable media.

At Taiyo Yuden, Ishiguro and Hamada were awarded the National Commendation for Invention: Science and Technology Prize (2000, Japan Institute of Invention and Innovation) and the Nakajima Heitarō Prize (CDs21 Solutions) for their commendable achievements. Hamada was also awarded the Optics and Quantum Electronics Achievement Award (Takuma Award) in 2002 in recognition of contribution to applied physics. Meanwhile, the invention of the CD-R was registered under patent numbers 2134979, 2137118 and 2135363. Fig. 7-1-2 shows a piece of technology history: the world's first CD-R disc by Taiyo Yuden (1988).

7.1.4 CD-R Structure and Recording/Playback Principle

Fig. 7-1-3 shows the CD-R structure proposed by Taiyo Yuden compared to the CD.

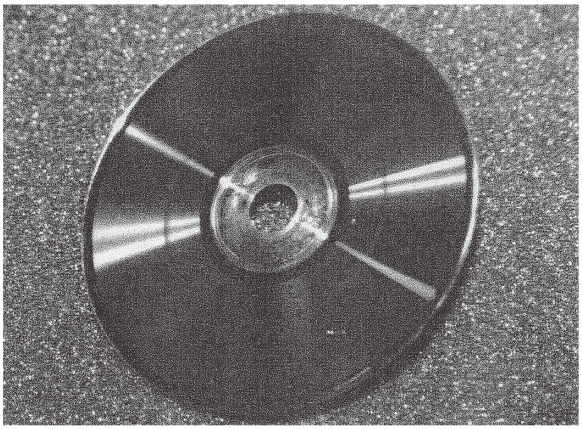

Fig. 7-1-2 The World's First CD-R Disc (1988)

The main difference between the pressed discs is the green, dark green or blue color of the CD-R recording/playback area. This is very different from the shining silver of pressed CD-DA or CD-ROM discs. Simply put, the colored recording surface physically changes as the laser turns on and off, leaving a mark (the material burned off). The on and off is recorded on the disc as in digital data 0 and 1.

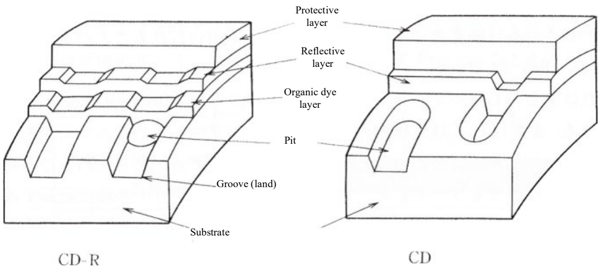

Fig. 7-1-3 CD and CD-R Disc Structure

The CD-R structure is made up of the follow four layers.

(1) Polycarbonate substrate
(2) Organic dye layer
(3) Reflective layer
(4) Overcoat (protective layer)

Depending on the disc, an additional protective layer may be added to increase the commercial appeal of the disc. Although the organic dye in the CD-R recording layer has been given a lot of attention, it is the molding precision of the 1.2mm polycarbonate substrate that significantly affects the overall characteristics of the CD-R. The transparent substrate is etched with a very fine micro-order guide groove known as the pregroove, which subtly deviates with FM modulation. The laser follows this groove while recording. Fig. 7-1-4 shows the CD-R layout, while Fig. 7-1-5 shows a CD-R image. The disc layout is designed to optimize recording, with the inner lead-in area containing a power calibration area (PCA) and program memory area (PMA). These are used to calibrate the recording data. The CD-R image shows the groove prior to recording and the pits formed in the groove after recording.

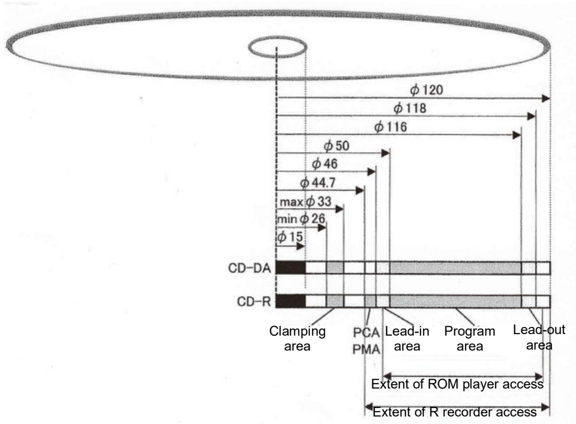

Fig. 7-1-4 CD-DA/CD-R Disc Layout

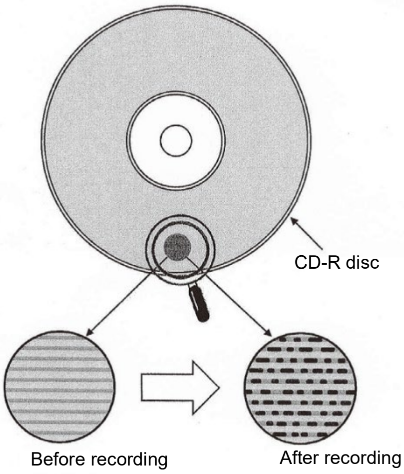

Fig. 7-1-5 CD-R Image

The shape and precision of the pregroove significantly affects the performance of the CD-R. The CD-R also has a means of collecting the dye in the pregroove and using it in the recording. The organic dye characteristic to the CD-R is coated onto the polycarbonate substrate using a spin coating method (coating formed by rotation). The spin coated layer is not uniformly thick, as it differs inside and outside the groove, with the dye intentionally collected in the groove. The difference in land and groove coating thickness is utilized to increase the reflectance to CD level. This difference significantly affects the recording properties. For example, the thinner amount of coating outside the pregroove makes that area less sensitive to recording, thereby serving as a boundary for the pits and improving the recording quality. In that sense, the recording properties of the CD-R are not simply determined by the thickness of the coating and the shape of the pregroove, but also a wide range of very analog factors, including the physical properties of the organic dye used, the characteristics of the solvent, process control and spin coating specifications. High quality CD-R production required a lot of experience and expertise. Japanese companies led the development of this market. Fig. 7-1-6 shows the CD-R manufacturing process. Everything from molding the substrate to applying the organic dye and forming the reflective layer requires a lot of expertise. This manufacturing process was only achieved by building up technology. Mass production is a matter of process industry. As production costs decreased, the expertise was exported and transferred overseas along with the machinery as production bases were gradually shifted offshore.

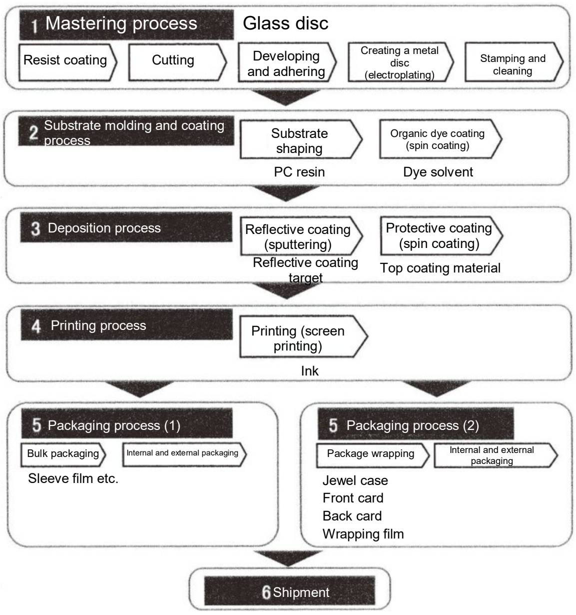

Fig. 7-1-6 CD-R Disc Manufacturing Process

One of the most important elements in the CD-R was the reflective layer. In the early 1990s, when CD-R production was still low, most discs had reflective layers of thin gold film. To begin with, gold was chosen because it worked well for the refractive index of the organic dye, the reflectance and the recording wavelength. Most discs today have reflective layers of thin silver alloy film, mainly because it lowered the cost of mass production. Another reason was to improve peeling. If tape were applied to the protective coating on early CD-R media and then peeled off again, the gold layer would peel off with it. This poor peeling property made the media difficult to handle. However, using silver alloy significantly improved the disc's resistance to peeling, thereby raising the credibility of the media product overall.

Incidentally, a project was carried out make good use of the poor peeling properties to retrieve the expensive gold film. Inspired by the gold collected from the sandals of gold miners in Sado, chemical engineers eagerly set about experimenting by trial and error. At the end of 1996, just when a proper retrieval method was about to get under way, there were indications that mass production was going to increase and that the price of CD-R discs was going to drop. As a result, in 1997, the material used in the discs underwent careful review and the expensive gold reflective layer was replaced by a silver alloy. Although this dropped the price to less than one third, from around ¥1000 per disc to around ¥300 per disc, it also turned the situation into a "phantom gold gaining tale". The several hundred grams of gold collected in the experiments were cast into a golden name seal for Nakajima Heitarō, which is still used today, carefully stored away. This situation provided inspiration for other opportunities to reuse materials. A system was later developed for retrieving the valuable polycarbonate substrate material. However, there were instances of collected substrates being sold off to China and other places for a high price, leaving the idea of retrieval at an impasse. The information written on CD-R also needed to be disposed safely, and products emerged like the "Mr. Crunchy" shredder. Fig. 7-1-7 shows the gold seal of Nakajima Heitarō, a reminder of the gold collecting anecdote.

Seal impression

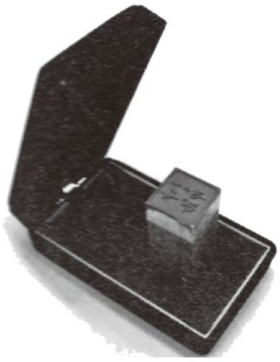

Fig. 7-1-7 Gold Seal of Nakajima Heitarō

The organic dye used in the CD-R had to have an optical constant that maximized the reflectance in the wavelength range corresponding to the substrate with a refractive index of 1.59 and the 780nm laser. It also had to be compatible with solvents. The world's first CD-R, made by Taiyo Yuden, used an organic substance called cyanine. If cyanine had been the only organic dye, there may have been more peaceful competition in the CD-R industry (the Orange Book Part II Ver 1.1 provides specifications for cyanine dye). Unlike inorganic substances, it is possible to control the molecular structure of organic substances to alter their properties little by little. Unwilling to be bound by patents, media manufacturers and chemical manufacturers developed their own organic dye products for CD-R using their own products that were easier to work with. These included the organic dyes phthalocyanine and azo. Fig. 7-1-8 shows the molecular structure of organic dyes used in CD-R.

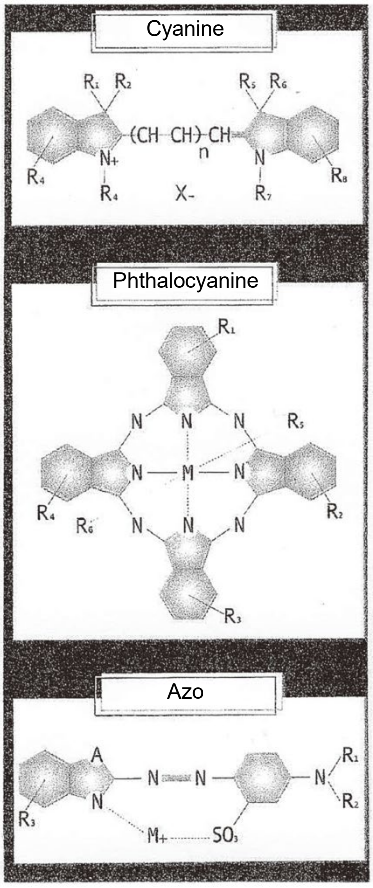

Fig. 7-1-8 Molecular Structure of CD-R Organic Dyes (Cyanine, Phthalocyanine and Azo)

Although CD-R properties are determined by more than just the organic dye, there are subtle differences between these three types of dye (cyanine, phthalocyanine and azo) in terms of the speed of their response to light. There are slight differences between each dye in the shape of the mark that appears on the disc when exposed to the laser and in the rise and fall of the edges. These become apparent in the effect they have on the write speed. If the mark is not recorded properly with the target position, shape and depth, the signal becomes corrupted, with increased jitter and deviation affecting the error rate. Jitter refers to any variation in the length of the recorded mark relative to the theoretical position value. Deviation refers to a bias in distribution. These values are stipulated in the Red Book as basic physical specifications for the playback signal.

The optical pickups in the CD-R drives varied between companies. Media manufacturers also used different organic dyes. These differences came to light when issues arose with the spot size shape and the write strategy (pulse pattern for signal writing) being incomplete. This became a major practical problem when the different factors began to overlap, and the media would not record or play. A disastrous situation arose where there was no compatibility, despite the fact that the CD-R was essentially supposed to be CD compatible. To resolve this dire situation, drive manufacturers and media manufacturers developed the Orange Study Group to examine the technical specifications for CD-R and created the Orange Forum (a voluntary association named after the common name of the standard, the Orange Book, with participants from 50 related companies, chaired by Ihashi Takao of Sony). The weighty matter of CD-R compatibility was left to these groups to resolve.

7.1.5 Disc Identification Method

The Orange Study Group had been in existence for around two years before the Orange Forum was established. The study group was a place for likeminded drive and media manufacturers to share ideas. Many CD-R engineers were highly independent and struggled with resistance in their own companies but found support in this rare group. If a CD-R engineer proposed something new, there would be strongly voiced opinions from the company. “Don’t we already have write-once media?” “Have you resolved the copyright issue?” “Let’s just stop developing the CD-R.” “Commercialization is unthinkable!” No progress was being made at all. On top of that, the issue with compatibility only served to increase the “I told you so” reaction.

Sony had been developing the CD-MO, and even at Sony there was slander, with comments ranging from “CD-R traitor” to “Are you trying to ruin software manufacturers?” One can only imagine it was the same or worse for engineers at other companies. However, the foresight and solidarity of the members of the Orange Forum were powerful against company resistance, and they were determined to resolve the compatibility issue and turn it into a business. The significant growth of the CD-R business was actually triggered by the foresight and rebellious spirit ignited in the engineers as a result of company resistance. They formed strong bonds outside of their companies and created a foothold for business promotion. Although there were other favorable conditions, such as an expectant market, it would have been a very rare case in the history of Japanese industry if this alone had driven the CD-R business in the face of significant resistance. Incidentally, the members at the time got on very well and still hold CD-R media meetings to this day. There were "bullied members" from Sony, Matsushita, Pioneer, TDK, Ricoh, Taiyo Yuden, Mitsubishi Chemical, Mitsui Chemicals, JVC, Philips and Mitsubishi Electric.

The aims for founding the Orange Forum were to facilitate interaction and information exchange between CD-R manufacturers, to resolve the disc and drive compatibility issues and to benefit end users. Accordingly, it was the duty and one of the main research topics of the Orange Forum to eliminate all theoretical, physical and logical compatibility issues. Specific activities included formulating a standard disc identification method, which then appeared in the products of each participating company.

The disc identification method defines the so-called "identity" of the disc. The identity is imprinted on the disc beforehand. The drive reads the identity to ascertain the characteristics of the disc it is trying to write to. The dye characteristics are particularly important. If the drive were to write to a phthalocyanine disc in a way that was optimized for a cyanine disc, the result would be of poor quality and playback would not be compatible. The proposal to read the identity of the disc and record on it using the optimum method was revolutionary. Fig. 7-1-9 shows the effectiveness of using disc ID. This confirms a wider and more stable error rate in relation to recording power. Table 7-1-1 shows a sample disc ID code list. The table also shows where each company's information was stored. For example, start time of lead-in: 97:23:00 (9a:bc:de), where 9a:dc:d represents the media manufacturer and e represents the organic dye material.

Table 7-1-1　Disk ID Code List

Prohibited to use　Tentative Code　Permanent Code

	00f–09f	10f–19f	20f–29f	30f–39f	40f–49f	50f–59f	60f–69f
97m15s	Company A	Company B	Company C		Company D		
97m16s			Company E		Company F		
97m17s	Company G			Company H			
97m18s		Company J		Company K			Company L
97m19s							

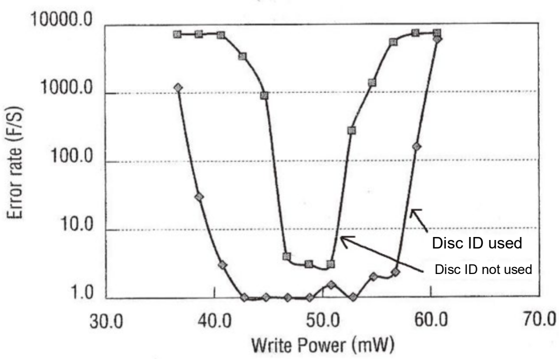

Fig. 7-1-9 Effect of Using Disc ID

The idea of incorporating a disc identification method to enable the drive to recognize the media was not limited to disc and drive compatibility issues. It could also be used to determine whether the write speed should 2×, 4× or 8× (or higher) and to ensure optimal recording in cases where there was a major change in the disc recording properties through an alteration in the dye. This system achieved the idea of "being able to adapt flexibly to technological advances" and was a unique plan devised for the CD-R, as there were multiple types of organic dyes and multiple types of optical heads used for recording.

Following this, the drive actually determined the power of the laser directed at the disc (OPC, PMA) using a technology called optimum power control (OPC). It would then write the actual signal. There were two methods of do this. One was to apply the initial OPC value to the entire recording area. The other was called "running OPC" and involved using a low-powered laser to detect the state of the recording surface (changes in reflectance due to foreign matter or uneven dye coating) and then adjusting the laser power as needed. The running OPC method is the main method used today. It is now capable of taking in the individual characteristics of the media and maximizing those characteristics when writing to the disc.

In 1995, there were seven manufacturers registered for Disc ID. This number rose rapidly from around 1997, and by 2003 there were around 73. Today, most media manufacturers around the world are registered for Disc ID, and all drive manufacturers use Disc ID. In 1998, extended specifications were formulated to use outer circumference address information to distinguish between disc types. This made it possible to increase the number of possible media manufacturer Disc IDs from ten to unlimited. Disc ID became vital to ensuring CD-R recording and playback compatibility and has been adopted by drive manufacturers and media manufacturers around the world, allowing users to use CD-R with confidence.

Disc ID came into being at the Orange Forum and was later managed by CDs21 Solutions (the Orange Forum successor organization). Very unfortunately, the Disc ID method was not patented. There are still regrets to this day that no patent was filed for this rare invention that ensures perfect compatibility by using a disc ID to record recording film properties and other necessary information in advance and then optimizing the recording based on this information. At the time, it was a proposal by the Orange Forum and invented by everyone together. There was no inventor that could be identified, as the Orange Forum was an unincorporated organization and could not own patent rights. Since this valuable technology resolved the issue of CD-R compatibility, the anticipation was that many companies would want to use it. Everyone involved had this common understanding, and so there was hesitation over applying for a patent. Considering that the technology was used in around 10 billion discs per year in CD-R alone, as well as identical technology used to ensure compatibility in DVD-R and Blu-ray-R, the revenue from royalties would have been an enormous sum. Looking back, the reason why the group did not push for a patent application may have been largely due to the personality of the chair at the time (Ihashi). In any case, it remains a matter of regret, simply because this was a valuable piece of technology in the history of the optical disc industry.

7.1.6 Policies to Ensure Compatibility

Combined initiatives between drive manufacturers and media manufacturers and improvements in related technology were successfully eliminating the major challenge on the market, disc and drive compatibility. Nevertheless, the CD-R was growing at a tremendous rate, and the number of disc and drive manufacturers was also growing in full force. Spurred on by this growth, drive write speed was also making rapid advances, from 2× to 4× and 16×. With the CD-R advancing so rapidly, there were many cases in which the combinations of disc and drive were simply not compatible. To prevent this inconvenient situation from occurring as much as possible, the CD-R drive could be made compatible with firmware version upgrades for the inbuilt PROM. CD-R drive firmware was the control software responsible for the actual recording function and it received instructions from a computer. By upgrading the drive version, the disc identification method and write strategy could be refreshed with the latest information. This method was the same as that used for PC uploaded programs. The firmware upgrade was downloaded from the drive manufacturer's website and installed on the CD-R drive. Thus, various technologies started out with improving compatibility and resulted in providing end users with the best possible recording environment, based around the disc identification method. This was well on the way to resolving the major issue with CD-R compatibility.

However, end users' expectations of increased write speed presented a new compatibility challenge. A stable write speed required very advanced media and drive technology. The common opinion was that there were two technologies to be improved to increase CD-R speed: media sensitivity and mechanical precision. Increasing media sensitivity by simply increasing its responsiveness to light would make the recorded pit marks unstable. If the sensitivity were too high, the recording film would become too fragile. Similarly, increasing the speed by simply writing the signal faster than before would cause interference between the written area and the area being written. It was exponentially more difficult to manage the heat of the media. If the recorded pits were to deform, waveform distortion would occur. Depending on the level of distortion, recording would not even be possible. CD-R write speeds increased rapidly from 8× to 16× and 32×, but this did not necessarily mean that the drive responded accurately. Various self-regulating technologies were developed for different drives, such as recording at a reduced speed. Recording the signal at the optimal speed ensured compatibility with efforts from both sides, drive and media.

7.1.7 Practical CD-R Examples

The first dream for the CD-R when the idea was first conceived was to enable anyone to make an audio CD easily. With its high audio quality, easy operation (ease of random access) and durability, the CD-R is best suited to recording music. For music fans, the "CD had status", although to true music lovers, whether professional or amateur, skilled or novice, the "CD-R had status". It was also the friendliest format in that it allowed them to record music for themselves. The following are a few typical examples of practical CD-R usage.

First, there were widespread uses that made the CD-R into the most used audio CD of all. One example was that since people could easily make their own recordings, it was widely used to make recordings of piano recitals and other music performances. In many cases, music students were made to record their actual performance or voice recital and submit it on CD-R instead of submitting a report. Another common example is the karaoke booth. The karaoke booth business began with people singing but is now incorporating means of recording as well. It is now common for people to record their own singing and distribute the recording on CD-R among their friends, either to showcase their skill or to test their progress. With the karaoke industry having already shifted its business target to include meeting rooms for business and private use rooms, it has become a practice grounds for music students. The performance or practice is recorded on CD-R and used for distribution or submission. In this way, the CD-R has gained a position as an irreplaceable recording medium for music lovers.

Second, the CD-R drew attention in relation to digital photos and other high capacity media. With digital cameras growing more widespread in use in the 1990s, the high capacity CD-R began to be used for storing the captured data. Many people were of the opinion that the CD-R with its capacity of just under 1GB was well suited for usability. Digital photographs have now become far higher in resolution, and the less than 1GB recording capacity of the CD-R is no longer enough to store the recorded data. People are transitioning to DVD-R and Blu-ray-R, although there are many everyday users still using CD-R. Some digital photography professionals are "visual creators" who go beyond simply storing recorded data to create digital compositions with special effects. These experts are acutely aware of the need for technology to build databases that can effectively select and sort every shot photographed. To that end, some professionals manage their own databases using 500-disc CD-R/CD-ROM changers. Since the data stored is the original image, the CD-R/CD-ROM is optimal, as it is not susceptible to virus or data loss. The CD-R in particular has been lauded as being an "excellent changeable media that can be played anywhere". CD-RW, DVD-R and other types of discs are also used as needed, although there is a lot of confidence in the CD-R for product delivery, as it cannot be tampered with by third parties.

Third, the CD-R is used in professional fields, especially for medical applications. It has become so commonplace that now when a patient asks a doctor for photographic data, the data is given on a CD-R. A pioneer in this field was the Cardiovascular Institute, well known nationally and internationally as an institution that specializes in cardiovascular diseases. In 1998, the affiliated hospital set up a Siemens computer network server system based on DICOM Ver 3.0 (the standard format for digital imaging in the medical field) and a cardiac diagnosis system (automated cardiac output measurement, ACOM) using CD-R. Digital imaging has progressed to the point where it can be used for medical applications in place of the conventional film (X-ray, etc.). The captured data is sent to the server, where it is stored in a 1.7TB MO jukebox and can be copied to CD-R as needed. The main advantage of this system is that any data written in DICOM format onto CD-R, which is standardized and inexpensive, can be read by any computer in the world. This became the standard system, and similar digital systems began to be introduced into medical institutions around Japan. It would not be possible to share medical data without the CD-R. The secure data storage and international playback compatibility makes the CD-R very valuable in the medical community. Later, as the medical industry became increasingly more digital, almost all medical institutions came to have digital databases, with CD-R used as distributable media.

Uses in other professional fields include the CD-R and CD-ROM system created by the Japan Patent Information Organization (JAPIO) in 1996. This fast and reliable service is used to provide customers with their needed information extracted from vast amounts of patent data. Fig. 7-1-10 shows a set of 500-disc CD-R/CD-ROM changers used for this service. One unit such as these would be used by photographers for small scale applications.

Finally, the CD-R can be used as a distribution media anywhere, networked society or not. Fig. 7-1-11 shows a photograph from a press report during the Iran-Iraq War at the beginning of the 21st century.

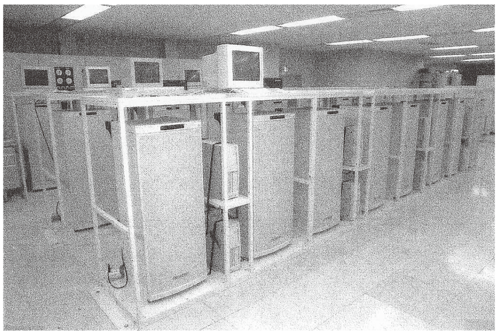

Fig. 7-1-10 Japan Patent Information Organization CD-R/CD-ROM Changers

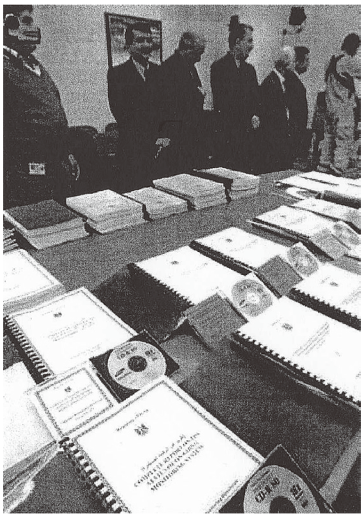

Fig. 7-1-11 CD-Rs on the Iran-Iraq War

Vast amount of resources (data) were stored and sent on CD-R and used to clarify situations. The article commented that since this was highly classified data, the safest delivery method was to take it by hand. Storing vast amounts of newspaper information on small, light CD-R meant there was no danger of it being falsified or erased along the way, making it possible to safely exchange confidential information. This comment confirmed again the advantage of the CD-R. In the present day, with society fully networked, the CD-R is used for storing and distributing highly confidential data that must not be overwritten, serving as a security measure for the recorded data. For this reason, the CD-R continues to be used and goes on fulfilling its purpose.

7.2 The Emergence of CD-RW

CD-RW stands for "compact disc rewritable" and is the first rewritable member of the CD family. CD-RW is often grouped together with CD-R as CD-R/RW. On CD-R, a laser makes physical changes in the organic dye coated on the disc surface. These changes are recorded as digital information. A laser is also used in the CD-RW phase change method, changing the recording material from crystalline to amorphous. Rewriting is possible because the recording layer can undergo subsequent phase changes. Although both CD-R and CD-RW are easy to use technology, there are parts to them that are completely different. As such, this chapter discusses CD-RW technology and its distinguishing characteristics.

7.2.1 CD-RW Phase Change Recording Principle

The rewritable function of CD-RW happens as the name "phase change" implies. The signal is recorded using changes in phase. Incidentally, "phase" means "an area in a physical system that has uniform and clear boundaries and is distinct from other areas". Also, "parts of a physical system that have exactly the same physical or chemical properties are in the same phase". Specifically, the signal is recorded on CD-RW using a physical transition between crystalline and amorphous structures. Amorphous means a physical state that has no crystalline structure. Some alloys have atoms that remain in a liquid state despite being solid. Phase change recording uses a laser to induce physical changes between crystalline and amorphous in this type of alloy. During playback, a laser is used to read the difference in reflectance between the two phases. Specific phase change materials include quaternary alloys such as silver-indium-antimony-tellurium (Ag-In-Sb-Te). Fig. 7-2-1 shows the CD-RW disc structure. The basic structure is similar to the CD-R in that the substrate has a pregroove and the recording layer is sandwiched between upper and lower protective layers. A protective UV coating is applied on top.

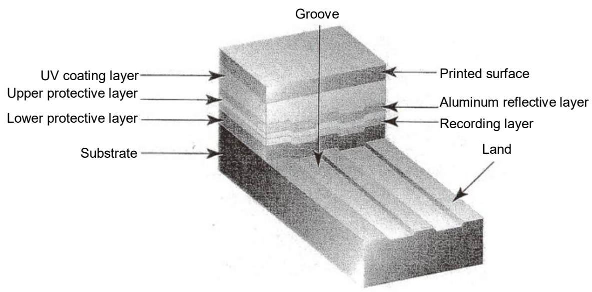

Fig. 7-2-1 CR-RW Disc Structure

The phase change recording principle was proposed by Stanford Ovshinsky in 1968. Ovshinsky identified the difference in optical properties, such as refractive index, and electrical properties, such as conductivity of the respective states of chalcogenide materials. The first practical implementation of this principle was research by Yamashita et al. of Matsushita Electric, using a tellurium oxide material. Licensing the Ovshinsky patent was expensive, and many companies gave up investigating this technology, although Matsushita Electric, Ricoh and Hitachi continued developing. This led to the CD-RW and phase-change disc (PD, a special computer disc developed by Matsushita) and paved the way for the next generation of DVD-RW and RAM.

The phase changing material begins as a crystalline structure. During recording, a laser traces the pregroove and exposes the disc to the EFM modulated signal. Fig. 7-2-2 shows the phase change recording principle. The CD-RW recording principle can also be explained using a temperature profile. The crystal phase is rapidly heated to melting point to produce an amorphous state with irregular atoms. If the amorphous state is rapidly cooled, the atoms do not have the chance to reorganize, producing a frozen amorphous state. This is the amorphous phase recording mechanism. If the material is heated to a mid-range temperature rather than to melting point and then cooled relatively slowly, the atoms are given time to return to form into their original crystal phase again. Thus, phase change recording essentially involves highly controlled heating and cooling to produce amorphous phases. This results in highly reflective crystalline structures and less reflective amorphous structures. The difference between these structures can be detected as a signal. Despite the crystal phases being highly reflective, the reflectance of the CD-RW is only around 10-15%, nowhere near the level of reflectance of the CD and CD-R (65% or higher) in the 780nm wavelength range. This requires some form of countermeasures on the drive side. When the CD-RW was introduced, there was a proposal for a multi-read standard, mentioned later.

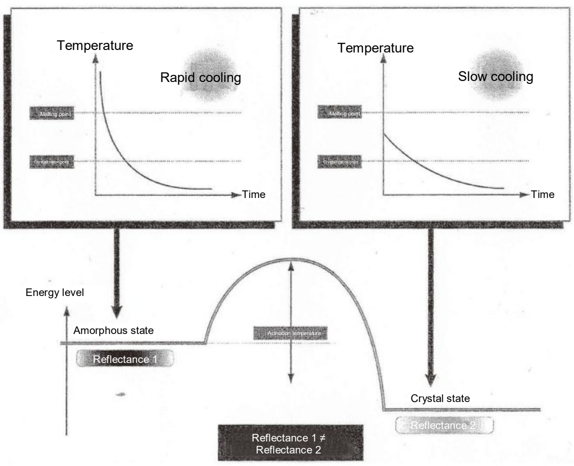

Fig. 7-2-2 Phase Change Recording Principle

Erasing data recorded on CD-RW involves a technology called the one-beam direct overwrite method. Phase changing material has a temperature that is not enough for melting, but enough for crystallization (around 200°C for the erase power level). The material is heated to this level using a lower intensity laser and cooled gradually, allowing the amorphous phases to return to being crystalline phases, able to be recorded again.

7.2.2 CD-RW Recording Format (Write Strategy)

The write strategy refers to how the power of the laser is controlled during recording. The recording principle varies according to the properties of the disc. There are different optimum control methods for CD-R and for CD-RW. The EFM signal recorded on the disc is made up of a physical length from 3T to 11T and a space, as mentioned previously. Essentially, the switching off and on of the laser should correspond to the EFM signal. However, the CD-RW requires subtle, precise control over heating and cooling and will not record properly if the laser simply matches the EFM signal without some adaptation. If it were exposed to the raw EFM signal, the areas that require rapid cooling would undergo slow cooling, which would distort the shape and edges of the pit marks, leading to a deterioration in jitter and deviation. The signal would be close to what it should be, but not close enough. The CD-RW is unique in that the accuracy of the signal is determined by the positioning of the edge even more so than by the sharpness of the pit and land edges. CD-RW recording requires the edges to rise steeply and the centers to be written with as little unevenness as possible.

Fig. 7-2-3 shows an example CD-RW write strategy (laser power control). This is the CD-RW multi-pulse recording method. For example, when recording a 4T EFM signal, the laser power first reaches melting point, then rapidly cools for 1T, followed by “0.5T→rapid cooling→0.5T”. This is repeated three times for 4T, and twice for 3T. The “nT” signal records with a pulse of “nT-1”. The initial 1T interval is the time required for the recording material to reach melting point, since it has cooled. As soon as the crystalline phase becomes amorphous, the laser turns off to rapidly cool the material and freeze it in the amorphous state. This precise laser power control is necessary for CD-RW recording.

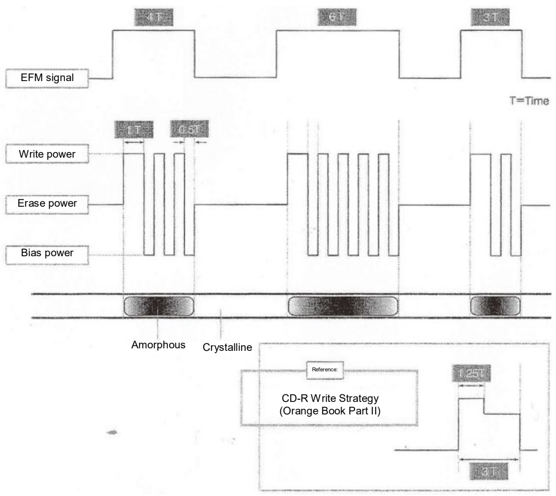

Fig. 7-2-3 CD-RW Write Strategy

The CD-R has a laser power during recording of 4-11mW (Orange Book Part II), while CD-RW has 8-14mW (Orange Book Part III). According to the standard, the CD-RW requires a higher powered laser, although CD-R recording at 8× can require laser power of over 20mW (around 18mW for highly sensitive media at 8×). The CD-RW can record at around 14mW, and it is better for a system to be able to write data at lower power. Using a high power laser increases the cost of the drive, making the system less consumer-oriented. There are also technical concerns, such as reducing the physical change cycle (cyclability) of the recording layer, making it less durable. CD systems are fated to be low laser power systems. Fig. 7-2-4 shows an electron photomicrograph of the signal recorded on a CD-RW disc (supplied by Ricoh).

CD-RW applications include substituting large capacity floppy disks and audio cassettes, CD authoring proof discs and backup/storage. It is not a substitute for a hard disk. As such, recording layer cyclability of up to around 1000 times is considered to be sufficient. The idea of a “substitute sector” was introduced to the CD-RW. If a sector on the disc was unsuitable for recording, the CD-RW file system (UDF) would automatically allocate a new sector in place of the unsuitable sector. This system was not difficult to implement.

However, the challenge with CD-RW is that phase change recording is in principle not compatible with ultrafast recording, which makes writing to CD-RW slower than writing to CD-R.

7.2.3 Playback Compatibility with Multi-Read

Optical disc playback essentially involves a laser reading a signal from differences in reflectance. If a designated reflectance can be achieved and the physical and logical formats are the same, then playback compatibility is guaranteed. However, there is a major difference in reflectance between CD-R and CD-RW. Where CD-R maintains reflectance of around 65% or higher, CD-RW only maintains reflectance of around 15-20%. The CD format based on the Red Book stipulates reflectance of around 65% or higher to ensure playback compatibility. Without resolving this issue, the CD-RW would become an unrelated media, despite recording the identical signal to the CD. Current technology is not capable of raising the reflectance of CD-RW to 65% or higher. Using a more powerful laser to increase the reflectance would damage the recording layer. One method devised has been to increase the amp gain (sensitivity) of the drive. However, simply increasing the gain at will also increases the noise, which lowers the S/N ratio. Meticulous amp design has made it possible for the system to adequately maintain the S/N ratio of the circuits. This drive-side method is called “multi-read” and has been relatively easy to commercialize, introduced on the market as the “multi-read CD-ROM drive”. In fact, many CD-ROM drives meet the multi-read standard, and almost all drives that are 16× or higher are “multi-read CD-ROM drives”.

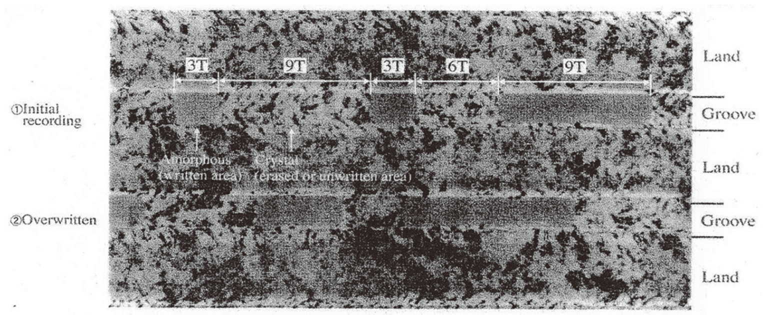

Fig. 7-2-4 Signal Recorded on CD-RW Disc

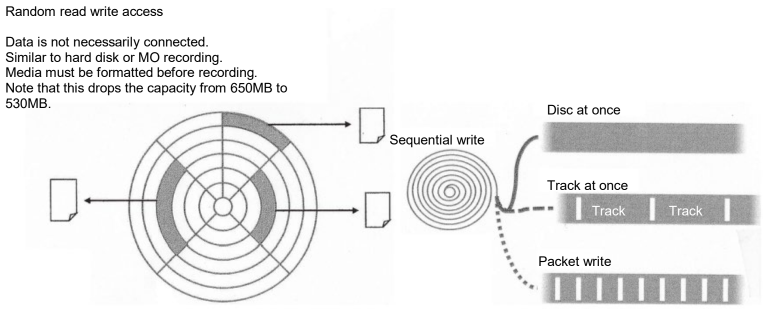

Fig. 7-2-5 CD-R Recording Method

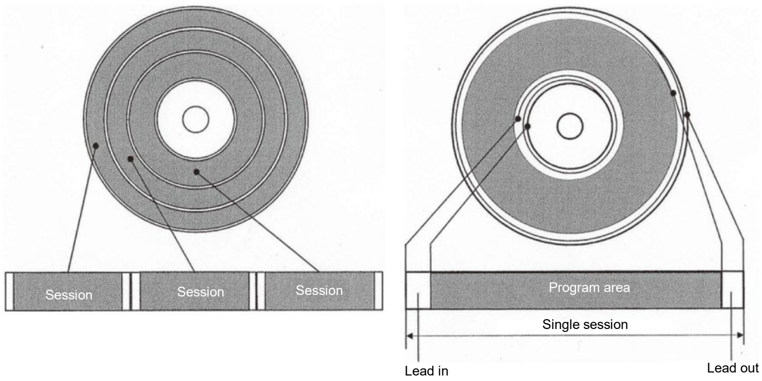

Fig. 7-2-6 Single Session and Multi Session

The CD-RW emerged as a commercial product in 1997 and a playback environment for it was rapidly established. It is estimated that by early 2000, around 70% of newly purchased household PCs in Japan had multi-read CD-ROM drives. There is no data available on how many household CD-DA players supported multi-read, although consumer audio CD-R/RW recorders could play CD-DA data recorded on a PC CD-RW drive. DVD drives played a role in multi-read compatibility, with some DVD players and DVD-ROM drives also capable of playing CD-RW discs. In that sense, the CD-RW had an important position as the bridge between CD and DVD.

7.2.4 CD-RW File Format

A technology unique to CD-RW is the method of writing to disc. This is compatible with hard disk random read write access (although not strictly the same). Since the CD is fundamentally an audio disc, it has a "sequential write" recording method. CD-R follows the CD, with recording spiraling from the inner diameter of the disc to the outer diameter. As follows, there are three sequential write methods for CD-R, all of which are incapable of allowing only a portion of the written data to be altered.

(1) Disc at once method, which writes the entire disc's worth of data to disc all at once and does not allow so-called postscripts to be added afterwards
(2) Track at once method, which writes in track units and allows additional writing
(3) Packet write method, which allows writing in packet units (such as bars of music)

Fig. 7-2-5 illustrates the three methods. Run in and run out refer to where the data "joins". These are guard areas designed to serve as buffers for areas where error protection is not possible. The (2) track at once (TAO) method differs significantly from the (1) disc at once (DAO) method in that it records the data first and then writes the lead in and lead out areas. This is closely linked to the "multi session" recording method. A session refers to a unit combining lead in, user data and lead out. Multi session means several such sessions on a disc. The recording method used for creating a multi session disc is TAO. Fig. 7-2-6 shows the concepts of single session and multi session. The first system to use the multi session concept was the Photo CD by American company Kodak. The Photo CD is widely known as the Orange Book Part II multi session compatible format.

It is also possible to write to CD-RW using these CD-R recording methods (1) to (3). The distinguishing feature of the CD-RW, rewriting to disc, is best achieved using rewritable packet units. This requires a file system similar to a hard disk or magneto-optical disc (MO). To make maximum use of the rewriteable characteristics of the CD-RW, intelligent data management is used, whereby if a certain block is unreadable or unwritable for some reason, that block is disabled and the data is written to another block. The ability to write and erase the data in each block is called "random read write". The file system used in CD-RW that makes this random read write possible is the universal disc format (UDF) standardized by the Optical Storage Technology Association (OSTA) in the United States.

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8 Establishing ISO Standards for Estimating the Life Expectancy of Optical Media

Optical discs such as CD-R/DVD-R are a means of storing various types of text data, still images from digital cameras and videos from digital television. As such, demand for this media has grown significantly. However, there were concerns in Japan and overseas over the reliability of this media, due to the fact that there were many short-lived media products on the market that did not meet quality standards, as well as the fact that there were no specific standards on product lifespan.

Recording media for long term digital archive data storage must have a long lifespan, high capacity, fast data transfer rate and low price. Optical discs showed a lot of promise, as they had high capacity and a low price, and recording and playback devices for them were available worldwide. An international standard was established to specify a quality evaluation method for optical discs so that they could be promoted as a recording media for long term storage. The common goal of everyone in the industry was to ensure that optical discs evaluated by that international standard were good for long term storage.

Initiatives for optical disc reliability began in Japan in the early 1990s, when the Ministry of International Trade and Industry (now Ministry of Economy, Trade and Industry) established a research group to standardize a system for gauging optical disc media. Later, prominent companies also started engaging in research towards standardization. In the United States, the National Institute of Standards and Technology (NIST) and other organizations began researching the use of optical discs with the aim of storing images electronically. This resulted in the formulation of "Compact disc - Method for estimating the life expectancy of based on the effects of temperature and relative humidity" by ISO Technical Committee 42. This was enacted and standardized in 2002 as ISO 18927.

From 2000, CDs21 Solutions, a voluntary group established by optical disc related companies (chaired by Nakajima Heitarō) started conducting independent experiments on the lifespan of CD-Rs on the market, with the aim of organizing the disarray among the quality and lifespan of products on the market. From 2005, the knowledge gained from these experiments was used to develop optical disc lifespan testing methods, in collaboration with American optical disc organizations OSTA and NIST. A proposal was made to the European Computer Manufacturers Association (ECMA) in 2006. Following deliberation, the methods were standardized as ECMA-379. Later, ECMA-379 was proposed to the ISO, and officially established as an international testing method in 2007 as ISO/IEC 10995. It had taken around five years to get to this point, thanks to the admirable efforts of everyone involved in attending countless international meetings and developing the technical theories. Fig. 8-1 shows a correlation diagram of all this activity. Despite the support of NIST and others, it is very rare for an ISO standard to be established from a proposal from volunteer organizations. Meanwhile, optical disc production was increasing worldwide, which meant that inferior products were being introduced to markets all over the world in the name of "globalization". Deciding on a standard for estimating disc lifespan, which had never been done before, was a very useful means of countering this situation. Currently, at the request of manufacturers everywhere, the Archive Disc Test Center (ADTC), an NPO, provides a third-party site for impartial lifespan estimate testing in accordance with ISI 10995/18297. This has gained much confidence from users as a result.

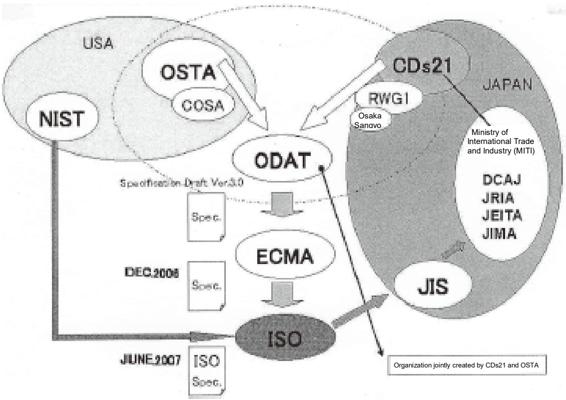

Fig. 8-1 Correlation of Activity to do with Establishing the ISO Standard

8.1 Lifespan Estimating and Causes for Faults in Optical Discs

An optical disc fault is defined as "a point at which digital data cannot be restored from the reproduced signal due to physical factors that occur due to aging of the characteristics of the recording film etc. during long-term storage in a general storage environment". The mean time to failure (MTTF) represents the general lifespan of a product and is defined in JIS Z8115 as the "average value of the lifespan of non-repair items". Non-repair items are "items that cannot or will not be repaired if a fault occurs". In order to avoid being unable to recover the data from the failure, the optical disc failure time is not defined as the MTTF, but as the operating time with a failure rate of 5% (survival probability of 95%). This method of estimating the lifespan involves accelerated testing with environmental temperature changes with a failure rate of 5%, followed by statistical processing of the data. Fig. 8-2 shows the general concept of lifespan estimation.

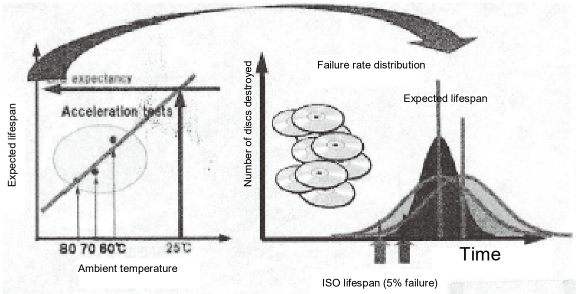

Fig. 8-2 Concept of Lifespan Estimation

The initial quality of an optical disc before any time passes is maintained by stipulating the amount of jitter the disc should have. For ROM discs, this is during manufacture. For R and other recordable discs, this is after recording. The jitter value correlates to the data error rate. This makes it possible to know the quality of the data recorded on the disc without any demodulation signal processing. As mentioned previously, CDs have an error correction code added to them. This has been standardized to enable stable data playback in spite of initial errors, errors from deterioration and errors from defects such as scratches or foreign matter on the disc surface. Accordingly, optical disc faults are considered as the point when error correction becomes impossible. As stipulated, CDs should have no more than 220 C2 errors and DVDs should have no more than 280 parity of inner code (PI) errors. At these figures, a decision is made as to whether the disc has a fault or not. The main physical factor that deteriorates optical disc lifespan is moisture coming in from the exterior or the substrate. This causes a chemical reaction that alters the characteristics of the recording film or the reflective layer. When the cause of deterioration follows chemical kinetics, the relationship between the resulting stress and the reaction speed can be modelled using the Arrhenius equation or the Eyring model. This makes it possible to test the estimated lifespan using accelerated testing under temperature and humidity stress.

Swedish scientist Svante Arrhenius (b. 1859) is known around the world for the Arrhenius equation, which expresses the temperature dependence of reaction rates using activation energy. In 1903, Arrhenius was awarded the Nobel Prize in Chemistry for his electrolytic theory of dissociation.

$$t = Ae\Delta h/kT \quad (1)$$

Here t is the rate constant, A is the pre-exponential factor, Δh is the activation energy, k is the Boltzmann constant (8.617×10^{-5} ev/k) and T is the absolute temperature (in kelvins, 273.15+degrees Celsius). In the Arrhenius model, formula (1) above can be used to express the temperature dependence of rate constants for many chemical reactions. A general model has been created based on this to determine how long a reaction will continue for.

American chemist Henry Eyring (b. 1901 in Mexico) developed the activated complex theory (transition state theory). The activated complex theory focuses on the transient chemical species that break apart near the peak of activation in the reaction. These transient species are called the activated complex or transition state. In activated complex theory, a reaction is a two-stage process in which the reactant and the activated complex are considered to in equilibrium.

$$A + B \leftrightarrow AB\ddagger \rightarrow P \quad (2)$$

Here A and B are reactants, AB++ is the activated complex and P is the product. Fig. 8-3 shows the reaction cross section according to activated complex theory. The Eyring formula is given below.

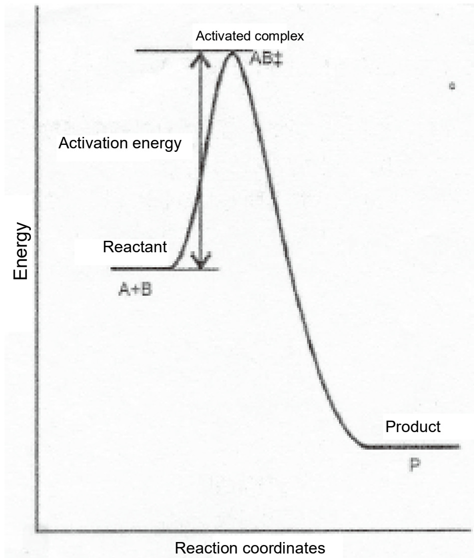

Fig. 8-3 Reaction Cross Section

$$t = AT^{a}e\Delta h/kTe\ (B + C/T) \times RH \quad (3)$$

Here, t is the rate constant, A is the pre-exponential factor, T is the pre-exponential humidity factor, Δh is the activation energy, k is the Boltzmann constant, Ta is the absolute temperature, B and C are exponential factors for relative humidity and RH is the relative humidity.

A simplified version of the Eyring formula is used in ISO/IEC 10995, mentioned later.

$$t = Ae\Delta H/kTeB \times RH \quad (4)$$

Generally, the Eyring formula can be extended as follows.

$$t = AT^{a}\exp\{\Delta H/kT + (B + C/T) \times S_1 + (D + E/T) \times S_2 + \ldots\} \quad (5)$$

Related stresses as well as humidity can also be added.

8.2 ISO/IEC 10995

ISO/IEC 10885 (referred to as 10995 below) prescribes the evaluation methods for estimating the lifespan of CD-R/RW, as well as DVD-R/-RW/-RAM/+R/+RW. The lifespan estimated here is the expected lifespan of a product stored at an ambient temperature of 25°C and relative humidity of 50% with a lower confidence interval of 95% where the survival probability is 95%. For DVD-R/RW, the lifespan is the length of time until the number of PI errors makes playback impossible.

A simplified Eyring formula takes a natural logarithm as follows.

$\ln(t) = \ln(A) + \Delta H/KT + B \times RH$ (6)

This can be further modified with ln(t) given as y, ln(A) as a_0, $\Delta H/k$ as a_1, $1/T$ as x_1, B as a_2 and RH as x_2 to be represented as follows.

$$y = a_0 + a_1x_1 + a_2x_2 \qquad (7)$$

This can be thought of as a multiple regression equation with two explanatory variables. When undertaking multiple regression analysis, the required number of individuals can be calculated as four or more based on equation (8) below, given that there are two explanatory variables in equation (7).

Number of individuals – explanatory variables – 1 = number of individuals – 2 – 1 > 0 (8)

According to this, Eyring model accelerated testing must be accomplished with a minimum of four temperature and humidity conditions. 10995 stipulates finding the mean logarithmic value of failure time under four conditions of 85°C 85% RH, 85°C 70% RH, 65°C 85% RH and 70°C 75% RH. Fig. 8-4 shows a summary of lifespan estimation using the Eyring model.

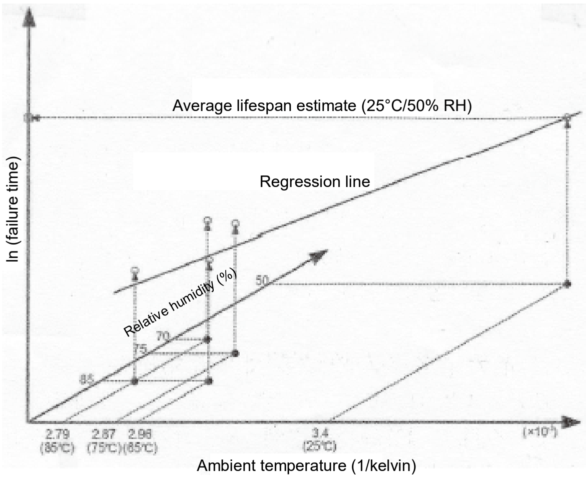

Fig. 8-4 Summary of Lifespan Estimate Using the Eyring Model

10995 indicates the analysis procedures for determining the estimated lifespan, assuming that lifespan data distribution follows log-normal distribution. Accelerated testing is conducted on sample optical discs under the four conditions given above and a retrogression equation is used to determine the time until failure. The order statistic median rank method is used for the cumulative distribution of the failure data. A log-normal graph is used for the cumulative distribution of the data for each condition. These are used to check if the values are within the assumptions.

More specifically, the lifespan data for each condition is represented as a line on a log-normal graph. The incline of the line represents the logarithmic standard deviation. This is equal if the samples are taken from the same parent population. Checking this ensures that the failure under each condition falls within the 10995 model. Fig. 8-5 shows an example of cumulative failure distribution.

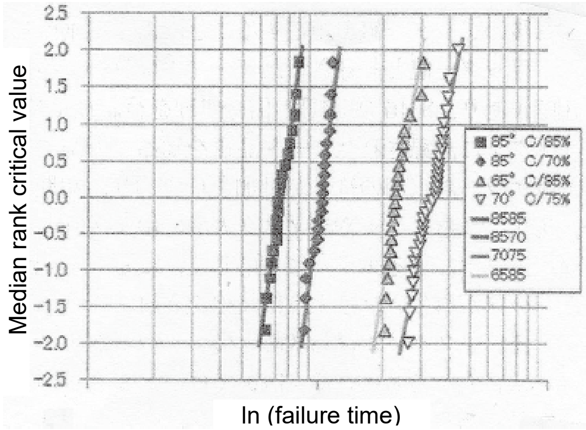

Fig. 8-5 Cumulative Failure Distribution

The log-normal graph shows the log average values for the failure data under each of the conditions. Multiple regression analysis can be used to find the constant term and partial regression coefficient, or ln(A), ΔH/k and B in the simplified Eyring equation. The obtained constant term and partial regression coefficient can be used with the simplified Eyring equation to find the estimated lifespan for complement conditions by entering values of absolute temperature 281.15K (25°C) and 50% RH.

The acceleration coefficient of the failure data (the ratio between the average lifespan estimate from accelerated testing and the average lifespan estimate under storage conditions) is calculated for each condition and the lifespan data normalized for complement conditions. At 25°C 50% RH with a confidence interval of 90%, the lifespan can be estimated, assuming a confidence level of 95% survival. Fig. 8-6 shows an example of normalized lifespan estimate using the acceleration coefficient.

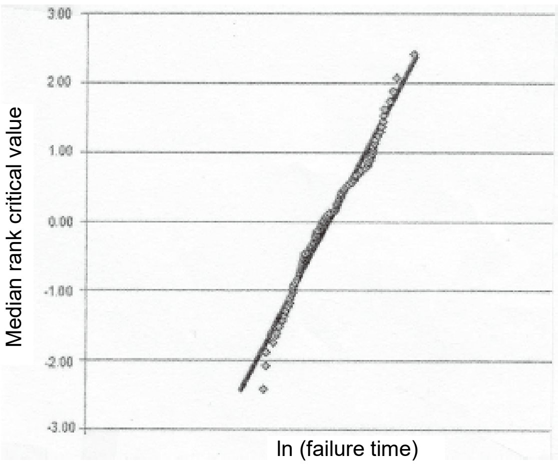

Fig. 8-6 Estimated Lifespan Normalized by Acceleration Coefficient

8.3 Archive Disc Test Center (ADTC)

The Archive Disc Test Center (ADTC) is an independent third-party not-for-profit organization (NPO) established in August 2008 to carry out optical disc lifespan estimates and decide whether the disc is capable of long term storage. With users wanting to use optical discs to store recorded data, this decision helps these users to determine whether a disc is suitable for long term storage. The ADTC laboratory started operating in March 2009. As well as testing CD-R/RW, the ADTC laboratory also conducts accelerated testing based on ISO/IEC 18926, an extension of ISO/IEC 10995 intended for estimating DVD-R/RW/RAM lifespan. There are plans to progressively extend the range of discs that can be tested. Archival grade optical discs (lifespan of 30 years or more) are issued with a certificate and logo as shown in Fig. 8-8. The laboratory also has a monitoring function to confirm that the discs sold on the market are actually certified discs. This is done by selecting discs with the logo from the market and carrying out lifespan testing on them. If a breach is discovered, the company is instructed to discontinue sales and is subjected to measures including losing the right to use the logo. Fig. 8-7 shows the ADTC laboratory. There are multiple thermostatic chambers for accelerated testing, as well as error measuring equipment, all of which is used to estimate disc lifespan from the data provided.

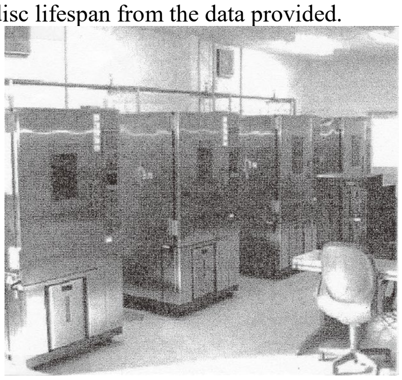

Fig. 8-7 ADTC Laboratory

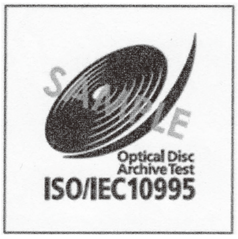

Fig. 8-8 Certification Mark Issued by the ADTC

All digital data recording media has a lifespan. When digital data is stored long term, the state of the recording must be checked every few years. If it has deteriorated, then the data must be recorded onto a new recording medium. Optical disc data migration is provided for in ISO/IEC 29121 and JIS Z 6017. These standards also recommend maintaining continuity by checking for optical disc deterioration and re-recording data as necessary.

The ADTC continues its activities in 2017. The test center laboratory is established in the laboratory of Prof. Irie Mitsuru of Osaka Sangyo University, who made a significant contribution to the ISO standardization of lifespan estimation. Every year, five or six different optical discs are tested for lifespan estimates based on ISO/IEC 10995 (18926), which serves to improve the quality of archive grade optical discs. There is no doubt that the unobtrusive activities of the ADTC secured the position of the optical disc as long term storage media and have laid the foundation for the widespread use of a more consistent quality of optical discs. There is now greater demand for impartial third-party testing rather than in-house evaluations, and the demand for the ADTC continues to grow. It is very significant that one of the bidding conditions for government and university archive businesses is usually to “use recording media evaluated by an impartial third-party organization”.

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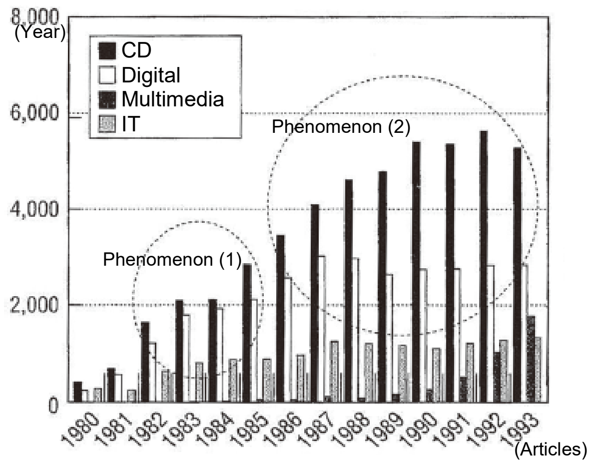
2) “Chōki Hozon Baitai to shite no Hikari Disuku no Hinshitsu Hyōka to Jumyō Suitei [Quality Evaluation and Lifespan Estimate of Optical Discs as Long-term Storage Media]” Ihashi Takao and Suzuki Toshio, Tokyo City University Journal of the Center for Information Studies No. 12 (Mar. 2011)
3) “OplusE No. 365 Archive Optical Storage Feature” Advanced Communication Media (2010)
4) ISO/IEC10995, ISO/IEC18927

9 The Cultural Revolution Triggered by the CD

Chapter 6 discussed the emergence and scale of the CD business, covering the introduction of CD media and the CD family to the market, the emergence of successive new products with various new features added and how this technology became established on the market. In that sense, it is no overstatement to say that the spread of CD media itself was a cultural revolution. This revolution brought about by CD media can be categorized into three main areas: (1) digital culture, (2) interactive culture and (3) recordable (R) culture.

9.1 Digital Culture and CD-DA

Due to its major impact, the achievement of the CD-DA is at the forefront of the “popularization of digital culture”. In the 1980s, the leading product that embodied the term “digital” was the CD. The term “digital” became more widely used as the CD grew in popularity. Fig. 9-1 shows the number of articles in which the words “CD”, “digital”, “multimedia” and “IT” appeared in four newspapers published by Nihon Keizai Shimbun: “Nihon Keizai Shimbun”, “Nikkei Financial Daily”, “Nikkei Business Daily” and “Nikkei Marketing Journal”. This data indicates how far these words and concepts had entered economic and industrial topics. It is clear that the words “CD” and “digital” appeared in articles in the early 1980s. Through to the mid-1980s, the number of articles mentioning “CD” and “digital” showed a similar growth trend (phenomenon (1)).



Source: Nikkei Telecom 21

Fig. 9-1 Four Words Mentioned in Articles in Four Newspapers Published by Nihon Keizai Shimbun (1980-1993)

This suggests that since the CD was at the center of digital discussions and that the two words appeared in articles together. The CD was indeed considered to be the symbol of digital technology. This also led to a rise in use of the term “analog” to refer to existing technology. While watches and other digital products also emerged, these were simply products with digital displays and had little to do with developments that led to the creation of digital society.

CD digitization of music triggered a “baptism” in digital culture and widespread popularity. According to the NHK lifestyle survey conducted every five years, there were subtle changes in consumer lifestyles as a result of music digitization. This included questions on “change in the time spent listening to CDs or other music”. The time spent listening to music during the week for people in their 20s and 30s peaked in 1990 and gradually declined, while time spent listening to music during weekends continued to increase through to 1995, suggesting some influence from the emergence of the CD. One possible factor for this is that the living environments of these young people were affected by the waves of digitization that came with the CD, and their lifestyles changed as a result.

As mentioned previously, the CD family expanded as new functions were added to CDs. The CD-ROM emerged in 1985, followed by the CD-I in 1986 and the CD-R in 1989. This resulted in an increasing number of articles about CDs in the late 1980s as various CD media products became the topic of attention as the embodiment of “digital culture”. At this stage, the word “digital” was already in common use as a concept word. It was even used to express personality traits, such as a “digital personality” or a “digital person”. As text, images and data became digitized as well as music, the term “digital” became more commonplace. As a result, this term no longer appeared in newspaper articles at the same growing rate as CDs (phenomenon (2)). Fig. 9-2 shows the trends in music media production sales (in Japan) for the 20 years between 1984 and 2004. CD-DA discs peaked in 2000 at around ¥500 billion, although it was over ¥400 billion for around 10 years, which indicates the scale of the business. This proves how far digital culture had permeated as a result of the CD-DA disc. Fig. 9-3 shows the trends in domestic CD player production volumes. Production also peaked in 2000, at 18.64 million units, with 15 million units produced each year in the five years before and after. Sales reached as high as ¥276 billion in 1998. With a scale of business at over ¥200 billion, this major industry continued for a decade and contributed to the spread of digital culture.

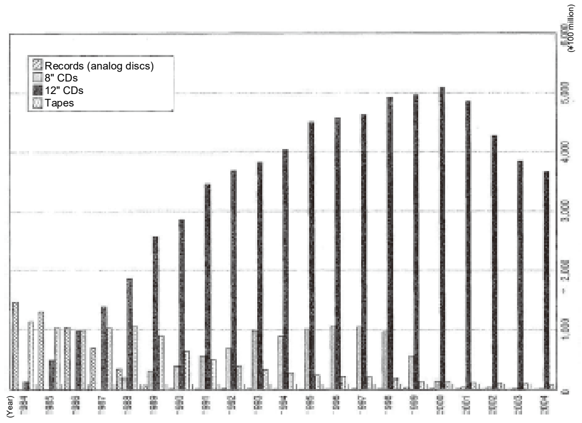


Fig. 9-2 Trends in Music Media Production Sales

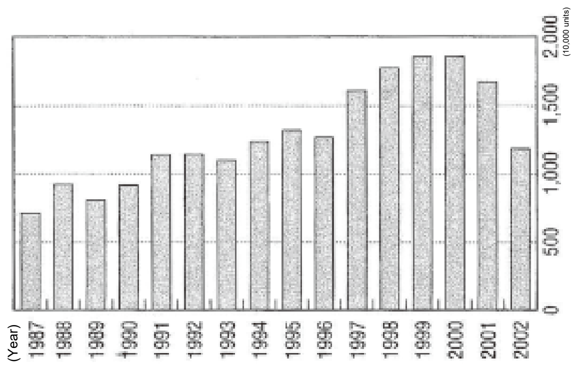


Fig. 9-3 Trends in Domestic CD Player Production

As digitization continued, it was used for material other than music, with various expressions coming into being. The CD family expanded, and the "multimedia" concept emerged with it. The term "multimedia" also appeared in newspaper articles in the early 1990s. As this word appeared, the word "digital" also reappeared frequently (phenomenon (3), Fig. 9-4). Fig. 9-4 shows the number of articles in which four words ("CD", "digital", "multimedia" and "IT") appeared in four newspapers published by Nihon Keizai Shimbun in the decade from 1994 to 2003. Multimedia was a new concept based on the idea of digital. It was used to represent the industry in the 1990s, and the CD family played a major role in its embodiment. In short, digitization began with music information and came to include characters and images. "Multimedia" was a necessary next step to include all of this digitized information. However, times change, and it sounds a little old fashioned now to say one has CDs. However, networked society is lacking substance. All information is hidden away in the cloud, invisible. We need to take another look at what the culture was that was ushered in by CDs we could actually see, and at what it means to have digital technology that hones our sensitivity and works our five senses.

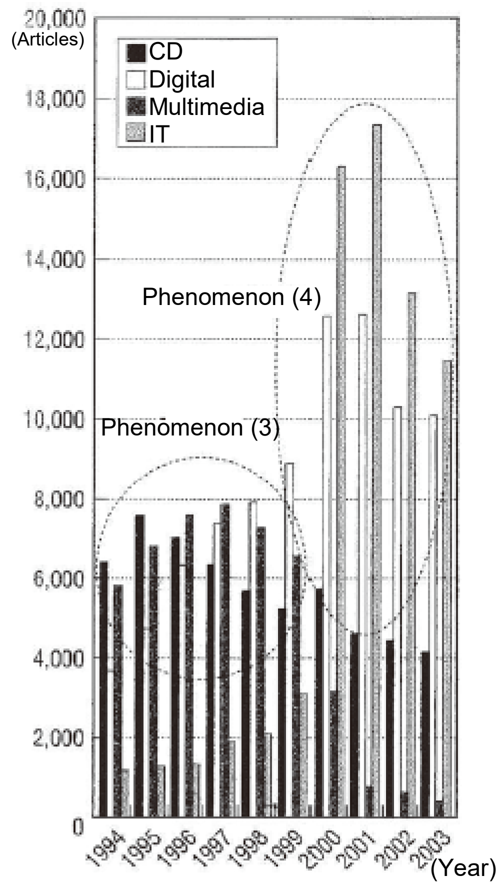


Fig. 9-4 Four Words Mentioned in Articles in Four Newspapers Published by Nihon Keizai Shimbun (1994-2003)

9.2 Interactive Culture and CD-ROM/CD-I

As touched on in Chapter 6, CD-ROM and CD-I began to emerge with the idea that multi-information = multimedia. CD products with various functions began to emerge and spread to provide multimedia infrastructure. These "multimedia CDs" laid the foundation for information devices. Multimedia CDs handle multiple types of information and are equipped with an "interactive" function, thus offering new levels of operability and enjoyment. This functionality was essentially an extension of the search function developed from the CD-DA "song selection function". As a result, various software and product functions emerged that offered a bidirectional operability, as if the user were interacting with the machine. The term "interactive multimedia" emerged to describe the concept of that function.

Of course, a search function was already a standard function in the world of computing. However, computers were not as widespread for household use as they are now, and there were fewer opportunities for people to experience such interactive functions. These experiences came about through multimedia CDs, such as photo CD, CD-G, CD-

ROM, CD-I and VCD. Previously, computer games could only be enjoyed as arcade games at certain locations. Software developers used every skill they had to make it possible for users to enjoy arcade-like bidirectional interactivity at home. This developed into a major industry almost instantly. At this stage, a succession of products was emerging with various interactive multimedia functions, including dictionaries and other electronic publications with search functions, vehicle navigation through advances in GPS, educational software and other CD-ROM titles and household karaoke. In a general sense, these multimedia CDs were an indication of new developments that could well be called a new civilization or “interactive culture”. One machine that played a role in this development was the multimedia PC, a computer with a built-in CD-ROM drive. From around 1990, software products with shorter lifespans emerged, such as 8cm CD singles and CD-ROM titles issued with magazines. The culture became more “consumable-oriented”, with mass production, mass consumption and mass disposal increasing. Digital culture became convenience culture. Once curiosity was satisfied, the item had no further use and was simply thrown away. This everyday occurrence was a side effect of delivering high volumes of content on CD-ROM. Nevertheless, the CD-ROM hardware market rapidly expanded from around 1994, as shown in Fig. 9-5. This huge market totaled over ¥1.8 trillion (including the PCs), with CD-ROM drives installed on all computers.

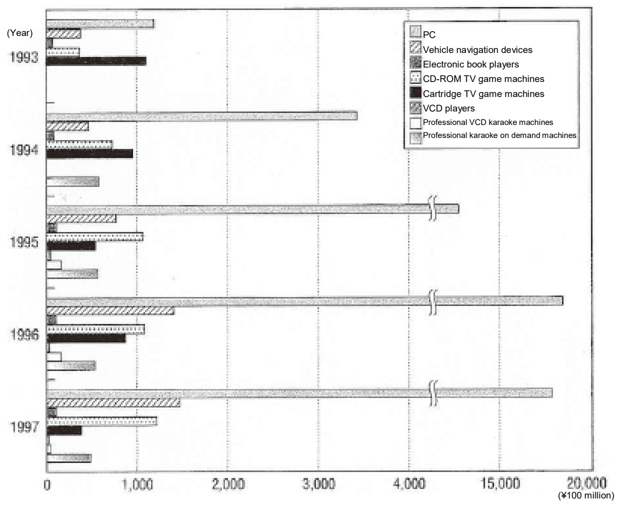


Fig. 9-5 CD-ROM Hardware Market Trends

This interactive functionality provided significant possibilities for representation in software using such functions. Systems for carrying out various experiments and challenges and having them evaluated on the market gave rise to new types of software creators. As mentioned in 6.4.2, such trends were put to use in web and content creation in the networked society that followed. This served as a kind of rehearsal for creators for networked society. In that sense, multimedia CDs and other packaged media laid the foundation for today’s networked society. Although it took place gradually, since the year 2000 this cultural revolution has been accompanied by a rapid uptake in the concept of “information technology” (IT) in place of multimedia. Shown as phenomenon (4) in Fig. 9-4, this is truly a result of cultural revolution.

9.3 R (Recordable) Culture and the Most Widespread Medium in History

Floppy disks (FDs) and magnetooptical disks (MOs) gained widespread use as recording media for computers. Their successor, the CD-R, emerged in the fall of 1989. Details of the technology are outlined in Chapter 7 “Emergence of Recordable CDs”. A researcher specializing in cultural theory made the following statement: “Until now, all media thought up and popularized by people has been ‘unseemly’. In that sense, it is a great delight to see an ‘unseemly’ media (CD-R) born into the CD family.” The researcher also pointed out that “thanks to the CD-R, we finally have real media that the adventurous can make use of!” In Nakajima Heitarō’s memoranda, he says that when he was explaining the successful development of the CD-R to the RIAJ, it was criticized as the “media from hell”. It is not difficult to imagine that this would have been very ‘unseemly’ media to those who had to protect their copyrights. Even at Sony, who had taken part in the development, there were concerns about the potential for illegally copying software, as the company had the CBS Sony record company under its umbrella at the time. The media had an ‘unseemly’ air from the outset, to the extent that full-scale commercialization was delegated to Start Lab, a joint venture with Taiyo Yuden (Sony Taiyo-Yuden Advanced Recording Laboratory). In the words of the cultural theory researcher mentioned above, “the unseemlier it is, the more real the media”.

The CD-R spread rapidly in use due to the following conditions.

(1) It maintained compatibility with the CD family
(2) It was possible to exchange data in Windows, Macintosh, UNIX and other environments
(3) The price was able to drop around 1997
(4) High speeds of up to 48× were possible for media and drive
(5) The infrastructure was already in place due to the popularization of CD-R compatible drives

While the CD was mainly intended for use in place of floppy disks, as IT society spread, it rapidly expanded in use to various other applications, including digital cameras, personal music, saving and sharing PC data and electronic filing for public institutions. By the year 2000, a decade after its release, total worldwide production reached 10 billion, second only to the analog medium of "paper" as a recording and delivery medium. This was entirely due to its robust compatibility and standardization as a recordable medium. Fig. 9-6 shows the main global trends in recording media for the 10 years between 1993 and 2003 (with reference to research by Fujiwara-Rothchild, Ltd.) and how rapidly this medium spread. The CD-R market grew rapidly in scale from around 1998, with a product reaching 10 billion for the first time in human history. This statistic has a certain margin of error, although according to information from the research company the figure is somewhere between 9 billion and 11 billion, which is the revised figure published by CDs21 Solutions. According to figures tabulated manufacturer by manufacturer, the actual volume is almost 30% higher. With estimates including the low quality CD-Rs produced by backdoor Asian manufacturers, some information suggests that production peaked at over 14 billion. Global production in 2003 compared by region reveals overwhelmingly high production in Asia, especially Taiwan, with Asia accounting for 89% (Japan 8%, Taiwan 52%, India 11%, other 18%), Europe accounting for 9% and the Americas 2%. Taiwan took on a national strategy of expanding its optical disc production facilities by buying up large amounts of used Japanese equipment and creating its own production system. As a result, when production costs peaked in 2006 and then dropped, as is inevitable for the equipment industry, Japanese manufacturers could not stay competitive in price. Taiyo Yuden stopped production in 2015, spelling the end of Japanese-made CD-Rs and the end of the Japanese CD production industry itself.

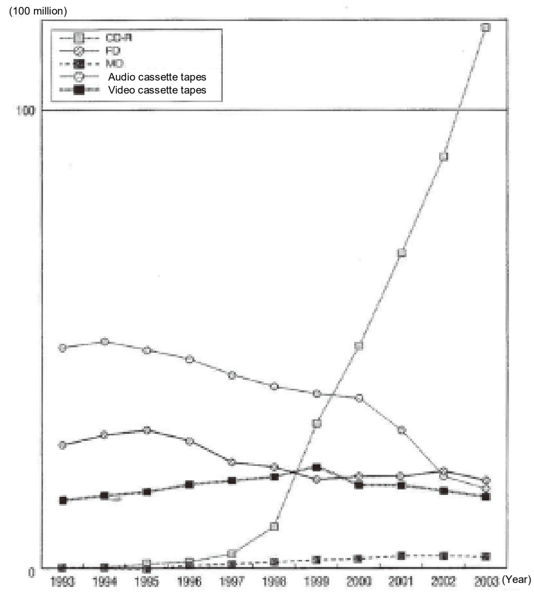


Fig. 9-6 Global Scale Market Trends in Recording Media

However, there is strong demand for high quality Japanese-made CD-Rs and there are some applications for businesses that seek quality over price (such as data archives).

Fig. 9-7 shows the advantages and disadvantages of the CD-R system (1) and how the playback environment was established for many CD-R/RWs. Worldwide estimates in 2001 indicate that CD-R/RW drives were built into or connected to around 50 million multimedia PCs, with a playback environment including around 1 billion CD players, 1 billion CD-ROM drives and around 300 million other devices such as game machines and DVD players, totaling to a system of over 2 billion devices on which playback was possible. This vast system formed the basis for the peak in 2003 at 10 billion discs. Fig. 9-8 shows the advantages and disadvantages of the CD-R system (2) in terms of illegal copying and rampant piracy. The data is based on the IFPI piracy report, which states that around 2.8 billion packaged CDs are sold each year, while ordinary users make around 3.8 billion illegal CD-R copies. This is the unfortunate 'unseemly' reality. The advantages and disadvantages of the CD-R system are what makes it a true media.

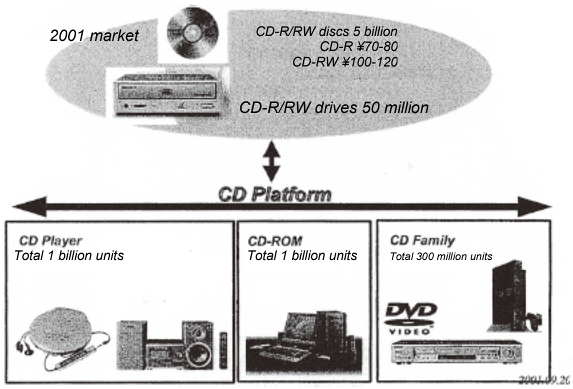


Fig. 9-7 Effects of the CD-R System 1

The first stage of demand for CD-R had a huge impact on software production for multimedia CD rather than simply for its function as a recording media.

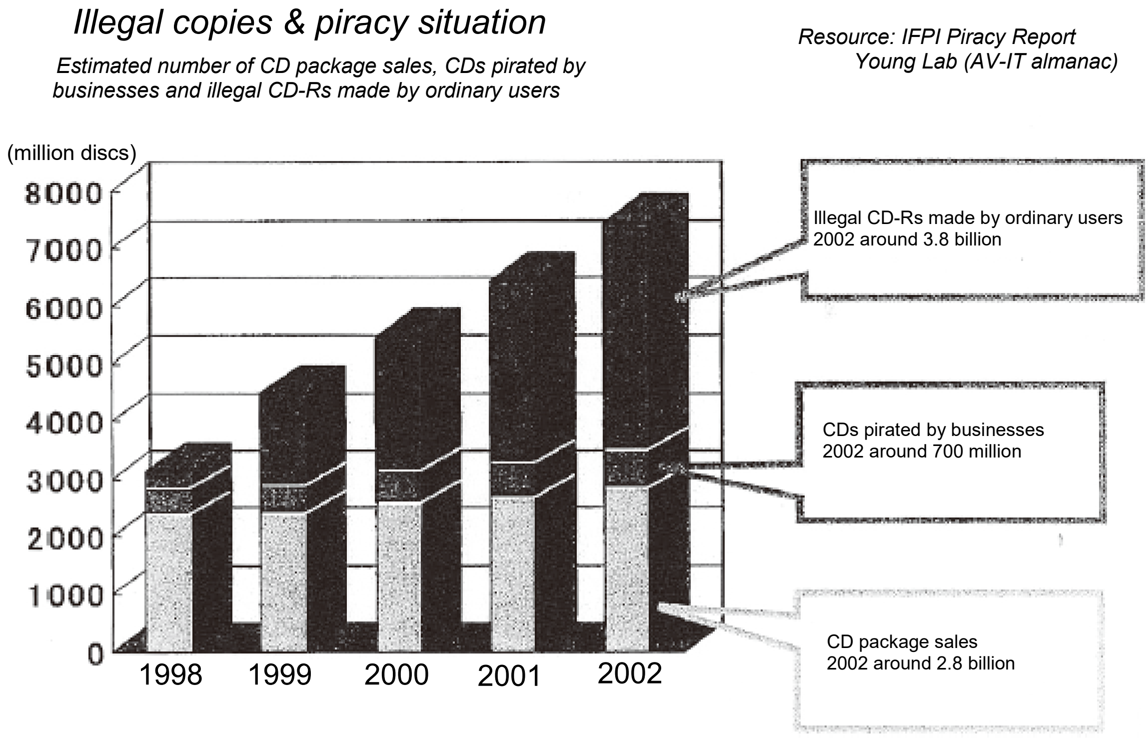


Fig. 9-8 Effects of the CD-R System 2

As mentioned in 7.1.2, in the early 1990s, the CD-R significantly reduced the amount of time and cost spent on the verification and checking processes in at the prototype stage in multimedia CD software production. Since the CD-R was compatible with the CD family, it was possible to verify and check software as soon as it was prototyped. This provided a system that gave an accurate prediction of the completed disc, thus offering "revolutionary convenience" to multimedia CD production. So many CD-Rs were used in manufacturing game software that without the CD-R, there would have been none of the CD-ROM games that later took the world by storm. In fact, the early CD-R business is said to have started with game software production. As it grew more widespread in use, people became familiar with digital software, had interactive experiences and accessed information in digital archives.

This basic learning of to handle information is thought to be one of the cultural factors that allowed a smooth transition into IT/networked society.

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10 | Conclusion

This year marks 35 years since the CD emerged in the fall of 1982, and the time has gone quickly. Throughout 20 years of improvements, the CD family has continued to expand and grow. This system is unusual in that it has brought about huge business. Throughout the history of technology, consumer media has had a lifespan of around a generation (25 years). In that sense, the CD was destined to be replaced by a new generation of media in the early 2000s. However, no next generation of package media for distributing music has emerged to date. In the world of audio, despite the current networked/IT age, the CD-DA is still at the core of the business, and many music artists continue to put out albums on CD-DA. There is no clear answer as to why this media has had such a long lifespan. Perhaps this package media is the optimum means of distributing music content. Perhaps the music and systems created using the technology 35 years ago have yet to be fully appreciated. However, technology did advance in the last 35 years. The Super Audio CD (SACD) was proposed in 1999 in response to demand for optical discs with better sound quality. The proposal involved using direct stream digital (DSD) coding technology and the latest A/D conversion technology to reduce digital noise and produce much higher quality audio, but it did not grow widely in use, perhaps because of the limited playback environment due to downward compatibility.

The past 35 years have seen major technological advances in recording density. Recording capacity increased by six times to 5GB on a DVD in 1996, then a further five times to 25GB on a Blu-ray disc in 2003. Multiple layers were standardized, making it possible to hold almost 10GB on DVD and 50GB on Blu-ray. Further advances in layering technology allowed up to three or four layers on a disc and recording capacity of over 100GB. Fig. 10-1 shows a comparison of these technologies. This capacity size is best suited as a distribution media for high resolution video content. For music content, DVD audio and Blu-ray audio standards have been created to enable high sound quality that can support 24-bit sampling at 192kHz, although this is a specialized media and not widely used for music distribution. This field of music is known as “high resolution music” and is mainly limited to the “computer audio” genre and downloaded from online. Today, listeners use smartphones to access large volumes of music data online, download the music they like and enjoy a reasonable quality of sound.

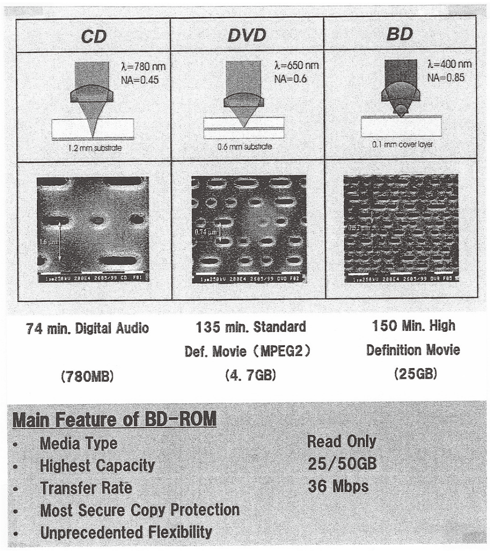


Fig. 10-1 Comparison of Recording Density between Technologies

Meanwhile, in the world of CD-DA, people still want good quality music. There are always comments such as, “The music sounds harsh” or “There’s no bass coming through”. Today, there are fans who prefer the bygone LP records to CD, and are returning to analog music. However, it is extremely difficult to express in quantitative terms what “good music” is. Various attempts have been made in the past to solve this challenge, but it is an “eternal question” that would require going as far as quantifying the unconscious human mind, which no studies have done. As far as challenges remaining for CD-DA, the first is to speed up research on “the human condition”. That is to say, the only criterion for defining “good sound” is the way the listener feels. If the mechanism that determines how the listener regards “good sound as good sound” cannot be identified, there is little point continuing the discussion. Unfortunately, there is no system that can measure human feelings. Experimental attempts have been made in the past to measure brain waves and pulse waves for any fluctuations and map the spectral components on a 1/f incline, but this does not prove that the listener was in a good state of mind or felt comfortable. There have been reports of attempts to measure the state of mind in connection with sympathetic and parasympathetic nerve activity, but no clear results have emerged. This technology has been used in brewing to increase the enjoyable taste components of wine and sake, but it is unclear how far it can apply to understanding people’s state of mind. There has been a recent proposal to develop a new technology to detect brain waves (pulse waves) from the ear. The only place to fit this sensor on the human body would be in the ear, near the brain, which would allow researchers to detect various information that has not previously been known. Experimentally, this would provide a stable signal. If it were possible to sense the pulse waves (brain waves) while the subject was listening to music through headphones, this could facilitate rapid advances in the field of health as well as the field of research on the human state of mind. The technology to do this just needs to be completed.

The second challenge is to account for “inaudible sound”. The sampling frequency on CD was set at around 20kHz, based on medical evidence that this is the upper limit of human hearing. However, human hearing ranges varies from person to person between, with some people even able to hear ultrasonic waves at 30-100kHz. The CD system was also designed on the assumption that ultralow frequency vibrations below the lower limit of 10 Hz could only be heard by animals. However, a major topic in recent research has been how humans handle this “inaudible sound”. There is a hypothesis that inaudible sound in itself can contain some important hidden information. There are hopes that it will be possible for technology to provide the key to understanding this area of sound quality. Fig. 10-2 shows the “distribution of sounds/vibrations that affect humans”. While this also depends on acoustic pressure, it is evident that ultralow frequencies below 10 Hz and ultrasonic frequencies near 30kHz are within the human audible range. Further, a music includes a vibration range over 100kHz and it is possible that these ultralow frequencies may overlap with the sounds of the body (pulse, breathing) and be perceived as noise. Further research is required on how to quantify this “inaudible sound” and to develop a technology system for it.

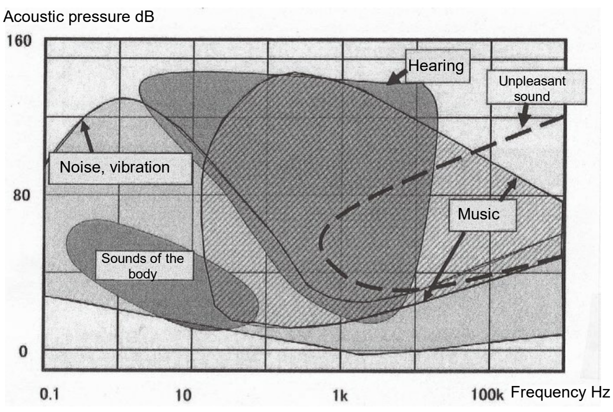


Fig. 10-2 Distribution of Sounds/Vibrations that Affect Humans

The third challenge is working out how to shift the position of optical discs in an expanding broadband network environment. Optical discs are already no longer the main form of computer recording device, having been overtaken by semiconductor memory. There has been a recent drop in the exchange of information on CD-ROM, which dominated the world until around 2006. The standard built-in PC CD-R/RW drives and CD-ROM drives are now becoming an external device. In the field of electronic publishing, optical discs still hold their position as a means of distributing additional information with books and publications due to their being a rapid means of publishing multimedia, as mentioned previously. However, in the future, as information is handled through broadband networks, this data will be incorporated into the cloud system and the media will become completely invisible. The discussion continues as to what kind of role 1-100GB optical discs will play and whether their position will continue to exist, even for music content, video content and electronic publications. However, package media such as CDs is a tangible form of media. Music is full of sensations. The album liner notes convey the creator’s intentions and thoughts on the product. The product even has a smell to it. In that sense, there is a possibility that real optical discs will continue to play a leading role in fields where sensation is part of the product, such as music artists publishing albums on CD. For example, first-generation CD-ROM game software is very popular in places such as Europe. As a result, there are cases of CD-DA production plants now solely producing CD-ROM game software. There is no clear answer as to why game enthusiasts still enjoy CD-ROM games. One reason could be that there is more pleasure in a game with substance (allowing the user to feel the feelings of the manufacturer) than in playing an online game with no physical substance. Meanwhile, in places like the United States, DVD video content is now being sold off cheaply in bargain sales and package deals. There is not even a “crumb of sensitivity” in this market, as the core of the business migrates to Netflix and other online video distribution services. In any case, the focal question for CDs and other optical disc systems with a “best before” date is how to maintain any utility value in the future. Fig. 10-3 shows a diagram of the relationship between optical discs and networks.

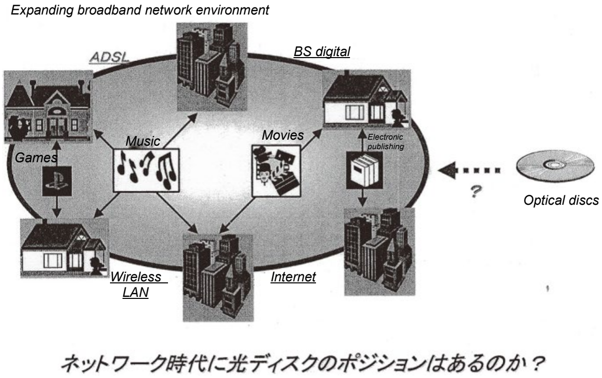


Fig. 10-3 Network and Optical Discs

Finally, a noteworthy movement is the use of optical discs by data centers, the trump card of the network age. This began with the awareness of economic loss involved in having so-called cold data, or high volume data that is used very rarely, stored long term on hard disk data systems by data center operators. Systems were set up to handle cartridges of several terabytes, made up of 10 optical discs (Blu-ray) each holding around 100GB. A robotic system is then used to search for necessary information as needed and retrieve it in an instant. The greatest point of difference is the cost per bit unit, including the cost of hard disk electricity consumption and maintenance costs. Generally, lifespan is also an important parameter for data that is recorded once and only has a low frequency of use. There remains a demand for optical discs that have passed the ISO lifespan test described previously. While this is categorized as business use for optical discs, the production scale is expected to be huge. According to reports, around 80% of all data held by data centers is cold data. A new challenge is expected for optical discs to preserve and store this vast amount of data that is rapidly growing.

The CD is a soldier of fortune that appeared in the last two decades of the 20th century. The family grew and the business expanded significantly, leaving a new networked / IT society as a parting gift. However, even today, no new media has emerged to take the place of the CD in the music industry: there were no CDs before the CD, and there will be no CDs after the CD. Three major companies in Japan continue to produce CD-DA (CD-ROM), Sony DADC Japan, Memory-Tech and JVC/Kenwood.

Philips was awarded the IEEE Milestone Award in 2009 in recognition of its contribution to CD technology. This award was for formulating the CD international standard ISO/IEC908 “Compact Disc Digital Audio”. Fig. 10-4 shows a photograph of the Milestone Award presented to Philips. This standard was adopted into Japanese standards as JIS8605 “Compact Disc Digital Audio Systems”, as well as the CD-related industry standard by the Recording Industry Association of Japan (RIAJ) as RIS204 “Audio CD Label Content and Format” and RIS203 “Compact Disc Accessories”. The lifespan estimate standard ISO/IEC 10995 and ISO/IEC 18926 have also been adopted into JIS standards.

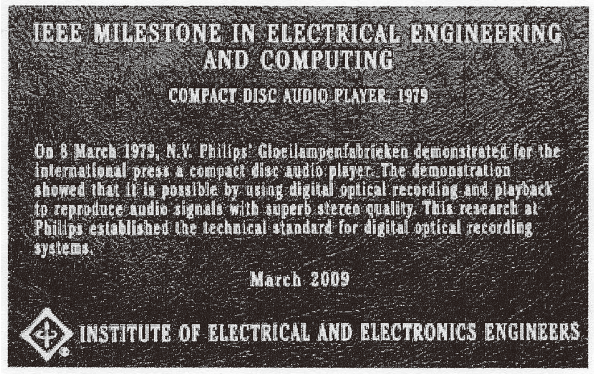


Fig. 10-4 IEEE Milestone Award Presented to Philips

The challenge with a systematized survey report on CD technology is that much has been left out. A systematized survey requires surveying and reporting on a great number of CD-related businesses. However, the technology of three decades ago and the organizations, engineers and resources from the different companies involved have all disappeared in the relentless restructuring of the electronics industry. Only Sony/Philips had any traces left, which has unfortunately meant that the content of the report and the technology system may come across as somewhat biased, as this has been the only reference information to draw from. Other reference materials include “Konpakuto Disuku: Sono 20-nen no Ayumi [The Compact Disc: Its 20-year History]”, a commemoration of the first 20 years of the CD, published by CDs21 Solutions (with the present author as its secretary), which has also already played its part and closed its doors. The content and chronology are recorded in minute detail, with heartfelt thanks to the editors at the time. The “CD-R/RW Official Guidebook”, published by the Orange Forum, of which the author served as secretary prior to the founding of CDs21 Solutions, is also referred to in Chapter 7 (Emergence of Recordable CDs). Again, heartfelt thanks go to the editors for the extremely detailed content.

This systematized survey report on CD technology comes with sincere gratitude for three decades spent in CD-related businesses, captivated by the beam of light.

References

1) "Zukai Konpakuto Disuku Dokuhon [An Illustrated Compact Disc Reader]" Nakajima Heitarō and Ogawa Hiroshi, Ohmsha (1996)

Acknowledgements

On December 9, 2017, as I neared the end of writing this survey report, Nakajima Heitarō, major contributor to the Japanese audio industry and inaugural chairman of the Japan Audio Society, passed away.

He had been my mentor during my many years at Sony, my most respected advisor awaiting the completion of this survey report, and a veteran in the industry from whom I learnt a lot. The contributions made by Dr. Nakajima to the field of audio, especially in the development of digital audio (CD), are beyond words. With heartfelt condolences I will remember him in prayer. At the same time, I would like to express heartfelt gratitude for his aid in completing this survey report, as his notes and publications appear in various places in this report and have been a major source of reference material. When this report is finally complete, I will present a copy to him at his grave first of all.

I would like to express sincere thanks to Mizushima Masahiro, former head of Sony R & D, who took very detailed notes at the Sony/Philips meetings discussed in Chapter 2. This level of detail in notetaking was priceless, and made it possible to recreate the situation for future generations. For Chapter 4, I received much support from President Ishihara, Mr. Yasuda Yōichi and Okamura Yasuhiro of Sony DADC in providing materials and explanations. My deepest thanks to them for graciously allowing me to photograph their new facility.

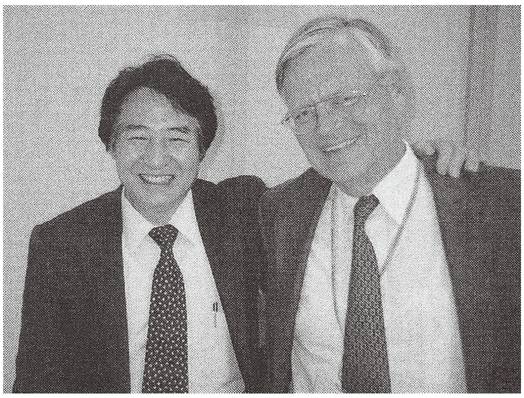
For Chapter 6 on the emergence of CD-related businesses, I could mainly only write about how Sony's business expanded. I am deeply grateful to division manager Matsumoto Yoshinori, head, Mr. Sekine Kazuhiro and Mr. Hasu Toshiya of Sony V & S, as well as former employee Mr. Fukuyama Yutaka, for providing materials and a wealth of advice.

For Chapter 7, I received a lot of material from Mr. Arai Tōru of the intellectual property division of Taiyo Yuden. I am profoundly grateful for his information and technology resources on electronic components manufacturers' 50-year struggle with recording media production. For Chapter on standardizing lifespan estimates, I am very grateful to have received enthusiastic assistance from the start from Prof. Irie Mitsuru of Osaka Sangyo University, who made significant contributions to formulating the ISO standard and even involved me in the operation of the ADTC.

The CDs21 Solutions publication "Konpakuto Disuku: Sono 20-nen no Ayumi [The Compact Disc: Its 20-year History]" was a significant and frequently cited reference source. As I was also involved in some products that were never made into commercial products, this survey report was a means of making mention of these. My heartfelt thanks to the many companies that worked with me, to the many people involved in editing, and to the members of the publishing editorial committee, especially Mr. Nishizawa Toshiharu and Mr. Taniguchi Isao in their central roles.

Finally, my dear friend Dr. Heemskerk of Philips, who as chief engineer was the leader of the technical field from the beginning of CD development. He was well-versed in "Japanese English", and was involved as an engineer in creating all of the standards from CD-DA to CD-R. I am so very grateful to him for providing all of the materials still held by Philips for compiling this survey report.

Dr Nakajima Heitarō



Dr J. Heemskerk and the author

CD Related Chronology

1877	Dec: Edison (USA) invents the phonograph (tinfoil cylinder recorder)
1937	Reeves (UK) discovers the pulse-code modulation (PCM) principle
1951	LP record launches (Japan)
1952	Oct: Japan Audio Research Society founded; renamed Japan Audio Society (JAS) in 1953
1953	Feb: NHK commences television broadcasting
1956	Schnell (Germany) invents polycarbonate
1958	Townes and Schawlow (USA) publish optical maser (laser) theory
1960	Jul: Maiman (USA) successfully demonstrates solid state (ruby) laser oscillation
1961	Industrial production of polycarbonate begins NEC successfully demonstrates Japan’s first ruby laser oscillation
1962	Successful semiconductor laser demonstration (USA)
1963	SP record production ends
1964	Philips (Netherlands) develops the compact cassette tape
1969	NHK STRL announces the world’s first professional digital audio tape recorder
1970	Teldec (Germany) and others announce TeD format video discs
1972	Mar: Nippon Columbia develops the PCM digital recorder Sep: Philips announces the optical video disc (VLP format)
1974	First PCM digital recording in Europe
	Philips/MCA announce unification of optical video disc standards
1975	First commercial digital recording in the USA using PCM digital recording Sony launches Betamax
1976	Sony announces PCM processor prototype Single records (EP) reach 100 million JVC launches VHS
1977	Sony launches PCM processor PCM-1 Oct: Three groups, Sony, Hitachi/Nippon Columbia and Mitsubishi Electric/TEAC/Tokyo Denca, exhibit optical DAD prototypes at the All-Japan Audio Fair Philips develops the optical DAD (ALP format)
1978	Mar: Sony launches PCM processor PCM-1600 Apr: DAD committee launched (15 companies) Sep: JVC announces electrostatic video disc VHD format and electrostatic DAD (AHD format)
1979	Mar: Philips demonstrates optical DAD (115mm diameter concept model) May: Consumer PCM processor standard established Aug: Sony/Philips start discussions on CD specification policies Oct: Sony announces a 30cm DAD capable of 13 hr 20 min playback
1980	May: Sony/Philips reach a basic agreement on CD format specifications Jun: Pioneer USA launches the household LD player VP-1000 Jun: Three formats proposed by DAD committee: CD, AHD & MD
1981	Jan: Red Book (CD-DA) standard proposed Apr: DAD committee ends evaluation of three formats (51 companies participating) Apr: Sony/Philips hold a CD demonstration in Salzburg Jun: Sony/Philips officially announce the CD in New York Oct: CD and AHD format prototypes exhibited at the All-Japan Audio Fair Oct: Pioneer launches household LD player in Japan
1982	Aug: Red Book (CD-DA) announced Sep: Red Book made public Oct: Sony launches the tabletop CD player CDP-101, followed by other companies releasing their own CD players Oct: CD format proposed for IEC standardization
1983	May: Red Book subcode channels R-W standardized Oct: Yellow Book (CD-ROM standard) proposed In-car CD players start appearing in high-end vehicles
1984	Apr: CD-G standard proposed Sep: Pioneer announces LD/CD compatible player Nov: Sony launches low-price portable CD player D-50 (leads to widespread popularization of the CD player) Daiichi Kosho and Nikkodo launch business CD karaoke

1985	Jan: Philips/Sony/Microware Systems agree on CD-I standardization May: DEC manufacturers the first CD-ROM drive Sony/Philips announce Yellow Book (CD-ROM standard) Victor Music Industries launches business CD-G karaoke
1986	May: High Sierra Group proposes the High Sierra Format May: Philips/Sony announces provisional Green Book (CD-I standard) version Jun: Sony/Philips hold the first recordable CD standardization meeting Microsoft holds the first international conference on CD-ROM (USA) ISO establishes International Standard Recording Code (ISRC)
1987	Sony/Philips add CD-V standard to the Red Book Sony/Philips add CD-single specifications to the Red Book Feb: Sony/Philips determine CD-WO specifications Mar: GE (USA) announces DVI technology at second international conference on CD-ROM Jun: Green Book (CD-I standard) proposed Oct: CD-V player launched Nov: Sony/Philips announce basic agreement on CD-WO standard
1988	Feb: Sony/Philips Blue Book (CD-WO standard) proposed Feb: CD single title launched Apr: ISO 9660 standardized Aug: Sony/Philips/Microsoft agree on CD-ROMXA development Aug: Sony/Taiyo Yuden agree on recordable CD standardization and propose it to Philips Sep: Taiyo Yuden announces recordable CD Sep: Sony/Philips propose 8cm CD-ROM and cartridge Oct: Green Book specifications determined, CD-I player prototype disclosed
1989	Mar: Sony/Philips/Microsoft propose CD-ROMXA standard Apr: Sony/Philips distribute provisional Orange Book specification documents Jun: Sony/Taiyo Yuden establish joint venture Start Lab, commence CD-R manufacturing service Oct: Sony/Philips announce first edition of the Green Book Dec: DAVIS established to promote DVI
1990	Jan: CD-MIDI standard added to the Red Book Jun: First international conference on CD-I held (London) Jul: Orange Book Part 1 (CD-MO standard) and Part 2 (CD-WO standard) announced Jul: Sony launches the Data Discman Sep: Philips/Kodak announce the photo CD system Sep: CD single standard and CD-V single standard added to the Red Book Nov: Japan Standards Association establish JISX0606-1990 Microsoft formulates basic specifications for MPC Toyota, Nissan, Nihon Denso and Sumitomo Electric announce an automotive navigation system (Naviken format) Sony/Philips/Microsoft hold the first “Multimedia Conference on Interactive CD”
1991	Mar: CD-ROMXA standard added to the Yellow Book Mar: CD-I Consortium Japan established Oct: Household CD-I player and software titles launched in USA Oct: First “International CD-I Publishing & Developers Conference & Exposition” held Nov: CD-MIDI operating standard established (EIAJ) Dec: Nikkodo launches business CD-I karaoke system Dec: Ban announced for CD rentals of American labels and new releases Hardware manufacturers work together to achieve compatible CD-R drives and media
1992	Apr: Philips Japan launches consumer CD-I player CDI205 and CD titles Jul: Orange Book Part 2 (CD-R standard) announced Sep: Kodak Japan starts photo CD service in Japan Oct: Pioneer launches the world’s first 4× speed CD-ROM changer Oct: Daiichi Kosho, JVC and other companies launch business CD video karaoke Optical Storage Technology Association (OSTA) founded in the USA Sony launches business portable CD-I player “Intelligent Discman”
1993	Mar: White Book Ver 1.0 (karaoke CD standard) announced Aug: White Book Ver 1.1 (video CD standard) announced Oct: White Book Ver 1.1 (video CD standard) standards book distributed ISO MPEG-1 standard (ISO11172) announced
1994	Jan: Orange Book Part 2 Ver 2.0 (speed mode standard) standardized Jun: White Book Ver 2.0 (standard video CD with PBC function) announced Nov: 13 CD-R drive/media manufacturers launch the “Orange Study Group” for ensuring compatibility and examining standards Dec: Sony Computer Entertainment launches the PlayStation

1995	Jan: Seven companies, including Toshiba, Matsushita Electric and Pioneer, announce the next-generation optical disc "SD format" Jan: CD-ROM approved for publication appendices May: Orange Study Group standardizes the "Disc Identification Method" to ensure compatibility Aug: Sony/Philips/HP/Mitsubishi Chemical/Ricoh announce CD-E (CD-RW) Dec: Nine companies, including Matsushita/Toshiba and Sony/Philips, agree to unify the next-generation optical disc DVD standards. Standards group "DVD Forum" established at the same time.
1996	Mar: Orange Study Group renamed, 24 manufacturers establish the Orange Forum Jun: Open MPEG Windows Forum proposes video CD-ROM standard Sep: CD text standard added to the Red Book Oct: Orange Book Part 3 (CD-RW standard) announced Nov: Matsushita Electric and Toshiba launch DVD players
1997	Apr: Four licensers and Hitachi announce the "Video CD Internet Guidelines Version 1.0 1997" Apr: 10 companies, Matsushita Electric and Sony, announce unified DVD-RAM standard Oct: Pioneer launches the world's first DVD-R drive Dec: CCC commences DVD hardware/software rentals
1998	Aug: Orange Book Part 3 Ver 2.0 (CD-RW4× speed mode standard) announced Dec: Sony/Philips, Matsushita Electric and JVC announce Super VCD standard Ver0.9 Dec: Orange Book Part 2 Ver 3.1 (CD-R4× speed mode standard) announced
1999	Feb: DVD Forum establishes DVD audio format Mar: Sony/Philips announce the Scarlet Book (Super Audio CD standard) May: Sony launches SA-CD player Oct: Pioneer launches DVD audio player Nov: IEC approves Super VCD as international standard (IEC/SVCD standard)
2000	May: Orange Book Part 3 Vol 2 Ver 1.0 (CD-RW high speed mode standard) announced Jun: Matsushita Electric launches the world's first DVD-RAM video recorder Jul: Sony/Philips announce Purple Book (Double Density CD standard)
2001	Mar: CDs21 Solutions established (merge between the Orange Forum and MMCD) May: Orange Book Part 2 Vol 2 Ver 1.0 (CD-R high speed mode standard) announced DVD video sales surpass video cassette sales
2002	Feb: Blu-ray Disc standards group BDF (Blu-ray Disc Founders) established (participated by Sony/Philips, Matsushita Electric, Hitachi, Pioneer, Samsung, LG Electronics and Thomson) Mar: Copy controlled CD (CCCD) titles launched Sep: Orange Book Part 3 Vol 3 Ver 1.0 (CD-RW ultra speed mode standard) announced
2003	Apr: Sony launches Blu-ray standard video recorder (BDZ-S77) Apr: CDs21 Solutions announces recommended standards for optical cards (card CD-R)
2004	May: CDs21 Solutions announces that worldwide CD-R disc production topped 10 billion in 2003

Compact Disc (CD) Confirmed Location of Production Technology Historical Resources

No.	Name	Year manufactured	Manufacturer	Type of resource	Status of resource	Location	Reason for selection
1	CD player CDP-101	1982	Sony Corporation	Mass produced product	On display	Sony Archives, Kitashinagawa, Shinagawa, Tokyo	Sony’s first CD player, launched at the cutting edge of the industry. The player was released with the world’s first 50 titles on CD from CBS/Sony. With features such as side loading, this player established the basic pattern for CD players and is marked as the commemorative model, with later CD history considered to have started with this model.
2	CD compact player D-50	1984	Sony Corporation	Mass produced product	On display	Sony Archives, Kitashinagawa, Shinagawa, Tokyo	The portable CD player that triggered the sudden rise in CD popularity. Having achieved significant downsizing and successfully marketed at drastic prices, this player drove major expansion of the market and boosted the mainstream adoption of CD music media.
3	Super Audio CD player SCD-1	1999	Sony Corporation	Mass produced product	On display	Sony Archives, Kitashinagawa, Shinagawa, Tokyo	The first model of Super Audio CD (SACD) player, developed to be the successor to the CD with higher sound quality. Although the SACD itself was not widely adopted, the underlying direct stream digital (DSD) codec technology was well received for its high sound quality and was a forerunner in the evolution of high-resolution audio.