

INTRODUCTION BY EDITOR

The article following on the history of the development of the CD, written especially for this column by one of the engineers who participated in the development effort, should be of interest to all readers of this magazine. As one of the reviewers of the article noted, "CDs and successor optical discs are so much a part of our lives, it is fascinating to read about their genesis." As he goes on to note, "As an engineer, it is equally fascinating and insightful to see how technologies which now seem so obvious and inevitable were once open to debate." I venture to guess that this is true of almost all technologies, whether large systems or devices within systems. This is what makes reading about the history of a technology written by a participant in the development process so interesting. We learn not only of the successes in the

development process, but of the pitfalls and difficulties encountered and eventually overcome before the system could be deemed successful. As another reviewer noted, "I also appreciated the depiction of the human elements that are invariably part of these projects," in this case the initial naming of the project or the reasons for the choice of the final dimensions of the CD. The ability of two major companies, Philips and Sony, from two different parts of the world, to collaborate and come up with such a successful product is another fascinating lesson taught by this particular history. I suggest you read on to see all of this for yourself.

—Mischa Schwartz

THE EMERGENCE OF THE COMPACT DISC

HANS B. PEEK

INTRODUCTION

This article describes how the compact disc digital audio system, also known as the CD system, was the result of the successful merger of two major existing technologies. They are first, optical readout of information stored on an optical disc of 11.5 cm diameter, and second, the digital coding/decoding and digital processing of audio signals. I will describe how a complete digital version of this new audio system gradually emerged, within Philips, during the period 1973–1979. Finally, this paper recounts the partnership and collaboration between Philips and Sony that resulted in a common CD standard in June 1980 which soon after became the world standard. More details on the history of the CD not discussed here can be found in a lively, and accurate, doctoral thesis (in German) by J. Lang [1] and in a recent book [2].

A LOOK INTO A SUCCESSOR OF THE RECORD PLAYER

In the 1970s the high-fidelity (Hi-Fi) record player and its LP (long play) vinyl record became increasingly the weakest product in the audio product range. Whereas most audio equipment was downscaled in size, this was impossible for the Hi-Fi player with its large disc with a 30 cm diameter. Furthermore, the LP record was vulnerable and had to be handled with care. A scratch or accumulation of dust could spoil the enjoyment of the reproduced music.

Aware of these limitations, L. Ottens, the technical director of the

audio industry group within the Philips Corporation in Eindhoven, the Netherlands, started to look for smaller and better performing alternatives for the record player and its LP record. The small size of a compact cassette was an attractive feature. Although its sound quality improved in the 1970s, mainly by using better magnetic tape-coatings and companding, it became no better than an LP record.

At that time, when Ottens was looking for a suitable successor of the record player, the optics department, headed by P. Kramer, of the Philips research laboratory in Eindhoven, also known as the Nat.Lab. (Natuurkundig Laboratorium), was experimenting with a completely new system for recording and playback of analog video color signals.

THE VLP SYSTEM: A HARDLIMITED ANALOG PRECEDENT OF THE DIGITAL AUDIO CD

The Video Long Play (VLP) system, presented to the press in 1972, used a laser to record a video color signal on an optical disc and another laser in a VLP player for playback. In 1974 the VLP was released to the market. Later, in 1978, this optical video system was introduced on the market in the United States, known as LaserVision.

In the VLP system a frequency-division multiplex signal consisting of a TV luminance and chrominance signal plus a sound (stereo) signal is frequency modulated (FM) and then hardlimited, after which it is ready for recording on an optical master disc [3]. Production "stamps" made from this master disc

replicate the information as a consumer product by compression or injection molding of a transparent plastic disc of 30 cm diameter. The information appears on a spiral track consisting of microscopic pits separated by flat areas called lands. Finally, after receiving a reflective coating over which a transparent and protective lacquer is applied, the VLP disc is ready for playing. In a VLP player [2, Sec. 2.3, 4] the spiral track on the disc is scanned by a 1 mW Helium-Neon laser with a wavelength $\lambda = 633$ nm. The laser beam in the player is focused by an objective lens on the information layer of the disc that lies underneath a transparent protective layer. When the spot of the beam falls on a land, the light is almost totally reflected and reaches a photodiode. However, when the spot falls on a pit, the depth of which is about a quarter of the wavelength of the laser light, interference and extinction occur, which causes less light to be reflected and reach the photodiode. The output signal of the photodiode is ideally a fair representation of the original recorded signal.

Unfortunately, there are several sources of errors that can occur in or on an optical disc. First, small unwanted particles or air bubbles in the plastic material, or pit damage, may occur in the replication process. Second, fingerprints or scratches may appear on the disc when handled. As a consequence, damage can occur not only to isolated pits but also a sequence of pits and even a substantial burst of pits, resulting in dropout.

There are two reasons why these bursts do not seriously affect the pic-

ture quality in the VLP system. The first reason, generic to all optical storage systems, is that the diameter of the beam at the surface of the disc is much wider than the diameter of the spot at the information layer. As a result, local defects and imperfections at the disc surface effectively get blurred and de-emphasized in the readout signal. This effect is inherent in reading out a disc through a transparent substrate, and constitutes one of the essential patents of the CD system [5]. The second reason is that in a TV picture there is a high correlation between successive lines that causes a burst to be less visible. Furthermore, there is a high correlation between successive TV frames, which in addition enhances the masking of an error burst.

In the period 1972–1979 Philips was not the only company that was active in the research and development of optical recording and playback of video, audio, and data. For many an attractive property of optical systems was also that there was no contact between the disc and the pickup unit: thus, no wear

and tear. Another important feature was that an optical system made random access possible. Several companies such as Sony, Mitsubishi, Hitachi, Pioneer, Toshiba, TEAC Corporation, Tokyo Denka Corporation, and Nippon Columbia investigated optical signal registration and playback on 30 cm diameter discs.

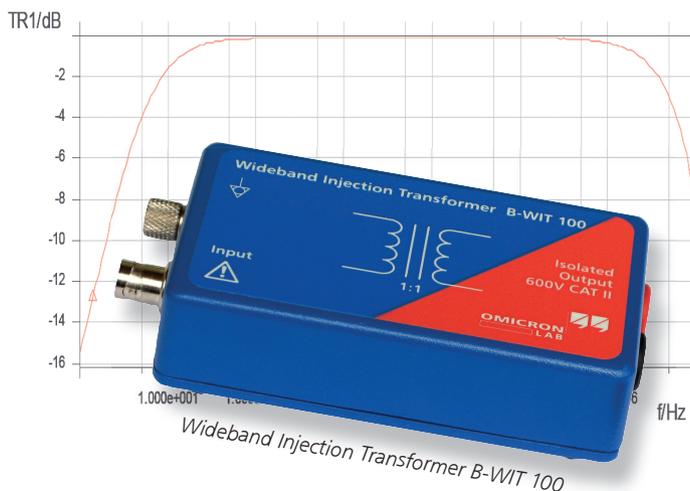
After 1972 most of these companies started investigating analog signal optical recording systems, but at the end of the 1970s some turned to digital signal optical recording. Digital signals are those for which both time and amplitude are discrete. The signal recorded on a VLP is discrete-amplitude but not discrete-time and is an analog signal. Already in 1965, J. T. Russell at the Battelle Northwest Laboratory in Richland, Washington, considered storage of digital information on an optical disc. In 1970 he was granted a patent on an analog-to-digital photographic recording and playback system (U.S. Patent 3,501,586). In 1969 M.D. Gregg was granted a patent on an optical video disc [U.S. Patent 3,430,966]. It is not

easy to describe, briefly, the differences between the systems described in these two patents and the Philips-Sony CD standard established in 1980. But let me mention only one crucial difference. The recording and playback in the CD system of two digital audio signals during one hour and with for the most part a signal-to-noise ratio (SNR) of 97 dB was impossible without using error correction and error concealment. The signal mentioned in Gregg's patent is analog, which excludes the use of an error correcting code. Although the signal described in Russell's patent is digital, no error correction is mentioned.

THE ALP PROJECT

Ottens, who was well informed about the VLP technology, asked his engineers, T. van Alem and L. Boonstra from Nat.Lab., to investigate the possibilities for optical recording and playback of four (quadro) Hi-Fi audio signals stored on an optical disc with a diameter of 20 cm. Quadro sound was seen as an enriched sound experience compared to stereo sound. After a pre-

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liminary study, the Nat.Lab. was asked for additional support in this project.

Consequently, a project group was formed early in 1974. This project group consisted of engineers T. van Alem, C. Vos, and J. van Veerdonk, all from Audio, and three researchers from the Nat.Lab., one of whom, L. Boonstra, also functioned as project coordinator and reporter. The other two were engineer L. Vries and his assistant M. Diepeveen, who were both members of my research department. In 1975 J. Mons from Audio joined the project group. The project was named ALP (Audio Long Play), which indicates its affinity with VLP.

For L. Vries and myself there was an important reason to prefer a digital registration of audio signals above an analog one. Since we were aware of the existence of dropouts on a VLP disc, we seriously doubted the possibility to play back Hi-Fi sound using an analog registration. Audio did not have the same kind of redundancy as video. With digital registration, we knew that an error correcting code could be used

that would correct random errors and burst errors to a certain extent.

Those errors that could not be corrected but only detected could be made inaudible by using suitable masking (concealment) techniques. The human auditory system as well as the human visual system can be deceived.

However, a digital ALP system would be more complex and expensive to implement at that time. This was precisely the problem for Audio. The restricted development capacity for digital equipment at that time, and the likely higher price for a digital player, prohibited consumer audio systems from going digital. We agreed, however, that if an analog ALP would not function properly, we would turn to a digital ALP. While the Audio industry group started the development of a small analog player with a 20 cm optical disc, L. Vries and M. Diepeveen began by studying, and later building, a modem for the ALP. The following concept for the modem was adopted. In the modulator, four Hi-Fi analog sound signals were modulated in quadrature on two

subcarriers. This frequency-division multiplex signal was then FM modulated. Finally, this FM signal was hardlimited and thus made suitable for recording on an optical master disc. Two different demodulators were built and compared for their different responses to dropouts. One was a conventional time-delay demodulator and the other a phase-locked loop.

At the end of 1975 the ALP player and disc were ready for playing and testing. It turned out that the dropouts caused too many audible clicks and other disturbances, and neither of the two demodulators delivered Hi-Fi sound. Thus, the analog ALP turned out to be a dead end.

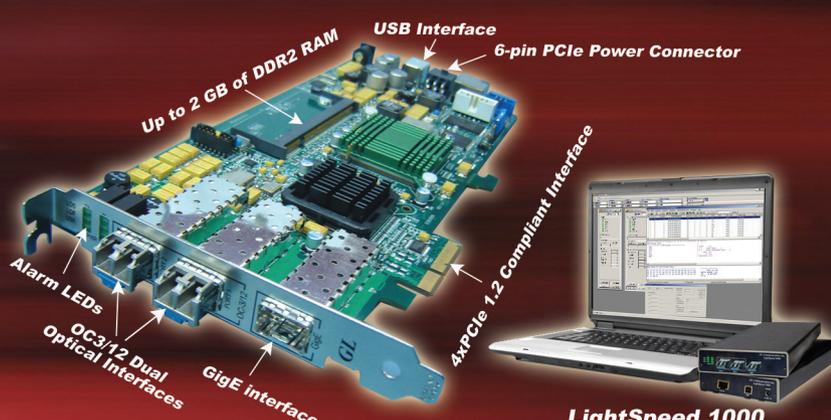
The next step the ALP project group took was an ALP system using delta modulation (DM), but without applying an error correcting code. Delta modulation, with slow companding, required almost twice the bit rate of pulse code modulation (PCM) but was easier to implement. With slow companding, a DM signal did mask single and double bit errors. However, with the near instantaneous companding required for a lower bit rate, the DM signal became sensitive to single bit errors that caused audible clicks. No masking of dropouts was applied. Application of an error correcting code was inevitable.

Nevertheless, a DM-ALP was demonstrated to the Philips Board of Management on 25 November, 1977. The Board of Management concluded that the sound quality had to be improved and must be made superior to that of an LP record. They also emphasized that the directors of the Audio industry group must aim at achieving a world standard for this new optical audio system. They did not want a repetition of multiple standards as had occurred with television, which had three standards: NTSC, PAL and SECAM, and with the videocassette recorder (VCR), which also had three standards: VHS, Betamax, and V2000.

THE PHILIPS PROTOTYPE COMPACT DISC SYSTEM

With these directions of the Board of Management in mind, the directors of the Audio industry group decided to increase their efforts. On a suggestion of J. van Tilburg, Audio's general director, the name "ALP" was changed to "compact disc" or just CD. The word "compact" was in line with another Philips product, the compact cassette. The diameter of a CD disc was set at 11.5 cm, equal to the diagonal measure

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of a compact cassette. The playing time of the digital optical disc was limited to one hour. What's more, the Audio directors decided to establish a Compact Disc Laboratory with the mission of creating a prototype of a CD player and disc that could be shown and demonstrated to the outside world. J. Sinjou, head of the CD Lab., had a 35-person team. He was also given the task of coordinating the CD project within Philips.

At the start of 1978 discussions followed, both within the CD Lab. and between the CD Lab. and the Nat.Lab., with the purpose to determine the technical parameters of a CD system. The Nat.Lab. had excellent expertise not only in optics but also in digital communications, digital signal processing and solid state D/A converters. This expertise was essential for Audio in realizing a CD system. After a brief period of discussions between the CD Lab. and the Nat.Lab., a number of technical specifications and parameters were determined, such as:

- With PCM and 14 bits uniform quantization for each of the two sound signals, a SNR of 85 dB for each signal was guaranteed, sufficient to make the quantization noise inaudible.
- Specification of a recorded bandwidth of 0–20 kHz for each of the two sound signals with a sampling frequency of 44.3 kHz.

The error correction code should ideally be based on the error statistics of mass produced CD discs, but that was not yet possible. However, preliminary measurements made by M. Carasso of the Nat.Lab. optics department had shown that most errors on a digital optical disc were single, double, or triple bit errors [2, Sec.2.4, 8]. There also occurred now and then an error burst (dropout) with a maximum length of about 200 bits. To correct these errors, L. Vries had developed a 2/3 rate convolution code that was based on ideas put forward by E. Berlekamp [6] and E. Preparata [7].

The input to the coder was a serial stream of blocks, each consisting of 14 bits (one audio sample). The coder divided a 14-bit block into seven symbols, each consisting of two bits. In the coder a parity bit was added to each 2-bit symbol resulting in a 3-bit output symbol. This gave output blocks of 21 bits, corresponding to a 2/3 rate code. This code was able to correct at most two erroneous 3-bit symbols in two consecutive output blocks. If more than two 3-bit symbol errors in an output

block of 21 bits occurred, the decoder detected an erroneous output block. This erroneous block, corresponding with one 14-bit audio sample, was replaced by a sample obtained by linear interpolation from two adjacent reliable samples. The remaining error was inaudible.

The longer bursts with length up to 200 bits were corrected by using interleaving in combination with the rate 2/3 convolution code. By using interleaving before recording, a burst of errors in the input stream of the decoder is, after de-interleaving in a CD player, spread out in time, allowing these now scattered errors to be corrected by the convolutional code. In this way a maximum burst length of 210 bits was corrected [2, Sec. 2.4, 8]. If the interval between two successive long bursts was too small, correction was impossible. Such a situation, however, could be detected and muting of the audio signal applied. Muting can be inaudible provided the time duration did not exceed 10 ms. B. Cardozo and G. Domburg observed in [9] that a dropout occurring in music

recorded on magnetic tape was inaudible provided its duration was below 10 ms. Muting can occur, or be obtained, in two ways. One way is to turn off the audio signal, which takes it abruptly to zero and lets it later return abruptly to the normal audio level. This way of muting is audible [9]. The second type of muting as observed by dropouts in magnetic recording was a different type and inaudible. In that case, the signal did not go to zero abruptly but gradually, and later gradually returned to the normal audio level. This type of muting can be used to suppress audible disturbance caused by a scratch on a record [10], but it was also applied in the CD prototype when an error burst could not be corrected but was still detected.

The science of psychoacoustics evaluates the perceptual implications of linear interpolation, muting, companding, quantization noise, and many other processing or environmental factors affecting audio signals. L. Vries and M. Diepeveen took this work into account in building a codec, delivered to Audio in the summer of 1978, that included

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Figure 1. From left to right: J. Vig, President of the IEEE, at the Milestone Award ceremony on March 6, 2009, and R. Harwig, CTO of Royal Philips Electronics.

linear interpolation and muting [2, Sec. 2.4, 8].

After encoding for error correction at the recording side in a CD system, it is necessary to modulation code this output signal. There are several reasons why modulation coding (also known as line coding) is required. The first reason is that direct recording of the error

correction encoder output signal would seriously disturb the servo subsystem in the player that keeps the beam on track. The disturbance is caused by the energy present in the lower frequency range of a binary signal. A first purpose of modulation coding is to shape the spectrum of the signal to be recorded in such a way that it has very little spectrum con-

tent at low frequencies. This requirement is similar to that found in data transmission and digital magnetic recording on tape or disc. Numerous modulation codes have been proposed and used in the past. Many of these were aimed at a specific application.

Another reason for modulation coding is that the light spot with which a CD in a player is scanned has finite dimensions. This causes intersymbol interference (ISI). By imposing, through a modulation code, a lower limit on the length of a recorded run of only ones or zeros, the ISI can be minimized.

Finally, the binary signal transferred to the master disc must be such that it is possible to regenerate the bit clock frequency from the signal picked up from a CD disc. This requirement can be met by imposing an upper limit on the length of a run of all ones or zeros.

A modulation code called M3, invented by M. Carasso from Nat.Lab., and W. Kleuters and J. Mons from the Audio industry group, was used in the CD prototype. This M3 code is a modified Miller code. Although this code was not described in a journal or conference paper, it is covered in a U.S. patent [11]. If T is the bit period at the input of the M3 modulator, the minimum run length at the output of the M3 modulator is T , while the maximum run length is $3T$. Furthermore, the M3 code is DC free.

A further significant contribution of the Nat.Lab. was a completely monolithic 14-bit digital-to-analog (D/A) converter, described in [2, Sec. 2.5, 12] by R. van de Plassche and D. Goedhart. Two of these D/A converters were used in the prototype system. In 1978 it was the only monolithic one available on the market with that resolution.

Just before Christmas in 1978, the small player was finished, and J. Sinjou showed it to the community of the CD Lab.. He said “this here is our small boy, shall we give him a name.” One of his engineers, J. Mons, shouted “his name is Pinkeltje.” Pinkeltje was a dwarf and the central figure in a Dutch fairy tale written by D. Laan. On many evenings Mons read this book to his children.

On February 6, 1979 the CD prototype system, or just Pinkeltje, with 11.5 cm discs made at the CD Lab., was demonstrated to audio experts (in German called Tonmeisters) from PolyGram in Baarn, the Netherlands. PolyGram was founded in 1972 by a merger of the Philips and Siemens LP record production units. They had also

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produced VLP records. Before deciding whether or not to produce CD discs, they wanted to determine if the sound quality of this new audio system was up to their standard. During the listening tests that day, the audio experts switched many times between the music from the CD player and that from the original analog master tapes. These audio experts could not determine any difference in sound quality. I noticed that the muting operation in the player was frequently activated, demonstrating that it was effective.

In line with their strategic plan, the directors of the Audio business division decided that the time had come to go public with the CD system. Thus, on March 8, 1979, at Philips in Eindhoven, the prototype CD system and disc were presented and demonstrated to an audience of about 300 journalists by J. Sinjou. The text of his presentation is printed in [2, Sec. 2.2]. Referring to this demonstration, R. Bernard noted in his paper [13] that “demonstration systems have been impressive, and the total lack of background noise of any kind during pauses in musical passages is particularly dramatic.”

The sequence and purpose of the successive signal processing operations in the CD prototype system, from the studio to the home of a listener, did not change when Philips and Sony established a joint standard in June 1980. What changed, however, in the Philips-Sony standard was that the successive signal processing operations became more powerful and effective. These successive signal processing operations were: A/D conversion, error correcting encoding, modulation coding, modulation decoding, error correction, concealment of detected errors, and finally D/A conversion.

THE PHILIPS-SONY COOPERATION

After the CD prototype system had been shown, demonstrated, and made public on March 8, 1979, it was essential for the directors of Philips Audio to find a strong industrial partner that would be interested in cooperating in attaining a common CD system standard. Consequently, the Audio directors approached several Japanese companies to ask if they would receive a delegation so that the Philips CD prototype could be shown and demonstrated. There were many positive responses, and the following companies were visited in succession: JVC, Sony, Pioneer, Hitachi, and MEI (Matsushita). The DAD (Digital Audio Disc Committee) was also visited. The Japanese Ministry

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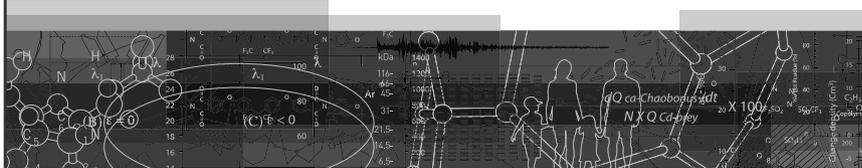
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of Industry and Trade had assigned DAD the task to evaluate various digital audio disc systems that were being developed and to recommend a world standard.

The period of the Philips Audio delegation visit was March 14–23, 1979. On the last day of their visit, J. van Tilburg received a phone call from A. Morita, the chairman of Sony. Morita said that, after consulting the management of Sony, he had decided to cooperate with Philips. Soon, the vice chairman of Sony, N. Ohga, would come to Eindhoven to discuss the contract. Sony was an ideal partner for Philips. It not only had an excellent position in products related to digital recording of audio on magnetic tape, but had also developed a prototype optical digital audio player and disc.

On September 2, 1977, T. van Kessel, also a department head at the Nat.Lab., and I visited Sony's research laboratory in Tokyo to observe the state of the art in their digital audio recording. In the morning T. Doi showed and explained to us two digital audio recording products of Sony. The first was a consumer product, the "PCM-1" that used 13-bit nonuniform quantization. The second was a recorder for the professional market, the "PCM-1600." This recorder had been developed together with NHK (Nippon Hoso Kyokai, the Japanese Broadcasting Corporation) and used 16-bit quantization and error correction, and later in the 1980s turned out to be essential for mastering CD discs. Doi said that Sony was studying optical digital audio systems.

Later that year at the "Tokyo Audio Fair," Sony and Hitachi exhibited prototypes of optical digital audio players and discs. The diameter of both optical discs, however, was 30 cm, much larger than the 11.5 cm of the Philips disc. At the 58th AES Convention in November 1977, three authors from three other Japanese companies presented a paper [14] on an optical digital audio system with a 30 cm diameter disc. These three companies were TEAC Corporation, Mitsubishi Electric Company, and the Tokyo Denka Company. Sony's digital audio optical disc system with a playing time of two and a half hours that used error correction and a 30 cm diameter disc is described in [15].

To establish a common standard for the CD system, Philips and Sony agreed to a sequence of meetings to be held alternately in Eindhoven and Tokyo. During these meetings, the technical experts from Philips and Sony worked out issues including the playing time of

*J. SINJOU PUT A DUTCH COIN,
A DIME, ON THE TABLE.
ALL AGREED THAT THIS WAS
A FINE SIZE FOR THE HOLE.
COMPARED WITH OTHER LENGTHY
DISCUSSIONS, THIS WAS
A PIECE OF CAKE.*

a disc, its diameter, the audio sampling frequency, the signal quantization (bits per sample), and the signal format to be used. The signal format specifies the purpose of each bit in a recorded frame on a disc.

To fix the signal format, Philips and Sony also had to agree on the modulation code and error correction code to be used. It turned out that these latter two issues would require the most time to settle. The reason for this is likely that the Philips-Sony team was informed about several decades of communications theory and practice; thus, there was a large variety of options from which to choose.

A period of intense discussions, correspondence, computer simulations, and performance measurements of discs followed. At the first of six meetings, on August 27 and 28, 1979 in Eindhoven, the two companies had different proposals not only for error correction but also for modulation coding. A detailed description of how Philips and Sony established, during their six meetings, the final error correction and modulation codes can be found in [2, Sec.3.1]. This description explains that these two final codes had superior performance to the initial proposals of Philips and Sony. In other words, these were the result of true interaction and cooperation. The standard for error correction was called "cross interleaved Reed Solomon code" (CIRC), whereas the standard for modulation coding was called "eight-to-fourteen modulation" (EFM). The last meeting in Tokyo was on June 17 and 18, 1980.

Philips and Sony decided, in June 1980, to apply for two patents, one on CIRC and the other on EFM. These two patents were later granted by the U.S. Patent office and are registered as:

- K. Odaka, Y. Sako, I. Iwamoto, T. Doi (all from Sony), L. Vries (Philips), "Error Correctable Data Transmission Method," U.S. Patent 4,413,340, 1983.
- K. Immink, J. Nijboer (both from Philips), H. Ogawa, K. Odaka (both from Sony), "Method of

Coding Binary Data," U.S. Patent 4,501,000, 1985.

Together with the patent of P. Kramer [5], these three patents are essential for the CD system.

Furthermore, the following important parameters were fixed during the Philips-Sony meetings: a 44.1 kHz sampling frequency, a 16-bit uniform signal quantization, a playing time of approximately 60 minutes, and a disc with a diameter of 12 cm.

The full Philips-Sony CD standard is described in the so-called "Red Book" but is also available in a publication of the International Electrotechnical Commission (IEC) [16].

According to J. Sinjou, the diameter of 11.5 cm of the prototype disc was, by a personal wish of N. Ohga, changed to 12 cm. Using a 12 cm disc, a particular performance of Beethoven's Ninth Symphony, a favorite of N. Ohga with a length of 74 minutes, could be recorded. Another anecdote is how the size of the central hole in a disc, which had to be standardized as well, was determined. When this issue turned up during one of the Philips-Sony meetings, J. Sinjou put a Dutch coin, a dime, on the table. All agreed that this was a fine size for the hole. Compared with other lengthy discussions, this was a piece of cake.

FINAL REMARKS

In 1982, CD players and CDs came on the market. Soon after that the music loving world embraced this new way of listening to music. The advent of the CD system was followed by several decades of development of digital optical disc systems for reproduction and recording of computer data, music, and video. To name only a few, they include CD-ROM, CD-R, CD-RW, DVD, and recently Blu-ray [2, chapters 4–6]. This evolutionary process was set in motion on March 8, 1979, when a prototype of a CD system, with a small disc, was publicly presented and demonstrated.

To commemorate this breakthrough, Royal Philips Electronics recently received a prestigious IEEE Milestone Award in Eindhoven. On March 6, 2009, IEEE President J. Vig presented this award to R. Harwig, chief technology officer of Philips Electronics, at a ceremony that was hosted by Eindhoven's Technical University and Philips. At the ceremony, a presentation on the history of the CD was given by J. Sinjou, and H. Ogawa, a member of the Sony team in 1979–1980, gave a presentation on Sony's developments related to the CD system.

During the award ceremony, I pre-

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sented the first copy of the Milestone Book with the title *Origins and Successors of the Compact Disc* [2] to J. Sinjou. This book provides much more detail, including reprints of key papers, on the origins of the CD system and the subsequent evolution of digital optical storage, with a focus on the contributions of Philips.

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BIOGRAPHY

HANS B. PEEK [SM'75, F'87, LF' 06] received his degree in electrical engineering from the Technical University of Delft, the Netherlands, in 1959, and his Ph.D. degree from the Technical University of Eindhoven, the Netherlands, in 1967. In 1961 he joined Philips Research Laboratories, Eindhoven, where he was involved in the areas of digital signal processing and communications, and was a department head from 1969 to 1987. From 1987 to 1991 he was chief scientist at the same laboratories, and from 1987 to 2001 he was a part-time professor at Nijmegen University, the Netherlands. He was the recipient of various awards, including the Gold Medal from the Dutch Veder Foundation in 1967, the *IEEE Communications Magazine* Best Paper Award in 1985 for his paper, "Communications Aspects of the Compact Disc Digital Audio System," and the IEEE Millennium Medal 2000. He is a member of Eta Kappa Nu.



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