Champions in Our Midst

By Peter Corcoran

WELCOME TO A NEW SERIES OF ARTICLES FOR *IEEE Consumer Electronics Magazine*. One of the benefits of joining the IEEE Consumer Electronics (CE) Society is that you get access to senior engineers and researchers from our industry. They are often at our conferences, workshops, and local Chapter meetings and frequently play an active role in the organization of Society activities.

Immink helped jump-start the digital video and audio revolution.

Many of our members are also well known professionally within their own field and have championed some of the many foundation technologies on which our industry relies. There are a few of these champions within our Society, and this series of articles is intended to introduce you to them so that should you bump into them at one of our conferences or workshops, you will know who they are and why they are involved in the CE Society.

I met the first of our "Champions of CE" while presenting a poster at the International Conference on Consumer Electronics, and he was kind enough to engage me in a very interesting discussion at the time. Thus, I am very pleased to introduce as our first champion, a gentleman who is an acknowledged guru of coding in CE applications, Kees Immink.

It is virtually impossible to hear digital audio or watch digital video that does not reflect the work of Kees A. Schouhamer Immink. His contributions to coding systems quite literally jump-started the digital video and audio revolution, by enabling reliable data storage at information densities previously thought unattainable. Immink's coding methods are crucial to compact disc (CD), CD-ROM, CD-1, MiniDisc, CD-Video, DVD, digital compact cassette, digital video recorder, the optical digital video recorder, and other tools. He holds almost 70 U.S. patents for the coding systems he has developed.

Immink was born in Rotterdam, The Netherlands, on 18 December 1946. He earned his B.S. degree from Rotterdam Polytechnic and his M.S. and Ph.D. degrees at the Eindhoven University of Technology. He joined Philips Research Laboratories in 1971. In his years there, he

Digital Object Identifier 10.1109/MCE.2014.2338571
Date of publication: 2 October 2014

2162-2248/14©2014IEEE

and his colleagues conducted some of the world's earliest experiments with optical video-disc recording. A few years later, he was a technical leader in the negotiations between Sony and Philips that led to industry standards for the CD.

During his long career at Philips, Immink served in many capacities in various research groups, including Electronic Systems, Optics, and Magnetic Recording Systems. In 1992, he was appointed a Philips Research Fellow.

Immink is the author of *Coding Techniques for Digital Recorders*, which has become the standard reference book of the field. He has also written several papers, articles, and book chapters. Since 1995, he has been an adjunct professor at Essen University's Institute for Experimental Mathematics in Germany and also affiliated with the National University of Singapore as a visiting professor since 1997.


Kees Immink.

Immink is a fellow of the Audio Engineering Society (AES) and the Society of Motion Picture and Television Engineers. He is a member of the Royal Netherlands Academy of Arts and Sciences, and the (U.S.) National Academy of Engineering. For his contributions to the digital audio and video revolution, he received the Golden Jubilee Award for Technological Innovation from the IEEE Information Theory Society, the IEEE Masaru lbuka Consumer Electronics Award, the IEE J.J. Thomson Medal, both the Silver Medal and Gold Medal awarded by the AES, and the IEEE Edison Medal in 1999 "for a career of creative contributions to the technologies of digital video, audio, and data recording." He received an Emmy for his groundbreaking contributions to DVD and Blu-ray disc television technology. Immink is an IEEE Fellow.

The Story of the Compact Disc

… and Beethoven's role in the specifications!

This article was originally published in the IEEE Information Theory Newsletter, *December 2007*.

An audio compact disc (CD) holds up to 74 min, 33s of sound, just enough for a complete mono recording of Ludwig von Beethoven's Ninth Symphony ("Alle Menschen werden Brüder") at probably the slowest pace it has ever been played, during the Bayreuther Festspiele in 1951 and conducted by Wilhelm Furtwängler. Each second of music requires about 1.5 million b, which are represented as tiny pits and lands ranging from 0.9 to 3.3 μm in length. More than 19 billion channel bits are recorded as a spiral track of alternating pits and lands over a distance of 5.38 km (3.34 mi), which are scanned at walking speed, 4.27 km/h.

It is now more than 30 years ago that Philips and Sony first introduced the CD. In this article, we discuss the various crucial technical decisions that would determine the technical success or failure of the new medium.

Shaking the Tree

In 1973, I started my work on servo systems and electronics for the videodisc in the optics group of Philips Research in Eindhoven. The videodisc is a 30-cm-diameter optical disc that can store up to 60 min of analog FM-modulated video and sound. It is like a DVD, but much larger, heavier, and less reliable. The launch of the videodisc in 1975 was a technical success but a monumental marketing failure since the consumers showed absolutely no interest at all. After two years, Philips decided to throw in the towel, and they withdrew the product from the market.

While my colleagues and I were working on the videodisc, two Philips engineers were asked to develop an audio-only disc based on optical videodisc technology. The two engineers were recruited from the audio department, since my research director believed a sound-only disc was a trivial matter given a video and sound videodisc, and he refused to waste the precious time of the researchers. In retrospect, given the long-forgotten videodisc and the CD's great success, this seems a remarkable decision.

The audio engineers started by experimenting with an analog approach using wideband frequency modulation as in FM radio. Their experiments revealed that the analog solution was scarcely more immune to dirt and scratches than a conventional analog LP. Three years later, they decided to look for a digital solution. In 1976 and later, Philips and Sony independently demonstrated the first prototypes of a digital disc using laser videodisc technology. In 1977, Sony completed a prototype with a 30-cm-diameter disc, the same as the videodisc, and 60-min playing time [2].

In October 1979, a crucial high-level decision was made to join forces in the development of a world audio disc standard. Philips and Sony, although competitors in many areas, shared a long history of cooperation, for instance, in the joint establishment of the compact cassette standard in the 1960s. In marketing the final products, however, both firms would compete against each other again. Philips brought its expertise and the huge videodisc patent portfolio to the alliance, and

Sony contributed its expertise in digital audio technology. In addition, both firms had a significant presence in the music industry via CBS/Sony, a joint venture between CBS Inc. and Sony Japan Records Inc. dating from the late 1960s, and Polygram, a 50% subsidiary of Philips [4].

The Sony–Philips Liaison

Within a few weeks, a joint task force of experts was formed. As the only electronics engineer within the optics research group, I participated and dealt with servos, coding, and electronics at large. In 1979 and 1980, a number of meetings, alternating between Tokyo and Eindhoven, were held. The first meeting, in August 1979 in Eindhoven, and the second meeting, in October 1979 in Tokyo, provided an opportunity for the engineers to get to know each other and to learn each other's main strengths. Both companies had shown prototypes, and it was decided to take the best of both worlds. During the third technical meeting on 20 December 1979, both partners wrote down their lists, of preferred main specifications for the audio disc.

> The audio engineers started by experimenting with an analog approach using wideband frequency modulation as in FM radio.

Although there are many other specifications, such as the dimensions of the pits, disc thickness, diameter of the inner hole, etc., these are too technical to be discussed here. As can be seen from Table 1, a lot of work had to be done, as the partners agreed only on one item, i.e., the 1-h playing time. The other target parameters—sampling rate, quantization, and, notably, disc diameter—look very similar but were worlds apart.

Shannon–Nyquist Sampling Theorem

The Shannon–Nyquist sampling theorem dictates that to achieve lossless sampling, the signal should be sampled with a frequency at least twice the signal's bandwidth. So for a bandwidth of 20 kHz, a sampling frequency of at least 40 kHz is required. A large number of people, especially young people, are perfectly capable of hearing sounds at frequencies well above 20 kHz. That is, in theory, all we can say. In 1978, each and every piece of digital audio equipment used its own "well-chosen" sampling frequency ranging from 32 to 50 kHz. Modern digital audio equipment accepts many different sampling rates, but the CD task force opted for only one frequency, i.e., 44.1 kHz. This sampling frequency was chosen mainly for logistics reasons, as will be discussed later, once we have explained the state of the art of digital audio recording in 1979.

Table 1. Philips' and Sony's initial preferences for the audio disc specifications in December 1979.

Item	Philips	Sony
Sampling rate (kHz)	44.0–44.5	44.1
Quantization	14 b	16 b
Playing time (min)	60	60
Diameter (mm)	115	100
EC code	To be discussed	To be discussed
Channel code	M3	To be discussed

Toward the end of the 1970s, PCM adapters were developed in Japan that used ordinary analog videotape recorders as a means of storing digital audio data, since these were the only widely available recording devices with sufficient bandwidth. The best commonly available video recording format at the time was the 3/4-in U-Matic.

The presence of the PCM video-based adaptors explains the choice of sampling frequency for the CD, as the number of video lines, frame rate, and bits per line end up dictating the sampling frequency one can achieve for storing stereo audio. The sampling frequencies of 44.1 and 44.056 kHz were the direct result of a need for compatibility with the NTSC and PAL video formats. Essentially, since there were no other reliable recording products available at that time that offered other options in sampling rates, the Sony–Philips task force could only choose between 44.1 or 44.056 kHz and 16-b resolution (or less).

During the fourth meeting held in Tokyo 18–19 March 1980, Philips accepted, following Sony's original proposal, the 16-b resolution and the 44.1-kHz sampling rate. For the simple reason that it was easier to remember, 44.1 kHz (as opposed to 44.056 kHz) was chosen. Philips dropped their wish to use 14-b resolution: they had no technical rationale as the wish for the 14 b was, in fact, only based on the availability of their 14-b digital–analog converter. In other words, the CD sound quality equals the sound quality of Sony's PCM-1600 adaptor.

Thus, quite remarkably, in recording practice, an audio CD starts life as a PCM master tape, recorded on a U-Matic videotape cassette, where the audio data are converted to digital information superimposed within a standard television signal. The industry standard hardware to do this was the Sony PCM-1600, the first commercial video-based 16-b recorder, followed by the PCM-1610 or PCM-1630 adaptors. Until the 1990s, only video cassettes could be used as a means for exchanging digital sound from the studios to the CD mastering houses. Later, exabyte computer tapes, CD-Rs, and memory sticks have been used as a transport vehicle.

Coding Systems

Coding techniques form the basis of modern digital transmission and storage systems. There had been previous practical applications of coding, especially in space communications, but the CD was the first mass-market electronics product equipped with fully fledged error-correction and channel-coding systems. To gain an idea of the types of errors, random versus burst errors, burst length distribution, and so on, we made discs that contained known coded sequences. Burst error length distributions were measured for virgin, scratched, or dusty discs. The error measurement was relatively simple, but scratching or fingerprinting a disc in such a way that it can still be played is far from easy. How do you get a disc with the right kind of sticky dust? During playing, most of the dust fell off the disc into the player, and the optics engineers responsible for the player were obviously far from happy with our dust experiments. The experimental discs we used were handmade and not pressed as commercial mass-produced polycarbonate discs are. In retrospect, I think that the channel characterization was a far from adequate instrument for the design of the error-correction control (ECC).

There were only two competing ECC proposals to be studied. Experiments in Tokyo and Eindhoven—Japanese dust was not the same as Dutch dust—were conducted to verify the performance of the two proposed ECCs. Sony proposed a byte-oriented, rate 3/4, cross interleaved Reed–Solomon code (CIRC) [6]. Vries of Philips designed an interleaved convolutional, rate 2/3 code having a basic unit of information of 3-b characters [9]. CIRC uses two short Reed–Solomon codes, i.e., (32, 28, 5) and (28, 24, 5), using a Ramsey-type interleaver. If a major burst error occurs and the ECC is overloaded, it is possible to obtain an approximation of an audio sample by interpolating the neighboring audio samples, thus concealing uncorrectable samples in the audio signal. CIRC has excellent features to make error concealment possible, extending the player's operation range [10]. CIRC showed both a much higher performance and code rate (and thus playing time), although it was extremely complicated to cast into silicon at the time. Sony used a 16-kB RAM for data interleaving, which cost around US$50 at the time and added significantly to the sales price of the player. During the fifth meeting in Eindhoven, May 1980, the partners agreed on the CIRC error-correction code since our experiments had shown its great resilience against mixtures of random and burst errors [11]. The fully correctable burst length is about 4.000 b (around 1.5 mm of missing data on the disc). The length of errors that can be concealed is about 12.000 b (around 7.5 mm). However, the largest error burst we ever measured during the many long days of disc channel characterization was 0.1 mm.

We also had to decide on the channel code. This is a vital component, as it has a considerable impact on both the playing time and the quality of disc handling or playability. Servo systems follow the track of alternating pits and lands in three dimensions, i.e., radial, focal, and rotational speed. Everyday handling damage, such as dust, fingerprints, and tiny scratches, not only affects retrieved data but also disrupts the servo functions. In the worst cases, the servos may skip tracks or get stuck, and error-correction systems become utterly worthless. A product with such devastating weaknesses would remain a laboratory toy. A well-designed channel code would make it possible to remove the major barriers related to these playability issues.

The system designer should find a good tradeoff between long playing time and playability. Both partners proposed some form of (d, k) runlength-limited (RLL) codes, where d is the minimum number, and k is the maximum number of zeros between consecutive ones. The differences between the various proposals were the code rate, runlength parameters d and k, and the spectral content. The spectral content has a direct bearing on the playability. In their prototype, Philips used the propriety M3 channel code, a rate 1/2, d=1, k=5 code, with a well-suppressed spectral content [1]. M3 is a variation on the M2 code, which was developed in the 1970s by Ampex Inc. for their digital videotape recorder [5]. Sony started with a rate 1/3, d=5, RLL code, but since that did not work, they changed horses halfway and proposed a propriety rate 1/2, d=2, k=7 code, a type of code that had been used in magnetic disk data storage. Both Sony codes did not have spectral suppression, and the engineers had opposing views on how the servo and synchronization issue could be solved. In May 1980, the choice of the channel code therefore remained open, and more study was needed. Now, before continuing with the coding cliffhanger, we take a musical break.

> The presence of the PCM video-based adaptors explains the choice of sampling frequency for the CD, as the number of video lines, frame rate, and bits per line end up dictating the sampling frequency one can achieve for storing stereo audio.

Playing Time and Beethoven's Ninth

Playing time and disc diameter are probably the parameters most visible to consumers. Clearly, these two are related: a 5% increase in disc diameter yields 10% more disc area, and thus an increase in playing time of 10%. The technical director of Philips' audio division made the proposal regarding the disc diameter. They argued, "The compact audio cassette was a great success," and "we don't think the CD should be much larger." The cross diameter of the Compact Audio Cassette, very popular at that time and also developed by Philips, is 115 mm. The Philips prototype audio disc and player were based on this idea, and the Philips team of engineers restated this view in the list of preferred main parameters. Sony, no doubt with portable players in mind, initially preferred a smaller 100-mm disc.

During the May 1980 meeting in Eindhoven, something remarkable happened. The minutes of the meeting read:

> Disc diameter: 120 mm
> Playing time: 75 min
> Track pitch: 1.45 μm
> This can be achieved with the Philips M3 channel code. However, the negative points are: large numerical aperture needed which entails smaller (production) margins, and the Philips' M3 code might infringe on Ampex M2.

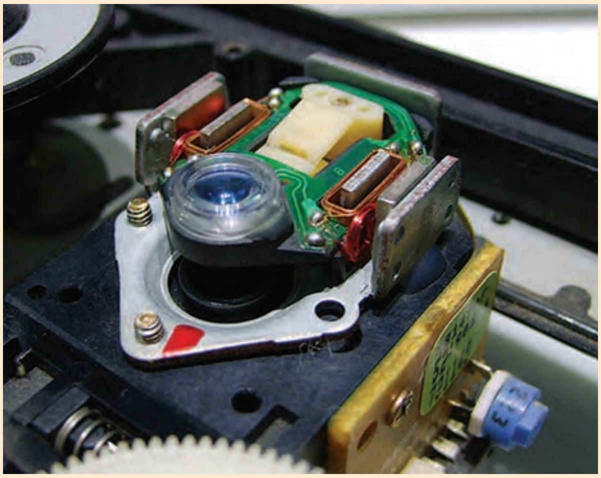
Both the disc diameter and playing time differ significantly from the preferred values listed during the Tokyo meeting in December 1979. So what happened during the intervening six months? The minutes of the meetings do not give any clue as to why the changes to playing time and disc diameter were made. According to Philips' Web site with the "official" history: "The playing time was determined posthumously by Beethoven." The wife of Sony's vice-president, Norio Ohga, decided that she wanted the composer's Ninth Symphony to fit on a CD. It was, Sony's Web site explains, Ohga's favorite piece of music. The Philips Web site says:

The performance by the Berlin Philharmonic, conducted by Herbert von Karajan, lasted for 66 min. Just to be quite sure, a check was made with Philips' subsidiary, Polygram, to ascertain what other recordings there were. The longest known performance lasted 74 min. This was a mono recording made during the Bayreuther Festspiele in 1951 and conducted by Wilhelm Furtwängler. This therefore became the maximum playing time of a CD. A diameter of 120 mm was required for this playing time.

Everyday practice is less romantic than the pen of a public relations guru. At that time, Philips' subsidiary Polygram—one of the world's largest distributors of music—had set up a CD disc plant in Hanover, Germany, that could produce large quantities of CDs with, of course, a diameter of 115 mm. Sony did not have such a facility yet. So if Sony had agreed on the 115-mm disc, Philips would have had a significant competitive edge in the music market. Ohga was aware of that and did not like it, and something had to be done. It was not really about Ohga's great passion for music but the money and competition in the market of the two partners. The decision regarding diameter/playing time was taken outside of the group of experts responsible for the CD format. So I, a former member of that group, can only guess what happened at the upper floor. But something unforeseen happened: at the last minute, we changed the code.

Servo systems follow the track of alternating pits and lands in three dimensions, i.e., radial, focal, and rotational speed.

Popular literature, as exemplified on Philips' Web site, as mentioned previously, states that the disc diameter is a direct result of the requested playing time and that the extra 14 min of playing time for Furtwängler's Ninth subsequently required the change from a 115- to 120-mm disc. It suggests that there are no other factors affecting playing time. Note that in May 1980, when the disc diameter and playing time were agreed upon, the channel code, a key factor affecting playing time, was not yet settled. In the minutes of the May 1980 meeting, it was remarked that diameter, playing time, and track pitch could be achieved with Philips' M3 channel code. In the meantime, but not mentioned in the minutes of the May meeting, I was experimenting with a new channel code, later coined *EFM* [3]. EFM, a rate 8/17, d=2 code made it possible to achieve a 30% higher information density than Philips' M3. Because of its good spectral suppression, EFM also showed a good resilience against disc-handling damage such as fingerprints, dust, and scratches. Note that 30% efficiency improvement is highly attractive, since, for example, the disc diameter increase from 115 to 120 mm only offers a mere 10% increase in playing time.



A typical laser optical assembly. Note that all six focusing and tracking coils can be seen. While tracking of the laser system could introduce random bit errors, the main challenge was that of long burst errors due to scratches or dust. (Photo courtesy of Wikipedia.)

Coding Challenges

A month later, in June 1980, we could not choose the channel code, and again more study and experiments were needed. Although experiments had shown the greater information density that could be obtained with EFM, it was, at first, rejected. At the end of the discussion, which at times was heated, the Sony people were specifically opposing the complexity of the EFM decoder, which then required 256 gates. My remark that the CIRC decoder needed at least half a million gates and that the extra 256 gates for EFM were irrelevant was jeered at. Then, suddenly, during the meeting, we received a phone call from the presidents of Sony and Philips, who were meeting in Tokyo. We were running out of time, they said, and one week for an extra, final, meeting in Tokyo was all the lads could get.

Sony stated that if the EFM hardware were less than 80 gates, they would accept it. I had a week to reduce the gate count. I used the first Apple II computer in the lab, which was much handier for such an interactive design using trial and error than the IBM mainframe, especially as I had to walk to the IBM computer center for every job. I succeeded in bringing the gate count down to just 52 gates, and on 19 June 1980, in Tokyo, Sony agreed to EFM. The 30% extra information density offered by EFM could have been used to reduce the diameter to 115 mm or even 100 mm (with, of course, the requested 74 min and 33 s for playing Ohga's favorite Ninth). However, such a change was not considered to be politically feasible, as the powers that be had decided 120 mm. The option to increase the playing time to 97 min was not even considered. We decided to improve the production margins of the player and disc by lowering the information density by 30%: the disc diameter remained 120 mm, the track pitch was increased from 1.45 to 1.6 μm, and the user bit length was increased from 0.5 to 0.6 μm. By increasing the bit size in two dimensions, in a similar vein to large letters being easier to read, the disc was easier to read and could be introduced without too many technical complications.

The maximum playing time of the CD was settled at 74 min and 33 s, but in practice, however, the maximum playing time was determined by the playing time of the U-Matic video recorder, which was 72 min. Therefore, rather sadly, Mrs. Ohga's favorite Ninth by Furtwängler could not be recorded in full on a single CD until 1988, when alternative digital transport media became available. On a slightly different note, Jimi Hendrix's *Electric Ladyland*, with a playing time of 75 min, was originally released as a two-CD set in the early 1980s but has been on a single CD since 1997.

The Inventor of the CD

The Sony–Philips task force stood on the shoulders of the Philips engineers who created the laser videodisc technology in the 1970s. Given the videodisc technology, the task force made choices regarding various mechanical parameters, such as disc diameter, pit dimensions, and audio parameters, such as sampling rate and resolution. In addition, two basic patents were filed related to error correction, CIRC, and channel code, EFM. CIRC, the Reed–Solomon ECC format, was completely engineered and developed by Sony engineers, and EFM was completely created and developed by the author.

Let us take a look at the numbers. The size of the task force varied per meeting, and the average number of attendees listed on the minutes of the joint meetings is 12. If the people carrying the hierarchical responsibility of the CD project are excluded, then we find a very small group of engineers who carried the technical responsibility of the CD *Red Book* standard.

Philips' corporate public relations department (see *The Inventor of the CD* on the Philips Web site [7]) states that the CD was too complex to be invented by a single individual, and the CD was invented collectively by a large group of people working as a team. It persuades us that progress is the product of institutions, not individuals. Evidently, there were battalions

> A well-designed channel code would make it possible to remove the major barriers related to these playability issues.

of very capable engineers who further developed and marketed the product, and success in the market depended on many other innovations. For example, the solid-state physicists who developed an inexpensive laser diode, a primary enabling technology, made the CD possible in practice. Credit should also be given to the people who designed the transparent CD storage case, the jewel box, and made a clever contribution to the visual appeal of the CD.

Philips and Sony agreed in a memorandum dated June 1980 that their contributions to channel and error-correction codes are equal. Sony's Web site with their official history is titled "Our Contributions Are Equal" [8]. The Web site states, "We avoid such comments as, 'We developed this part and that part' and to emphasize that the disc's development was a joint effort by saying, 'Our contributions are equal.' The leaders of the task force convinced the engineers to put their companies before individual achievements." The myth building went so far that the patent applications for both CIRC and EFM were filed with joint Sony–Philips inventors.

Sony D-5 Discman—the first CD-Discman introduced to the market in 1984. (Photo courtesy of Wikipedia.)

Everything Else Is Gaslight

A favorite expression of audiophiles—particularly during the early period, when they were comparing both vinyl LP and CD versions of the same recordings—was: "It is as though a veil has been lifted from the music." Or, in the words of the famous Austrian conductor Herbert von Karajan, when he first heard CD audio: "Everything else is gaslight." Von Karajan was fond of the gaslight metaphor. He first conducted *Der Rosenkavalier* in 1956 with the soprano Elisabeth Schwarzkopf. Later, when he revived the opera in 1983 with Anna Tomowa, he referred to his 1956 cast as gaslight, which rather upset Schwarzkopf.

Philips and Sony settled the introduction of the new product to be on 1 November 1982. The moment the ink of the *Red Book*, detailing the CD specifications, was dry, the race started, and hundreds of developers in Japan and The Netherlands were on their way.

In early January 1982, it became clear that Philips was running behind. The electronics were seriously delayed, and they asked Sony to postpone the introduction. Sony rejected the delay but agreed upon a two-step launch. Sony would first market their CD players and discs in Japan, where Philips had no market share, and half a year later, in March 1983, the worldwide introduction would take place by Philips and Sony. Philips Polygram could supply discs for the Japanese market. This gave Philips some breathing space for the players, but it was not enough to make the new deadline. The first generation of Philips CD players was equipped with Sony electronics.

Sony CDP-101 from 1982, one of the earliest CD players affordable to consumers. (Photo courtesy of Wikipedia.)

Philips CD100 Player—the first model from Philips. (Photo courtesy of Wikipedia.)

The first CD players cost more than US$2,000, but just two years later, it was possible to buy them for under US$350. Five years after the introduction, sales of CDs were higher than vinyl LPs. Yet, this was no great achievement, as in 1980, sales of vinyl records had been declining for many years, although the music industry was far from dead. A few years later, the CD had completely replaced the vinyl LP and cassette tape. CD technology was ideal for use as a low-cost, mass-data storage medium, and the CD-ROM and record-once and rewritable media, CD-R and CD-RW, respectively, were developed. In 1995, the CD was succeeded by DVD, which offers a sixfold-higher storage capacity. Now, 25 years after the introduction of the CD, home cinema on DVD accounts for 70% of Hollywood's worldwide film revenue. DVD has replaced VHS videotape. Hundreds of millions of players and more than 200 billion CD audio discs have been sold.

Acknowledgment

The author warmly acknowledges the hospitality of the Rotterdam Radio Museum.

References

[1] M. G. Carasso, W. J. Kleuters, and J. J Mons, "Method of coding data bits on a recording medium (M3 Code)," U.S. patent 4,410,877, Oct. 18, 1983.

[2] T. Doi, T. Itoh, and H. Ogawa. (1979, March). A long-play digital audio disc system, aes preprint 1442. presented at the 62nd Convention, Brussels, Belgium, Mar. [Online]. Available: http://www.exp-math.uni-essen.de/~immink/pdf/aes1442.pdf

[3] K. A. S. Immink and H. Ogawa, "Method for encoding binary data (EFM)," U.S. patent 4,501,000, Feb. 19, 1985.

[4] T. Kretschmer and K. Muehlfeld. (2004, Oct.). Co-opetition in standard-setting: the case of the compact disc. [Online]. Available: http://papers.ssrn.com/sol3/papers.cfm?abstract_id=618484

[5] J. W. Miller, "DC free encoding for data transmission (M2 Code)," U.S. patent 4,234,897, Nov. 18, 1980.

[6] K. Odaka, Y. Sako, I. Iwamoto, T. Doi, and L. Vries, "Error correctable data transmission method (CIRC)," U.S. patent 4,413,340, Nov. 1, 1983.

[7] The inventor of the CD, Philips' historical Web site. [Online]. Available: http://web.archive.org/web/20080206032051/http://www.research.philips.com/newscenter/dossier/optrec/index.html

[8] Our contributions are equal, Sony's historical Web site. [Online]. Available: http://web.archive.org/web/20080802133849/http://www.sony.net/Fun/SH/1-20/h5.html

[9] L. B. Vries, "The error control system of Philips Compact Disc," AES Preprint 1548, New York, Nov. 1979.

[10] K. A. S. Immink, "Reed-Solomon codes and the compact disc" in S. B. Wicker and V. K. Bhargava, Eds., Reed-Solomon Codes and Their Applications. Piscataway, NJ: IEEE Press, 1994.

[11] J. Nathan, *SONY, The Private Life*. Boston, MA: Houghton Mifflin 1999, pp. 140.

[12] K. A. S. Immink, "The CD story," *AES J.*, vol. 46, pp. 458–465, May 1998.

—Kees A. Schouhamer Immink
Turing Machines Inc,
Rotterdam, The Netherlands,
Institute for Experimental Mathematics,
Essen, Germany.

ABOUT THE AUTHOR

Peter Corcoran (cesmagazine@ieee.org) earned his Ph.D. degree from Trinity College Dublin, Ireland, in 1987. He is currently an active researcher with interests in home networking, multimedia and communications technologies, biometrics, embedded systems, and consumer imaging. He is a coinventor on more than 150 granted patents and is an author of over 70 journal publications. He is currently the editor-in-chief of *IEEE Consumer Electronics Magazine* and the vice-dean (engineering) of research and graduate studies at the National University of Ireland, Galway. He was elevated to IEEE Fellow in 2010 for his contributions to digital camera technology.