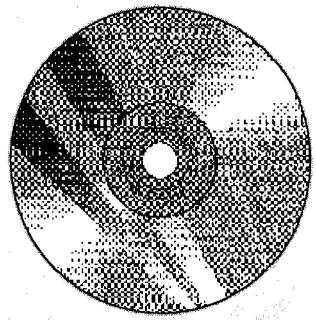

The Compact Disc Story*

Kees A. Schouhamer Immink, AES Fellow

Philips Research Laboratories, Eindhoven, The Netherlands

INTRODUCTION

I should say at the outset that I am not a historian but an engineer, and that what I will say comes from my personal recollections of the meetings that took place over 15 years ago between engineers at Philips and Sony. Even so, like the best historians, I shall give you a brief summary of the 100 years of disk recording that led up to the launch of the CD.

A BIT OF HISTORY

As you will see from Fig. 1, the equivalent storage density of recording media in bits/mm^2 grew gradually from that of the original Edison cylinder to the recent DVD. We are now dealing with storage densities some one million times greater than those available at the end of the last century. Fig. 2 shows some key points in the evolution of audio disks. One must remember that it was at least 10 years after Edison's cylinder before Berliner and others came along with a method of disk recording. In fact, I visited Edison Labs and was told that all recording devices up until about 1920 were effectively prototypes and that there was no way of replicating media, so to have a recording hit at that time must have been quite an achievement I think! In the 1950s, the stereo LP record delivered a major step in sound quality, but as far as optical recording is concerned everything before 1969 must be called prehistory.

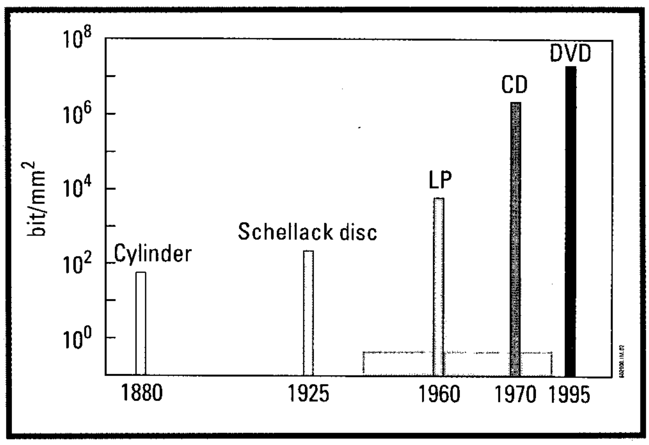

Fig. 1. Growth of storage density of recording media.

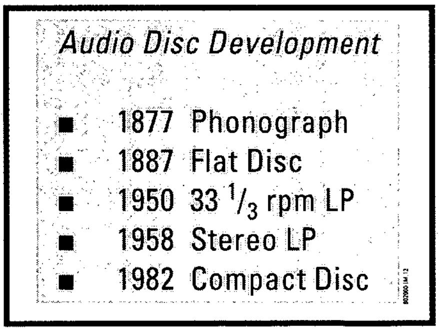

Fig. 2. Key points in audio disk evolution.

OPTICS AND LASERVISION

In 1969 a colleague of mine suggested that it might be worthwhile developing the use of optics for storing pictures. We threw around the idea of a spiral track with bits or pits, and from that time it took six years before Laservision was born. In 1973 I started working on servo systems and electronics, and we considered that if one could store video information optically then one could also manage audio. The management at the time dismissed this idea saying that audio was far too simple and not worth the effort, so we left it alone for the time being. And then came the launch of Laservision in 1975, which was an unexpected flop. It flopped in a big way, and of some 400 players that were sold some 200 were returned because buyers had been under the misapprehension that it would also record programs—of course it could not. After two years the Philips management decided to withdraw it.

EARLY DIGITAL AUDIO

It is my view that digital audio was made possible at that point, and between 1970 and 1980 numerous meetings were held between Philips and Sony. In order to understand the tech-

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Kees Immink presents a research engineer's view of the years leading up to the launch of the CD, and the various crucial decisions that were made during that time which would determine the technical success or failure of the medium. From a personal perspective he comments on the history of the first mass-market digital audio medium and delivers some predictions for the future of optical media in data storage.

Manufacturer	Type	f_s	Resolution
BBC	Microwave	32	13
Soundstream	tape	37.5/42.5	16
Many	PCM adaptor	44.056	13/16
Denon	tape	47.25	13

Fig. 3. Early sampling-frequency/resolution choices.

nical choices concerning sample resolution and such at that time, one must look to what was happening with studio equipment and with digital audio in broadcasting (Fig. 3). The BBC in the UK was one of the first to adopt digital sound, and they were working with a 13-bit distribution system for the transmitter network, sampled at 32 kHz. Stockham's experiments in 1972–73 with the Soundstream system involved sample rates averaging around 40 kHz. He used computer tape as the means of storage, which made it practical to store data at 16-bit resolution because of the byte-oriented nature of computer data storage. Eight bits would have been too few, and 14 bits would have meant inefficient use of the storage space, so 16 bits seemed logical. Computer tape was really the only way of storing perhaps one hour of sound at that time.

Toward the end of the 1970s PCM adapters were developed, which were digital recording processors that used ordinary analog video recorders as a means of storing digital audio data, since video recorders were the only devices widely available with sufficient bandwidth. This helps to explain the choice of sampling frequency for the CD, because the number of video lines, frame rate, and bits per line end up dictating the sampling frequency one can achieve if wanting to store two channels of audio. The sampling frequencies of 44.1 and 44.056 kHz were thus the result of a need for compatibility with the NTSC and PAL video formats used for audio storage at the time.

AN OPTICAL AUDIO DISK

From 1973 to 1976 two Philips engineers were given a mandate to develop an audio disk based on optical technology, and they started by experimenting with an analog approach using wideband frequency modulation. The problem with this was that it was not really much more immune to dirt and scratches than an analog LP, although there was a certain improvement in sound quality, so they decided to look for a digital solution. In 1977–78 Philips and Sony both demonstrated the first prototypes of a digital sound system using a laser disk, and in 1979 a high-level decision was made to join forces in the development of a world standard. Philips had lost the market for Laservision, but had considerable optical expertise, as well as expertise in servo systems and digital and analog modulation systems. Sony's huge expertise in error correction, PCM adapters, and in channel coding would complement this ideally. A reasonable summary would be that most of the "physics" was provided by Philips and the digital audio experience by Sony.

THE SONY–PHILIPS LIAISON

In 1979–80 a number of meetings were held in both Tokyo and Eindhoven. The first, in August 1979 in Eindhoven, and the second, in October '79 in Tokyo, provided an opportunity for engineers to get to know about each other and to discover the main strengths of each team. There was a great deal to learn from each other. Both teams had working prototypes and decisions had to be made concerning modulation and error- ➥

correction systems. Parallel experiments were conducted in both locations, and naturally there were numerous occasions on which each team felt it had the best or most practical solution—either theirs could correct the longest burst errors or give the longest playing time, and so on. The delicate prototype electronic equipment had to be transported with the engineers across the world, and consequently traveled first class in a separate seat booked especially for it. The airline KLM really loved us for that, because, as you know, boxes of electronics do not drink champagne or ask for more food!

By May 1980 almost everything was in order. The modulation system was still a point of contention, with each party still claiming one was better than the other, and then there was a phone call from the current chairman of Sony, Mr. Ohga, who told us that if we could not make a decision within a week, management would make it for us. I was tempted to say that if they were able to make a decision so easily, why did they not do so six months ago? but refrained in the interests of diplomacy. So we moved quickly and made all the decisions concerning the mechanical specification of the disk and so forth.

DECIDING THE PARAMETERS

The disk diameter is a very basic parameter, because it relates to playing time. All parameters then have to be traded off to optimize playing time and reliability. The decision was made by the top brass of Philips. "Compact Cassette was a great success," they said, "we don't think CD should be much larger" (Fig. 4). As it was, we made it 0.5 cm larger. (There were all sorts of stories about it having something to do with the length of Beethoven's 9th Symphony and so on, but you should not believe them.)

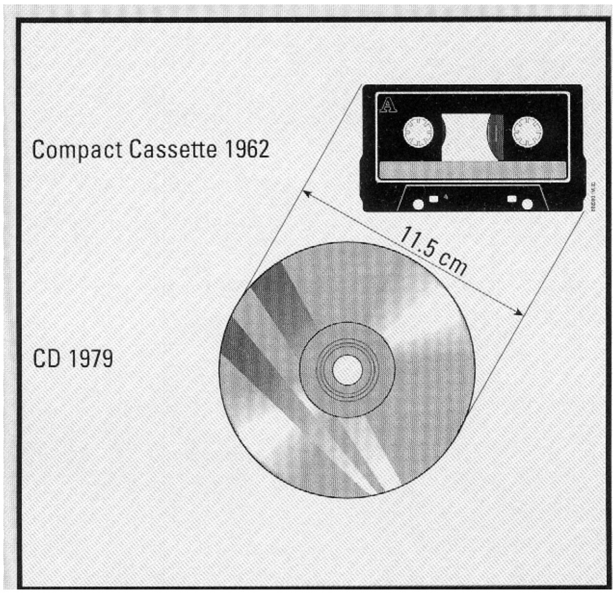


Fig. 4. Choice of CD diameter was based on size of Compact Cassette.

The sampling frequency of 44.1 kHz was decided. It was the only choice we could make after long deliberation, and the selection of 44.1 kHz as opposed to 44.056 was simply for the reason that it was easier to remember—there was no other reason. Sony made the excellent choice of 16-bit resolution, although Philips had developed a 14-bit D/A converter at the time, leading Philips to argue initially that it was impossible to redesign its converters for 16 bits in a short enough time. But my colleague Carel Dijkmans said, "No problem. I know a small trick to turn a 14-bit converter into a 16-bit converter—it's called oversampling," So we managed to solve that problem quite easily as it happened. As a result, all the first Philips players had oversampling converters in them.

The cross interleaved Reed–Solomon code (CIRC) chosen was much better than that proposed by Philips, although extremely complicated at the time. Sony was proposing using 16-kbyte RAMs for interleaving, which would have cost around $50 to us, and added significantly to the commercial cost of the players. "Are they crazy, those Sony guys?" asked many at Philips, but in fact the price of RAM and its capacity have changed so quickly that it is impossible to buy less than about 1-Mbyte RAMs today, and for less money than 16 k then—so fast have we moved. So that turned out to be a good decision.

The 8–14 bit channel code was agreed and all the specifications between them led to a playing time of 75 minutes. Geometry and the other physical parameters were decided, and a plastic layer covering the pits was added (a basic paradigm of all optical disks) to protect the data surface from damage and to insure that dirt and scratches on the surface were well out of focus for the laser pickup (Fig. 5). (I should note that the recent DVD has lost a small part of this paradigm, as it is only 0.6 mm thick, and so the optical pickup will be more vulnerable to dirt and scratches. Modern error-control codes can easily cope with the resulting errors.) Just to show how important the AES was, and I think always

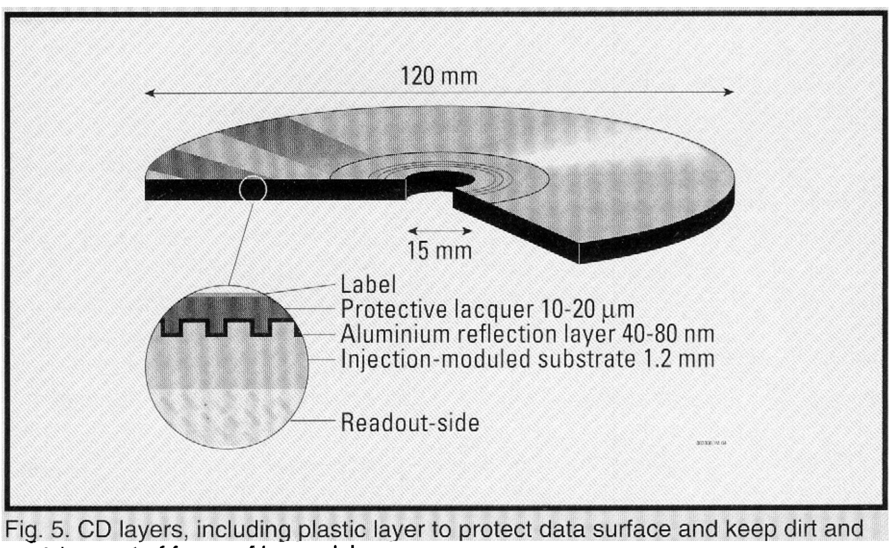


Fig. 5. CD layers, including plastic layer to protect data surface and keep dirt and scatches out of focus of laser pickup.

will be, the CD system including modulation and error correction was described by some of the engineers involved in a convention preprint published in 1980 in New York [1]. Fig. 6 shows the block diagram of the encoding model used for CD, resulting in the well-known 4.3-Mbit/s data rate.

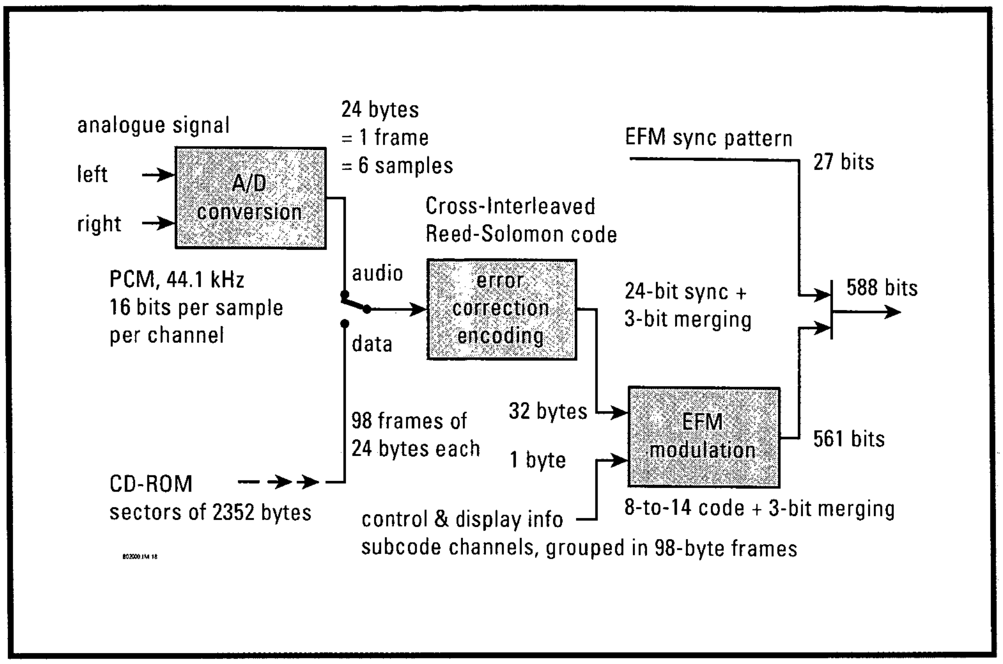


Fig. 6. Block diagram of CD encoding model resulting in 4.3-Mbit/s data rate.

THE RISE AND RISE OF CD

So Compact Disc was born and, as you can see from Fig. 7, the audio disk market shows a gradually declining sale of LP and an exponential increase in sales of CD. The sale of players also climbed sharply (Fig. 8). Personally, I was not at all sure that CD would succeed, as I had seen the problems that arose with Laservision, but I am happy to see that it is expected some 5 billion CDs will be sold in the world in 1997, which makes it a very successful market. (I saw also that 100 billion hamburgers would be sold in the U.S. this year as well, so perhaps it is not so big after all....) Now we have numerous other "books" in the CD standard, with CD-ROM players outselling CD Audio by about 70% to 30%, which is something I never expected (Fig. 9).

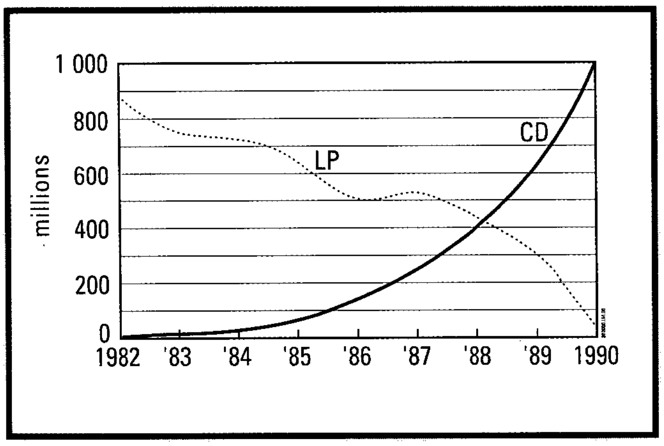


Fig. 7. Sales comparison of LP and CD between 1982 and 1990.

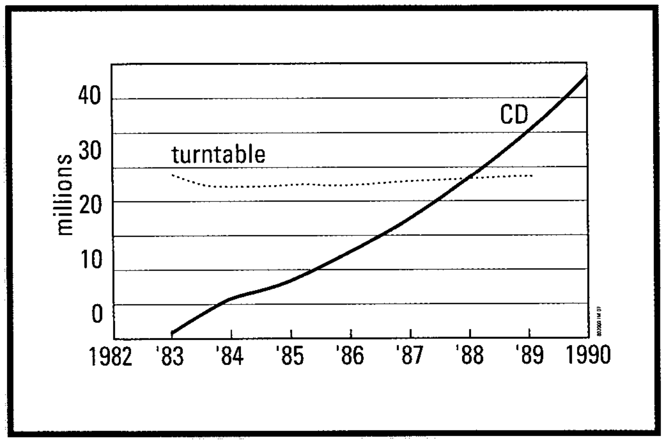


Fig. 8. Sales comparison of turntable and CD players between 1983 and 1990.

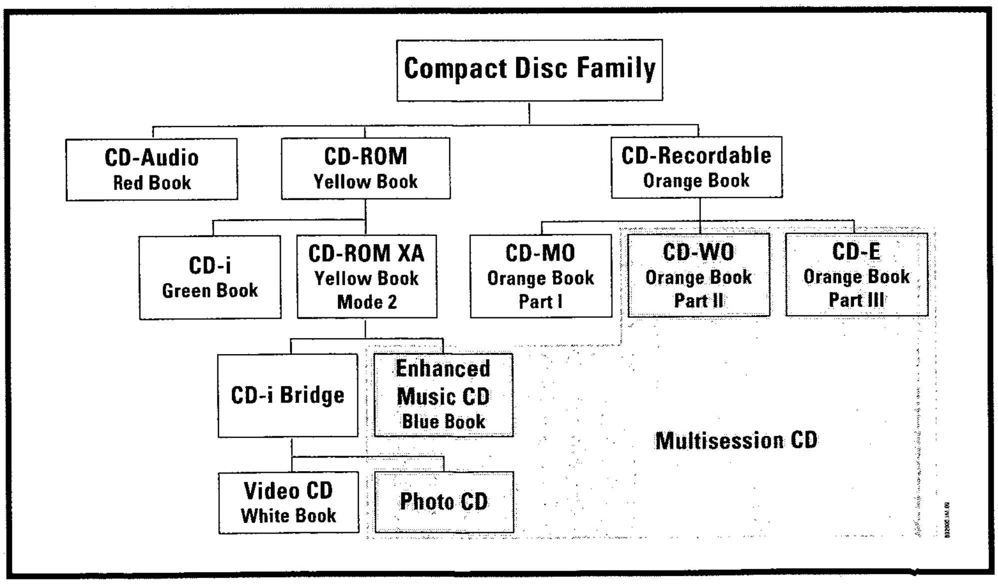


Fig. 9. Expansion of CD-based systems.

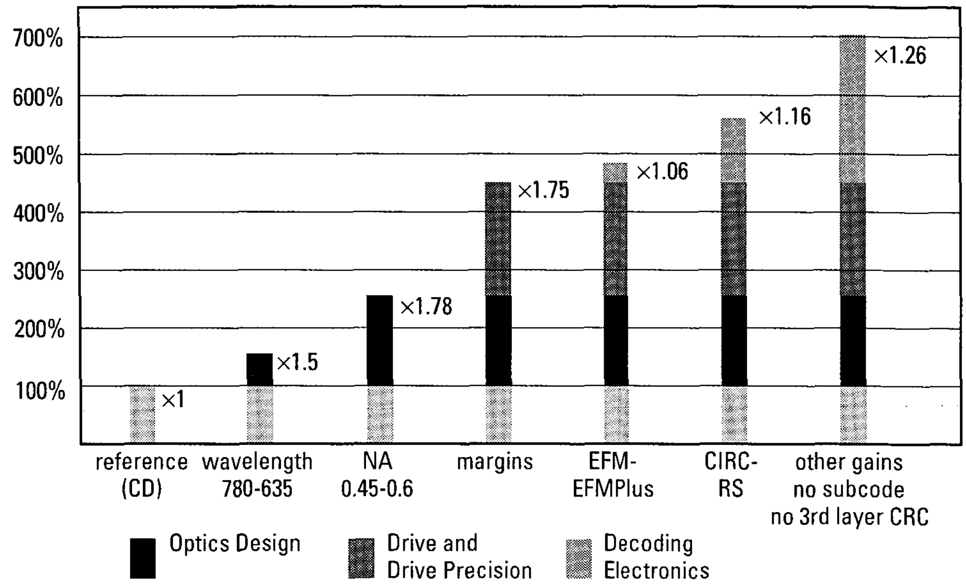


Fig.10. Different characteristics contributing to increase in DVD capacity compared with CD.

LOOKING FORWARD

As a researcher I like to look forward as well as back, and I should like to make some predictions for the future of optical disk media, based on DVD. This new disk has a capacity some seven times larger than CD, and we need to look at this to see how the optical disk growth path will be defined.

Looking at Fig. 10 it can be seen that a number of different characteristics have led to the increase in capacity of the DVD compared with the CD. The wavelength of the laser and the numerical aperture (NA) of the objective lens have both been altered, and new research is making further advances possible in this area. The greater NA of the lens is only possible if the disk is made thinner, so future improvements here will only be possible if the disk is made thinner and thinner. Blue and green lasers are already possible. It will be appreciated that a large part of the potential increase in capacity is purely dependent on physics, not on recording specialists.

Table 1. Comparison of DVD and CD-ROM main parameters.

	DVD	CD-ROM
read-out wavelength (nm)	635	780
reference NA	0.6	0.45
disc diameter (cm)	12	12
disc thickness (mm)	0.6	1.2
layers	single or dual layer	single layer:
data capacity (GByte)	1 layer: 4.7	mode I: 0.68
	2 layer: 9.4	mode II: 0.78
reference scanning speed (m/s)	3.27	1.2
reference channel bit rate (Mbit/s)	24.5	4.32
min. pit (or land) length (μm)	0.4	0.85
track pitch (μm)	0.74	1.6
recording code	EFMPlus	EFM
sector size (bytes)	2048	2048
error correction	RS	CIRC
max. user bit rate @ ref speed (Mbit/s)	11.1	1.41

Other advances in capacity have already been made for DVD. Some things can only be done once—for example, removing the third layer of CIRC and removing subcode. Reducing the track pitch and other physical margins has been possible because we now know how to manufacture and read optical disks well. The main parameters of the DVD compared with the CD can be seen in Table 1. This leads me to make some predictions to the year 2010, concerning the physical density of various storage media, as shown in Fig. 11. The recording density is compared with CD, which has a density of 1 bit/μm^2 compared with the 6–7 bits/μm^2 of DVD. High-density forms of DVD will extend this further, so that in 2002 (probably in May!) we shall see a 20-Gbyte disk, and in 2006 (almost certainly in ➥

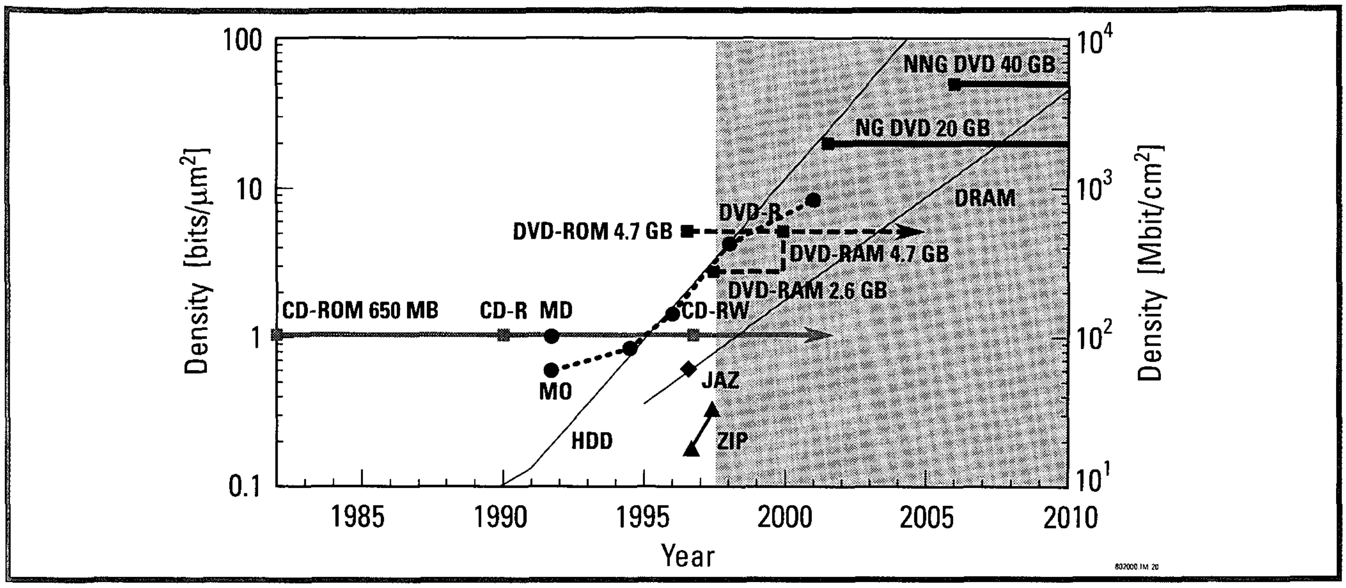


Fig. 11. Predictions of future physical density of storage media.

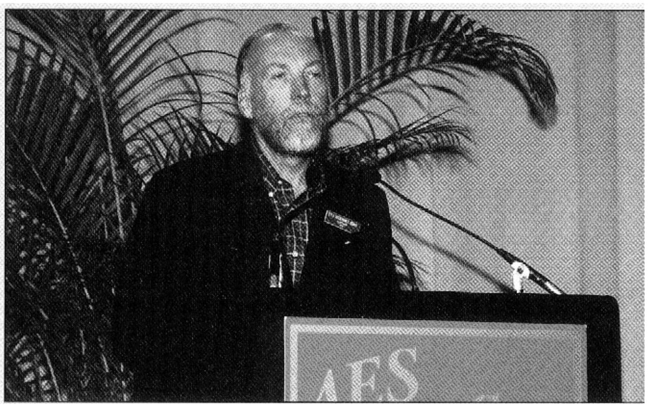
June...) we shall see a 40-Gbyte disk. Meantime the growth in DRAM and magnetic disk capacity continues to grow at an exponential rate, although the price of DRAM is currently very much higher than that of optics. Whether companies will market these products is another matter entirely—this is just a prediction made by an engineer.

So that is the end of my story, and of course it has been biased. I am an engineer and I have told the story from an engineer's point of view. Many of the decisions concerning the CD were made by very clever marketing people —for example, the idea of using a jewel case for storing the disk. Those decisions are not the responsibilities of engineers, for very good reasons.

REFERENCES

[1] L. B. Vries, K. A. Immink, J. G. Nijboer, H. Hoeve, T. T. Doi, K. Odaka, and H. Ogawa, "The Compact Disc Digital Audio System: Modulation and Error-Correction," presented at the 67th AES Convention of the Audio Engineering Society, *J. Audio Eng. Soc. (Abstracts)*, vol. 28, p. 931 (1980 Dec.), preprint 1674.

THE AUTHOR



The author presents The CD Story to the 103rd Convention of the Audio Engineering Society, New York, 1997.

Kees A. Schouhamer Immink was born in Rotterdam, The Netherlands, in 1946. He received an M.S. degree in electrical engineering in 1974 and a Ph.D. in 1985 from the Eindhoven University of Technology, The Netherlands. Dr. Immink has worked his entire professional life at the Philips Research Laboratories in Eindhoven, where he is currently a research fellow. He is also adjunct professor at the Institute of Experimental Mathematics, Essen University, Germany. He has contributed to the design and development of a variety of digital audio recorders such as the Compact Disc, Compact Disc Video, DAT, DCC, and, very recently, the Multimedia CD.

Dr. Immink holds 35 U.S. patents, is coauthor of three books, and has written numerous papers. He was a member of the technical advisory board of the Magnetics Technology Center, Singapore, is cofounder and trustee of the Shannon Foundation, and is a distinguished lecturer of the IEEE Communications Society. He served as program and conference chairman of various international conferences, and received many awards for his part in the digital audio revolution. A fellow of the IEE and IEEE, he was awarded the IEE Sir J. J. Thomson Medal in 1993, and the SMPTE Poniatoff Gold Medal for Technical Excellence in 1994. Dr. Immink joined the AES in 1980, and has been a member of the *Journal*'s Review Board since 1984. He was a committee member of the Netherlands Section from 1986 to 1992, and its chairman from 1988 to 1990. He was papers chairman of the AES 96th Convention and papers vice chair of the 104th Convention held in Amsterdam in March 1994 and May 1998, respectively. He became an AES fellow in 1985, was awarded the Society's Silver Medal in 1992, and was elected to its Board of Governors in 1997.