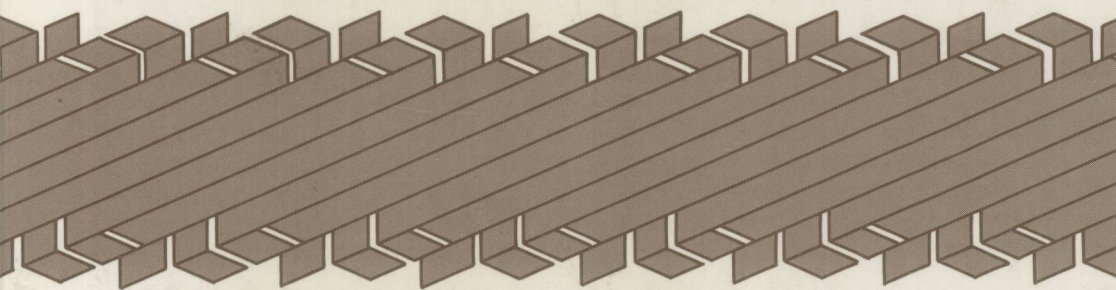


# The Art of Digital Video

John Watkinson



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**John Watkinson**



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## Preface

There would be very little to document in the subject of digital video were it not for the persistence of those who overcame countless obstacles in order to make it happen.

It is not so long ago that many of the devices described in these pages existed only in the imagination of those who dreamed of a better way of conveying and processing video. This new approach would not be some refinement of existing technology, offering modest gains, but a totally different approach, which would wipe away existing problems and introduce dramatic opportunities.

It was not enough simply to have the dream, because dreams don't pay bills. It was necessary to implement the dream, and this would require the adoption of technologies which had previously little or no relevance to television: computation, laser optics, mass storage, simulation, error correction. Most of these disciplines were described in their own idiomatic terminology, and this in itself is a major obstacle to progress.

As yet there is no documented process which teaches us how to balance conflicting requirements of numerous disparate technologies to achieve a reliable end product. It can only be described as an art, and it has inspired the title of this book. Because there are so many disciplines involved, digital video is a fascinating and stimulating subject. It is a source of some regret that the intellectual content of modern digital video equipment generally exceeds that of the program material which it handles.

Digital video continues to develop, but it has reached a point where a book of this kind becomes feasible. The basic principles are largely agreed, there are real products with which to earn a living, and we now have standards for recording and interconnection of digital video. The picture quality obtained with these machines is of a high standard, but techniques which are yet to be widely applied can result in a further improvement within the existing line standards.

This book describes all of the essential theory of digital video and a great deal of the practice, but the subject is too great to attempt to include any history. The current position in High Definition is too fluid to document at the present time and has been consciously omitted except where general principles apply.

The range of disciplines to be covered is so great that this cannot be a conventional book. The need for understanding is too great for a book to assume a high academic level in all these subjects.

This book adopts the same approach as that used in *The Art of Digital Audio*. Every concept begins with the basic mechanism involved and defines its terminology. Wherever possible, explanations are given in plain English, equations being used as a last resort.

There are few stated facts, since these are easily forgotten. Instead there are reasons, arguments and mechanisms from which facts can be deduced. The approach works equally well from basic levels to advanced concepts, so there is also plenty in this book for the expert, and there are references for those who wish to go further.

Words have been carefully chosen to reduce the chances of misunderstanding, and where a misnomer is in common use, it will be identified.

A lot of care went into *The Art of Digital Audio*, but I was not prepared for the overwhelming support of the approach. It would be unthinkable to do anything different in this book.

---

# Acknowledgements

For Anne

I must first thank David Kirk, who invited me to write a series on digital video for 'Broadcast Systems Engineering', which he then edited, and Ron Godwyn, who succeeded him. The response to this series provided the impetus to turn it into a book.

The publications of the Society of Motion Picture and Television Engineers and of the European Broadcasting Union have been extremely useful.

I am indebted to the many people who have found time to discuss complex subjects and to suggest reference works. Particular thanks go to David Lyon and Roderick Snell of Snell and Wilcox, Takeo Eguchi, Jim Wilkinson, David Huckfield and John Ive of Sony, Luigi Gallo of Accom, Graham Roe of Pro-Bel, Dave Trytko, Joe Attard, John Watney, Fraser Morrison and Ab Weber of Ampex, John Mallinson of CMRR San Diego, Roger Wood of IBM and John Baldwin.

Last but not least thanks to Margaret Riley of Focal Press for helping it along.

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# Contents



## Chapter 1 Why digital? 1

1.1 The advantages of digital video	1
1.2 The opportunities	5
1.3 Some typical machines outlined	6
1.4 Disadvantages	8
References	9

## Chapter 2 Conversion 10

2.1 The discrete picture	10
2.2 Sampling	11
2.3 Aperture effect	15
2.4 Kell effect	18
2.5 Interlace	18
2.6 Types of video	20
2.7 Spectrum of video	21
2.8 Choice of sampling rate – component	28
2.9 Choice of sampling rate – composite	29
2.10 Motion and definition	30
2.11 Quantizing	32
2.12 Filter design	37
2.13 Oversampling	40
2.14 Basic digital-to-analog conversion	43
2.15 Basic analog-to-digital conversion	45
2.16 Successive approximation	48
2.17 Imperfections of converters	48
References	51

## Chapter 3 Digital video coding and processing 52

3.1 Introduction to logic	52
3.2 Binary codes	55
3.3 Binary adding	61
3.4 Digital fading and mixing	63
3.5 Concentrators/combiners	70
3.6 Blanking	72

3.7	Digital dither	73
3.8	Keying	75
3.9	Chroma keying	75
3.10	Simple effects	77
3.11	Timebase correction	81
3.12	RAM timebase correction	83
3.13	FIFO timebase correction	86
	References	90

## **Chapter 4 The C-format timebase corrector 91**

4.1	Introduction to C-format	91
4.2	Track following	92
4.3	Instabilities in C-format	101
4.4	Basic timebase correction	102
4.5	Generating the write clock	105
4.6	Velocity compensation in Zeus	110
4.7	Starting in the right place	111
4.8	Colour processing	117
4.9	Colour processing in Zeus	119
4.10	Memory control	122
4.11	Memory line addressing	124
4.12	Vertical locking	129
4.13	Dropout compensation	132
4.14	Output processing	132
4.15	Variable-speed recording	133
4.16	Multigen	134
	References	134

## **Chapter 5 Advanced digital processing 136**

5.1	Phase linearity	136
5.2	FIR and IIR filters compared	137
5.3	FIR filters	137
5.4	The need for sampling-rate conversion	145
5.5	Categories of rate conversion	145
5.6	Integer-ratio conversion	147
5.7	Fractional-ratio conversion	150
5.8	Variable-ratio conversion	153
5.9	Luminance/chrominance separation	154
5.10	Simple bandpass filters	154
5.11	Advanced composite decoders	157
5.12	Line synchronous digital chroma decoding	162
5.13	Converting 625/50 4:2:2 to D-2 PAL composite digital	163
5.14	Converting 525/59.94 4:2:2 to D-2 NTSC composite digital	168
5.15	Delays in digital filters	170
5.16	Planar digital video effects	171
5.17	Mapping	172
5.18	De-interlacing	173
5.19	Separability and transposition	178
5.20	Address generation and interpolation	180

5.21	Skew and rotation	186
5.22	Perspective rotation	188
5.23	DVE backgrounds	197
5.24	Non-planar effects	201
5.25	Controlling effects	202
5.26	Digital standards conversion	203
5.27	Character generators	210
5.28	Graphic art/paint systems	219
5.29	Recursive filtering for noise reduction	221
5.30	Recursive filtering for effects	222
5.31	Data reduction and transform coding	223
	References	224

## **Chapter 6 Digital magnetic and optical recording 226**

6.1	Magnetic recording	226
6.2	Head noise and head-to-tape speed	226
6.3	Basic digital magnetic recording	228
6.4	Fixed heads	229
6.5	Flying heads in disk drives	230
6.6	Playback	233
6.7	Azimuth recording and rotary heads	235
6.8	Equalization	238
6.9	Types of optical disk	239
6.10	Optical theory	240
6.11	The laser	243
6.12	Polarization	244
6.13	Thermomagneto-optics	246
6.14	Optical readout	247
6.15	Shortcomings of recording channels	249
6.16	Jitter windows	250
6.17	Simple codes	256
6.18	Group codes	257
6.19	CCIR-656 serial video code	261
6.20	Tracking signals	263
6.21	Randomized NRZ and 10 bit serial video code	263
6.22	Partial response	265
6.23	Synchronizing	270
	References	273

## **Chapter 7 Error correction 275**

7.1	Sensitivity of message to error	275
7.2	Error mechanisms	275
7.3	Error handling	276
7.4	Interpolation	277
7.5	Noise and probability	278
7.6	Parity	280
7.7	Wyner-Ash code	283
7.8	Product code	283
7.9	Hamming code	283

7.10	Hamming distance	287
7.11	Applications of Hamming code	292
7.12	Cyclic codes	293
7.13	Burst correction	300
7.14	Fire code	301
7.15	B-adjacent code	308
7.16	Reed-Solomon code	310
7.17	Interleaving	317
7.18	Cross-interleaving	319
7.19	Error correction in D-1 and D-2	323
7.20	Concealment and shuffle	326
	References	327

## **Chapter 8 Digital video interconnects 328**

8.1	Introduction	328
8.2	Component digital parallel interfacing	330
8.3	Composite digital interface	335
8.4	PAL composite digital interface	335
8.5	NTSC composite digital interface	337
8.6	The parallel electrical interface	339
8.7	Component serial interfaces	340
8.8	Scrambled serial interface	341
	References	344

## **Chapter 9 Rotary-head tape transports 345**

9.1	Why rotary heads?	345
9.2	Helical geometry	346
9.3	Segmentation	352
9.4	Head configurations	353
9.5	The basic rotary-head transport	356
9.6	Controlling motor speed	357
9.7	Phase-locked servos	357
9.8	Tension servos	359
9.9	Tape-remaining sensing	361
9.10	Brushless DC motors	363
9.11	Switched-mode motor amplifiers	365
9.12	The digital video cassette	369
9.13	Threading the tape	373
9.14	Operating modes of a digital recorder	378
9.15	Framed playback	378
9.16	Assembly editing	379
9.17	Insert editing	379
9.18	Tape speed offset	380
	References	380

## **Chapter 10 The D-1 Colour difference DVTR format 381**

10.1	Introduction	381
10.2	Data rate, segmentation and control track	382
10.3	Distribution	385

10.4	Video mapping	387
10.5	Constraints on the error-correction strategy	389
10.6	Interleaving for shuttle	391
10.7	Sync block generation	393
10.8	The shuffling mechanism	394
10.9	RNRZ channel coding	399
10.10	Synchronization and identification	403
10.11	Gaps, preambles and postambles	406
10.12	Block diagram of a D-1 machine	407
10.13	Variable speed	411
10.14	Track following in D-1	412
	References	414

## **Chapter 11 The D-2 composite digital format    416**

11.1	History of D-2	416
11.2	Introduction to D-2	417
11.3	Track layout and segmentation	420
11.4	The active line	427
11.5	Distribution and concealment	428
11.6	The error-correction strategy	429
11.7	The shuffling mechanism	431
11.8	Implementing the shuffle in PAL	434
11.9	Implementing the shuffle in NTSC	435
11.10	The D-2 sync block	438
11.11	Miller <sup>2</sup> code in D-2	440
11.12	Synchronization and identification	441
11.13	Gaps, preambles and postambles	443
11.14	Block diagram of a D-2 machine	445
11.15	Variable speed in D-2	448
11.16	The actuator	449
11.17	Detecting the tracking error	450
11.18	The ramp generator	450
11.19	Track-following block diagram	453
11.20	Colour processing	454
	References	454

## **Chapter 12 Disk drives in digital video    456**

12.1	Types of disk drive	456
12.2	Disk terminology	458
12.3	Structure of disk	458
12.4	Principle of flying head	459
12.5	Reading and writing	460
12.6	Moving the heads	462
12.7	Controlling a seek	464
12.8	Rotation	468
12.9	Cooling and filtration	469
12.10	Servo-surface disks	469
12.11	Soft sectoring	473
12.12	Embedded servo drives	475

12.13 Winchester technology	478	
12.14 Servo-surface Winchester drives	480	
12.15 Rotary positioners	482	
12.16 Floppy disks	484	
12.17 Structure of optical disk drives	487	
12.18 Focus systems	488	
12.19 Tracking systems	490	
12.20 The disk controller	494	
12.21 Defect handling	498	
12.22 Bad-block files	498	
12.23 Sector skipping	499	
12.24 Defect skipping	499	
12.25 Revectoring	500	
12.26 Error correction	502	
12.27 Defect handling in WORM disks	502	
12.28 A disk-based still store	502	
12.29 Browsing files	504	
12.30 Editing in a disk system	505	
<b>Chapter 13 Digital audio with video</b>	<b>509</b>	
13.1 Typical digital audio equipment	509	
13.2 Choice of sampling rate for digital audio	510	
13.3 Audio quality considerations	512	
13.4 Types of digitization	513	
13.5 Basic digital-to-analog conversion	518	
13.6 Basic analog-to-digital conversion	522	
13.7 Oversampling	528	
13.8 An oversampling DAC	530	
13.9 Oversampling ADCs	531	
13.10 Spectral coding	534	
13.11 Digital audio interconnection	534	
13.12 AES/EBU interconnect	534	
13.13 Fibre-optic interfacing	542	
13.14 Parallel interfacing	542	
13.15 Audio in the scrambled serial video interconnect	544	
13.16 Synchronizing	545	
13.17 Introduction to NICAM 728	547	
13.18 NICAM 728 frame structure	550	
13.19 The NICAM sound/data block	550	
13.20 Companding, scaling and parity	553	
13.21 Digital audio in production DVTRs	555	
13.22 Problems of analog audio in VTRs	555	
13.23 Track sectoring	556	
13.24 Writing audio sectors	560	
13.25 D-1 audio error correction	560	
13.26 D-2 audio error correction	563	
13.27 Audio functions in DVTRs	565	
References	573	
<b>Index</b>	<b>575</b>	

# Why Digital?

## 1.1 The advantages of digital video

The first methods used in television transmission and recording were understandably analog, and the signal formats were essentially determined by the requirements of the cathode ray tube as a display, so that the receiver might be as simple as possible and be constructed with a minimum number of vacuum tubes. Following the development of magnetic audio recording during the Second World War, a need for television recording was perceived. This was due to the number of time zones across the United States. Without recording, popular television programmes had to be performed live several times so they could be seen at peak viewing time in each time zone. Ampex eventually succeeded in recording monochrome video in the 1950s, and the fundamentals of the Quadruplex machine were so soundly based that to this day analog video recorders still use rotating heads and frequency modulation.<sup>1</sup> Study of every shortcoming in the analog process has led to the development of some measure to reduce it, and current machines are capable of excellent performance. The point to appreciate, however, is that analog recording has become a mature technology and has almost reached limits determined by the laws of physics. The process of refinement produces increasingly small returns.

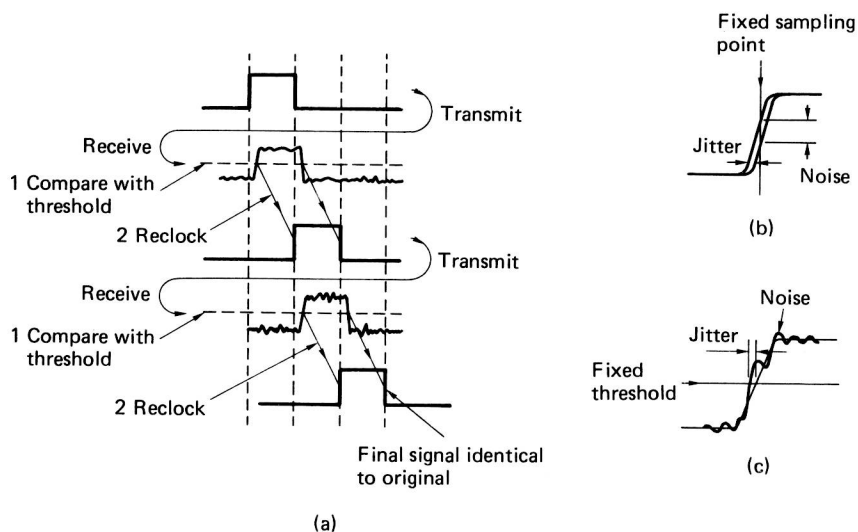
As there is now another video technology, and known as digital, the previous technology has to be referred to as analog. It is appropriate to begin with a comparison of the fundamental differences between these technologies.

In an analog system, information is conveyed by the infinite variation of some continuous parameter, such as the voltage on a wire or the strength of flux. When it comes to recording, the distance along the medium is a further analog of time. However much the signal is magnified, more and more detail will be revealed until a point is reached where the actual value is uncertain because of noise. A parameter can only be a true analog of the original if the conversion process is linear, otherwise harmonic distortion is introduced. If the speed of the medium is not constant there will not be a true analog of time and the result is known as timebase error.

It is a characteristic of an analog system that the degradations at the output are the sum of all the degradations introduced in each stage through which the signal has passed. This sets a limit to the number of stages a

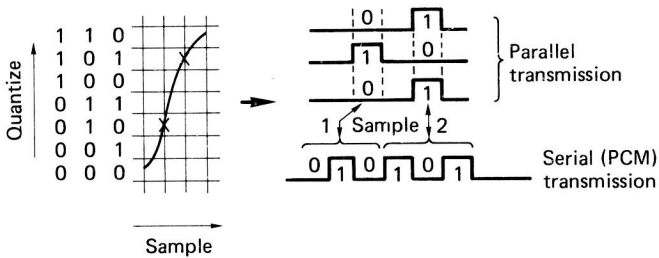
signal can pass through before it becomes too impaired to be worth watching. Down at signal level, all impairments can be reduced to the addition of some unwanted signal such as noise or distortion, and timing instability such as group-delay effects and chroma phase errors. In an analog system, such effects can never be separated from the original signal; in the digital domain they can be eliminated.

Although it is possible to convey signals which have an arbitrary number of states, in most digital video systems, the information is in binary form. The signals sent have only two states, and change at predetermined times according to a stable clock. If the binary signal is degraded by noise, this will be rejected at the receiver, as the signal is judged solely on whether it is above or below some threshold. However, the signal will be conveyed with finite bandwidth, and this will restrict the rate at which the voltage changes. Superimposed noise can move the point at which the receiver judges that there has been a change of state. Time instability has this effect too. This instability is also rejected because, on receipt, the signal is reclocked by the stable clock, and all changes in the system will take place at the edges of that clock. Fig. 1.1 shows that, however many stages a binary signal passes through, it still comes out the same, only later. It is



**Figure 1.1** (a) A binary signal is compared with a threshold and reclocked on receipt, thus the meaning will be unchanged. (b) Jitter on a signal can appear as noise with respect to fixed timing. (c) Noise on a signal can appear as jitter when compared with a signal threshold

possible to convey an analog waveform down such a signal path. That analog waveform has to be broken into evenly spaced time elements (a process known as sampling) and then each sample is expressed as a whole number, or integer, which can be carried by binary digits (bits for short). Fig. 1.2 shows that the signal path may convey sample values either in parallel on several wires, where each wire carries a binary signal representing a different power of two, or serially in one channel, at higher



**Figure 1.2** When a signal is carried in numerical form, either parallel or serial, the mechanisms of Figure 1.1 ensure that the only degradation is in the conversion processes

speed, a process called pulse code modulation (PCM). The only drawback of this scheme is that a single high-quality video channel requires about 200 million bits per second. Digital video only became viable when advances in high-density recording made such a data rate available at reasonable cost.

In simple terms, the signal waveform is conveyed in a digital recorder as if someone had measured the voltage at regular intervals with a digital voltmeter and written the readings in binary on a roll of paper. The rate at which these measurements are made and the accuracy of the meter now wholly determine the quality of the system, because once a parameter is expressed as discrete numbers, those numbers can be conveyed unchanged through a recording process. This dependence on the quality of conversion is the price paid to make quality independent of the signal path. As it is so critical to picture quality, a whole chapter of this book is dedicated to sampling and conversion. Since a digital system faithfully conveys the original analog waveform, it is equally feasible to digitize component or composite video signals. In the case of composite digital, there is complete freedom from differential gain error.

A magnetic head cannot know the meaning of signals which are passed through it, so there is no distinction at the head/medium interface between analog and digital recording. Thus a digital signal will suffer all the degradations that beset an analog signal: particulate noise, distortion, dropout, modulation noise, print-through, crosstalk and so on. However, there is a difference in the effect of these degradations on the meaning of the signals. As stated, digital recording uses a binary code, and the presence or absence of a flux change is the only item of interest. Provided that flux change can generate a playback pulse which is sensibly bigger than the noise, the numerical meaning will be unchanged by reasonable distortions of the waveform. In other words, a bit is still a bit, whatever its shape. This implies that the bits on the medium can be very small indeed and can be packed very close together; hence the required data rate is achievable. If the trivial example of the paper tape recording is pursued further, suppose that the tape upon which the voltages were written became crumpled up. If it were smoothed out, the numbers would still be legible and could be copied without error to a new piece of paper. By comparison, if a photograph is crumpled up, it will look like a crumpled-up photograph for evermore.

Large disturbances of the recording, such as dropout or severe

interference, may cause flux changes to be missed, or simulate ones which did not exist. The result is that some of the numbers recorded will be incorrect. In numerical systems, provision of an error-correction system is feasible; in analog systems it is not. In PCM systems, corruption of high order bits can cause severe disturbance of the video waveform, and at the recording densities necessary to give economy of tape usage, a properly engineered error-correction system is absolutely essential to return the corrupted numbers to their original value. It is probably true to say that, without error-correction systems, digital video recording would not be economically feasible.

In the digital domain, signals can be easily conveyed and stored in electronic circuitry. Unavoidable speed variations in recorders cause the numbers to appear at a fluctuating rate. The use of a temporary store allows those numbers to be read out at constant rate, a process known as timebase correction. In this way, timebase errors and chroma phase errors can be eliminated. The rock-solid vector display of a composite digital recorder is uncanny at first. The C-format timebase corrector, which made professional helical scan recording possible without field segmentation, was one of the first major applications of digital video. Chapter 4 treats this subject in some detail. The ease with which delay is provided also allows phase-linear filters and interpolators to be created in a straightforward manner, because the group-delay problems of analog filters cannot occur. Filters can be constructed which work with mathematical precision and freedom from component drift and with a response that can be easily changed.

The main advantages of digital video can be summarized as follows (they are not in order of importance because this will change with the application):

- \* The quality of a digital video link is independent of the characteristics of the channel in a properly engineered system. Frequency response, linearity and noise are determined only by the quality of the conversion processes. In recorders there is complete freedom from moiré and other analog recording artifacts. The independence of the quality from the medium also means that a recorder will not display different picture or audio quality if different brands of tape are used, provided that they all have acceptable error rates.

- \* A digital recording is no more than a series of numbers, and hence can be copied through an indefinite number of generations without degradation. This implies that the life of a recording can be truly indefinite, because even if the medium begins to decay physically the sample values can be copied to a new medium with no loss of information.

- \* The use of error-correction techniques eliminates the effects of dropout. In consumer products, error correction can be used to advantage to ease the handling requirements.

- \* The use of timebase correction on replay eliminates timebase error and can be further used to synchronize more than one machine to sample accuracy, eliminating the need for lengthy timing-in processes.

- \* The use of digital recording and error correction allows the signal-to-noise ratio of the recorded tracks to be relatively poor. The tracks

can be narrow and hence achieve a saving in tape consumption despite the greater bandwidth. Professional analog recorders must use wide tape tracks to give extremely good first-generation quality which then allows several generations of dubbing.

\* The advantages listed also apply to the audio channels of video recorders. It is natural to digitize both audio and video, so that much common circuitry can be used. The audio quality possible in a digital DVTR then exceeds that of a professional analog audio recorder, which could not be said for analog VTRs. The rigid timebase control prevents phase errors between channels, which is particularly important with the advent of stereo audio in television.

\* It is possible to construct extremely precise and stable digital filters and equalizers with inherent phase linearity. Such devices need no adjustment, and so the cost of manufacture can be less than the analog equivalent. The adoption of digital filtering makes possible such devices as picture manipulators and other effects devices which, though complex, are extremely reliable.

## 1.2 The opportunities

Digital video does far more than merely compare favourably with analog. Its most exciting aspects are the tremendous possibilities which are denied to analog technology. Once in the digital domain, the original picture is just a series of numbers, and these can be stored, conveyed and processed in many and varied ways. The computer industry has spent decades perfecting machines to store, convey and process streams of numbers at high speed and at a cost which continues to fall. Computers can generate artificial images for computer-aided design systems and simulators. Work has been done on the improvement of resolution and the elimination of flicker and other artifacts for computer displays, and broadcast digital video can take full advantage of such techniques. Recordings can be stored on computer disk drives, magnetic or optical, whose radially moving heads allow rapid random access to the information. For animation or editing of video, this is far superior to waiting for tape recorders to shuttle and preroll, although the sheer data rate of digital video prevents current disk-based machines from making lengthy recordings. An edit can be effected by reading samples from two sources and fading or switching between them in digital circuitry. The edit can be simulated, so that the outcome can be assessed, and the edit points can be moved around at will until the result is satisfactory. The final edited version can be recorded on a different medium if necessary, leaving the source material intact.

The cable and satellite communications networks around the world are increasingly being used for digital transmission, and a packet of digital video information can pass through as easily as a telex message or a bank transaction. Provided the original numbers are fed in the correct order at the correct rate to the final destination, for conversion to a picture, it does not matter how they have been conveyed.

The worlds of digital video, digital audio, communication and computation are closely related, and that is where the real potential lies.