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Digital Archaeology: Rescuing Neglected and Damaged Data Resources

A JISC/NPO Study
within the
Electronic Libraries (eLib) Programme
on the Preservation
of Electronic Materials

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Executive summary

The brief for this project is outlined in Appendix 1. The study examines the approaches to accessing digital materials where the media has become damaged (through disaster or age) or where the hardware or software is either no longer available or unknown. The study begins by looking at the problems associated with media.

Planning for disaster recovery situations is commonplace in many organisations from businesses to higher education (e.g. Campbell 1988, Cunningham 1987, Heikkinen & Sanrkis 1996, Kahane et. al. 1988, Leduc 1991, Meater 1996, Menkus 1994, Meredith Corp 1996, Millen 1993, Neaga 1997, Robbins 1988, Rohde 1990, Stamps 1987, 'Thank…' 1996, Underwood 1997), but much less attention has been paid to data recovery. The assumption is that with good disaster planning data recovery will be, under most circumstances, unnecessary. The problem is that while attention has been paid to disaster planning and the identification of good recovery procedures the effectiveness of these tend to depend upon pre-disaster effort. This effort often never takes place. Backing up and off-site storage of backup media are good examples of activities, which although paid lip service are often not carried out rigorously. Of the 350 companies unexpectedly relocated by the World Trade Centre (NYC) bombing 150 ceased trading, many because they lost access to key business records held in electronic form (McAteer 1996, 100). More generally '43 per cent of companies which lose their data close down' ('When…' 1996, 31). The National Security Association (Washington DC) estimated that the 'cost of rebuilding just 20 megabytes of data in a US engineering firm is $ 64,400' (ibid.,). Of course even if it is possible to recreate the data it is often not possible to do it in a timely enough fashion. Less attention has been paid on the other hand to data recovery. The demand for data recovery has however promoted the development of commercial data recovery companies that specialise in addressing the post-crisis situation. Even in the technical literature there is little discussion of data recovery techniques and this is fast becoming a black box area in which the great bulk of the techniques are developed and understood only in commercially sensitive organisations.

Because of the way magnetic media are written it is very difficult to lose everything. With sufficient resources much material that most of us would expect to be lost can be recovered. Using for example a magnetic force microscope it is possible literally to read the magnetic tracks on media such as disks (Rugar, et al 1990; Saenz 1987). It might be possible to use optical image recognition technologies to recapture these digital sequences. While in its current state of development this would be an impractical way to recover data itself it does tell us much about how this material is actually recorded on the surface of media from tapes to disks and indicate future directions in data recovery.

The range of techniques involved in data recovery includes baking, chemical treatments, searching the binary structures to identify recurring patterns, and support for the reverse engineering of the content. As far as recovery is concerned we need to make a significant distinction between data recovery and data intelligibility. Essentially it may be quite feasible to recover the binary patterns from almost any piece of media, but it may not be so easy to understand what the content of those patterns actually represents. Developments in head technology will make it increasingly difficult to build a reader on the fly, especially when considering developments such as IBMs No-ID technology for writing disks and magneto-resistive heads.

Our initial understanding of the stability and life expectancy of particular types of media often depends upon the claims made by the media manufacturers themselves. These claims tend to reflect the exuberance of scientists compounded by the hype of their marketing teams. As a result it often proves difficult to take well-informed and secure decisions about technological trends and the life expectancy of new media. In the case of the Alberta Hail project the team felt a great deal of data useful to the study of hailstorm physics and dynamics were at risk because they were stored on magnetic tape. They felt that the best way forward was to copy the data to CD-R technologies which the team perceived as a more stable medium than magnetic tape (Kochtubajda, et al 1995).[I] There is plenty of evidence that the stability of CD-R is over-rated (see below Section 1.1.6). Far from being a secure medium it is unstable and prone to degradation under all but the best storage conditions.

Hardware collection and conservation is attracting increasing attention (Keene & Swade 1994). Numerous institutions are preserving computer hardware and many of these are keeping it in working order (see Appendix 2). Emulation of both hardware and software and its role in ensuring access to digital materials is the subject of a number of investigations. The HATII team conducted a small experiment to appraise the viability of more detailed work in this area. We have described a small experiment conducted by HATII, which indicates to us that more research should be conducted in this area. Of all the techniques currently available we believe that the work in the area of binary retargetable code holds the most promise.

When some media have been identified which supposedly hold digital materials five main obstacles may inhibit their recovery.

- **Media degradation**
  This can be the result of:
  - storage under conditions of high temperatures,
  - high relative humidity during storage,
  - media coming into contact with magnetic materials,
  - disaster (e.g. lightning strikes),
  - wear as a result of excessive use, and
  - manufacturer defects;
- **Loss of functionality of access devices**
  This can be the result of such factors as:
  - technological obsolescence (e.g. devices going out of use),
  - the fact that components in mechanical devices are prone to wear out. The mass manufacturing of tape devices has resulted in their being made of less durable components, and
  - the fact that device drivers for older hardware are generally not supported by newer hardware;

I Many projects are taking similar decisions. For instance the National Sound Archive's Project Digitise opted for CD-Rs. Peter Copeland argued that the destination medium was selected because of its long shelf life, high quality, wide acceptance and distribution, flexibility, robustness, reasonable cost, and 'long uninterrupted playing-time' (1998, 128). The sensibility of this decision may be questionable.

- **Loss of manipulation capabilities**
  This is often the result of:

  - changes in hardware and operating systems which have made it impossible for applications to perform the same functions or access the same data manipulation routines (e.g. primitives, sub-routines, system libraries);

- **Loss of presentation capabilities**
  This might result from:

  - a change in the video display technologies,

  - the fact that particular application packages do not run in newer environments etc; and,

- **Weak links in the creation, storage, and documentation chain**
  This might result from:

  - a situation where it is possible to read the magnetic polarity changes and thereby recover the bits from the media itself, but then it is not feasible to interpret the data because the encoding strategy cannot be identified;

  - the inaccessibility of encrypted data because of a loss of the documentation in which the encryption key was stored; or,

  - a situation where an unusual compression algorithm was applied to the data before it was encoded and written on the media.

The data recovery company Ontrack (1996) did a study of the causes of data loss from among 50,000 of its clients. They found that the main causes were:

- hardware or system malfunction (44%) (e.g. electrical failure, head/media crash, controller failure);

- human error (32%);

- software program malfunction (14%) (e.g. corruption caused by diagnostic or repair tool, failed backups);

- viruses (7%); and,

- natural disasters (3%) (*Document Manager* 1996, 31-32).

This report examines five main topics:

- media and data recovery;

- hardware restoration and simulation, emulation, and binary retargetable code;

- case studies on data recovery;

- ways of preventing data and information loss; and,

- possible further studies in this area.

There are 7 appendices and bibliographies of both printed and electronic resources. Appendices 2 (List of preservation institutes and emulation software sites) and 3 (Data Recovery companies) will be of special interest, but it is worth noting that this is a fast changing landscape and new sites appear daily.

Information about data loss, recovery, and risk is very difficult to acquire. As part of a continuing project which HATII will be undertaking to produce a definitive study of the Post-Hoc Rescue of Digital Materials we have launched a website where users can log and access information on this topic: http://www.hatii.arts.gla.ac.uk/rescue. In the concluding section we have proposed that:

- more case histories about data loss and rescue need to be collected;
- more research needs to be conducted into the viability of the preservation of media access devices to ensure the possibility of access to a diversity of media types in the future. Even where emulation can be used to run programs and manipulate data created in other environments, devices to read the media prove much more difficult to recreate. Writing device drivers for older devices, although tricky, is far simpler;
- documentation for hardware and software although initially ubiquitous when products are first released become increasing difficult (and in some cases prove impossible) to locate over time. A concerted effort should be undertaken to collect documentation, including designs;
- more research needs to be carried out in the area of emulation;
- the use of magnetic force microscopy to recover data from magnetic media needs to be the subject of a programme of research;
- further work into the use cryptography to decode bit sequences is necessary; and,
- a media quality index needs to be developed. Some factors which might be included in any such index include: adhesion, abrasivity, durability, chemical stability, and error rates. Every piece of storage media should be marked with a quality rating.

It is also that clear that archivists, librarians, and information scientists need to extend their investigations of media and studies of its durability to the scientific journals where this material is published such as the *Journal of Applied Physics*.

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The project was directed by Seamus Ross and Ann Gow acted as principal investigator. Our work was aided by our colleague Richard Alexander (HATII Technical Resources Co-ordinator) who assisted Ann Gow with visits to and research on data recovery companies. Gerrard Sweeney (HATII Technician) advised on the experiments with emulation and contributed to the production of Section 2.3.

This report was completed in December 1997.

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Contents

1. Media and data recovery

1.1 Recording media and recording (magnetic & optical)

1.1.1 MAGNETIC MEDIA

The most commonly used media for storing information in digital form are still magnetic. Although disks offer the most convenient storage medium tapes remain the most widely used medium for mass storage. Tapes come in a range shapes, sizes, and packages (e.g. reels, cartridges, and cassettes) and they can store information in varying, but increasing, quantities. In order to understand the issues surrounding data storage and long term access it is necessary to have a basic understanding of the concepts of magnetics. The processes of magnetism, what particles hold a magnetic charge and why, developments of new particles and how these particles are suspended are central to this discussion. Of the types of materials showing magnetic properties only those with ferromagnetic capabilities are relevant to this particular inquiry. Ferromagnetic materials are those materials that can be permanently magnetised by an external magnetic field such as an electromagnet or another permanent magnet. Materials having ferromagnetic properties include Fe_2O_3 (iron oxide), CrO_2 (chromium dioxide), and Co-Fe_2O_3 (cobalt-modified iron oxide).

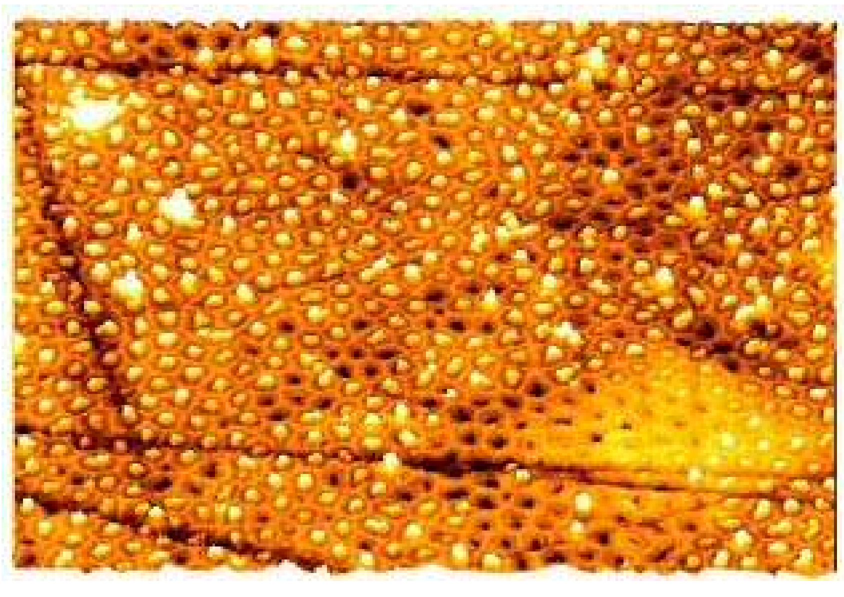
These ferromagnetic materials are magnetised by using an external magnetic field to increase their induced magnetism. These types of material saturate when they cease to be effected by increases in the magnetic field. The point at which this occurs varies from one ferromagnetic material to another. This transition from unmagnetised to saturation is known as the magnetisation curve. After the material has been saturated if the magnetic field is reduced the level of induced magnetism will fall, but for ferromagnetic materials it will neither follow downward the same magnetisation curve that it followed to saturation nor will it, necessarily, be reduced to zero. As a result the ferromagnetic material acquires a degree of magnetic remanence. Magnetic remanence is measured by the amount of applied magnetic field required to reduce the magnetic induction to zero. This is known as coercivity. The value of the coercivity of a ferromagnetic material is important to the recording process because it reflects the ease with which the magnetic induction can be reduced to zero from its remanent state. Where data were recorded a reduction of the magnetic remanence of the material to zero would lead to total data loss. Once the ferromagnetic material has permanent magnetism, the recording process can start. Digital data, 1s and 0s, could be converted into an alternating pattern of magnetic orientations or polarity.

Basically there are two kinds of magnetic media: hard and soft. To achieve permanent magnetism, hard media, must be subjected to a extremely strong electro-magnetic field. As a result they achieve high levels of magnetic remanence. Soft media require lower applied electro-magnetic fields to reach saturation. They have correspondingly low magnetic remanence and low coercivity. It is hard media, with its high saturation remanence and high coercivity, that are especially suited to digital data storage. The materials used to create ferromagnetic media has varied over the years and are even now subject to intensive research in the search for particles better able to hold magnetic charges under varying conditions (e.g. Okamoto, et al 1996). In some of the earliest machines ferrous wire provided the recording medium. Most media now consist of a fine layer ferromagnetic materials suspended in, for example, a polymer-based mixture (e.g. polyvinylchloride or polyamide). This is laid on a non-magnetic substrate.

Magnetic media tend now to be either particulate media or thin metallic oxide coatings. Particulate media are composed of ellipsoidal particles suspended in a polymer binder (see Figure 1 below). To make certain that the particles are evenly distributed in the mixture solvents and other chemicals are added. Some of these chemicals assist with the manufacturing process by reducing sedimentation and particle clumping, while others are intended to improve the usability and life-span of the materials; for example lubricants are included in mixtures for coating tapes to reduce wear during their use and increase their life expectancy (but see BASF below). After the binder is deposited on the substrata a magnetic field is applied to align the ellipsoidal particles.

The magnetic properties of film deposited magnetic media are created by metal crystals formed during the film depositing process. These came into use in the 1980s and have been instrumental in the development of 'winchester-type' disk drives. Whereas the substrates of flexible media (e.g. tapes) are commonly polyester, the substrates for rigid media (e.g. hard disks) tend to be aluminium. In the manufacture of disk drives this aluminium strata is coated with a binder to reduce corrosion and to increase likely adherence of the metal film to the substrata. The magnetic layer is either deposited using vacuum sputtering or evaporation (Comstock and Workman in Mee and Daniel (eds) 1996, 2.2). To protect the magnetic layer from damage it is also coated with an additional layer. Because of the wear to the overcoat through use this is a subject of much research (e.g. Akiyama et al 1991). Not only are hard disks produced by the film deposit process but this process is also used to make high quality videotapes.

FIGURE 1:
AN ATOMIC FORCE IMAGE OF MAGNETIC RECORDING MEDIA SHOWING THE SUSPENDED MAGNETIC PARTICLES (used courtesy of Park Scientific Instruments, http://shell7.ba.best.com/ ~wwwpark/appnotes)



1.1.2 DETERIORATION OF MAGNETIC MEDIA

Magnetic media are not stable, they are susceptible to deterioration for a number of reasons. For example in magnetic particle media the 'particles have problems with chemical stability and are susceptible to oxidation and corrosion' (Okamoto, et al 1996, 63). Oxidation and corrosion can lead to a decrease in the magnetic remanence or coercivity of the particles and cause data loss as a result. All the components from the particles to the binder to the substrata are likely to deteriorate.

Systems managers are well aware of the lack of reliability of even new media however. In the 1970s the team at the Missouri University Atmospheric Science Center would put 'new tapes through a process that wrote and then attempted to read back binary ones for the length of the tape. Some new tapes could not pass this test' (http://www.cclabs.missouri.edu/~ccgreg/tapes.html). Tape manufacturing has become generally more reliable and the materials more stable, but it is not uncommon to encounter new tapes which fail.

The material used to hold the magnetic particles vary and only a small number of firms actually make formulas for coating tapes[1]. Even fewer firms actually undertake the coating activity. In the UK, for instance, there is only one firm specialising in tape coating and it does it for all the major tape badge-engineers. Anacomp, is based in North Wales because it is only in Wales and Scotland that the air is pure enough to build cost effectively tape coating plants, and the tape it coats are distributed under all the major tape names (*Anacomp Magnetics). The quality of the tape production process is key to the creation of good media, but as a purchaser of tapes it is one quality about which it is almost impossible to gather information. The National Media Laboratory, which does evaluations of categories of media, does not rate tapes from different manufacturers (see http://www.nta.org). There have been some disasters as a result of the production process. BASFs Willstatt plant in 1992 was making around 20 million tapes per year. As a result of a poorly implemented system for re-cycling chemical solvents used in the production process BASF released more than 10 million 3084-class cartridges which contained the seeds of their own destruction within the tape itself (*Computer Weekly* 30/1/92, 6/2/92, 20/2/92). BASF replaced more than 4 million of the tapes made prior to 1991. Because of the error the tapes were more likely to shed oxides onto the read-write heads. Several large UK users, British Steel and Asda, discovered the problem following chemical analysis to help it understand why it was losing data. It was these users who alerted the manufacturer.

Some of the oxides are more stable than others and the material is coated (as described above) to avoid oxidisation of iron-based particles. However, over time, even with the coatings, the particles will oxidise (say as a result of absorbing moisture by the tape) and the magnetic properties be reduced. The remanence itself will lessen over time particularly if poorly stored. The most stable particles are iron oxide, barium ferrite and metal particle. Chromium dioxide is much less stable, as it converts to non-magnetic oxide forms. There is also a danger that the media will lose their magnetic remanence and thus the ability to retain the data. Any changes in the magnetic properties of the media could result in a reduction of magnetic strength. For example some materials are prone to oxidise if the medium absorbs water. If the magnetic material's ability to resist demagnetisation decreases then it becomes more likely that demagnetisation will take place.

The most significant threat to media is the breakdown of the polymer chains that compose the binder itself. The polymer chains are susceptible to deterioration caused by exposure to moisture. Tapes absorb water when left in humid environments. As a result they undergo the process of hydrolysis which causes the polymer chains to disintegrate. As the polymer chains disintegrate the binder will become tacky. As with the breakdown of nitrate and acetate film once this process has begun it progresses quickly and it is difficult to stop. It creates an adhesive build up that makes the tape almost impossible to play. This is commonly called sticky shed syndrome, where the magnetic material literally "sheds" off the backing. Where this occurs the impacts include both temporary and permanent data loss to damaged equipment. The sticky shed syndrome is characterised by extreme tape friction and low coating integrity. As John Van Bogart, of the National

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1 It is worthy of note in this regard that the most recent advances in coatings has taken place in Japan and Korea. Firms developing coatings are less and less likely to license tape manufactures to coat media and increasingly inclined to protect the coating technology by coating the media themselves. The tape manufacturers then produce the actual storage media from the large rolls of coated material.

Media Laboratory in the US, who has produced the leading studies of the breakdown of media (see for example, Van Bogart 1995, 1996 and presentations available on the web of 14 March 1996, September 1995 and July 1994) has noted the damage may not be confined to the media itself however. As a result of shedding during read or write the tape mechanisms themselves may become damaged and may in turn damage other media played in them. Damaged tapes can be treated by baking them, but this is very much a temporary measure (*Ampex, *Lindner).

The substrate can also deteriorate under humid conditions causing mistracking and playback mechanisms not locating the data. Humidity often poses major problems during seismic survey work in countries with less developed infrastructures. The substrate supports the magnetic layer for transport through the recorder. Typically this will be composed of polyethylene terephthalate film (PET). PET is stable, resistant to oxidation and hydrolysis. It will survive longer than the binder will. However there are scenarios where the substrate will cause damage to the tape and thus result in data loss or dropouts (Weick & Bhushan 1995; 1996; 1997). The substrate can suffer from the dimensional instability of the PET, where it can physically change dimensions due to temperature or humidity. If the track is not where it was originally laid down, the read head will not find it and mistracking will occur. Some companies are now producing substrates that are less susceptible to dimensional changes, polyethylene naphthalene is one in question which would seem to be more stable than PET (Weick & Bhushan 1996). Common dimensional changes include curvature of the substrata and shift in tape angle both of which can cause data dropouts.

These are the deteriorations that can happen over time as a result of the physical and chemical changes in media itself. We can also look at the results of bad storage that in turn will cause damage to the tape and possible data loss. Tapes are normally stored in a tape pack, wound round a central hub. The sides of the reel are known as flanges. If the tape is wound too loosely, then air pockets will occur within the pack and these will allow moisture in which in turn will contribute to the development of sticky shed syndrome (*Ashton, et al). The tapes can be wound too closely to the flanges, allowing the edges, where the recording data is mostly stored, to extend physically beyond the pack and these segments of the tape will bend and even tear. If the tape is wound erratically and unevenly this can cause stress, leading to substrate deterioration. This kind of stress can lead to mistracking, as it is likely to cause the tape to take on a non-uniform shape. Horizontally stored tapes are susceptible to tape slip if they suffer a vertically shock. This results in the edges of the tape extending beyond the pack and makes them susceptible to damage. Papers by Van Bogart published in 1995 and 1996 and slides from presentations given in March 1996, September 1995 and July 1994 discuss the issues associated with data recovery in detail.

The problems associated with magnetic tapes have been exacerbated by the increasing storage densities at which the media have been and are being written (see Table 1). This means that problems associated with tape segments result in greater data loss than they did when tapes were written at lower densities. Writing and reading tapes can subject them to wear even under optimum conditions. Bhushan & Lowry have undertaken research to define metrics for measuring the wear created by various head materials and the impact this will have on the life of media (1995). Tapes must have some abrasive quality because without it they do not maintain head contact, but a delicate balance must be struck between sufficient abrasivity in tapes so they can maintain head contact but not creating tapes which are so abrasive as to create excessive wear on the read-write heads (Rogers & Hintereggen 1993). Heads and tapes made of different materials (Mn-Zn ferrite, SiC) wear in different ways and therefore have either longer or shorter lifespans. Bhushan & Lowry have produced optical micrographs of $Cr0_2$ wear patterns after 125 passes which show that the tape is beginning to breakdown (see 1995, Figure 7). In addition to the level of abrasivity and the tape-head interface such factors as tape tension, thickness, width, and speed all impact on wear. Temperature and humidity also have a role to play (Xu, et al 1997).

TABLE 1:
INCREASING STORAGE DENSITIES OF MAGNETIC TAPE
(Based on research conducted by Clive Jenkins of Emmarc Ltd, The Reel World Environment, 1990, 30)

Year	Media Form	Storage Density*
1953	IBM 726 Tape	100 cpi
1963	reel	200 bpi
1965	reel	556 bpi
1969	reel	800 bpi
1971	reel	1600 bpi
1981	reel	6250 bpi
1985	cartridge	37,871 bypi
1991	cartridge	77,000 bypi

* cpi = characters per inch, bpi = bits per inch, and bypi = bytes per inch

The condition of the drives used for handling tapes is of critical importance in the continuing access to the content on the media. Tape drives and standards are replaced on a regular basis, and because manufacturers wish to minimize production costs and maximize profits the components used to produce drives are of variable quality. Tape drives pose problems of their own; as they are mechanical devices tape drives tend to fail because of component wear. They tend to become dirty and as a result can pass dirt onto the tapes themselves (e.g. excess lubricant attracts dust particles which are then embedded in the tape pack). The lubrication squeezed out of the tape is not all reabsorbed by the tape and some of it begins to collect on the tape mechanisms. Some lubricants contribute to wear of the heads (Mizok 1996, 256) as do the mechanical properties of the tape and the abrasive agent. The main problem is the interaction between the head and the media which passes across it; not only does the tape wear during use but the head on the device which is reading or writing the tape also wears (Osaki 1993; Osaki, et al 1992; Osaki, et al 1993). Studies of 'Wear of tribo-elements of video tape recorders' provides a backdrop for other magnetic media:

> the head wear is in proportion to the contact pressure and the sliding distance in the abrasive mode. Contact pressure depends on the head load and the contact area which is determined by head contour, head protrusion, tape tension and tape stiffness. Also, the head wear depends on the hardness of the head material and tape roughness (Mizoh 1996, 253).

Mizoh collated the studies of the various factors which contribute to head wear. His list is reproduced in Table 2, but not the extensive list of references he cites for each item for these see his article (Mizoh 1996, 254 [Table 2]).

TABLE 2:
PARAMETERS EFFECTING TAPES

Head parameters	Tape parameters	System parameters	Environmental parameters
material	structure	tension	temperature
hardness	magnetic powders	relative velocity	humidity
direction of crystal	abrasive	head protrusion	
grain size	lubricant	contact pressure	
protective layer	surface roughness	running time	
head structure	surface finishing	multiple passes	
contact area	stiffness	internal temp	
	thickness		

Part of the reason why tapes are more widely used than disks for mass storage is not just the higher density they can achieve, but is primarily a function of costs. In 1956 the first disk drive sold for around a one million dollars and could hold only about 5 megabytes. In the period between 1991 and 1998 the cost of disk storage has fallen from five dollars a megabyte to less than five cents a megabyte. There are DLT tapes on the market which can store up to 70 gigabytes. Indeed tape storage costs have over the past few decades dropped significantly in cost.

On tape data is stored sequentially. This can result in slow access as the read/write head has to scan the tape linearly, which can cause retrieval times to be extremely slow. Each system will store the data blocks differently, but they all have an additional set of bytes at the beginning and end of each block which has information about the block itself, block number etc. Most tapes will store the data sequentially, so retrieval, although lengthy, is a matter of reading a set of data blocks until the end of the sequence is reached. However, data may not be stored in sequential order, and thus the bits at the beginning of the block are highly important for retrieving a complete set of data. Most systems have a directory, similar to that of disks, at the beginning of the tape that stores the location of the data blocks on the tape. Most tape systems use multiple tracks on the tape to increase storage facilities. Until recently when tapes finished reading or writing they returned to the beginning of the tape. In newer tape systems tapes are returned to the mid-point after reading or writing because this improves access speed by reducing the search space. This exposes data regions to excessive wear.

As the storage density has risen the tape devices have gone from the size of a home refrigerator (an American one that is) to the size of a bar of soap and the electronics controlling the devices have become much more sophisticated and even more miniaturised. Changes have also occurred in software as well. For example the software to manage the tape reading and writing includes error correction functionality to compensate for data loss caused by such factors as dropouts or mis-registration of the device. This is generally done without alerting the user to the fact that the system encountered problems, therefore masking the difficulties with the media.

1.1.3 RIGID AND FLEXIBLE DISKS

Hard disks are electro-mechanical devices. They consist of platters coated top and bottom by magnetic oxides. Unlike tapes which are transported past the read-write heads, the heads on a disk are moved from the edge of the disk toward (and away from) the centre of the media. The platters spin above and below the heads. To read data the controller positions the arm above the correct track and where it waits (a very relative term) until the spinning disk brings the correct sector into position below the heads. Hard disks have been shrinking in size, requiring less power while storing vastly increasing amounts of data accessible at increasingly fast seek times. For instance, the two-year old 3.5 inch Ultrastar 2 drive from IBM stores upwards of 10.8GB, spins at 5400 RPM, has an average seek time of 8.9ms, has the ability to read data at between 8.4 and 14.2 MB per second. It also only requires 14 watts of power. It is composed of 10 disks and 20 magneto-resistive heads (http://www.ibmlink.ibm.com/HTML/SPEC/goem7058.html). This is a major change from storage capabilities of the first hard disk released by IBM (IBM 350) in 1957 which could only store 5 million characters.

In the case of modern drives even such factors as the type of interface the drive is equipped with will have an impact on our ability to recover data from it. For example, the programming interface on early IBM PCs limited the available disk space to 528 megabytes and older integrated disk electronics (IDE) disk interface chips are not likely to support data beyond this. Enhanced IDE and SCSI exceed this and can support multiple devices. Essential data is held in three areas of the disk and access to this data is essential to the data recovery process. These are: partition tables, the boot block, and file allocation tables. The partition table contains the structure of the disk including start and end points, errors and details of corrupt areas.

A disk, hard or floppy may contain a boot record, a file allocation table, a directory and the data area. A hard disk contains a Master Boot Record (MBR). Each disk is divided into tracks, sectors and clusters. The MBR on a hard disk has information about the disk partitions (i.e. the drives into which the storage areas on the disc are divided.) Each partitioned drive acts like a separate hard disk. A fixed disk consists of platters of equal diameter, each platter has two magnetic surfaces where data can be stored. The disk is subdivided into concentric circles, called tracks. Each track is further divided into sectors. A cluster is a set of sectors, the size of which depends on which operating system was used and which version.

A contiguous set of cylinders must be allocated for storing the operating system. Each partition on a disk can hold one operating system, no more than one partition per operating system and vice versa. There is always only one active partition in a hard disk and it is the operating system on the active partition that is loaded when the disk is booted. Early hard disks had to be partitioned before they could be used, DOS used a program called FDisk. We have to remember that any data stored in a partition on an early fixed disk may be of a different operating system to the previous partition.

Each track is divided into short areas called sectors. A sector is addressed by its track number and sector number. A disk can be hard sectored or soft-sectored. Hard sectored means that the sector sizes and positions are fixed by the manufacturer and are inflexible. Soft sectored disks have the sector size and position fixed when the disc is formatted. The gaps between sectors allow the processing of records and also the storage of address bytes. Generally sectors are 512 bytes in size. Older disks used constant angular velocity recording which means that each track has the same number of sectors; modern disks use multiple zone recording which creates different numbers on each track. A cluster is a group of sectors on a hard disk or floppy disk that forms the fundamental unit of storage allocated by the operating system. The number of sectors in a cluster is determined by the operating system, not the hardware.

The Boot record is a short program (in machine code) which issues the instruction to load the operating system into memory. It also contains information about the disk such as the number of bytes per sector and the number of sectors per cluster. The boot record is stored in the first sector of the first track on a disk or platter containing the active operating system, e.g. MSDOS. Once the code for the operating system has been found, the boot record starts loading that code into memory and then hands over the control of the system to it. The operating system then completes the boot-up process. Even in newer PC's that come as "plug and play", the boot sector is in the first sector of a disk, so if it gets damaged, it is still not possible to access the data that is stored after it.

As explained above, hard disks are partitioned into logical disk areas. The Master Partition Table (MPT) keeps track of the physical partition on the disk. This table is stored in the first sector of the disk. Each partition (4 possible) has an ID number to identify it. The MPT is 64bytes in size, each area then 16 bytes. The first byte is a boot flag to indicate if the partition is bootable, a bootable partition has a value of 80(hex) and a non-bootable partition has a value of 00(hex) this is applicable for any operating system. The MPT defines the size of a partition by its start and finish sectors. The three bytes starting at offset 01(hex) hold the starting head, sector and cylinder numbers, while the three bytes at offset 05(hex) hold the finish head, sector and cylinder numbers (Rosch 1997). These values therefore describe the physical geometry of the disk. Knowledge of the structure of the disk depends upon the availability of this information.

The File Directory is another section of the disk that is stored in the first sectors. It stores the information about the directory structure, including subdirectories. It also holds information about the files stored in these directories. The attributes of files are commonly the name, the extension (if it has one) which can help identify what type of files are stored, the size of the file, whether it was stored as read-only, a system file or if it was archived, i.e. compressed. All this information is very valuable when recovering data from disks that have no further documentation.

Files are broken into clusters when they are stored on a disk. A cluster can be physically stored anywhere on a disk and they are not necessarily stored consecutively. In some architectures a file allocation table (FAT) is used to identify where the data are stored on the disk. The FAT works by storing extra bytes of information about the file. As well as its name and last use date in its listings, there is the address of the first cluster of the stored file. Using this information the operating system can access the first cluster. It then looks at the directory entry for that cluster which has the address for the next cluster and so on. The FAT links the clusters together by storing the addresses in the table. When a file is deleted, the FAT entries are changed to zero (indicating an available or empty cluster), the actual data remains intact on the disk and can be restored, until a new file overwrites the clusters (Rosch 1997). Undelete programs look at the FAT and find those entries with zero as a value and display what data exists in the clusters, this may be nothing or lost data. Files can be recovered partially or fully. The likely success of efforts at recovery depends on how many writes to disk have happened since the deletion.

Data is stored on different media depending on the physical structure. On a magnetic tape, the data is stored linearly while on hard disks and floppy disks the data is stored in circular tracks on the disk which are in turn divided into sectors, and several sectors make up a cluster, the main storage unit for data on a rotating disk. Each cluster has an address that can be accessed through the FAT so the head can move to the correct track and cluster to retrieve the data. In magnetic tape, the read head must be able to work out where it is on the tape to know whether to move forwards or backwards to reach the point to be accessed.

The position of the heads is controlled by the drive electronics based on a servo pattern previously written on the surface of at least one disk. The read-write head records or retrieves data from tracks pre-formatted in the magnetic layer of the disk. Most disks now have the servo pattern on the same side of a platter as data, in older discs, this pattern was stored on a separate platter surface. The servo pattern gives information on where the head is and where the next cylinder is to move the head to read/write. When the servo pattern is held with the data, this is called an embedded servo drive. A problem facing researchers trying to increase storage by scaling down disks, is that as track sizes decrease, the amount of information that the servo has to return increases and thus the size of storage area for the servo will increase. Attempts have been made to address this problem. For example IBM has introduced a No-ID format which significantly enhances disk storage by delivering faster access times, better disk defect management, and increased storage density. To achieve this it stores the header or ID information in solid state memory rather than on the disk itself. While this will be very effective in improving access times it does create a risk of information loss by severing the relationship between the raw data and the information about its location and meaning.

A similar phenomena to ‘Sticky shed syndrome’ known as ‘Stiction’—as combination of friction and sticking—plagues hard disks. This occurs when the silica based disk platters are subjected to high temperatures, through either excessive use or bad storage (Van Bogart, 1996). The silica becomes sticky and the disk heads stick to the surface. (Often as a result of stiction the drives burn out as users keep restarting the system and the drive tries to power-up again and again against the locking caused by the stiction.) More common causes of failure stem from the read-write heads crashing onto a platter of the drive. This is often caused by a severe shock, such as dropping the machine. The g-forces which drives can withstand have increased significantly over the past few years. In some cases smoke particles may end up between the head and the platter. This can damage both the surface of the medium and the heads. More common problems with drives are associated with mechanical or electrical system failures. As the figure below makes clear disk drives still have a significant number of mechanical parts, which are more prone to failure than electronic components, all the same the mean time before failure (MTBF) for most drives is measured in the 100,000s of hours of usage.

In the same way that a great deal of effort has gone into the improvement in media densities a great deal of changes have taken place in the reading and writing heads on disks as well. The work of Tokumaru and his colleagues (1993) and that of the teams at the IBM laboratories in Almaden, CA. all show just how complex this arena has become. The specialised facilities needed to construct magnetic heads make it nearly impossible to replicate them. It is some of the developments in disk drive technologies that will cause us new worries. Magnetoresistive recording heads and No-ID disk writing technologies. The problems with the MR recording technologies are the complexity of construction and the low tolerance for error. 'MR recording heads have an inductive 'write element' and a MR 'read' element. The electrical resistance of materials inside the head that exhibit the MR effect changes according to the strength of any magnetic field present' (http://eagle.almaden.ibm.com/storage/press/hdd/5gb.htm, 09/10/97 15:59). MR heads read data from the disk by monitoring changes in resistance. The heads pass less than two millionths of an inch away from the disk surface.

1.1.4 FLOPPY DISCS

Of some concern should be floppy disks because they tend to be the primary medium used by researchers for storing data. As early as 1983 concerns about the care and longevity of the media were expressed (Ahl 1983; Marshall & Attikiouzel 1983). The media is produced in much the same way as tapes. Essentially it is a polymer with a magnetic coating. The difficulties with this category of media does not rest with the media itself, but with how it is housed: in flexible and easy to damage casings, with media segments which can easily become exposed to the elements (including in the case of 5.25" diskettes finger prints). Floppy disk drives function at much lower speeds, 300 to 360 RPM (although duplicators often spin at 600 to 720 RPM). Because the drive heads are more easily exposed to the elements (e.g. dust, debris, moisture) they are more susceptible to damage. There is also much variability in recording (e.g. Li & Xun 1990; Miller & Good 1987). There are already obsolete formats, such as 8" disks, for which readers are extremely difficult to find and 5.25" disk drives are also becoming more unusual. Experience has shown that problems with mechanical aspects of drives and the alignment of read-write heads tends to plague these disks (*Ava Instrumentation). However if essential data are present on this media it is usually possible to recover them even if the oxide data-holding wafer has been crumpled and mangled.

1.1.5 THE IMPACT OF MAGNETISM ON MEDIA

Loss of information because magnetic media have come into contact with magnetic fields is a constant worry. However there is little reason to be concerned about this eventuality. Manufacturers are producing media with increasingly high coercivity, but as Clive Jenkins has pointed out small magnets used in cabinet and door catches have field densities of 1500 Oersteds (1991, 56). Contact with them could lead to data loss, but it may not because other factors such as casing type and density often help to protect the disks. It is not the X-rays in airport scanners which pose a threat to the contents of hard disks, but it is rather the magnets in the motor which drives the belt. Newer kinds of motors are reducing the threat—although within archives and libraries it may be dangerous to move media using motorised devices. Occasionally in freak accidents material can be destroyed: John Tolansky, Director of the Music Performance Recording Centre had collected off-air recordings since he was a young lad and when his house was struck by lightning he found that about 10 percent of his collection of 2000 recordings was destroyed as a result of print through (pers comm). Most media has a coercivity value of at least 315 Oe and recent media has much higher ratings than 750 Oe and many media have a coercivity of 1500 Oe. (Oe=Oersteds which is a unit of magnetic field strength.). A simple rule of thumb is that iron oxide media can achieve 325-350 Oe, chromium dioxide media can achieve 350-750 Oe, and cobalt-modified iron oxide levels can be greater than 750 Oe.

TABLE 3:
MEDIA COERCIVITY
[Sources:_http://www.weircliffe.co.uk/deguassi.htm; 09/08/97 12:03:07 and http://www.cs.auckland.ac.nz/~pgut001/secure_del.html]

Media Category	Oersteds
Floppy disk 5.25", 360k	300 Oe
Floppy disk 5.25", 1.2MB	675 Oe
Floppy disk 3.5", 720k	300 Oe
Floppy disk 3.5" 1.44MB	700 Oe
PC, Mini, Hard disk	550 Oe
1980s hard disks	900 – 1400 Oe
1990s hard disks	1400 – 2200 Oe
Mainframe spool ½"	310 Oe
Cartridge	550; 650 Oe
TK50	1500 Oe
Reel ½" or 1"	310 Oe
Cassette	675; 750 Oe
8mm/4mm	1050; 1500 Oe
Cartridge 3840	300 Oe
¼ QIC Tape (DC600A)	550 Oe
Credit Card Strip	600 Oe
Library ticket	600 Oe
Cassette VHS	675; 700 Oe

Often there is a need to completely erase the contents held by a magnetic medium. A degausser or bulk eraser can be used to reduce a magnetic field stored on magnetic media to as near to zero as possible (*Audiolab). It does this by subjecting the media to a magnetic field greater than the coercivity of the material. This is a much faster way of demagnetising an object than writing information across the medium. The degausser creates a magnetic field greater than that used to magnetise the medium and it must be strong enough to reduce the field to zero. As Weircliffe explains it, if all traces of the stored magnetic fields are to be removed, 'the degaussing field must be strong enough to saturate the medium tracing the hystersis loop path and thus to swamp all the information already recorded there but the field must then be gradually reduced…if unacceptable levels of the erase field are to be avoided' (http://www.weircliffe.co.uk/degaussi.htm). An excellent overview of the issues and ways of disposing of magnetic media has been developed by the US Department of Defence: 'A Guide to Understanding Data Remanence in Automated Information Systems' (NCSC-TG-025). The National Security/ Central Security Service has published a specification for degaussers LI.4-4-A. Even the current generation of degausers are not powerful enough provide us with confidence that they will succeed in erasing the contents of the media. As a result we recommend that if total obliteration of data is necessary that disk drives, tapes and all media be physically broken up and incinerated (using appropriate environmentally controlled facilities).

1.1.6 OPTICAL MEDIA

Up until now, we have concentrated on magnetic media, its structure and problems. Optical media, and in particular optical disks, are increasingly used for data storage. They have problems of their own. Since their invention by Phillips and Sony in 1978 the CD-ROM has become the primary distribution medium for recorded sound and is fast becoming a primary medium for data storage and distribution. Optical discs are a multi-layer sandwich. In the case of CD-ROMs they consist of a substrata, a metallic reflective layer, and a protective lacquer layer. CD-Rs are composed of a substrata, a data layer, a reflective layer, and a protective coating. (see for example: http://www.kodak.com/daiHome/techInfo/permanence1.shtml or http://www.sanyo-verbatim.com/pitbyte.html).

In the twelve centimetre CD-ROM the data layer is a reflective layer of aluminium with pits and plateaux that reflect and diffuse the laser beam. CD-ROMs are mastered. In this process a metal mould (stamper) is created with the reverse impression of the pits. This electroplated nickel alloy mould (or a copy of it) is used in an injection moulding system to press the data into the polycarbonate substrate of the CD. The substrata is then coated with an aluminium reflective layer and sealed with an acrylic protective coating to guard it against abrasion or corrosion.

Magneto-optical discs have a magnetic layer that changes the polarity of the laser depending on the magnetic field on the surface. Temperature has an impact on the coercivity of materials. Magneto-optical storage devices take advantage of this by using a laser beam to heat areas of the disk to change its coercive properties. Under normal environmental conditions magneto-optical disks can have coercivities as high as 6000 Oe, but when heated by a laser their coercivity can drop to as low as 200 or 300 Oes. At the latter level of coercivity the intensity of the magnetic field needed to change their storage capabilities is correspondingly low. This means that once heated it is relatively easy to write data to the magneto-optical disk, but when cool it is very difficult to change its magnetic properties. This makes this media an extremely effective storage media. As the magneto-optical drives and the media itself have a decreasing market penetration the costs are increasing and although it is a viable media for long-term storage it would be a risky media because of the problems posed technological obsolescence.

Optical discs are typically constructed of either polymers or metallics. Metallics are prone to corrosion and delamination. Polymers deform and degrade. Where this happens data can become lost. For instance a scratch on the surface of an optical disc can disrupt the transmission of the laser beam. The resulting mistracking can result in data loss. Looking at optical media in detail, we find that each type has its own shortcomings. The least stable optical media are magneto-optical discs, yet they have the highest coercive capabilities. The magnetic layer, which is metallic and therefore subject to corrosion is the weakest component. Some of the alloys used can be subject to de-alloying and change the magnetic properties of the data layer. Magneto-optical disks are also more susceptible to temperature and humidity changes that can cause the magnetic layer to fracture. WORM (Write once read many times) technology is difficult to generalise about as there are many technologies available, however as with other optical media, any change in the optical properties of the recording layer will result in data loss.

Various studies of ‘writable and rewritable organic optical recording media’ have shown that although these materials are sensitive, easy to process, and non-toxic unlike their metal counterparts, they ‘suffer from a lack of stability’ (Kim, et al 1997). The reflective layer of a CD-ROM is generally made from aluminium that can degrade either by oxidation or corrosion. The protective overcoat can also deteriorate and expose the aluminium layer to possible damage. The polycarbonate substrate is susceptible to crazing, which clouds the definition of the substrate. The handling of CDs can contribute to their deterioration.

The dangers include those caused by the oils in our hands or created by accidental scratches left on discs when they are carelessly loaded into CD players or being returned to their cases. Not only do scratches and residues cause data 'drop-outs', but they provide sources of contamination which will gradually break down the substrate and the protective coating of the disk and increase the chances that the data layer will break down.

Essentially the causes of loss of access to information on Compact Disc-recordable media are listed in Table 4 below.

TABLE 4:
CAUSES OF DATA LOSS FROM CD-R MEDIA

Environmental Influences	Handling Factors	Mechanical Factors
corrosive gases (e.g. caused by air pollution)	shocks (e.g. resulting from dropping the disk)	degradation of access hardware (e.g. misalignment of the laser)
temperature	abrasions	
humidity	scratches	
exposure to UV light	dirt and oil residues	

COMPACT DISC-RECORDABLE

CD-Rs consist of a 'pregrooved polycarbonate substrata, dye recording layer, gold reflective layer, and a UV cured protective layer' (Kim, et al 1997, 88). The dye organic layer is photosensitive. The dye layer tends to be cyanine-based. Phthalocyanine, a metal-stabilised cyanine based compound, is also used. Data are written to CD-Rs by focusing light on the dye layer which causes it to heat up and changes its local optical properties. Where the surface has been heated the light from the reading laser is refracted rather than reflected back. The difference between the reflected and the non-reflected light is used as the basis for the binary signal.

As with magnetic tape all compact disks are not created equally. The variation media can be caused by:

- materials used in manufacturing the raw media. For example,
  - in a study of CD-R disks Kim and his team (1997, 88) found that changes in the thickness of the layers had a significant impact on the recording properties of CD-Rs. This was because the media depends upon consistent optical properties, for example the dye's own reflectiveness needs to fall into a very tight range [ibid., 92],
  - in the case of CD-ROMs impurities in the protective overcoat could result in its breakdown);
- in the process of manufacturing the raw media. For example,
  - in the case of CD-Rs the composition of the dye is critical because the optical properties of the dye layer depend upon it,
  - deformations through bumps, pits, and bubbles at any of the strata interfaces will impact on the recording properties of the media (Huh, et al. 1997), and
- in the process of encoding the data onto the compact disk (e.g. etching, pressing or stamping, or CD-R recording).

A major shortcoming with CD-Rs is that the dye layer tends to breakdown (Södergård, Martovaara & Virtanen 1995). While this is less of a problem with phthacyanine dyes (i.e. metallic stablised) it is still a difficulty. The frightening prospect is the rapid growth of the CD-R market itself. Freeman Associates Inc noted that in the US in 1996 the CD-R drive market ‘at 1.3 million units was six times larger than what it was in 1995’ (http://www.nikkeibp.com/nea/october/octsr.html).

The manufacture of the access devices is important. The last problem is less important in the case of CDs than it is in the case of magnetic media because CDs never come into contact with the reader. CDs are read by a laser beam which shines through the polycarbonate strata of the CD. This surface must be kept free from scratches and dirt as these are likely to change the properties of the polymer strata and cause the beam to lose focus. Data loss from damage to the CD itself is likely to be the most common way data will be lost. Although CD-players are complex devices composed of a range of components and are susceptible to mechanical failures, electrical misalignments and electrical component failure (see Goldwasser 1995). There are tens of millions of such devices are in general use and as they are simple devices to manufacture it is unlikely that device obsolescence will in the near future pose any difficulty for CDs. For example in there were some 2.53 million CD-ROM drives shipped in 1992, 11.07 million in 1993, and over 25 million units in 1994. With this level of consumer market penetration access to standard devices should be less of a problem than media stability.

Some optical discs have a much longer life expectancy than magnetic tape. Manufacturers make a range of claims about the viable life of their media. IBM, for example, claims that its WORM disk cartridges ‘have an archive life expected to be greater than 500 years’ (http://www.as400.ibm.com/as400/three.html 7/18/97 7:15:16pm) however one must still consider the other factors such as software and hardware obsolescence and costs of storage density before regarding the future of archiving and storing data as resolved. Fernando L. Podio of the National Institute of Standards and Technology in the US worked on the Development of a Testing Methodology to Predict Optical Disk Life Expectancy Values (NIST Special Publication 500-200; Michelson 1992). He worked out an end of life benchmark for media at ‘an error rate of five bytes out of every 10,000 bytes, which exceeds the capacity of error correction codes to correct’. Of course as he points out this does not mean that all the data on the media will be lost. In the end he proposed a standardised test methodology for predicting life expectancy. He concluded for WORM technologies that at nominal room temperature and 90% relative humidity: ‘the conservative estimate is 57 years, while a more liberal estimate is 121 years’ (http://palimpsest.stanford.edu/byorg/nara/nistsum.html).

1.1.7 ENCODING AND COMPRESSION

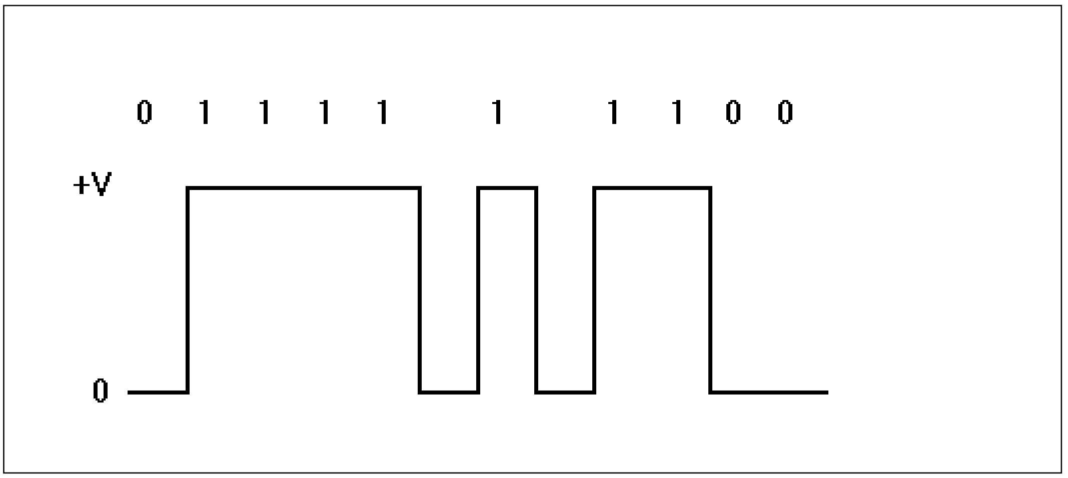
Initially, as tape and then disk devices were developed for data storage purposes there was a transparent relationship between data which was being stored and how it was written to the storage media. The binary data, 0s and 1s, being recorded had a direct relationship to the patterns of magnetisation which were laid down on the media. In an effort to address the demand for increased storage capabilities manufacturers sought out ways to increase the quantity of data that could stored. There were a number of ways of doing this. For instance researchers worked on increasing the real storage density of the media itself and on identifying encoding or compression strategies which would use fewer bits to represent more data. The efforts to pack more data onto the surface of the disk involved the use of a range of techniques to process the binary representations before they were written to the medium and after they were read off it. These developments severed the direct relationship between the data and its representation. The result was a loss of transparency evident in earlier systems.

Algorithms are used to handle the compression of data before it is written to the storage device. These compression algorithms make it feasible to store more logical data on a drive of given physical size. When the bits, or raw data, are read off the storage media a set of decompression algorithms are necessary if the data are to be correctly decoded. In addition to the use of compression to enhance storage capabilities a variety of other performance enhancement techniques are used particularly on disk drives to ensure that the media device can produce maximum input-output capacity. This can be done by minimising unnecessary head movement and defining how the sectors of data are laid out on the drive. The data layout that achieves maximum performance is not inherently obvious when attempting to interpret the contents of a disk. These pressures to provide increased capacity along with better performance and all at a lower cost have resulted in media manufacturers using highly complex dedicated chipsets on the device controllers (see Section 1.1.8 Controllers). These chipsets are highly integrated items which have been tailored for the specific needs of one particular media device. One of the findings from our survey of data recovery companies is that the most successful companies are aware of the role that these chipsets play in their ability to recover data and that they actively collect them.

Essentially compression removes redundancy from data so that more data can be stored using fewer bits to do the storage. By reducing the number of bits the actual storage requirements are decreased. In other words it is possible to store more files on a disk in compressed format than would be possible if they were stored in uncompressed format. Compression tends to applied on-the-fly, working with each data block separately, therefore the patterns in each block may differ considerably. If a compressed file is to be recovered and there is no information on the compression method, it cannot be assumed that once one pattern is decoded that the same method can be used for the remainder of the data. The decoding key should be included as part of the data stream.

Data is written on to the media either linearly, in magnetic tape or by accessing available clusters, in rotating dics format. The basic form of recording data on to the magnetic surface is called NRZ - Non Return to Zero. This mode allows a 1 (one) bit to be represented by a change in magnetic polarity and a 0 (zero) by no change. Disruptions to the signal from particles or damage to the media might led to some misreads of the polarity of the surface and therefore to the loss of data, but error correction coding is often used to compensate for limited numbers of misreads.

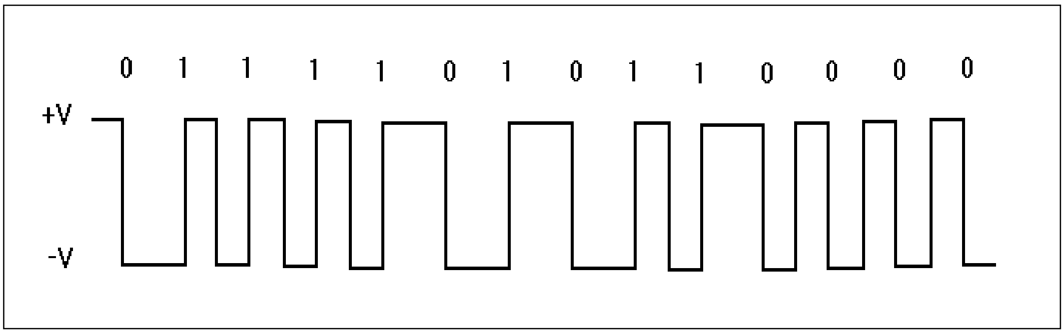
FIGURE 2:
NON RETURN TO ZERO
FROM: http://bbs-koi.uniinc.msk.ru/tech1/1994/dig-enc/main.htm



There are other possibilities of encoding on disk, RZ - Return to Zero, NRZI - Non Return to Zero Invertive, AMI - Alternate Mark Inversion, HDB3 - High Density Bipolar 3[2].

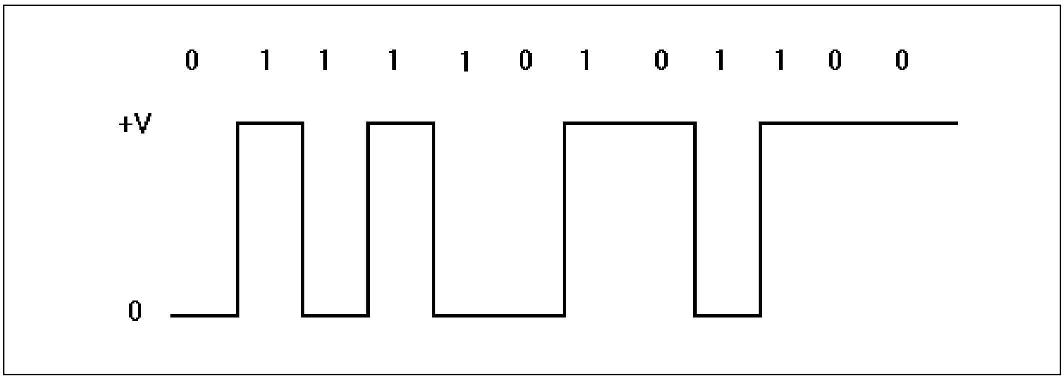
A main alternative to NRZ is PE - Phase Encoder. In this scheme a 1 bit is represented by a given level of magnetism and a 0 by another given level. Only bits with fixed levels of magnetism are recognised the others are ignored. PE encoded tapes will have a synchronisation signal at the beginning of each block.

FIGURE 3:
PE - PHASE ENCODE
(FROM: http://bbs-koi.uniinc.msk.ru/tech1/1994/dig-enc/main.htm)



A data recoverer would have to understand the various procedures, a 1 bit and a 0 bit will have different magnetic forces depending on the system used, it cannot be assumed that a positive polarity is a 1 bit or that all the bits with the same polarity are 1's or 0's. The voltage changes in some systems depending on the voltage of the previous bit. NRZI, Non Return to Zero Invertive represents data as 0 volts for a 0 bit whereas the 1 bits are represented according to the previous voltage - if it was 0 then the bit becomes positive voltage or 0 volts of the previous bit was positive.

FIGURE 4:
NON RETURN TO ZERO INVERTIVE
(FROM http://bbs-koi.uniinc.msk.ru/tech1/1994/dig-enc/main.htm)



2 See http://bbs-koi.uniinc.msk.ru/tech1/1994/dig-enc/main.htm for explanation of these encoding systems.

When the encoding system has been selected the bits have to be encoded to a standard that can be read, such as EBCDIC, ASCII or ANSI. This code assigns each character to a seven or eight bit binary number. So the bit-stream can be read if the standard code is known, it is most likely to be ASCII or ANSI. However it is not a trivial task to start decoding this bit stream, particular if there is no documentation to help identify the encoding used. The actual process is simple, count off every seven or eight bits and match the pattern with the ASCII code to decode them. This has huge scope for errors which is why every block of data is preceded by a block of bytes that show where the data begins and is predicated on the assumption that no intermediate levels of compression were used. This is why the FAT and Directory are very important in recovering data.

Chris Burton from the Computer Conservation Society has had experience of recovering data from old computers in his work in restoring old machines such as the Ferranti Pegasus - he gave us some valuable information and insight into encoding and decoding magnetic media. He also related some of his experiences working with Tony Sale from Bletchley Park and describes the recovery process as similar to the work that Alan Turing was doing there during the war:

> "It is very much like deciphering intercepted enemy radio messages. You make some plausible assumptions to see if they fit and the rest often falls out. During WWII, the people at Bletchley started to intercept high speed teletype code. The only thing they knew was that it was probably the International Telegraph alphabet (an assumption actually), and it was encoded in some totally obscure way. Brilliant work by the mathematicians enabled them to form a picture of the logical structure of the hitherto quite unknown encoding machine. They modelled this using telephone exchange type equipment, to help with the decoding, and it was not until after the war that they had any idea of what the enemy machine was like physically, which was in fact entirely mechanical.
>
> I have done a fair amount in the past of trying to decode material such as program code in ROM. In one case, not knowing what (micro)computer was the target, it became obvious after a lot of scrutiny how the bytes related to each other such that it was clear that it was code for an Intel 8085. The relevant point is that a human being can recognise the "style" from his experience or exposure to that kind of coding previously. I think that skill will always be highly valuable for the kind of analysis you are implying.
>
> A rather loosely-related problem which is of current interest to me concerns the Manchester Mark 1 Prototype computer, which I am reconstructing as a replica. Here the question was how the typewriter buttons were wired up, a matter which is undocumented, and where the pioneers who did it have no recollection. As an engineer, I would just have chosen a wiring sequence which would seem natural to me.
>
> However, a few seconds of contemporary film shows one of the designers actually using the typewriter, and the way his fingers move give very strong evidence as to the wiring, contrary to my intuition. Every scrap of evidence is crucial!" (Chris Burton, pers comm).

As we discuss in the emulation experiment (see Section 2.3), much of the success of data recovery can be attributed to professional or amateur experience and recognising familiar structures allowing quicker solutions. Chris Burton, of the Computer Conservation Society, has recovered data from very old media using a mixture of specially designed hardware and software. This method is very possibly the same as that of specialist data recovery companies. Certainly for media that has no documentation and limited information as early media is prone to it may prove to be only possible way of recovering the data. The tremendous value of FAT, directories and boot records is evident when there is no such information available to start the recovery process. This is where professional expertise and experience lead the field. Chris Burton has experience for instance of recovering data where there is little evidence surviving. With the help of a colleague Tony Sale he succeeded in extracting the 'initial orders' (equivalent of bootstrap code) from the Elliott 401 drum. Using some specially built hardware they captured the analogue waveform from the drum and converted this into a bit stream which they could analyse to identify the word-length of the computer, and to establish word boundaries in the bit stream.

Because tape subsystems use an error correction code system some of the redundant information in the ECC table can be used to reconstruction lost data but this is not viable with diskettes because these drives do not support ECC tables and as a result a lost data bit on a floppy is a lost data bit. Newer encoding strategies such as Partial Response Maximum Likelihood (PRML) (*Analog Devices; Kurihara, et al 1996; Lin & Yuan 1995; *Taratoria; Yada, et al 1993) and No-ID will make it increasingly difficult to recover data where the format of the data is unknown.

1.1.8 CONTROLLERS

Companies specialising in media recovery would face an uphill struggle recovering data from the hard disk media of such devices without access to the appropriate controllers (*Data Recovery Labs). Since reproducing such modern controllers from scratch would be prohibitively expensive, these companies tend to circumvent the problem by buying new devices as they come on the market and storing them for subsequent use. The sums involved in purchasing such units means that only companies carrying out the volume of business which can support such overheads can be expected to survive in the business. We see this need to maintain access to suitable controller technologies as major obstacle to the recovery of data from disks. In the case of disks that use the Servo technology which puts IDs at the start of each data segment there should be no problem, but some of the newer drive technologies will use IBMs No-ID technique and for these it will be impossible to recover this data.

1.2 Recovery

Having described some of the ways in which magnetic and optical media can deteriorate and thus result in data loss, what techniques are available for restoring the data from damaged media. Most data can be rescued, if there is enough time and money. For example, increasingly legal cases are turning to evidence recovered through computer forensics (Leimkueller 1995). The value of the data must be weighed against the cost of the recovery.

Loss of data can occur as a result of natural disasters, such as fire, flood, earthquake or even hurricanes. Some of these are looked at in the case studies. As the Ontrack (1996) evidence cited in the Executive Summary makes evident disasters account for only a small percentage of any data that is lost. Very early in the use of magnetic media the problem of its restoration was recognised (Armour 1967). Improper storage conditions accounts for more damage to the media than do disasters:

- High levels of humidity causes tapes to deteriorate and become sticky. This leaves the tape unusable because the residue causes the tape to catch the read-head or the transport mechanism and shed from the surface of the tape backing. This phenomena known as sticky shed syndrome can be addressed by heat treatment. John Van Bogart and colleagues at the National Media Laboratories have shown that if tapes are heated for 24 -72 hours at 45-55 ºC the low molecular weight oils and residues will either evaporate off the surface of the tape or be reasorbed into the surface. This process does not permanently restabilise the media and should only be done so that the media can be accessed and the data extracted and copied to a more stable medium. As the symptoms of sticky shed can be mistaken for other faults on the tape where heat treatment would not be advisable this process should only be carried out with professional advice.

- Tapes also suffer from lubrication loss over time. Improper storage can account for this but natural evaporation will have an effect only over many years. More common is lubrication loss as a result of heavy use; as tapes pass through the transport lubrication is squeezed out and reabsorbed as the tape exits the mechanism. Not all the lubricant is reabsorbed, but with each pass small amounts are lost. Some of the lubricant which is not re-absorbed into the tape remains on the read-write heads and tape guides of the tape drive and becomes a factor in the adherence of dust and other particles to the read-write heads. This can lead to data loss because the dirt on the heads causes drop-outs. It can also further damage the media because the particles are often brushed off the heads and onto the surface of the tape.

- Over time lubricant loss can result in a deterioration in tape flexibility. This lubricant loss can be corrected by re-lubricating the tape. The work of the National Media Laboratory reports that excessive relubrication can cause tape slippage. Tape slippage causes media to be misread and data loss.

- The only way to tackle mistracking is to re-spool the tape. If the tape is then stored for a reasonable length of time before reuse the distorted substrata may be reconditioned, although multiple respooling and re-packing might be necessary.

The methods for rescuing data after disasters are marginally different, but expert guidance is essential. A range of resources exist. Guidance can come from the *National Media Laboratory, *Eilers, *Lindner, *McCrady and many other similar sources.

- While water will damage tapes over time, its effects are not necessarily immediate. Hydrolysis (the cause of sticky shed, tape pack deformation leading to such changes as substrata curvature) takes a very long time to have an effect on tape (*Ashton, et al). The absorption rate is slow and tapes can survive in clean water for days, even weeks. If the water is salty or dirty, the tape should be removed and rinsed in fresh water. The tapes from the Challenger were immersed in salty sea water for six weeks and the data they held were recovered (see Case Studies). Older tapes should be recovered first as they are more susceptible to damage than newer ones. In some extreme cases, where the substrate is made of paper, these tapes should be cleaned and dried at once. Van Bogart notes that:

  > 'if the tape has been exposed to contaminants in the water, such as salt mud, sewage, it must be kept wet until a full recovery process can begin. If it dries out with contaminants lingering as residue, it can have a very harmful effect on the tape. All tapes should be rinsed in distilled water, those that were exposed to corrosive substances may have to be cleaned in soapy water - a mild detergent will remove oils or grease before the rinsing in distilled water. This is very important, as it removes any residue left over by hard water.'

- The heat treatments used to re-stabilise tapes suffering from sticky-shed syndrome will not work effectively to dry tapes which have become wet. The high temperatures can lead to data loss. Wet tapes should be cleaned, rinsed and dried at room temperature.

- Fire damage can do severe damage to tapes. If they have suffered extreme temperatures, the substrate and binder will melt and thus make them impossible to unwind. Where the tapes have not been damaged themselves the particles in the form of soot, smoke, and toxic chemicals which can result from the burning of many materials can contribute to the breakdown of the tapes and become embedded in the media itself. However, more extreme rescues are possible such as the recovery of the video tapes from the crashed F-16 fighter (see Case Studies below). Once again the cost of the recovery must be weighed against the value of the data.

Just as care must be taken in handling tapes in post-disaster situations similar care must be taken with optical disks. It is essential to avoid scratching on the substrate as this can cause data misreads. Damage to the protective coating can result in oxidation of the aluminium layer and change its reflective properties. In case of water damage, clean (if necessary) mild detergent, rinse in distilled water and allow to dry at room temperature. If an optical disk is particularly dirty then it may need to have any residue wiped from it. Van Bogart and his colleagues recommend that since the disk tracks are laid down as concentric circles or one continuous spiral, the disk should not be wiped in a circular motion, but from the inside out (see Section 3.2 below).

It is possible to recover data from damaged media if the correct approach is taken from the outset. In all cases it is best to seek advice from an expert before attempting rescue. Even the most damaged media can have full data recovery if the value of it is such that the cost of recovery is worth it. However, the best method of recovery is to take the correct precautions and prevent catastrophic damage. If a disaster does occur it is best to make a plan before proceeding to take any data recovery action.

1.3 Disaster and data recovery (with contribution by Richard Alexander)

Under specialised laboratory conditions it is possible to recover most data from magnetic tapes and disks. To see how this was done two members of our team (Richard Alexander and Ann Gow) visited four companies based in the UK working in the disaster and data recovery business sector (August 1997). The companies visited were: Guardian dr Ltd, Adam Associates, Vogon International, and Ontrack. This is only a fraction of the firms now working in this area (see Appendix 3). Prior to visiting the companies we faxed them an outline of the aims of the report and a list of the areas and issues we wished to address (see Appendix 4). We were aware that some of the companies would be hesitant to release full information about their methods and clients given the commercial sensitivity of such information. We therefore phrased the questions in a manner that we hoped would allow the companies to answer without breaching client or business confidentiality. In fact we met with a variety of responses, from complete openness to guarded discussion.

1.3.1 DISASTER RECOVERY

Although the companies concerned often advertise a range of disaster recovery services it soon became apparent that we were visiting two distinct types of companies dealing with significantly different areas of disaster recovery. Firstly, there were companies offering what we refer to as “business continuity services”. These companies offer clients access to alternative computing platforms in the event of a disaster affecting their primary systems. Secondly, there were companies offering what we refer to as “media recovery services”. These companies specialise in the recovery of data from media which for whatever reason has become unreadable from the client’s perspective.

Guardian and Adam, are among a large number of firms which specialise in the provision of business continuity services. Other UK organisations in this business sector include: Business Protection Services run by Digital, Safetynet, and IBM Business Recovery Services. The 1997 Spring issue of *Disaster Recovery Journal* has an up to date list of the businesses. They offer the client a service that will allow the company to continue operations in as short a time as possible following a disaster that affects the availability of that company's normal computing facilities. To provide such a service, these companies offer office accommodation, office equipment, access to the appropriate computer hardware and software environments and communications links. The clients of business continuity service providers are typically companies whose information systems form a highly critical element of the company's main operation. For such companies the loss of their information systems often represents the loss of their ability to trade. Financial institutions and direct sales companies are prominent examples of such companies. Adam Associates specialise mainly in the area of personal computers, local area servers and local area networks. Guardian by comparison included many users of large minicomputers and mainframes in their client list.

Although the sections of the market being targeted differed, the concept was essentially the same. These companies offer their clients recovery from a disaster in one of two ways. In the first method, the client mirrors their critical systems to a dedicated server or host at the disaster recovery company's premises and the client switches to that system in the event of a disaster affecting their primary system. In the second method, in the event of a disaster affecting their primary system, the client is provided with access to a non-dedicated standby hardware platform onto which the client's operating environment and applications can be loaded, thus allowing continued operation. These companies do not normally recover material from damaged media. They will give advice on storage and back-ups and allow the client to store the data with them. In effect, they offer "system recovery" rather than data recovery. Such services, though important to the business community they serve, are perhaps of less relevance to the academic community where the long term survival and availability of the data is more important than the day to day availability of operational systems.

1.3.2 DATA RECOVERY

In the more specialised field of media recovery, we visited two companies with international reputations. They have similarities in their basic business but function in different ways, both in the media they recover and in their position within the data recovery sector. Vogon International was in the process of merging with Vogon at the time of our visit. Their activities cover: media recovery, forensic computing and data conversion.

Vogon-Authentec deal mainly with recovering data from magnetic tape. They maintain a huge range of peripheral devices and are able to cope with most tape sizes and file formats. They have on occasion also built custom drives in instances where the original hardware was not available. Vogon-Authentec use their own custom built software utilities which can recognise the operating system and file structures used to store the data. They therefore do not need to have copies of all the operating systems whose file systems they support. This software is constantly being updated to include the latest formats. This approach avoids the overhead of having to purchase and maintain the native hardware and software environments in which each file format is found and ultimately must have a significant effect on the overhead costs associated with running such a service. The company was hesitant to discuss the details of the custom software and the methods used to clean damaged tapes. As they deal predominantly with tapes, they did not run a clean room at the time of our visit, they now have one.

They support a wide range of tape hardware (current and obsolete) including the following formats:

¼" DC2000 cartridges (Colorado, Connor, Ximat, Irwin, Rhomat, etc.); Travan, QIC-Wide

¼" DC6000 Cartridges (DC300XL/P, DC6250, Hewlett-Packard, Magnus formats, etc.)

TEAC proprietary digital Compact Cassette formats

4mm DAT(DDS, DDS-DC, DDS-2, Data-DAT)

8mm Exabyte

All 9-track open reel formats

All 3480 and 3490E formats

All optical disk formats, including CD-R

All removable disk formats, including SyQuest and Bernoulli

As mentioned, the company were reluctant to reveal the technical details of their methods but were willing to discuss some of the problems clients suffer from with which they have been able to help. “Sticky shed syndrome” is a common event in badly stored tapes. Vogon-Authentec have considerable experience in handling media in such a condition and can often read the data on it using specially cleaned and prepared transports and their custom software. Since such problems often affect areas of the media which contain critical header information from the backup sessions, Vogon-Authentec’s custom software is often able to recover data from the remainder of the media in the absence of such header information, allowing the possibility of the header information being rebuilt subsequently.

As Vogon-Authentec have access to a wide range of peripheral devices and can build custom platforms if required, data migration from one format to another becomes feasible. The drawback for single users is the cost. In practice, the custom software that this company uses emulates the file handling components of the relevant operating systems. The data is recovered or extracted in raw form and can then be imported into the appropriate application. Vogon-Authentec do not specifically emulate outdated software packages, but in theory have the resources to do so. As with the peripherals and operating systems, the company responds to client demand and supply what is required.

Obsolescence Recovery is an area of particular interest to archives, libraries, researchers and other institutions, where the results of research may be only available in a form where the software or hardware is obsolete. As discussed, Vogon-Authentec have many peripheral devices and can adapt existing ones to read outdated media. Once again the stumbling block is cost to the individual user. It may be possible for the data recovery companies to provide a service for the migration of data that would charge less, but take longer to deliver results.

Vogon-Authentec invest heavily in equipment, staff and new techniques and their results do not come cheaply either. A typical cost for recovery of around 2 GB of data from a DAT tape with a damaged backup session header might be around £1000. In common with other companies, Vogon-Authentec charges a diagnostic fee of a few hundred pounds to establish whether it is viable to recover data from a particular sample of media. But this may be cheaper than recreating the data itself. The National Science Foundation has produced evidence to suggest that on average recreating 20 megabytes of data can cost at least $64,000; so data recovery services are value for money.

Vogon-Authentec has become very influential in the emerging use of computer data in evidence. They have worked with HM Customs & Excise, HM Inland Revenue, the Ministry of Defence, the Serious Fraud Office and many of the UK Police Forces. They also have connections with the North American and European equivalents. Teams at Vogon-Authentec have found that little information is immune to recovery including hidden, deleted, and even encrypted data which can then be used in the investigation and which can subsequently be presented to a court as evidence. For legal reasons, the computer system itself must be left totally unaltered by the investigation process. Formats, in addition to those mentioned above, with which Vogon-Authentec reports it has worked include:

- Hard disks - virtually all know formats, including DOS, Macintosh, HPFS, NTFS, UNIX, mini-computer, mainframe; and,
- Many kinds of EPROM storage, including those in phones, faxes and personal organisers.

Vogon-Authentec rescue data for a range of clients. Their clients have included Microsoft and IBM. Examples include:

- Swedish National Archives - Vogon-Authentec worked with the team there on recovering data from tapes. The archives also uses software provided by Vogon-Authentec to convert older tape and data formats into more modern ones.
- A Swedish Petroleum company had all their seismic reports on an obsolete tape format. The costs and delays of carrying out the surveys again would have been enormous, running into hundreds of thousands of dollars. Vogon-Authentec managed to recover the data from the tapes after reconstructing a suitable tape transport using a more modern transport as the building block. This work was expensive, but in this instance the costs were well worth it when compared to the alternatives open to the company concerned.
- A national company about to be privatised managed to erase its system with no back-ups a week before going public.
- In one rather ironic case, a company which produces back-up software damaged the tapes that their source code was on. Vogon-Authentec were able to read the data beyond the damaged header and recover the source code files.
- During the Gulf war the Royal Bank of Kuwait had to leave the country in haste with untested back-up tape. Vogon-Authentec managed to restore the system and data to allow the Kuwaiti royal family to manage their investments while in exile.

Ontrack are a much larger company in the data recovery field. They specialise in hard disk recovery. They also market their own software for recovering data in the workplace. As with Vogon-Authentec, they have their own custom systems and they report they can recognise any existing system and platform (see Table 5).

Ontrack support these particular systems to meet existing market demands. They have technical research and development capabilities focused on developing new approaches to data recovery. In addition to data recovery from magnetic media Ontrack also handles non-oxide storage devices including: Optical-Magneto or Phase Change, PD, DVD, and CD-ROM.

TABLE 5:
ONTRACK DATA RECOVERY

Software Operating systems	Media Categories
DOS Windows 95 MAC OS/2 NetWare Windows NT UNIX (and 30 UNIX flavours) SUN VMS Amiga AS/400	diskette hard disk drive tape optical cartridge (MO and phase change) SyQuest Bernouli Jaz Zip PD cartridge

Ontrack have invested in equipment, expertise and facilities. The company states that it invests 18 - 20% of its total revenues on R&D. In order to be able to meet clients needs for data recovery from new storage devices, the company is constantly purchasing such devices from manufacturers. Because every data recovery situation is unique, Ontrack divides its service into two distinct processes in order to allow for the data recovery to be assessed. Therefore, they carry out a diagnosis first of all to determine the nature and the severity of the problem and to establish what data can be recovered. Usually, this first part of the service costs around £200.00. After the diagnosis is complete they are in a position to provide a quote for the recovery of the data itself and this fee will depend upon how badly damaged the media is and what the problem is that has caused data loss.

Ontrack produce a very useful Data Protection Guide that is available freely to clients and possible clients alike. However, it has been their experience that clients do not follow the guidelines and rules defined in the guide. It would seem that companies, although realising the value of their data, will not take the steps to ensure (as far as possible) its security.

Ontrack use operating system emulation. It is not necessary for the original operating system to be available in all cases. New operating systems' file formats are supported as market demand arises. Ontrack have the capability to provide an obsolescence recovery service. Ontrack offered several examples of data recovery projects.

- The customer placed an initial call to Ontrack on 12/06/97. A hard drive failure was reported. The equipment was a Seagate 400MB HDD and SCO Unix operating system. Media errors were also reported and it seemed the hard disk drive had suffered a head crash. Ontrack received the equipment on 13/06/97. The diagnosis was completed by 16/06 and it showed a severe internal failure of the hard disk. In addition there was some damage to the operating system. Ontrack were able to access the data and restore all of 391 megabytes consisting of 4430 files to the client. The total cost for this project was £1150.00.

- The customer reported that the hard disk drive would spin up and the heads moved but then it slowed down and stopped. This repeated itself. The customer could access no data. Ontrack received the equipment (Seagate 2.4 GB hard disk drive with NetWare 3 Operating system) and diagnosed a severe internal hard drive failure. They were able to recover all the 1.2 gigabytes of data stored in 14,000 files. The data was very sensitive, urgent and important. It took 6 months to create the data and would have taken at least 4 months to recreate it. The customer valued the data at approximately $20 million. Ontrack delivered the recovered data on 29/07/97 at a total cost of £1325.00.

1.3.3 DISASTER AND DATA RECOVERY LESSONS

Organisations should develop disaster recovery programmes which provide adequate support for academic staff so that their data is secure. Current central computing services do not in most cases satisfy standard best practice in the preservation of archival data (e.g. few organisations have off-site storage and where they do they rarely meet archival storage standards). Recovery of data is an expensive proposition, but it is viable. This limited review of data recovery companies here has found that it is worth retaining hardware for just-in-case situations.

1.4 Future possibilities in data recovery

1.4.1 MAGNETIC FORCE MICROSCOPY

There may be promising new opportunities in data recovery likely to emerge in the next couple of years. One of these is Magnetic Force Microscopy (MFM) which developed as a result of further research into the development of Atomic Force Microscopes (AFM) (Saenz et al, 1987; Rugger, et al, 1990). MFM (Figure 5) is already being used to assess the magnetic quality of media.

FIGURE 5:
ATOMIC FORCE MICROSCOPE

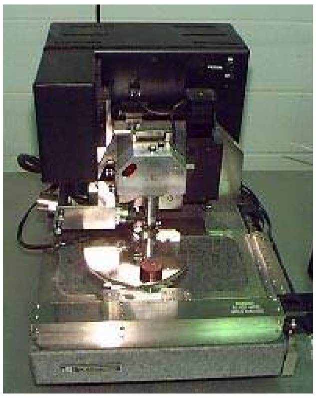


FIGURE 6:
MFM IMAGE SHOWING THE MAGNETIC DOMAINS IN THE SERVO TRACKS OF A HARD DISK
(Used with the permission of Park Scientific:
http://www.best.com/~wwwpark/appnotes/mfm/pages/app2014.htm)

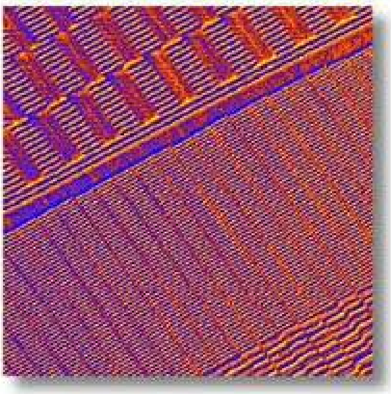
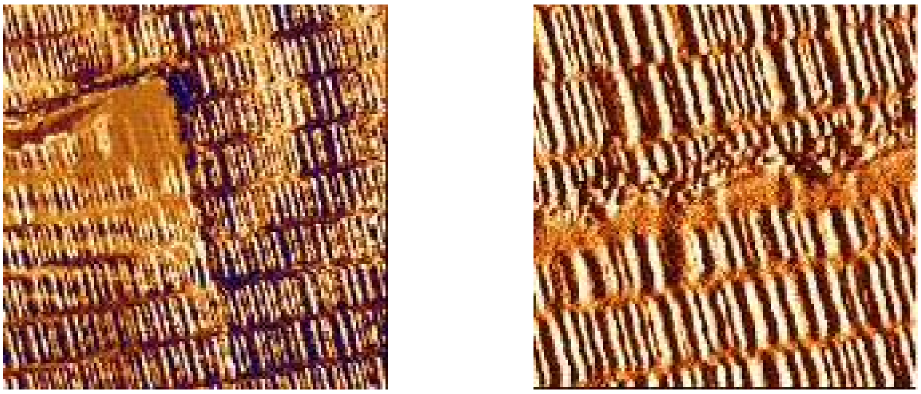


FIGURE 7:
MFM IMAGE OF DAMAGED MAGENTIC DISC SURFACE
(Used with the permission of Park Scientific:
http://www.best.com/~wwwpark/appnotes/mfm/pages/app2006.htm)



The image on the left shows the surface of a disk observed using an atomic force microscope and the image on the right shows the same surface as observed using a magnetic force microscope. The tracks can be seen running up the diagonal of the image.

In the case of damaged disks for instance by increasing the sensitivity of the MFM it is possible to observe the data in the damaged area. The image on the left here shows the damaged disk. The area with the indented region was caused by the crash of heads into the surface of the disk. By increasing the sensitivity at which the data is resolved it is possible to examine the magnetic signatures in the damaged areas.

Current work with MFM focuses on understanding the structure and properties of media with the aim to improving their properties (e.g. Malhotra, et al, 1997). Work completed by Kyusik Sin and his colleagues in 1995, but only published in 1997, provides support for the supposition we make here about the future role which MFM will play in data recovery. Although their work was focused on other issues, one of the conclusions they reached was that:

> 'Experiments show that MFM is a useful technique for studying magnetically recorded patterns and obtaining qualitative and quantitative recording information (readout signal, noise, S/N ratio, magnetic state of the medium, and effects due to WRITE head).' (1997, 1056)

It is still early days yet for the developments in the use of MFM, but it is only a matter of time before experiments with the technique are used to recover digital data.

Of course at this point it is essential to bear in mind that there is not a one-to-one relationship between the binary representation encoded on the surface of the disk and the data that was sent to the disk for writing. Above we discussed various kinds of encoding and compression algorithms which are applied as the data is sent to the disk for writing. But while this proposal may seem far fetched as a way of recovering data off disks; I suspect that engineers would in 1950 have found it hard to believe that eventually disk drives systems, which were then the size of refrigerators and could only store around 5 million characters, would eventually be the size of soap bars and capable of storing up to nine gigabytes of data.

1.4.2 Cryptography

While it is theoretically feasible to recover the digital bit stream from magnetic media and this could be done even when the media has become quite damaged, the interpretation of data recovered in this way depends upon the development of suitable strategies to support its interpretation. This is an area which depends upon the development of suitable crytographic techniques to take the raw data stream and break it into its original meaningful units.

Part of the problem is that there is not a one-to-one relationship between the binary representation encoded on the surface of the disk and the data that was sent to the disk for writing. A variety of encoding and compression algorithms are applied as the data is sent to the disk for writing. Research is needed into how to exploit the potential to use cryptography to interpret the binary patterns recovered using MFM. Because the logical structure of the data and its physical representation can be so very different (see above, for example encoding and compression) the algorithms must reconstruct the data and program by identifying segments of the bit stream which store information about the physical layout of the data on the media first and use these to establish an understanding of unknown segments of the disk. This area has the potential to be a significant research area in the next three to five years.

2. Restoration and simulation, emulation and emulators, and binary retargetable code

2.1 Restoration and simulation

A number of organisations have successfully maintained or restored computers to working order from the 1950s and 1960s (see Appendix 2). Often the problem is that the machines, as happened to the ENIAC were broken up and their components can not be recovered. Fortunately this has not happened in every case. In the United Kingdom the Computer Conservation Society (CCS), a joint venture between the Science Museum and the British Computer Society, has been undertaking work in the restoration of early computers and the recreation of software necessary to run them. Doron Swade (of the Science Museum) noted

> The CCS has restored to working order early computers and restored/ recreated period software involving various salvage technologies including designing and building electronic circuits to read and capture magnetic disk data for which no documentation existed and developing software to explore in a computer assisted way the structure of digital data so captured' (Swade, pers com).

The Ferranti Pegasus has been the subject of numerous articles because it represents the comparison of two techniques: the restoration of the original machine and the construction of a simulation to run in a windows environment on a PC-compatible machine (*CCS 'Ferranti Pegasus...').

FIGURE 8:
THE RESTORED FERRANTI PEGASUS ON THE LEFT AND THE SIMULATION ON THE RIGHT
(used with the permission of Doran Swade, The Science Museum).

Burnett and Supnik have begun work on restoring a PDP11/20 one of the most successful computers of the large computer age (Burnett & Supnik, 1996). They have found it difficult to obtain manuals, peripheral devices, and various interface cables. These activities are replicated at other institutions in Europe, Australia, and North America (*Billquist et al; *Carson; *CCS; *CHAC; *Computer Museum, *Toomey,). A large Computer History Simulator Project includes freeware simulators for the Data General Nova, the PDP-4, PDP-7, PDP-8, PDP-9, PDP-11, PDP-15, and the IBM 1401. They are intended for personal or educational use, unsupported, and provided on an as-is basis. The package also includes some demonstration software, including RDOS 7.5 for the NOVA, OS/8 for the PDP-8, and several versions of Unix for the PDP-11. The simulators out perform the original systems in nearly all cases and the more powerful the current hardware the better the performance.

Alternatives to restoration include simulation and emulation. This can be done either in hardware or in software or in a combination of both. Martin Campbell-Kelly of the University of Warwick has built a simulator of the 1949-50 Edsac built at the University of Cambridge (http://www.dcs.warwick.ac.uk/~edsac/). The Edsac simulator provides an environment which presents the user with the simulations of the displays and controls that the original operators of the machine used. *Brouklis has reported on work to produce an emulator for the last indigenous Soviet computer, the BESM-6. A group of students at the Moore School for Engineering at the University of Pennsylvania led by Professor Jan Van der Spiegel demonstrated the viability of hardware simulation when they constructed ENIAC on a chip for the 1995 celebrations of the 50th anniversary of the ENIACs launch. The chip had the full functionality of the original computer. Although in this case more strictly an emulation rather than a simulation the experiment was successful and it proved possible to run ENIAC programs using the chip (*Penn Printout* 1996). The Electronic Numerical Integrator and Computer (ENIAC) was developed at the Moore School of Electrical Engineering at the University of Pennsylvania in 1946. The computer, which was constructed of 18,000 vacuum tubes and 170,000 resistors measured 80 feet by 3 feet and weighed thirty tons, required a team of experts to run it. In addition to the hardware the team produced software to provide an interface which displays the instrument panel and included programming and control switches. Material is displayed on the interface in the same way it was displayed on the original operational ENIAC. This emulation demonstrates that it is possible to experience some of the aspects of the ENIAC and to comprehend the simplicity of the programmes it could actually handle. It is the borderline where the accessibility of a facsimile does not compensate for working with the original. In a similar way future scholars sitting ***in*** their virtual terminals and using visualization software to create interpretations of documentary evidence will be further removed from understanding text-based Internet communication than we are from clay tablet archives.

While there are numerous examples of computers which have been rebuilt this does not seem to offer an effective way to either preserve technological and processing environments. It is expensive, depends upon the availability of huge stocks of spare parts or on a specialised industry manufacturing bespoke components. This said numerous museums (see Appendix 2) are attempting to do just this. If we were to take the Hewlett-Packard calculator preservation work as our model, since this got started slightly earlier, when components become difficult to find researchers begin investigating ways of making new versions of the components (e.g. remaking original-type batteries). Lack of adequately skilled professionals capable of managing, programming, and running these computers poses a problem. The CCS has been successful because it has been able to attract professionals whose careers include experiences working with the machines they are repairing.

2.2 Emulation and emulators

A very subtle distinction can be drawn between a simulation and an emulation. Simulations recreate the entire environment of the hardware and software; it may often involve creating a new application which as in the case of the Pegasus computer not only ran the original programme, but also simulated the look and feel of the original system in a new environment. Emulations focus on either recreating the internal design of the system (whether hardware, software, or both) or on creating an environment in the case of software in which the original software can be run. A game, for example Pacman, written to run on a PC and providing the look-and-feel of the arcade game itself is a simulation. An emulation on the other hand would provide a suitable environment in which to run the original Pacman software. The obvious goal is to create an environment in which it is possible to run any software on any operating system and on any hardware platform. This is of course still merely an ideal, but one that would make recovery of obsolete data a trivial task. However, though still an ideal, emulation of older software packages and operating systems is happening and on quite a large scale. There are numbers of enthusiasts, computer scientists and students who are determined to keep their favourite software or operating system or applications alive and available. In some areas there are competitions between enthusiasts to produce better and more efficient emulators. There is a trend for software companies to produce emulators for legacy systems, a strategy encouraged by efforts to address the Year 2000 problem. When we first think of emulation the easiest example which comes to mind is that of terminal emulation which allows the user to link PC's running one operating system with a system running a different operating system by emulating the presentation layer on the PC. Simply, the emulators do not emulate the software or machine, but the functionality of the access terminal used for the device running the emulator.

Emulators for early game consoles are generally available as freeware. These exist at a multitude of web sites, created, maintained and contributed to by amateur enthusiasts. The expertise here and the profusion of systems and software demonstrates what can be done in the area of emulation. There may not be an immediate need for an Atari system from a researcher, but not only did these consoles run games, they acted as basic word processors. The lessons learned from this emulation can be adapted to help us to address much broader concerns.

An increasing number of sites are providing guidance for the development of emulators. Three basic approaches are commonly used when writing an emulator: interpretation, and static or dynamic recompilation. In the interpretative approach the emulator reads emulated code from the memory byte-by-byte, decodes it, and performs the appropriate commands on the emulated registers, memory, and input-output. In the case of static recompilation the program is written in the emulated code and translated into the host machine's assembly code to be run as a native executable program. Dynamic recompilation is essentially the same as static recompilation, but the translation happens during run-time. The code is not recompiled at once but as the program is executed.

There are a number of different approaches to what to emulate. These include:

- **Processor Emulation**

  This technique allows the host machine to carry out instructions exactly as the processor being emulated would have (Mockridge 1994).

- **Operating System Emulation**

  Older operating systems are emulated on more modern operating systems. The host machine will emulate the look and feel of the older operating system. This makes it possible to run older applications in new environments. Examples of this kind of emulation includes:

  AES
  Amiga Os
  CP/M: which has emulators for MS-DOS, Linux, Amiga and Unix.
  Flex
  MS-DOS: emulators for Unix & X, Amiga, Linux,Mach3, Solaris, Atari ST, NeXtStep, MacOs.
  MS-Windows: emulators for Unix & X, Mach3, Solaris, Amiga, Linux.
  MacOs: Solaris, Irix, HP-UX, MS-DOS, Linux, NeXtStep,AIX, PowerOpen Unix.
  Magic: Macintosh, MS-Windows, Windows 95, Windows NT.
  SunOS

- **Machine Emulation**

  Emulations have been developed to make it possible to emulate machines on PC-compatible hardware, Macintosh, and Unix computers. Some of the machines for which such emulators have been built include:

Acorn Amstrad Atari - 8-bit, 16-bit Apple - Apple II , Macintosh, Newton Amiga BBC CHIP8 Commodore - VIC20, Pet, C= 64/128 Coleco Adam Colour Genie CPC DEC: PDP-8, PDP-10, PDP-11 Eniac Enterprise 64/128 HP41	IBM PC Macintosh MSX NeXT Oric Psion Silicon Graphics Sinclair- ZX 80, ZX 81, Z88, ZX Spectrum, QL, Sam Coupe Sun TRS 80 Unisys Universal Turing Machine Zoomer

Emulation of game consoles and arcade games takes up an immensely large part of the activity of the emulation community. Spurred on to play old games on faster machines, with more processing power, enthusiasts compete against each other to produce newer and more efficient emulations. Some of the more popular consoles for which emulations are available include:

Atari 2600
Atari 5200
Atari Lynx
ColecoVision
Mattel Intellivision
NEC TurboGrafx-16 / PC-Engine
Nintendo Gameboy
Nintendo NES
Nintendo SNES

Sega Genesis
Sega Master System/Game Gear
Vectrex

Within these will be a variety of individual games, depending on the system. See Appendix 2 for a list of some of the web sites that support free emulators.

A mix of techniques and methods can be used to develop emulators whether they are restoring an acrade game or developing an environment to run an application on a different hardware platform. These firms include:

ARDI - Information about Executor, a commercial Macintosh emulator for DOS, Linux, and NEXTSTEP. Freetime-limited demos are available.

Boston Business Computing - provides software tools that eliminate the need for retraining when moving from OpenVMS to UNIX, MS-Windows, Windows-NT, Windows95, and MS-DOS.

Branch Always Software - Atari 8-bit and Atari ST emulators.

Bristol Technology Inc. - Bristol is a leading developer of graphical user interface development tools, such as HyperHelp, the on-line help standard, and Xprinter* for UNIX System-based products.

Fundamental Software - OPEN/370 emulates the System/370 in software on PC/UNIX platforms.

HiTech Equipment Corporation - line of low cost in-circuit emulators and single board computers for the 8051 family.

John Neil & Associates - software utility publisher that offers FPU (math co-processor) solutions for the Macintosh.

Nohau Corporation - High performance in-circuit emulators.

Unipress Software - the PowerTerm InterConnect Series.

Zephyr Development Corporation - develops and markets 3270 terminal emulation software for Microsoft WindowsPC to IBM host connectivity.

These are some of the better known emulators available for use. Some are freeware some are commercial products. All of them emulate one system on another. Wine is both a program loader and an emulation library that will allow UNIX users to run MS Windows applications on an x86 hardware platform running under range of flavours of UNIX (*Ashiem). The program loader will load and execute an MS Windows application binary, while the emulation library will take calls to MS Windows functions and translate these into calls to UNIX/X calls, so that equivalent functionality is achieved. Wine programmers all over the world are adding to the list of programs that are available as emulations. Another emulator, Wabi allows users to run Microsoft Windows applications on systems running the Solaris operating system systems whether these machines have a SPARC or Intel architecture (*Sun Microsystems). SoftWindows is a commercial package that allows Windows applications to be run on PowerMacs, Sun, HP, IBM, and SGI workstations. SoftWindows runs Pentium Programs from Windows 95 on the Power Mac.

There has been a tendency to dismiss emulators as a possible solution to the problems posed by technological change. Given the increasing interest in emulation technology and the array of people working in the area from computer scientists to computer junkies, it is probably much too early to discount the likely success of this approach.

2.3 An experiment in emulation

In order to test our assumptions about the possibilities of emulation we ran a very small scale experiment. The experiment was conducted by Gerard Sweeney (a Technician at HATII and an amateur writer of emulation software) and Ann Gow. The report of the experiment is instructive:

The experiment emulated one system on another. We chose a Sinclair Spectrum tape with the emulation to run on a PC. We perhaps had an advantage in our technician Gerard Sweeney, who is a Spectrum fanatic and has constant contact with the people writing emulators for various Sinclair systems. However, there was nothing in the experiment that could not be achieved by an average computer literate person.

He collects and owns all the variations of Spectrum machines. He provided a brief history of available Spectrums:

16K Spectrum (rubber keyboard, 16K memory)

48K Spectrum (identical in appearance to above but with 48K)

Spectrum + - identical specifications to the original 48K, but with something resembling a proper keyboard instead of the rubber keys. Also had a reset switch.

128K Spectrum - Almost identical in appearance to the 48K+, but with a heat sink running down the right hand side of the keyboard. Also had extra ports for a monitor, MIDI (out only), and something which no one could really quite agree on, but it was only ever for the 2 lightguns that came out.

Spectrum +2 - Almost identical to the original 128K, but now with a keyboard and built in tape recorder, giving it the appearance of an Amstrad CPC. Hardly surprising really, as this was made by Amstrad as they now owned the rights to Sinclair. A couple of technical differences included a slightly different internal processor, some new shortcut commands (which were never publicly released, as they didn't get finished in time, but 95% of them worked). Also lost the TAPE TESTER option on the main menu. Amstrad also introduced "The Sinclair joystick format", which just meant this external device had a different connection fitting. Their plans of making lots of cash out of this were thwarted by joystick companies bringing out 2-pronged joysticks, 1 fitting being a standard fitting, the other being a grey Sinclair fitting.

Spectrum +3 - Same keyboard as the +2, but now black with a 3 inch floppy disk drive. They also changed the version of BASIC, including the commands to access the RAM disk, so a LOT of BASIC programs created on the first 2 128Ks didn't work. There were also a couple of code games that didn't work in 128K for this reason. Not popular, as the disks were very expensive compared to 3.5". Plus, they held less (700K I think), and were single sided only.

Spectrum +2a - Same casing as the +2, but black like the +3, with the same innards and RAM disk as the +3 but with the disk handling processes moved from default to secondary.

The +2a and +3 also had problems with some external interfaces, like the external 3.5" disk drive (the +D), and required a fixer interface to be plugged in first.

The 3 most popular emulators for the PC (Z80 X128 and ZX32) are all capable of switching between which machines you can emulate.

There were actually some Spectrum clones. The most famous (or infamous) being Project Loki from Russia. It looked a mighty beast, with dual disk drives, multi-language support, built in along with many other fascinating functions.

THE EXPERIMENT

THE TARGET MACHINE: PC

The PC that the emulated program was to run on is an Apricot Pentium with 100 MHZ processor, 16MB RAM, 1.5 GB hard disk space, SVGA screen, SoundBlaster sound card running Windows 95. (Although it is a networked machine for the purpose of the experiment the network connection was disabled.)

THE TAPES

We used a sample of tapes from Gerard Sweeney’s collection. They were chosen randomly. They varied in quality from unused original games to copies bought from car boot sales. Sinclair Spectrum tapes are standard audio cassette size, some of the tapes were stored on computer tape and some on standard audio magnetic tape. The tapes were a mixture of 48K and 128K although many could run on either system. The content of the tapes is of course Sinclair Spectrum games ranging from “Master Chess” to “Wham! - the Music Box”.

The remaining description describes the restoration of one tape chosen at random: “Chess”, an original 48K tape.

THE PERIPHERAL DEVICE

To run an emulation you need to access the information on the tapes. We used a standard radio cassette recorder to “play “ the tapes. One of the advantages of having a Sinclair expert is the pleasure of watching him listen to the tapes to discern the difference between the Spectrum loader or earlier Sinclair systems, such as the ZX80 or ZX81. The different loaders sound different when played through a normal cassette recorder. This sort of knowledge only comes with experience. It is this experience that can assist in data recovery. Faced with unmarked cassettes, it is possible to identify a Sinclair Spectrum or indeed any system by listening to it. When the various clicks and beeps were explained, it is easy to make the distinction. But the expertise comes from many years of working with the tapes.

We chose to use freeware emulation and tape loader programs, however there is a shareware emulator which does both jobs in one. It merely requires a parallel cable from the average tape recorder to the parallel port on the PC, then the tape can be played straight into the emulator program. The special cable, which has a normal audio jack on one end and a parallel port connector on the other makes it possible to use the existing drive (in this case, a tape recorder) to connect to a modern PC. We can then retain the devices to play or load the original media on, while connecting to a modern system for display of results.

THE PROCESS

With the Spectrum tape in the recorder it was connected to the PC by a standard audio cable from the output socket to the input socket in the SoundBlaster card in the PC. (Another possible way is to purchase a special cable that connects from the recorder to the parallel port in a PC, but that only becomes viable when the data to be emulated is valuable enough to warrant the purchase.)

The emulation takes place in two stages.

In stage one the data on the tape is transferred to the PC through the SoundBlaster. In simple terms each block of data is read and saved as a block of code. The header, is stored as Program: xxxx on the PC and is saved as a header file, 19 bytes long. In these 19 bytes, the type of code it is is identified (i.e. BASIC program, CODE, SCREEN$, ARRAY etc), where it gets loaded into the memory (usually 16384 if it is a title SCREEN$ as 16384-23295 is the Spectrums screen area), and its length (usually 6912 if it is a title SCREEN$). The code + length can NEVER be more than 65535, as that is the maximum memory area of the Spectrum. The type of program is identified by a single number. Generally 1 for BASIC, 2 for CODE, 3 for SCREEN$.

(As we found in a subsequent experiment loading gets a bit more complicated with the 128K, as it uses memory pages.)

Tape2TAP saves each block of code as a HEADER for any block that comes up with Program: Bytes: Character Array: or whatever, and BYTES. It then assembles all of these together into one TAP file for convenience.

The emulation software called Tape2Tap.exe and was downloaded from ftp://nvg.unit.no/pub/sinclair/utils/pc/tape2tap.zip.

The software was unzipped using pkunzip.exe, a commonly available program. Any zip package will do this, winzip for example. (We unzipped the software to a new directory on the hard drive of the target machine.)

This gave us a set of files with an executable program called Tape2tap. We ran this while the tape was playing on the recorder, we could hear the tape play through the header and the data itself. The screen echoed what was happening, telling us when each block was copied read from the tape, transferred through the SoundBlaster card and stored on the PC. The screen shows whether it is part of the header or a data block by the colours on the screen – red/purple for header information and yellow for data.

(Here we encountered our first failure because the read of the tape failed. Further investigation suggested that the tape was damaged.)

We tried another randomly chosen tape, called BallCrazy which ran on a 48K Spectrum or a 128K. We followed the same steps as with the first tape. This time the transfer of data blocks was successful. A file was created on the hard drive of the PC called Ballcraz.tap.

It is preferable, where possible to use the parallel port, this will give better, more accurate and consistent results. There is a shareware program that will do the translation of the tape and run the emulation in one process, thus eliminating many possible errors.

Now we had the tape stored on the PC digitally through the SoundBlaster card, we had then to run the emulation program to translate the Spectrum codes to allow the game to run under Windows 95. The program to do this emulation was downloaded from the same site as the tape transfer program ftp://nvg.unit.no/pub/sinclair/emulators/spectrum/pc/dos/z80.zip this was unzipped as before to produce two files, a readme and the program zx32.exe. The 32 bit version is to allow emulation for Windows 95 system, a different program would be required for a different operating system many of which are available through this site as well as others.

The Z80 emulator loads the tape data on-the-fly and to the user it looks like a simple window with menus as you would find in any Microsoft Window program. The Tap file is chosen from a list and then the program part of the Tap file, rather than the data file. Z80 then loads the program into the emulator and we have the Spectrum Game running on the Windows 95 system.

Our task was made easier by having the expertise of Gerard Sweeney, however, nothing he did was difficult or required specialised knowledge. Any competent computer user could manage the process, it may take longer particularly when deciding which emulator to use and whether to use the freeware version or shareware versions. We saved time by knowing which emulator works best for Windows 95, and being able to locate the site quickly. The list of web sites with this report include a number of sites that support these freeware programs.

We also saved time by having identified the stages of the process in advance, such as converting the tape data into PC data through the SoundBlaster card. However, as before all this information can be found at the web sites. There are many specialised Newsgroups dealing with the different systems and emulators. When an emulator is chosen, it will invariably have good documentation, both technical and user manual.
It is interesting to note here that most of the emulators available are for the more popular systems. Some of the earlier Sinclair systems, e.g. the Z81 do not yet have emulators that will run on PC hardware, they will run on the Sinclair Spectrum but the community of experts that have a fundamental interest in these systems are slowly responding to demand. It is only a matter of time before emulators for the popular games are available for use on current operating systems.

REVIEW OF THE STAGES OF THE SPECTRUM EMULATION EXPERIMENT

SECTION 1 - STANDARD TAPE LOADERS USED

1. Copy of TAPE2TAP of TAPER.
2. Tape recorder and PC with SoundBlaster
3. Load TAPE2TAP and play entire tape through SoundBlaster
4. Step 3 generates a TAP file
5. Load TAP into emulator of your choice

SECTION 2 - NON-STANDARD TAPE LOADERS USED

1. Get registered version of Z80 and parallel cable (this costs approx. £30)
2. Get tape recorder
3. Load Z80 and select TAPE loader
4. Load tape into Z80 (if you like, select SAVE TO TAP)
5. If SAVE TO TAP not used, save as Z80 or SNA

Some general points...

- Because there were so many different loading systems used on the Spectrum, there is no 100% guarantee that your emulator whether it is TAPE2TAP or Z80 can handle them all, but Z80 is usually the best bet with the unusual ones as it does seem to have the best Z80 emulation.

- If the tape is damaged, even slightly, there is no easy way of retrieving the data it holds (but see above). In other words, if it could not be expected to load on a genuine Spectrum, there’s no way of getting it to load on an emulator (though TAPER is supposedly going towards this kind of fix). (As Doron Swade has noted, for programs functional intactness is essential.)

- If it is a multiload game, then you will probably only get the main game part, not the levels as these are counted as separate data blocks, and have the loading code hard written into the main game (level checking etc). With a little bit of work it is sometimes possible to obtain the loader code, and change it to a suitable format that the emulators will use (called LLT multiloads - Load Level Trap) where the emulator looks for a certain 12 byte loader command to be called up.

- The SoundBlaster must be of the type where the line SET BLASTER is added to the autoexec.bat file

Text from Gerard's initial excursion into using freeware emulators:

> "I think I have cracked the shareware way of loading a Spectrum tape in. It is nowhere near as good as the registered version of the Z80 emulator, as this method can only handle certain loader systems, whereas Z80 can handle almost all of them." [The Z80 is the shareware emulator that costs around £30]
>
> "In case you are wondering what I mean, the Spectrum programmers came up with lots of different loading systems - some were "turbo" loaders to make things load a bit faster, some were fancy loaders where the picture came in a funny way, some were countdown loaders where you got told how long you had to go, some were encrypted loaders to try and stop hackers (never worked though), and some were a combination of all of these. Some even had games like PacMan and Simon on the screen so you could play that while waiting for the real game to load."
>
> "Anyway, this program is called TAPE2TAP, and basically it lets you play in your Spectrum tape into the SoundBlaster (if you have one) or parallel port via a custom cable, and it converts the various blocks of code into one TAP file (the emulator equivalent of a tape file with header and main code files all rolled into one file). You can then load this TAP file into any emulator capable (which is almost all of them).
>
> The TAPE2TAP file is part of the archive that comes with the WSPECEM emulator, available from: ftp://ftp.nvg.unit.no/pub/sinclair/emulators/ibmpc/windows.
>
> If you are needing proof that there are a large number of games out there, then you can either peruse this FTP site, or you can jump straight to my index of this site at http://www.fortunecity.com/skyscraper/tyrell/95/.
>
> My page is still a work in progress, mainly because I'm more concerned with the cataloguing of the 10,000+ snapshots there than on the actual appearance of the WWW side of it for now.
>
> And if you need another example of the level of my respect (addiction?) to this great 8 bit machine, then go see my other site or others. The one I think you might be most interested in is Damien Burke's site which contains what is considered to be the definitive FAQ to the Spectrum both in terms of the machine itself and the emulation side of things. The URL for that is : http://www.jetman.demon.co.uk/speccy/index.html".

We concede that in some places the experiment sounds as though it was run with a bit of guess work, hypothesis testing, and good luck, but our evidence indicates that this is par for the course for experiments of this kind.

2.4 Retargetable binary translation

While migration and emulation plays an important role in digital preservation it is the translation of material which would provide the most cost effective way of moving applications and associated data from one environment to another (Afzal, et al 1996). Research in the area of Retargetable Binary Translation (RBT) shows promise as a way of automating the conversion of digital materials, in particular older programs, that are now unusable as a result of hardware and software obsolescence, into newer formats. The major centre for work in this area is at the University of Queensland in Australia, http://www.cs.uq.edu.au/groups/csm/bintrans.html. An excellent summary article by Cifuentes and Malhorta (1996) provided the main starting point for discussion of this topic. Essentially binary translation is the process of automatically translating a binary executable program from one machine (M1) running a particular operating system (OS1) and using a particular file format (F1) (i.e. platform (M1,OS1, F1)) to another platform (M2) running a different operation system (OS2) and using a different file format (F2) (*Cifuentes and Ramsey 1997; *Digital[1-4]; *Digital Semiconductor-12 February 1997 & 3 December 1996; *Ohrberg 1995, Engler, 1996, *The Tibbit Project). A binary translator is composed of three distinct components: the front-end, middle and back-end.

- The front-end processor loads the source code of the program, disassembles it and converts it into a transitional format.

- The machine independent middle-end component does not rely on any machine in particular or any operating system, it performs the core analysis for translation, optimising the code where necessary.

- The final stage, the back-end, is dependent on the machine to run the code, it generates the code for the target machine using the binary file formats of the host operating system. This task is performed using conventional compiler code generation techniques.

For the purposes of rescuing digital material, we have to look at when Retargetable Binary Code might be relevant. Assuming that the hardware is unusable or has reached obsolescence there are a variety of possible situations. The source code and the compiler could still be available on the superseded operating system. The user might still have the source code but no compiler and finally, there might be neither the source code nor a compiler, just the executable program.

- In the first scenario it may be possible simply to re-compile the program on the new machine, however there may be problems as compilers rely on library routines that come with the compiler. Unless the compiler is fully supported on the new platform, re-compilation may not be a simple task. It may be possible to translate the libraries required.

- Where no compiler exists the source code can be modified to compile on the new platform, or it can be decompiled to add the missing information that the new machine requires.

- Where no source code or compiler exists, we have to rely on reverse engineering techniques or decompilation to recover the source code or re-engineering techniques, binary translation - to translate the binary code to the appropriate format for the new platform.

Digital Equipment Corporation (now part of Compaq) have worked on translating VAX code to run on the newer Alpha AXP architecture (*Chernoff, 1992). They designed two tools which became the first binary retargetable translators. VEST translates OpenVMS VAX binaries to Open VMS AXP format. mx translates ULTRIX MIPS to DEC OSF/1 AXP (*Digital Equipment Corporation [1-4], Engler 1996, *Ohrberg). In both cases the binaries perform as fast or faster on the newer system without loss of functionality. They identified the process of translating a single program written in a standard programming language as a relatively simple task. The problem lay in complex applications that rely on various source codes, libraries and tools. They also identified common techniques used to tackle this problem. Digital identified binary translation as being the most efficient and successful method to transfer binary material from one platform to another. They designed two translators and managed to surmount the problems associated with the changes in environment. They were seeking to translate, not only discrete programs but to capture the older environment so that any programs could be run.

In simple terms, the VEST translator disassembles the VAX code and traces the flow of the program. It then builds a flow graph that consists of basic blocks of straight line code. It then analyses this flow graph to get context information such as register contents, stack depth and other information that allows VEST to generate optimised code. This worked up to a point, there are some difficulties associated with the specific architecture of the VAX and associated programs that caused problems, such as memory management. Digital found that building the two translators for their specific machines was a complex but not impossible task. The architecture of the machines was similar, as they were built by the same company, and used similar data types and memory addressing. They identified the problems associated with translating source code and executing it on the target machine, they realised that the problems would be greater when two machines of dissimilar architecture were involved. The work that is being done now on Retargetable Binary Code is attempting to tackle these issues.

At Queensland University Dr Cifuentes and her team are working on developing general, platform-independent techniques for binary translation (*Cifuentes; *Cifuenties & Ramsey; Cifuentes & Malhorta 1996). They are dealing with the architecture issues at run time, so that the whole process of translation can be handled in one operation. They are seeking approaches that will make it feasible for programmers to translate binary code to run on any machine. Their research has resulted in prototype binary translators and now a Simple Retargetable Loader (SRL) (Ung & Cifuentes 1997). The aim of SRL is to create a single procedure that supports the translation of one binary file with all its associated information about the native operating system and hardware to another, completely different machine with a different operating system in one operation. In many ways this is the holy grail of data preservation and although it is promising much work remains to be done before its potential can be realised.

3. Case studies

These are some examples of the type of recovery that has happened. They include disaster recovery, recovery of data stored in unknown formats, and recovery from severely damaged media. One of the problems with obtaining more mundane recovery stories is that most companies are unwilling to have their mistakes or bad planning advertised. In particular, it has been very difficult to get details of forensic computing cases because of the very nature of the subject matter, but as information collected from these cases comes to court details of the techniques used will become more commonly known. What is evident is that even when media has been subjected to extreme conditions material stored on it can be recovered. What is not covered are stories of data migration. Data migration has a long history and includes solving such problems as moving material from paper tape to magnetic media (Barnett 1976).

3.1 The Challenger Space Shuttle Tape Data Recovery (Bhushan & Phelan 1987, Kalthoff et al, 1987)

For six weeks following the Challenger disaster magnetic tapes recording data about the Shuttle's systems (e.g. its engines and conditions in the cargo bay) and monitoring cockpit communications were immersed in the sea off the Florida coast. As the instrumentation tape recorders had broken open during the crash the tapes they held were exposed to salt water. As a result of contact between the saltwater and the tapes and their housings a number of chemical reactions occured. The magnetic coating had been destroyed in some areas, while in others the substrata of the tape had broken down. In general the damage was limited. A more severe problem was that the recording side had adhered to the backside of the tape against which it rested in the spool. This was caused by the chemical changes. It quickly became evident that unwinding the tapes resulted in the loss of the data holding strata. An attempt by NASA to resolve the inter-layer adhesion by washing the tapes and vacuum drying them failed. The NASA team looked for specialist advice from a team at IBM led by Professor Bhushan. The team set out to determine the cause of the interlayer adhesion, to clean and unwind the tapes, to transfer the data onto new tapes, and to suggest ways that this situation might be avoided in the future.

Bhushan and his team made the critical decision to begin their work not with the shuttle tapes themselves but with a tape of the same type. This provided a controlled study of the chemical composition of the tapes and their hubs. In addition they studied the chemical composition of the residue on the recovered tapes. After subjecting the residues and tapes to a variety of analyses the team concluded that the deposits responsible for the sticking of the recording side to the backside of the tape was magnesium hydroxide. While they recognised that magnesium hydroxide can be easily dissolved using a dilute aqueous acid solution, they conducted several further experiments to demonstrate that this solution would not cause other elements of the tape to deteriorate. Once the cause of the problem had been identified the team needed to identify a way to apply the solution to the tapes.

As the tape coating was extremely fragile the team considered it was going to be a risk to unwind the tapes. The magnesium-based hub was replaced with a spring-loaded plastic ring. Following a soak in an aqueous acid bath the tapes were rinsed in a series of methanol washes and water rinses. After this chemical treatment and relubrication the tapes were slowly unwound (at the speed of 0.15m/minute). The chemical treatment had been so effective that it proved possible to unwind the tape without further damaging its recording surface. The contents of the tapes were transferred to new media and these tapes were sent back to NASA. The NASA team was able to read more than 90% of one tape and 100% of the others. The voices of the astronauts just before the crash were among the data that would never have been available to the crash investigation team or the general public if it had not been for the work of the IBM team.

The project demonstrates that even where the magnetic media has become chemically unstable and the structural properties of the media has changed it is possible to recover data it holds. Such extraordinary lengths while uncommon do indicate that it is very difficult both to destroy data or to lose it entirely.

3.2 Hurricane Marilyn

After Hurricane Marilyn devastated the Virgin Islands in September 1995 the National Media Lab assisted the National Archives and Records Administration in recovering data at risk from loss because of damage to equipment. NARA concentrated on paper records and John Van Bogart and his team focused on recovering electronic data. Of the government centres which suffered the effects of the hurricane among the worst hit were the USVI Legislature Building and the Department of Planning and Natural Resources. These organisations had used diskettes and 12 inch WORM disks to store their data. The hardware itself was considered to have been damaged beyond repair by the rain, salt-water, and sand. The sea-water proved the most devasting contaminant. Mechanical components and electrical connections which were in contact with it corroded rapidly (van Bogart 1995, 1). Parts of the media were damaged. Fortunately this damage was confined mainly to the steel hubs which were heavily corroded but in most cases the metallic reflective layer of the disk was not corroded because the lamination had not been ‘breached’. As a result it was possible to clean the WORM disks so that they could be read. The floppy disks needed to be taken apart, cleaned and set in new housings before reading, but this also proved possible. Floppy disk media is quite resilient and in other cases even where diskettes have been ripped apart and the data-holding wafer crumpled up it has been possible to press the media and recover the data held on it.

The method to recover the data was simple. The disks were cleaned using distilled water which was wiped with a cotton cloth ‘in a radial direction from the centre of the disk to the edge’ (ibid., 8) to remove sand and salt residue. While it might have been easier to dip the WORMs in distilled water the team was feared that this might breach the laminated edges of the media. Once the debris was removed it was possible to read the data held on the media.

The most detailed discussion of the National Media Laboratories work to recover records after the St. Thomas disaster can be found at http://www.nta.org as technical report RE0025; this report should form the starting point for anyone wishing to recover data from damaged media because it provides detailed guidelines and field tested best practice.

3.3 Video image recovery from damaged 8 mm recorders

This is another project that recovered data from badly damaged media after a disaster, although not digital data it is material stored on magnetic media (*Bachner et al). Three SonyModel EVO 520 videocassettes recorders salvaged from the wreck of a crashed F16 Fighter were sent to the Eastman Kodak Recording Systems Analysis Laboratory (RSAL) for cassette extraction and video image recovery. The Crash Investigation Board hoped that RSAL would be able to recover the data from the Left Multifunction Display (LMFD) and Heads-Up Display (HUD). The members of the Board felt that the chances of identifying the cause of the crash might be improved if the video images created just prior to the crash could be recovered. These would show the manoeuvres made by the pilot in the moments before the disaster (Bachner, et al 1994).

When the RSAL team opened the damaged recorders they found some tape correctly wound on its spool, other tape had damaged edges, and still other pieces of tape had been shredded into tiny bits. Damaged tape needed to be repaired. In some instances this required only limited splicing, in others it was necessary to recondition the tape by heating and pressing it, and it still other instances it was necessary to reconstructed the tape segments from tiny fragments. Before play back was attempted the repaired tape was wound on to new spools.

Once the reconditioned tapes had been put together a range of methods were used to recover the signal it held. This included disabling noise reduction features, and acquisition of the video signals after the playback device had read them. The mechanisms for coping with dropouts produced vast amounts of misleading data as the time-based corrector inserted erroneous synchronisation pulses. So the recovery of the video images began by capturing demodulated video signal prior to the processing of the signal by the dropout concealment circuitry in the recorders. The team used a converter to transform the analogue signal into a digital one. Once in digital form they were copied and subjected to such image restoration techniques as adjustment of brightness and contrast, noise reduction, and filtering. The team looked into the feasibility of using a variety of other techniques including a ferrofluid solution, a microscope and digital photography. In this instance the ferrofluid solution develops the signal as the particles in the solution gather on the most magnetised areas of the tape and a microscope equipped with a digital camera is used to capture the waveform. Optical recovery does work but unfortunately each digitisation only produces a 1/4 of a video line, so 800 digitisations are be needed for one video frame. This means that it is a time consuming and labour intensive task. Although these techniques were applied to video tapes they could as easily for the most part have been applied to magnetic tapes as well, see Section 1.4 above.

3.4 German Unification and the recovery of electronic records from the GDR

This case study explores another form of data recovery (Wettengel 1998). The data was inaccessible not as a result of physical deterioration, as in the Challenger tapes, but because of differences in hardware, software, data formats and encoding. The methods in this case allow us to explore recovery and gives us invaluable advice on the preservation of digital material.

West German archivists took responsibility for former East German data archives after unification. To cope with the deluge of electronic records they put together a group with responsibility for machine readable data. This group set out to establish a standard for the preservation of these records. The machine data had not been well curated: supporting documentation was lost, where it survived it was incomplete, and in other cases the data were lost. Until very shortly before unification electronic data in the GDR had been processed using mainframes in specialised data processing centres. Some data archives were closed and others privatised. Where centres were privatised the new managers began selling the historic data. Closed centres posed the least number of problems. Among the many problems facing West German Archivists was that as staff from the data centres found new posts they took not only their knowledge with them but also some of the documentation. Computer systems in use in Communist countries of the Eastern Block at the end of the 1980s were derivatives of hardware and software used in western systems in the early 1970s. The quality control in the production of digital storage media in the East was poor. Binders in 9-track tapes were prone to breakdown and the quality of the finish on the oxide surfaces of hard disks was often so uneven that it led to head damage. Because of the low quality of the media and their storage conditions significant amounts of data were at risk of loss.

As other cases have shown data without relevant contextual documentation has limited value. From among the data sets needing curation the Federal Archives began with recovery of personal data on 331,980 staff members of East German government agencies. The Kaderdatenspeicher or database of party functionaries contained critical data about the political and professional careers of officials. These data were essential for the insights it could provide into the East German state and the activities of its party members.

The team began by identifying and printing volume labels, headers, and initial data blocks. It was found that the labels and headers were easy to read because they were in native IBM format. With these data the team was able to workout the information held on each tape. There were innumerable problems identified at this stage: variable data types both in headers and within the data elements themselves, variable record lengths, lack of data or file structure information. Documentation proved essential. Even where it was feasible to reconstruct the data it was not possible without access to documentation to understand them. Using other paper and electronic records it was feasible to construct a description of the file structures. Different kinds of encoding had an impact on the success of recovery as the binary data proved difficult to evaluate. There was no getting around the important role that the code books played in this data reconstruction. A range of specialised software was developed to reconstruct the file structures, to address problems with date formats, and to decipher binary sequences. It still proved necessary to employ former staff from the GDR archives to identify certain compression algorithms and other encoding standards that the Federal Archives team were not able to interpret.

One of the main lessons learned from these reconstructions is that while the storage of media in correct conditions is essential it must be supported by relevant documentation. It has become apparent that archiving digital material has its own problems in varied data structures, programs and limited documentation, much of which seems to be held in private notebooks or in the brain of ex-system administrators. However, the results of the archivist shows that it is possible with time and expertise to restore the data from unknown tapes, structures and formats.

4. Prevention of loss through management of media & technology

The following suggestions can help to prevent some data loss and to assist in data recovery. The work of John Van Bogart and Ontrack (1996) are the sources for the guidelines below.

Always:

- keep areas where media are being used and stored free of smoke, dust, and dirt particles;
- keep media away from stray magnetism (although the high coercivity of the current generations of media means that the number of risky magnetic fields is relatively small);
- keep media in a cool dry place (the optimum storage conditions recommended by the National Media Laboratory are 15-18 ºC and 30%-40% Relative Humidity (RH));
- aclimatise media before using it (e.g. if you bring a tape in from archival store at say 15 ºC let it stand for a couple of hours so that its temperature rises to that of the room itself);
- keep floppy drives well maintained. (Disc read-write heads can become mis-aligned; a symptom of a 'drive problem is an error message when trying to read a diskette from another source' (http://www.aimnet.com/~avasales/tutorial.html), although the drive has had no problem reading diskettes it has written itself.);
- avoid poor quality read-write devices for magnetic media;
- keep tape drives well-maintained and clean;
- use high quality media;
- use new media from a known source (if media sits on the shelf at a supplier for month before your organisation purchases it then it is likely to have already begun to degrade); and,
- maintain good documentation of the contents of tapes, when they were created, what devices where used to write them and how often they have been respooled and read.

Never:

- leave tapes in drives for long periods as the tape may relax and come to rest against the tape heads and this may damage the both the media and the reading device;
- write in compressed format to archival tapes. It is especially important to avoid the use of hardware compression, even though hardware compression can double the capacity of the media;
- use CD-Rs as archival media. Their likely stability is unknown, not fully tested, and they are susceptible to damage.

5. Recommendations for further study

This study finds that there is much more research that is needed in this area.

- More case histories about data loss and rescue need to be collected. Good case histories are hard to find. In most instances organisations are embarrassed by their failures. We believe that more concentration of oil exploration firms might produce suitable case studies.

- More research needs to be conducted into the viability of the preservation of media access devices to ensure the possibility of access to a diversity of media types in the future. Even where emulation can be used to run programs and manipulate data created in other environments, devices to read the media prove much more difficult to recreate. Writing device drivers for older devices, although tricky, is far simpler.

- Documentation for hardware and software although initially ubiquitous when products are first released become increasing difficult (and in some cases prove impossible) to locate over time. A concerted effort should be undertaken to collect documentation, including designs.

- More research needs to be carried out in the area of emulation.

- The use of magnetic force microscopy to recover data from magnetic media needs to be the subject of a programme of research. For the purpose of this experiment it might be useful to image the surface of a 3.5” floppy. The images could then be scanned and with optical recognition software it should be possible to redigitise the data. This could then be compared to a master copy of the data which had been written to the disk. The reasons for suggesting that the tests should be conducted on a 3.5" floppy disk are that because of the way the data is encoded the likelihood that the experiment will be a success is very high. What is needed is proof of concept. This test could be expensive to run, but it might be possible to obtain commercial sponsorship for it.

- Further work into the use of cryptography to decode bit sequences is necessary. Our research into this area produced little positive evidence that sufficient work had been undertaken in the analysis of bit-patterns from recovered data to interpret them.

- A media quality index needs to be developed. Some factors which might be included in any such index include: adhesion, abrasivity, durability, chemical stability, and error rates. Every piece of storage media should be marked with a quality rating.

Bibliography of printed sources

Afzal, T., Breternitz, M., Kacher, M., Menyhert, S., Ommerman, M., and Su, W. (1996), 'Motorola PowerPC Migration Tools-Emulation and Translation', *COMPCON '96, IEEE Computer Society International Conference,* 145-50.

Ahl, D.H. (1983), 'Floppy Disk Handling and Storage', *Creative Computing,* 9/12: 205-6.

Ajluni, C. (1997), 'Advanced Emulation Tool Targets High-Speed Functional Verification', *Electronic Design,* 45/5: 80.

Akhan, M.B., and Yedekcioglu, O.A. (1995), 'A RISC Based Protocol Converter for IBM Mainframes', *Microprocessors and Microsystems,* 19/4: 223-9.

Akiyama, S., Nakagawa, S., and Naoe, M. (1991), 'Electrically Conductive Layer of Wear-Resistant Fe-Mo-B Alloy for Protecting Magnetic Recording Tape', *IEEE Transactions On Magnetics,* 27/6.2: 5094-6.

American National Standards Institute, (1994), *American National Standard for elecommunications: Network Performance: Tandem Encoding Limits for 32-Kbit/S Adoptive Differential Pulse-Code Modulation (ADPCM)* American National Standards Institute (New York).

American National Standards Institute, (1994), *American National Standard for Information Technology: Computer Graphics: Interfacing Techniques for Dialogues With Graphical Devices (CGI): Data Stream Binding Part 1, Character Encoding* American National Standards Institute (New York).

American National Standards Institute, (1992), *American National Standard for Information Technology: Computer Graphics: Metafile for the Storage and Transfer of Picture Description Information: Part 2: Character Encoding* American National Standards Institute (New York).

American National Standards Institute, (1992), *American National Standard for Information Technology: Computer Graphics: Metafile for the Storage and Transfer of Picture Description Information: Part 3: Binary Encoding* American National Standards Institute (New York).

American National Standards Institute, (1992), *American National Standard for Information Technology: Computer Graphics: Metafile for the Storage and Transfer of Picture Description Information: Part 4: Clear Text Encoding* American National Standards Institute (New York).

American National Standards Institute, (1992), *American National Standard for Information Technology: Computer Graphics: Interfacing Techniques for Dialogues With Graphical Devices (CGI): Data Stream Binding: Part 2: Binary Encoding* American National Standards Institute (New York).

American National Standards Institute, (1993), *American National Standard for Information Systems—130 Mm Write-Once Optical Disk Cartridge Using Sampled Servo and 4/15 Encoding* American National Standards Institute (New York).

Armour, A. P. (1967), *An Operations Research Study of Magnetic Tape Rehabilitation* (Florida Institute of Technology).

Arrott, A.S., and Templeton, T.L. (1996), 'The Power-Law Decay of a Collective Dipole With Cycle Number in Rotational Hysteresis of Magnetic Recording Media', *Journal of Physics D-Applied Physics,* 29/9: 2304-2312.

Barker, R. (1996), 'DEC's Multia Multiclient Desktop', *UNIX Review,* 14: 65-70.

Barnett, D. B. (1976), *Paper to Magnetic Tape Data Translator* (Physics Division, Saskatchewan Research Council, Saskatoon).

Bartee, T.C. (1977), *Digital Computer Fundamentals* (Harvard University).

Becker, H.B. (1995), 'Disaster Recovery Long-Range Planning: A Mandatory Evolution for Protecting Data', *International Journal of Network Management,* 5/4: 174-180.

Bhushan, B., and Phelan, R.M. (1987), 'Overview of Challenger Space-Shuttle Tape-Data Recovery Study', *IEEE Transactions On Magnetics,* 23/5: 3179-3183.

Bhushan, B., and Lowry, J.A. (1995), 'Friction and Wear Studies of Various Head Materials and Magnetic Tapes in a Linear Mode Accelerated Test Using A New Nano-Scratch Wear Measurement Technique', *Wear. An International Journal on The Science and Technology of Friction, Lubrication and Wear,* 190/1: 1-15.

Birkhead, E. (1990), 'Preserving Disk Technology', *The DEC Professional,* 9/3: 50.

Boyce, J.C. (1977), *Digital Computer Fundamentals* (New Jersey).

Brownie, C., and Pollock, K.H. (1985), 'Analysis of Multiple Capture-Recapture Data Using Band-Recovery Methods', *Biometrics,* 41/2: 411-420.

Brunt, M. (1985), 'Floppy Disk Developments', *Data Processing,* 27/7: 34-6.

Buchmann, W. (1989), 'Maschinenlesbare Daten und Datenträger im Archiv: Bedingungen für die Aufbewahrung, Konservierung und Benutzung', *Der Archivar,* 42: 193-200.

Burnett, M.M., and Supnik, R.M. (1996), 'Preserving Computing's Past: Restoration and Simulation', http://www.digital.com/info

Campbell, D. (1988), *Compu-Terror: Computer Terrorism and Recovery from Disaster* (Bethesda, MD).

Chang, T., Pinder, J., Gupta, S., and Money, J. (1986), 'Thin-Film Floppy Disk Head', *IEEE Transactions on Magnetics,* 22/5: 695-7.

Chonan, S., Jiang, Z.W., and Shyu, Y.J. (1992), 'Stability Analysis of A 2'' Floppy Disk Drive System and The Optimum Design of The Disk Stabilizer', *Journal of Vibration and Acoustics-Transactions of The Asme,* 114/2: 283-6.

Cifuentes, C., and Malhorta, V. (1996), 'Binary Translation: Static, Dynamic, Retargetable?', *Proceedings, International Conference on Software Maintenance,* 340-9.

Clark, D.A., and Hutchings, B.L. (1996), 'Supporting FPGA Microprocessors Through Retargetable Software Tools', *IEEE Symposium on FPGAs for Custom Computing Machines,* 195-203.

Copeland, P., (1998), 'Project Digitise', in *Towards the Digital Library*, L. Carpenter, S. Shaw and A. Prescott (eds.) (The British Library, London), 121-129.

Corb, B. (1994), 'High-Frequency Head and Playback Model for Thin-Film Recording-Heads', *IEEE Transactions on Magnetics,* 30/2.1.

Cross-Platform Conversion, Migration & Porting, (Computer Channel, Syosset, N.Y.) 1997.

Cuddihy, E.F. (1983), 'A Chemical Aging Mechanism of Magnetic Recording Tape', *Abstracts of Papers of The American Chemical Society,* 185: 93.

Cunningham, S. (1987), 'Developing A Disaster Recovery Plan (DRP) Using a Data-Base Package', *Computers & Industrial Engineering,* 13: 223-9.

Daharsh, R.S. (1981), *Short Circuit Data Recording Using Magnetic Tape as a Recording and Storage Medium for Long Duration Test Programs* (University of Wisconsin, Milwaukee).

Davis, G.B. (1971), *Introduction to Electronic Computers* (University of Minnesota).

'Disaster Recovery Services Survey', *Disaster Recovery Journal,* 10/2, (1997), http://www.drg.com/surveys/otherservices/other97.html

Engler, D.R. (1996), 'VCODE: a retargetable, extensible, very fast dynamic code generation system', *SIGPLAN Notices*, 31: 160 –70.

Fritsch, C.F. (1973), *Some Things You Always Wanted to Know about Magnetic Tape Handling Procedures, But Thought Nobody Knew* (Texas).

Geller. S.B. (1993), *Care and Handling of Computer Magnetic Storage Media* (Washington D.C.).

Goldwasser, S.M., 'Notes on CD Technology and Repair of CD Players and CD ROM Drives', http://isdl.ee.washington.edu/CE/repair/cdl.txt

Group Examines Optical Tape Data Storage Standards' (1995), *Journal of Research of The National Institute of Standards and Technology*, 100/5: 623.

Hamilton, S.E., and Longbottom, J.U. (1996), 'The Fox Movietone News Preservation Project: The Computer Control System', *SMPTE Journal*: *Publication of The Society of Motion Picture and Television Engineers,* 105/9: 60.

Hanson, O. (1982), *Design of Computer Data Files* (City University, London).

Harris, S. (1992), *PC Data Recovery and Disaster Prevention* (Manchester).

Heikkinen, D., and Sarkis, J. (1996), 'Disaster Recovery Issues for EDI Systems', *Industrial Management and Data Systems,* 96/2: 25-32.

Huh, Y.J., Kim, J.S., Nam, T.Y., and Kim, S.C. (1997), 'Deformation Effects and Recording Characteristics of Compact Disc-Recordables', *Japanese Journal of Applied Physics Part 1-Regular Papers Short Notes & Review Papers,* 36/1B: 403-9.

IBM 3480 Magnetic Tape Subsystem Reference: Channel Commands, Status and Sense Bytes, and Error Recovery Procedures (IBM Corporation, Tucson, Arizona), (1987).

Idell, P.S. (1994), 'Digital Image Recovery and Synthesis', *Optical Engineering,* 33/10: 3221.

Jeffers, F., and Bero, J. (1991), 'Record Head Saturation and Overwrite Performance of a Bafe Floppy Disk Drive', *IEEE Transactions On Magnetics,* 27/6.2: 4885-7.

Jenkins, C. (1990), *The Reel World Environment: Computer Data & Magnetic Tape Cartridges* (Hitchin).

Kadokura, S. (1992), 'Tribology of Co-Cr Thin-Film Media for Perpendicular Magnetic Recording', *Journal of Japanese Society of Tribologists,* 37/1: 29-34.

Kahane, Y., Neumann, S., and Tapiero, C.S. (1988), 'Computer Backup Pools, Disaster Recovery, and Default Risk', *Communications of The ACM,* 31/1: 78-83.

Kalthoff, C.H., Bradshaw, R.L., Bartkus, E.A., and Finkelstein, B.I.. (1987), 'Magnetic-Tape Recovery and Rerecording of Data', *Journal of Applied Physics,* 61/8: 4004-6.

Katz, E.R. (1984),'Erase Profiles of Floppy Disk Heads', *IEEE Transactions on Magnetics,* 20/4: 528-541.

Keene, S., and Swade, D. (1994), *Collecting and Conserving Computers - Conference Papers* (The National Museum of Science and Industry).

Kim, J.S., Nam, T.Y., and Huh, Y.J. (1997), 'The Optical Characteristics in The Layers of Compact Disc-Recordable', *Korean Journal of Chemical Engineering,* 14/2: 88-92.

Kitamoto, Y., Abe, M., and Naoe, M. (1996), 'Preparation of Co-Cr Alloy/Ni-Zn Ferrite Doublelayered Films for Perpendicular Magnetic-Tape', *IEEE Transactions on Magnetics,* 32/5//1: 3834-6.

Kochtubajda, B., Humphrey, C., and Johnson, M., 'Data Rescue: Experiences from the Alberta Hail Project', (Conference paper presented at the 21st Annual Conference of the International Association for the Social Science Information Service and Technology, IASSIST 95 [Quebec City]), http://datalib.library.ualberta.ca/AHParchive/Archive.html

Korst, J., and Pronk, V. (1996), 'Storing Continuous-Media Data on a Compact Disc', *Multimedia Systems,* 4/4: 187-196.

Kurihara, Y., Osawa, H., Okamoto, Y., Muraoka, H., and Nakamura, Y. (1996), 'Performance of PRML Systems in Perpendicular Magnetic Recording by a Bi-Layered Main-Pole Head', *Journal of Magnetism and Magnetic Materials,* 157-8: 262-263.

Larsen, T.L., Woodard, F.E., and Pace, S.J. (1993), 'A New Tape Product for Optical Data Storage', *Japanese Journal of Applied Physics,* 32/11B: 5461.

Lauer, J., Blanchet, T., and Ng, Q. (1994), 'Composition and Performance of Hydrogenated Carbon Overcoats on Magnetic Storage Discs', *ASLE Transactions,* 37/3: 566.

Leduc, P.G. (1991), *The Effects of Computer Viruses on Disaster Recovery Model Development* (California State University).

Lefkovitz, D. (1969), *File Structures for On-line Systems* (University of Pennsylvania, Philadelphia).

Leimkueller, H.J. (1995), 'Computer Evidence Analysis and Recovery of Magnetic Storage Media Data', *IEEE Annual International Carnahan Conference on Security Technology, Proceedings,* 147-153.

Li, G.X., and Xun, P.J. (1990), 'The Effect of Static Magnetic-Properties on Recording Characteristics of the Floppy Disk', *IEEE Transactions on Magnetics,* 26/1: 127-8.

Lin, Y., and Yuan, M.F. (1995), 'Post Compensation for Nonlinear Distortions in PRML Recording Channel', *IEEE Transactions on Magnetics,* 31/6.1: 3033-5.

Liu, Y., and Showalter, G. (1993), 'Design and implementation of an EPROM emulator as a low cost microprocessor tool', *Microprocessors and Microsystems,* 17: 627-630.

Ludwig, M., Halova, J., Subrt, J., Tlaskal, J., and Zak, P. (1993), 'Relationship between the Morphology of Maghemite and the Properties of Magnetic Tapes', *Chemometrics and Intelligent Laboratory Systems,* 18/2: 221-8.

Luis, F., Bartolome, J., Tejada, J., and Martinez, E. (1996), 'AC Susceptibility Study of the Magnetic Relaxation Phenomena in Cro2 Digital Compact Cassette Magnetic Tapes', *Journal of Magnetism and Magnetic Materials,* 157/158: 266.

Magnetic Recording Handbook :Technology and Applications (1990), (New York).

Malhotra, S.S., Lal, B.B., Alex, M., and Russak, M.A. (1997), 'Effect of Track Edge Erasure and On-Track Percolation on Media Noise at High Recording Density in Longitudinal Thin Film Media', *, IEEE Transactions on Magnetics*, 33/5, 2992-2994.

Marshall, T.G., and Attikiouzel, J.A. (1983), 'Floppy Disk Data Transfer Techniques', *IEEE Micro,* 3/6: 17-23.

McAteer, J. (1996), 'Ready for anything [disaster recovery]', *LAN Magazine,* 4: 99-107.

Menkus, B. (1994), 'The New Importance of Business Continuity in Data-Processing Disaster Recovery Planning', *Computers & Security,*13/2: 115-8.

Meredith, C. (1996), 'Learns the importance of work-area recovery sites after Midwest flooding', *I/S Analyzer,* 35: 12-6.

Michelson, A. (1992), *Development of a Testing Methodology to Predict Optical Disk Life Expectancy Values*, NTIS Special Publication 500-200 (Washington D. C.).

Miller, D.I., and Good, J.K. (1987), 'Experimental-Analysis of Squeal of Read-Write Heads upon Floppy-Disk Media', *Experimental Mechanics*, 27/2: 126-131.

Miller, H.W. (1993), *The Disaster Recovery Source Book* (Massachusetts).

Mita, S., Ouchi, Y., Takashi, T., Sato, N., Aoi, H., Minoshima, S., Hirai, T., Miyasaka, H., Shimokawa, R., Matsuura, T., Sawaguchi, H., Miyazawa, S., Hikasa, K., Shimokawa, R., Matsuura, T., Etal (1996), '150Mb/S PRML Chip for Magnetic Disk Drives', *IEEE International Solid-State Circuits Conference,* 39: 62-3.

Mitton, D.B., Walton, J., and Thompson, G.E. (1993), 'An XPS and AES Study of the Aging of a CO-20-Percent-NI Metal-Evaporated Tape', *Surface and Interface Analysis,* 20/1: 36-42.

Mockridge, D. (1994), 'EPROM Emulation', *Dr Dobbs Journal,* 19/10: 56.

Mohlhenrich, J. (1993), *Preservation of Electronic Formats and Electronic Formats for Preservation* (Chicago).

Monk, S., Mariani, J.A., Elgalal, B., and Campbell, H. (1996), 'Migration from Relational to Object-Oriented Databases', *Information and Software Technology,* 38/7: 467-475.

Moon, J.Y., and Zhu, J.G. (1993), 'Nonlinearities in Thin-Film Media and Their Impact On Data Recovery', *IEEE Transactions on Magnetics,* 29/1//1: 177-182.

Moran, R. (1987), *Magnetic/Opto-Magnetic Storage: Media & Materials* (Connecticut).

Myers, K.N. (1985), 'Interim Processing Strategies Provide Disaster Recovery Flexibility', *Data Management*, 23/10: 48-49.

Neaga, G. (1997), *Fire in The Computer Room, What Now?: Disaster Recovery, Preparing for Business Survival* (New Jersey).

Novellino, J. (1995), 'Emulators race to keep up with new devices', *Electronic Design,* 43: 151-2.

Oakley, W.S. (1996), 'Progress Toward Demonstrating a High Performance Optical Tape Recording Technology', *NASA Conference Publication,* 2/3340: 571.

Okamoto, K., Okazaki, Y., Nagai, N., and Uedaira, S. (1996), 'Advanced Metal Particles Technologies for Magnetic Tapes', *Journal of Magnetism and Magnetic Materials,* 155/1-3: 60.

Okazaki, Y., Hara, K., Kawashima, T., Sato, A., and Hirano, T. (1992), 'Estimating the Archival Life of Metal Partical Tape', *IEEE Transactions on Magnetics,* 9.

'Optical Cards and Optical Tape: An Overview of Their Characteristics and Potential Applications', *Library Computer Systems and Equipment Review,* 14: 41-7, (1992).

Osaki, H. (1993), 'Role of Surface Asperities on Durability of Metal-Evaporated Magnetic Tapes', *IEEE Transactions on Magnetics,* 29/1: 11-20.

Osaki, H., Oyanagi, E., Aonuma, H., Kanou, T., and Kurihara, J. (1992), 'Wear Mechanism of Particulate Magnetic Tapes in Helical Scan Video Tape Recorders', *IEEE Transactions on Magnetics,* 28/1: 76-83.

Osaki, H., Uchiyama, H., and Honda, N. (1993), 'Wear Mechanisms of Co-Cr Sputter Deposited Magnetic Tapes in Helical Scan Video Tape Recorders', *IEEE Transactions on Magnetics,* 29/1: 41-58.

Owen, D., 'Optical Tape Provides High-Density, Low-Cost Data Storage', *CD-ROM Professional,* 5/2: 73-75.

Podio, F. L. (1996), 'Digital Optical Tape: Technology and Standardization Issues', *NASA Conference Publication,* 1/3340: 265.

Prescott, A. (1994), *Product Data Exchange Using STEP (PDES). Part 21, Clear Text Encoding of The Physical File Exchange Structure* (Virginia).

Quarter-Inch Cartridge Drive Standards, Inc. (1989), *Serial Recorded Magnetic Tape Cartridge for Information Interchange: Streaming Mode, Read-While-Write 0.250 in. (6.35 Mm) Tape, 26 Tracks, Transition Density, 20,000 Ftpi (787 Ftpmm), Data Density, 16,000 Bpi (630 Bpmm), GCR 0,2 4,5 Encoding, Reed-Solomon ECC, Formatted Capacity, 525 Mbytes (With DC6525 or Equivalent Cartridge), 320 Mbytes With DC 6320 or Equivalent Cartridge* (California).

Richter, H. J., and Veitch, R. J. (1995), 'Advances in Magnetic Tapes for High Density Information Storage', *IEEE Transactions on Magnetics,*, 31/6: 2883.

Robbins, R.M. (1988), ‘Disaster Recovery - Trial by Flood’, *Infosystems,* 35/1: 41.

Roche, J.R., Yeung, R,W., and Hau, K.P. (1997), ‘Symmetrical Multilevel Diversity Coding’, *IEEE Transactions on Information Theory,* 43/3: 1059-1064.

Rohde, R., and Haskett, J. (1990), ‘Disaster Recovery Planning for Academic Computing Centers’, *Communications of The ACM*, 3/6: 652-7.

Roo, P., Spencer, R.R., and Hurst, P.J. (1995), ‘Analog Timing Recovery Architectures for PRML Detectors’, *Conference Record / IEEE Global Telecommunications Conference,* 1: 571-9.

Rosch, W. (1997), *Hardware Bible, Premier Edition*, (Indiana).

Rugar, D., Mamin, H.J., Guethner, P., Lambert, S.E., Stren, J.E., McFadyen, I., and Yogi, T. (1990), ‘Magnetic force microscopy: General Principles and Application to Longitudinal Recording Media’, *Journal of Applied Physics,* 68/3.

Saffady, W. (1991)*, Stability, care and handling of microforms, magnetic media and optical disks* (Chicago).

Sáenz, J.J., García, N., Grutter, P., Meyer, E., Heinzelmann, H., Wiesendanger, R., Rosenthaler, L., Hidber, H.R., and Gütherodt, H.-J. (1987), ‘Observations of magnetic forces by the atomic force microscope’, *Journal of Applied Physics,* 62/10.

Seif, M.A., Moslehy, F.A., and Rice, S.L. (1993), ‘Deformation and Warping in Magnetic Tapes by Laser Speckle Technique’, *The Journal of Elastomers and Plastics,* 25/3: 216-223.

Shibata, Y., Xiao-Ping L., and Amano, H. (1996), ‘An emulation system of the WASMII, a data driven computer on a virtual hardware’, *Proceedings: 6th International Workshop on Field-Programmable Logic and Applications* 55-64.

Sin, K., Glijer, P., Sivertsen, J. M., Judy, J.H. (1997), ‘Magnetic Force Microscopy Studies of Ultrahigh Density Magnetic Recording on Longitudinal and Perpendicular Media’*, IEEE Transactions on Magnetics*, 33/2, 1052-1056.

Smith, D.R., Cybrowski, W.J., Zawislan, F., Arnstein, D., Dayton, A.D., and Studwell, T.D. (1994), ‘Contingency Disaster Recovery Planning for Transmission-Systems of The Defense Information-System Network’, *IEEE Journal on Selected Areas in Communications,* 12.

Sniffin-Marinoff, M. (1991), ‘Taking a Byte Out of History: The Archival Preservation of Federal Computer Records by the Committee on Government Operations’, *Government Information Quarterly,* 8/4: 415-8.

Södergård, C., Martovaara, J., and Virtanen, J. (1995), *Research on the life expectancy of the CD-R (CD-R levyjen säilytyskestävyyden tutkiminen (Undersökning av CD-R skivors beständighet)* (Helsinki).

Speliotis, D. E., ‘Double-Layer Particulate Magnetic Recording Tapes’, *IEEE Transactions on Magnetics,* 29/6: 3613-5.

Srinivasan, D.R., Gawne, D.T., and Wales, J.L.S. (1988), ‘Wear of Co-Ni Thin-Film Magnetic Recording Tape Against Metallic and Ceramic Surfaces’, *Thin Solid Films,* 166/1-2: 375-385.

Stamps, D. (1987), 'Disaster Recovery - Who's Worried', *Datamation,* 33/3: 60-4.

Strategies for Successful Rightsizing: A Study of Seven Organizations' Rightsizing Experiences (Pennsylvannia & Oregon), (1993).

Stupp, S.E., and Bernards, J.P.C. (1996), 'Inter-Layer Variation in The Magnetic Properties in Multi-Layer ME Tapes', *Journal of Magnetism and Magnetic Materials,* 155/1-3: 300.

Suttinger, R. (1990), 'IR-Dichroism of Magnetic Tapes: Measurements With Polarized IR-Light', *IEEE Transactions on Magnetics,* 26/5: 2101.

Suzuki, T. (1992), 'Orientation and Angular Dependence of Magnetic Properties for Ba-Ferrite Tapes', *IEEE Transactions on Magnetics,* 28/5, 2388-2390.

Suzuki, T., Oguchi, T., Kishimoto, Y., and Saito, N. (1993), 'BA Ferrite 8 mm Data Tapes', *Journal of Magnetism and Magnetic Materials,* 120/1-3: 25.

Tamon, H., Takase, K., Tanaka, H., Miura, H., and Okazaki, M. (1995), 'Structure Formation During Drying of Coating Layer of Magnetic Particulate Containing Solvent Mixture', *Journal of Chemical Engineering of Japan,* 28/3: 324-8.

Texas Court of Appeals (9th) (1996), *Disaster Recovery Plan, Ninth Court of Appeals : Computer Resources* (Texas).

'Thank God it's Friday [disaster recovery]' (1996), *Secure Computing* 50-1.

Tharp, A.L. (1988), *File Organisation and Processing* (North Carolina State University).

The Ernst & Young International Information Security Survey 1995 (1996), *Information Management and Computer Security,* 4: 26-33.

The Storage and Care of Magnetic Tape (Audio, Video, and Computer) (The University, Buffalo, Washington), (1979).

Thompson, L.E. (1984), 'Floppy-Disk Formats', *Byte,* 9/10: 147.

Thompson, R.J. (1987), 'Disaster Recovery Is Silly', *Data Management,* 25/2: 46.

Tokumaru, H., Arai, K., Yoshimura, S-I., and Oshima, H. (1993), 'Recording Experiment With Rotating Optical Head for Magnetooptical Tape Recording System', *Japanese Journal of Applied Physics,* 32/11B: 5428.

Torabi, A.F., and McEwen, P.A. (1995), 'Monte Carlo Study of Inductive Heads With PRML Recording Channel', *IEEE Transactions on Magnetics,* 31/6//1: 3069-71.

Tuck, B. (1996), 'List of Emulators to Select is Growing', *Computer Design,* 35/2: 18.

Underwood, M. (1997), 'When Disaster Hits..', *Industrial Computing,* 16/2: 32-4.

Ung, D., and Cifuentes, C. (1997), 'SRL - A Simple Retargetable Loader.' *Proceedings of the Australian Software Engineering Conference* (to be published).

United States: National Bureau of Standards (1981), *Magnetic Tape Labels and File Structure for Information Interchange: Category, Software Standard, Subcategory, Operating Procedures* (Virginia).

Univeristy of Miami, (1996), ‘The University of Miami learns the importance of an enterprisewide plan in the wake of Hurricane Andrew’, *I/S Analyzer*, 35: 7-11.

Van Bogart, J.W.C. (1996), *Media Stability Studies. NML Final Report,* (Task 5.1.1 & 5.1.2 Media Stability -Optical and Tape).

Van Bogart, J.W.C. (1995), ‘Recovering Data in the Wake of Hurricane Andrew’, *Newsletter of the National Media Laboratory*, 5/2: 1,8.

Weick, B.L., and Bhushan, B. (1997), ‘The Relationship between Dynamic Mechanical Behavior Transverse Curvature, and Wear of Magnetic Tapes’, *Wear. An International Journal on the Science and Technology of Friction, Lubrication and Wear,* 202/1: 17.

Weick, B.L., and Bhushan, B. (1996), ‘Characterization of Magnetic Tapes and Substrates’, *IEEE Transactions on Magnetics,* 32/4.2: 3319.

Weick, B.L., and Bhushan, B. (1995), ‘Shrinkage and Viscoelastic Behavior of Alternative Substrates for Magnetic Tapes’, *IEEE Transactions on Magnetics,* 31/6.1: 2937.

Wettengel, M. (1998), ‘German Unification and Electronic Records, The example of the ‘kaderdatenspeicher’’, in Higgs, E. (ed), *History and Electronic Artefacts* (Oxford).

‘When Disaster Strikes’, *Document Manager,* 31-33, (1996).

Wilson, W.E. (1983), ‘Unix to CP/M - Floppy Disk File Conversion’, *Dr Dobbs Journal of Software Tools,* 8/10: 20.

Xie, Y., and Bhushan, B. (1997), ‘Fundamental Wear Studies with Magnetic Particles and Head Cleaning Agents Used in Magnetic Tapes’, *Wear. An International Journal on the Science and Technology of Friction, Lubrication and Wear,* 202/1: 3.

Xu, J., Kato, K., and Nishida, T. (1997), ‘The effect of temperature and humidity on the friction and wear of magnetic tape’, *Wear: An International Journal on the Science and Technology of Friction, Lubrication and Wear,* 203-204, 642-647.

Yada, H., Yamakoshi, T., Yamamoto, N., Erkocevic, M., and Hayashi, N. (1993), ‘External Clocking PRML Magnetic Recording Channel for Discrete Track Media’, *IEICE Transactions on Fundamentals of Electronics,* E76-A/7.

Webography

Abidi, A.A., and Pai, K.D. “CMOS Low-Power Front End ICs for Magnetic Storage.” UCLA Distributed MicroSystems Research Group: Student Research. http://www.janet.ucla.edu/stdnt.rsrch/stdnt.summs/ppai.html Accessed: 7/18/97 12:12 PM.

ADIC, “ADIC Product Line.” 1997. http://www.adic.com/Products/Tape_Storage_Libraries.Html Accessed: 7/3/97 10:11 AM.

Allison, J. “Towards the 50th Anniversary of the Manchester Mark 1 Computer.” 25 June 1996. http://www.cs.man.ac.uk/mark1/index.html Accessed: 6/14/97 6:01.

American Computer Museum, “American Computer Museum.” AMC. http://www.compustory.com/index.htm Accessed: 6/14/97 6:50 PM.

Ampex, “Ampex Homepage.” Ampex Corporation, 16 July 1997. http://www.ampex.com/index.html

Anacomp Magnetics, “Anacomp Magnetics.” http://www.anacomp.com/page3-3.html Accessed: 9/10/97 14:51:20.

Analog Devices, “Hard-Disk Drive PRML Read-Channel Optimized for Magneto resistive heads, Processor is First in a Family [ADRS120].” Analog Devices Inc, 1997. http://www.analog.com/publications/press/products/ADRS120_090695.html Accessed: 7/18/97 12:04 PM.

Apple Macintosh, “Macintosh Application Environment 3.0, White Paper.” Apple Computer Inc. 3 February 1997. http://www.mae.apple.com/technical/3.0/White_Paper3.html Accessed: 7/8/97 11:05 AM.

Archaic Ruins, “Archaic Ruins, Emulation File Archives.” http://archaic-ruins.parodius.com/ Accessed: 7/15/97 9:10 AM.

Archelon Inc. “User Retargetable Development Tools II.” Archelon Inc, 5/21/97. http://www.archelon.com/retarg.html Accessed: 7/8/97 11:29 AM, 7/24/97 3:19 PM.

ARDI, “ARDI Executor.” ARDI, http://www.ardi.com/ Accessed: 7/23/97 3:30 PM.

Arnold, R.L. “Hurricane Andrew. The Human Side of Hurricane Recovery.” Disaster Recovery Journal. 16 July 1997. http://www.drj.com/special/andrew.html Accessed: 7/25/97 11:07 AM.

Arnold, R.L. “1996 Mainframe Software Survey.” Disaster Recovery Journal. Volume 9, Issue 4, Fall 1996. http://www.drj.com/surveys/96Mainframe/96main.html Accessed: 7/25/97 2:18 PM.

Arnold, R.L. “Underground Flood Hits Chicago’s Loop, Shutting Down Businesses for Weeks.” Disaster Recovery Journal. 16 July 1997. http://www.drj.com/special/chicago.html Accessed: 7/25/97 11:01 AM.

Arrow Computer Systems Ltd, “Rewriteable/WORM MagnetoOptical Disk Drives.” ACS Ltd. http://www.arro.co.uk/magopt.htm Accessed: 7/15/97 10:14 AM.

Ashiem, D. “The Wine Project.” http://www.linpro.no/wine/ Accessed: 6/14/97 10:47 AM, 7/11/97 2:56 PM.

Ashiem, D. "The Wine Project, Developers Resources." http://www.linpro.no/wine/development/ Accessed: 7/11/97 2:56 PM.

Ashton, G., Ensminger, R., Van Bogart, J., and Vos, M. "Heat and Moisture Diffusion in Magnetic Tape Packs." Paper in IEEE Transactions on Magnetics, Vol 30, No.2, March 1994. National Media Library, National Technological Alliance. http://www.nml.org/Publications/Te…eports/Modeling/TapePackDiffusion/ Accessed: 7/7/97 9:42 AM.

Audiolab, "Degausser Overview." 17 June 1997. http://www.audiolabelectronics.com/Deg-ovr.htm Accessed: 7/3/97 10:25 AM.

AVA Instrumentation Inc. "Floppy Disc Alignment Tutorial." AVA Instrumentation Inc. 17 February 1997. http://www.aimnet.com/~avasales/tutorial.html Accessed: 7/11/97 10:20 AM.

Aviation Industry CBT Committee, "AICC Guidelines and Recommendations, Digital Audio." AICC 1997. http://www.aicc.org/agr003.htm Accessed: 7/15/97 3:56 PM.

Bachman, R. "Video Preservation: Glossary of Terms." Walker Art Center Archives, Bay Area Video Coalition. 1996. http://palimpsest.stanford.edu/byorg/bavc/bavcterm.html Accessed: 7/7/97 9:29 AM.

Bachner, M.B., Craven, J.A., Enders, T.M., Kaiser, D.R., Sillick, D.J. "Video Image Recovery from Damaged 8mm Recorders." NML Technical Report M1-0003 May 1994. http://www.nta.org/Publications/Tec…tionsSupport/8mmVideoImageRecov Accessed: 6/15/97 12:25 PM.

Bahl, P., Gauthier, P.S. and Ulichney R.A. "Software-only Compression, Rendering, and Playback of Digital Video." http://www.digital.com/info/DTJK04/DTJK04SC.TXT Accessed 7/23/97 2:32 PM.

Billquist, J., Muller, D.D., Sieving, A.R., and Smith, R. "The PDP-11 FAQ." http://www.village.org/pdp11/faq.html Accessed: 6/14/97 5:53.

Boeing, "777 Computing Design Facts." The Boeing Company, 1997. http://www.boeing.com/commercial/777family/Boe777Comp.html Accessed: 6/22/97 04:59.

Brader, M. "A Chronology of Digital Computing Machines (to 1952)." SoftQuad Inc. http://freeflight.com/fms/comp/misc/Ancient.txt Accessed: 7/8/97 12:05 PM.

Broukhis, L.A. "BESM-6 Emulator News." 1997. http://www.mailcom.com/besm6/emulnews.shtml Accessed: 6/14/97 7:30 AM.

Carlson,T. "Obsolete Computer Museum." Obsolete Computer Museum, http://www.ncsc.dni.us/fun/user/tcc/cmuseum/cmuseum.htm Accessed: 6/14/97 7:12 PM.

CCS "Archive Material." Computer Conservation Society. ftp://ftp.cs.man.ac.uk/pub/CCS-Archive/public_html/ccs_arch.htm Accessed: 6/14/97 6:21.

CCS "Computer Conservation Society." Computer Conservation Society. ftp://ftp.cs.man.ac.uk/pub/CCS-Archive/public_html/ccs_info.htm Accessed: 6/14/97 6:19.

CCS "Ferranti Pegasus Working Parties." Computer Conservation Society. ftp://ftp.cs.man.ac.uk/pub/CCS-Archive/public_html/pegasus/peghome.htm Accessed: 6/14/97 6:17.

CCS "SSEM Photo Gallery." Computer Conservation Society. ftp://ftp.cs.man.ac.uk/pub/CCS-Archive/public_html/ssem/ssemgall Accessed: 6/14/97 6:21.

CCS "Working Parties." Computer Conservation Society. ftp://ftp.cs.man.ac.uk/pub/CCS-Archive/public_html/ccs_proj.htm Accessed: 6/14/97 6:19.

The CD-Info Company, "Compact Disc Terminology." The CD- Information Center, The CD Information Company. 27 January 1997. http://www.cd-info.com/CDIC/Technology/Terminology.html Accessed: 7/4/97 9:59 AM.

CDSlab "Publications, Online Publications." Communications and Data Storage Lab, 12 June 1997. http://www.ee.umn.edu/groups/cds/papers.html Accessed: 7/18/97 4:53 PM.

CHAC, "History Pages." CHAC. http://www.chac.org/chac/chhistpg.html 9/23/97 Accessed :6/14/97 7:18 PM.

Chernoff, A., Kirk, M.B., Marks, M.P., Robinson, S.G., and Sites, R.L. "Alpha Migration Tools, Binary Translation." Digital, Digital Technical Journal Vol 4. No. 4. Special Issue 1992. http://www.digital.com/info/semiconductor/amt/dtj/dtj_1.html Accessed: 7/8/97 2:49 PM.

Chesters,D. "Computer Tapes." NASA, 14 January 1997. http://climate.gsfc.nasa.gov/~chesters/text/computer.tapes.html Accessed: 6/15/97 12:13 PM.

Charles Babbage Institute. "Charles Babbage Institute." Center for the History of Computing, University of Minnesota. http://www.cbi.umn.edu/ Accessed: 9/1/97 12:11.

Charles Babbage Institute. "Museums with Significant Holdings of Computer Hardware." Center for the History of Computing, University of Minnesota. http://www.cbi.umn.edu/museums.htm Accessed: 9/1/97 12:10.

Chris, "Emulators (1)." August 1997. http://members.aol.com/chrissalo/emu1.htm Accessed: 7/15/97 9:13 AM.

Cifuentes, C. "The dcc Decompiler." School of Information Technology, University of Queensland. 21 February 1997. http://www.it.uq.edu.au/groups/csm/dcc.html Accessed: 7/8/97 11:31 AM.

Cifuentes, C. "Honours Projects offered by Cristina Cifuentes." School of Information Technology, University of Queensland. 31 January 1997. http://www.it.uq.edu.au/~cristina/honours.html Accessed: 7/8/97 11:28 AM.

Cifuentes, C. "Cristina Cifuentes – Publication List." 16 July 1997. http://www.cs.uq.edu.au/~cristina/pubs.html Accessed: 8/7/97 10:12.

Cifuentes, C., and Ramsey, R. "A Retargetable Binary Translator." Department of Computer Science, The University of Queensland, 5 February 1997. http://www.cs.uq.edu.au/groups/csm/bintrans.html Accessed: 6/14/97 10:38.

The Computer Museum, "Collection Contents." The Computer Museum Network. 1996. http://www.tcm.org/history/collect-con.html Accessed: 6/14/97 6:42 PM.

The Computer Museum, "Visiting the Computer Museum in Boston." The Computer Museum Network. 1996. http://www.net.org/info/visiting/visiting-tcm.html Accessed: 9/1/97 12:32 PM.

The Computer Museum of America. "Coleman College." The Computer Museum of America. June 1995. Http://www.computer-museum.org/about_cma.html Accessed: 9/1/97 15:48.

Cook, N. “Code Generation for Heterogeneous Information Processing Systems.” CHIPS-9138, August 1994, ESPIRIT. http://cabernet.espirit.ec.org/esp-syn/text/9138.html Accessed: 7/24/97 3:36 PM.

Cornell University. “HPSS Data Recovery.” http://www.tc.cornell.edu/UserDoc/…dminGuide/AG-158.html#Heading158-0 Accessed: 7/11/97 10:11 AM.

Cornell University. “Storage Policy Considerations.” http://www.tc.cornell.edu/UserDoc/HPSS/Bookshelf/AdminGuide/AG-20.html Accessed: 7/11/97 10:11 AM.

Creative Digital Research, “HyCD Technology Now Available on Teac CD-R 50S.” Pr Newswire, Computer News Daily, June 10 1997. http://nytsyn.com:80/IMDS%7CCND%7Cr…-ONTRACK-VALTRON%7CData+Recovery% Accessed: 6/14/97 5:05.

CRHC “The Center for Reliable and High Performance Computing.” CRHC. http://www.crhc.uiuc.edu/index.html Accessed: 7/23/97 3:24 PM.

Cygnus Solutions, “The GNU-Win32 Project Page.” http://www.cygnus.com/misc/gnu-win32/ Accessed: 7/8/97 10:44 AM.

Data General, “Apple II (1977).” Data General. 1997. http://www.dg.com/about/html/apple_ii.html Accessed: 6/14/97 11:36 AM.

Data General, “Cray-1 (1976).” Data General. 1997. http://www.dg.com/about/html/cray-1.html Accessed: 6/14/97 11:43 AM.

Data General, “Data General NOVA (1969).” Data General. 1997. http://www.dg.com/about/html/data_general-nova.html Accessed: 6/14/97 11:36 AM.

Data General, “Digital PDP-8 (1965).” Data General. 1997. http://www.dg.com/about/html/digital_pdp-8.html Accessed: 6/14/97 11:40 AM.

Data General, “Digital VAX 11/780 (1978).” Data General. 1997. http://www.dg.com/about/html/digital_vax_11-780.html Accessed: 6/14/97 11:43 AM.

Data General, “IBM 360 (1964).” Data General. 1997. http://www.dg.com/about/html/ibm_360.html Accessed: 6/14/97 11:45 AM.

Data General, “IBM 1402 (1960).” Data General. 1997. http://www.dg.com/about/html/ibm_1402.html Accessed: 6/14/97 11:36 AM.

Data General, “Xerox Alto (1973).” Data General. 1997. http://www.dg.com/about/html/xerox_alto.html Accessed: 6/14/97 11:36 AM.

Data General, “Intel Microprocessor Evolution.” Data General. http://www.dg.com/about/html/intel_evolution.html Accessed: 6/14/97 11:45 AM.

Data Recovery Labs, “Hard Drive Basics, Section 1, History and Overview of PC Hard Drive Subsystems.”
Data Recovery Labs, Data Recovery Services Inc, 1996. http://www.datarec.com/hdtech1.html Accessed: 8/4/97 15:33.

Data Recovery Labs, “Hard Drive Basics, Section 2, Drives and Controllers.”
Data Recovery Labs, Data Recovery Services Inc, 1996. http://www.datarec.com/hdtech2.html Accessed: 8/4/97 15:32.

DAT Technologies Inc. “DAT Technologies Homepage.” 1996. http://www.dattech.com/ Accessed: 7/3/97 10:13 AM.

Dawson & Master, Watson and Underwood. “Three Views of Storage.” http://www.as400.ibm.com/as400mag/three.htm Accessed: 7/18/97 5:16 PM.

Diamonds Project. “Diamonds…Software Migration.” University of Zurich. 26 July 1995. http://www.ifi.unizh.ch/groups/richter/projects/diamonds2.html Accessed: 7/23/97 2:39 PM.

Digital, “DECmigrate Version 1.1 for OpenVMS AXP Systems.” Digital. ftp://ftp.digital.com/pub/Digital/info/SPD/39-44-XX Accessed: 7/8/97 3:28 PM.

Digital, “Digital Networker Save and Restore.” Digital, 1997. http://www.digital.com/info/LI018KSC.TXT Accessed: 7/23/97 2:37 PM.

Digital, “What is Binary Translation?” Digital, 18 October 1995. http://www.uruck.org/~erich/emu/gorton.txt Accessed: 7/11/97 3:26 PM.

Digital Equipment Corporation. “DECmigrate Version 1.2 for DEC OSF/1 AXP Systems SPD.” 1994. ftp://ftp.digital.com/pub/Digital/info/SPD/39-45-XX.txt Accessed: 7/8/97 3:30 PM.

Digital Semiconductor, “Binary Translation and Software Emulation.” Digital. 12 February 1997. http://www.digital.com/info/semiconductor/amt/techno/index.html Accessed: 7/8/97 3:23 PM.

Digital Semiconductor, “DECmigrate.” Digital, 3 December 1996. http://www.digital.com/info/semiconductor/amt/vestmx/index.html Accessed: 7/8/97 3:25 PM.

Disaster Recovery Journal. “Disaster Recovery Services Survey.” Volume 10, Issue 2. Spring 1997. http://www.drj.com/surveys/otherservices/other97.html Accessed: 7/25/97 2:19 PM.

Disk/Trend, “Disk Drive Array Report.” October 1997. http://www.disktrend.com/arryrep7.htm Accessed 7/15/97 9:32 AM.

Disk/Trend, “1997 Optical Disk Drive Report.” July 1997. http://www.disktrend.com/optrep7.htm Accessed 7/15/97 9:32 AM.

Disk/Trend, “1997 Rigid Disk Drive Report.” May 1997. http://www.disktrend.com/rigrep7.htm Accessed 7/15/97 9:32 AM.

Disk/Trend, “1997 Removable Data Storage Report.” August 1997. http://www.disktrend.com/remrep7.htm Accessed 7/15/97 9:32 AM.

DTC Data Technology. “DTC IDE Controllers.” DTC Data Technology. http://www.datatechnology.com/products/ide.htm Accessed: 8/26/97 15:16:13.

DTC Data Technology. “DTC SCSI Controllers.” DTC Data Technology. http://www.datatechnology.com/products/scsi.htm Accessed: 8/26/97 15:16:13.

Eilers, D.A., “Audio Magnetic Tape Preservation and Restoration.” Paper presented at Audio Engineering Society Convention Workshop, Vienna, 26 March, 1992. Paper presented at Association of Recorded Sound Collections, International Federation of Television Archives, International Association of Sound Archives September 17, 1995. Arlington, VA. http://www.nta.org/MediaStability/…ing/AudioMagneticTapePreservation/

Electronics Reference. “The Cassette.” Electronics Reference Audio Technology Handbook. http://www/magnavox.com/electreference/basicaudiotech/cassette.html Accessed: 6/14/97 11:59 AM.

Electronics Reference. “The Compact Disc.” Electronics Reference Audio Technology Handbook. http://www/magnavox.com/electreference/basicaudiotech/compactdisc.htm Accessed: 6/14/97 11:59 AM.

Electronics Research Group, “ Systems, Simulation and Software. Overview.” ERG, http://www.erg.abdn.ac.uk/public_html/research/sss/index.html Accessed: 7/10/97 2:38 PM.

Emmarc Ltd. “Emmarc Ltd Homepage.” Emmarc Ltd 1997. http://ourworld.compuserve.com/homepages/emm Accessed: 7/9/97 10:45.

Exabyte, “White Paper- half High 8mm Drives and Head Wear.” Exabyte, Strategic Research Corporation, March 1995. http://www.sresearch.com/search/105206.html Accessed: 6/15/97 12:39 PM.

Excalibur, “Excalibur Data Recovery Inc.” EDR. 5 January, 1997. http://www.excaliburdr.com/ Accessed: 6/9/97 10:13.

Excalibur, “Excalibur: Disc Pack and Magnetic Tape Product Line.” EDR. 5 January, 1997. http://www.excaliburdr.com/exprodct.htm Accessed: 6/9/97 10:12.

Excalibur, “Excalibur: Disc Pack Inspection and Cleaning Service.” EDR. 5 January, 1997. http://www.excaliburdr.com/exdiscjt.htm Accessed: 6/9/97 10:12.

Excalibur, “Excalibur’s Two-Tier recovery Process.” EDR. 5 January, 1997. http://www.excaliburdr.com/exc2tjt.htm Accessed: 6/9/97 10:12.

Excalibur, “Excalibur: Our History.” EDR. 5 January, 1997. http://www.excaliburdr.com/exchisjt.htm Accessed: 6/9/97 10:12.

FPC, “Welcome to FPC Inc.” FPC, Eastman Kodak Company, http://www.kodak.com/aboutKodak/bu/mptvi/fpc/protek/aboutFPC.shtml Accessed: 8/8/97 11:58.

Fujitsu, “General Notes on Hard Disk Head Design.” Fujitsu Europe Limited, 1997. http://www.fujitsu-europe.com/t_head_design.htm Accessed: 8/4/97 15:39.

Gerfelder,N. and Pipke, K. “Report of the Task Force on Digital Image Architecture.” SMPTE Task Force Report, SMPTE Publications, Society of Motion Picture and television Engineers, September 1993. http://icib.igd.fhg.de/icib/tv/org/smpte/s17.42/dia-fr.html Accessed: 7/15/97 4:39 PM.

Goldston, J.K. “A Guide to Understanding Data Remanence in Automated Information Systems.” National Computer Security Center, Department of Defense. September, 1991. http://www.ovnet.com/~dckinder/documents/darkgreen.htm Accessed: 102:41 PM.

Guardian dr Ltd. “Guardian dr Ltd.” http://www.guardiandr.co.uk/Home.htm 7/9/97 9:43 AM.

Guzik Technical Enterprises, “Guzik Technical Enterprises Announces a New Book. Characterization of Magnetic Recording Systems: A Practical Approach written by Alexander Taratorin.” List of book contents. GTI. September 16 1997. http://www.guzik.com/BOOK.HTM Accessed: 7/18/97 11:53 PM.

Guzik Technical Enterprises, “PRML and Guzik 1601/1632 PRML System 1 Day Training Course.” http://www.guzikguys.com/prml_training.htm Accessed: 7/18/97 5:01 PM.

Harada, M., and Imai, T. “Different PC Need Range of exchangeable Media. Table.” NEA Special Report, October 1996, http://www.nikkeibp.com/nea/october/sr_tab1.html Accessed: 7/15/97 9:54 AM.

Harada, M., and Imai, T. “FDD vs CD-ROM Drives. Diagram.” NEA Special Report, October 1996, http://www.nikkeibp.com/nea/october/sr_fig4.html Accessed: 7/15/97 9:53 AM.

Harada, M., and Imai, T. “High Density FDD, Optical Disk Drives as Standard Equipment in PC. Diagram.” NEA Special Report, October 1996, http://www.nikkeibp.com/nea/october/sr_fig2.html Accessed: 7/15/97 9:53 AM.

Harada, M., and Imai, T. “Market Pickup 1995. Diagram.” NEA Special Report, October 1996, http://www.nikkeibp.com/nea/october/sr_fig3.html Accessed: 7/15/97 9:53 AM.

Harada, M., and Imai, T. “OEM Prices of US$100 Expands Market. Diagram.” NEA Special Report, October 1996, http://www.nikkeibp.com/nea/october/sr_fig5.html Accessed: 7/15/97 9:53 AM.

Harada, M., and Imai, T. “Over 100MB Removable Drives Fight It Out: Magnetic vs Optical.” NEA Special Report, October 1996. http://www.nikkeibp.com/nea/october/octsr.html Accessed: 7/15/97 9:49 AM.

Harada, M., and Imai, T. “Standard Disks Needed for Storing Imagery and Graphics. Diagram.” NEA Special Report, October 1996, http://www.nikkeibp.com/nea/october/sr_fig1.html Accessed: 7/15/97 9:55 AM.

Hardman, D. “Translating with IBM’s Translation Manager Software.” Brigham Young University Translation Research Group, October 1995. http://humanities.byu.edu/trg/tm2.htm Accessed: 7/23/97 12:28 PM.

Harada, M., and Imai, T. “Using Appendable Disks as Rewritable Disks. Diagram.” NEA Special Report, October 1996, http://www.nikkeibp.com/nea/october/sr_fig6.html Accessed: 7/15/97 9:55 AM.

Harvard University and the University of Washington, “Instrumentation and Optimization of WIN32/Intel Executables.” Etch program, University of Washington. http://www.cs.washington.edu/homes/bershad/etch/ Accessed: 7/8/97 10:42 AM.

Harvey, R. “From Digital Artefact to Digital Object.” Paper at the 2nd National Preservation Office Conference: Multimedia Preservation- Capturing the Rainbow. Brisbane 28-30 November 1995. National Library of Australia. http://www.nla.gov.au/3/npo/conf/npo95rh.html#roth Accessed: 7/7/97 9:52 AM.

Helsinki University of Technology Digital Systems Laboratory. “ReFlEx 1.0, A Demonstration Prototype of a Code Generation Tool.” 27 November 1997. http://saturn.hut.fi/pub/reflex/ReFlEx-1 Accessed: 7/24/97 3:33 PM.

Hewlett-Packard, “Business and Technical Computing Directory.” Hewlett-Packard Company, 1997. http://hpcc920.external.hp.com/computing/sitemap.html Accessed 7/23/97 3:56 PM.

Hewlett-Packard Journal, Search Engine. Hewlett-Packard Company, 1997. http://www.hp.com:80/hpj/journal.html Accessed 7/11/97 2:52 AM.

Heydon, K. “Computers.” 15 December 1996. http://staff.motiv.co.uk/~kevan/old_collection/items_computers.html Accessed: 9/1/97 16:11.

Highpoint Technologies Learning Center, “FAQs About FATFS.” Highpoint Technologies, http://www.hptech.com/education.html Accessed: 7/25/97 10:29 AM.

Holography and Optical Data Storage Group Publications. "Recent Publications (from INSPEC)." http://aa.stanford.edu/~holovis/pub.html Accessed: 7/7/97 9:37 AM.

Hodgson, R. and Wright, D. "Semantics-directed Programming Language Translation." http://www.eecs.utas.edu.au/Deptin…rch/groups/csrg/plsig/sdtrans.html Accessed 7/23/97 3:27 PM.

Huston, C.J.S, "Unisys History Newsletter. Univac in Pittsburgh 1953-1963." Unisys History Letter, Vol 1, No. 1, September 1992. http://www.cc.gatech.edu/gvu/peopl…Carpenter/folklore/sep92-v1n1.html Accessed: 7/8/97 2:21 PM.

IBM "3.5-Inch Ultrastar2 10.8 GB High Capacity Disk Drive." IBM Corporation, 3/10/96. http://www1.ibmlink.ibm.com/HTML/SPEC/goem7058.html Accessed: 7/18/97 4:51 PM.

IBM "3490 Magnetic Tape Subsystem Family." IBM Corporation, 4/02/95. http://www2.ibmlink.ibm.com/HTML/SPEC/g2212426.html Accessed: 7/3/97 11:36 AM.

IBM "IBM 711 Card Reader, Gif Image." http://www.bs2000.com/talos/711.gif Accessed: 6/14/97 11:11 AM.

IBM Global Services, "IBM Business Recovery Services – Service Offerings." IBM Corporation. http://www.brs.ibm.com/brsprdsv.html Accessed: 7/25/97 2:36 PM.

IBM Research, "Almaden Research Center, Storage Systems and Technology." IBM Corporation. http://www.almaden.ibm.com/sst/ Accessed: 8/8/97 11:29 AM.

IBM Research, "Architecture for Disk Drives." IBM Corporation, 10 May 1996. http://www.almaden.ibm.com:80/sst/diskarch/index.htm Accessed: 7/8/97 10:23 AM.

IBM Research, "Error-Correction Codes." IBM Corporation, 1996. http://www.almaden.ibm.com/sst/signalp/error.html Accessed: 7/18/97 12:14 AM.

IBM Research, "Explore the Ever Shrinking World of Storage." IBM Corporation, http://www.research.ibm.com/research/storage.html#density Accessed: 7/8/97 10:27AM.

IBM Research, "IBM Research Homepage." IBM Corporation, http://www.research.ibm.com/research/intro.html Accessed: 7/17/97 10:51AM.

IBM Research, "IBM Scientists Demonstrate Multilevel Optical Disks." IBM Corporation, May 12, 1994. http://www.almaden.ibm.com/vis/models/multi.html Accessed: 7/15/97.

IBM Research, "Magstar MP Fast Access Linear Tape Cartridge." IBM Corporation, September 1996. http://www1.ibmlink.ibm.com/HTML/SPEC/g2256689.html Accessed: 7/3/97

IBM Research, "Recording Heads." IBM Corporation,1 July 1997. http://www.almaden.ibm.com:80/sst/rechead.html Accessed: 7/8/97 10:25 AM.

IBM Research, "Research in Signal Processing and Electronics for Hard Disk Drives." IBM Corporation, 29 August 1996. http://www.almaden.ibm.com/sst/signalp.html Accessed: 7/18/97 12:13 PM.

IBM Research, "Thin-film Disks." IBM Corporation, 3 September 1996. http://www.almaden.ibm.com/sst/tfdisk.html Accessed: 7/8/97 10:25 AM.

IBM Storage, "3490 Magnetic Tape Subsystem Enhanced Capability Models C10/C11/C22." IBM Corporation. http://www.almaden.ibm.com/storage/hardsoft/tape/3490c.htm Accessed: 7/3/97 12:04 AM.

IBM Systems Journal, "Table of Contents and Abstracts." IBM Corporation. http://www.almaden.ibm.com/journal/sjt.html Accessed: 8/8/97 10:56 AM.

ID Technologies, "Series 3800 Magnetic Stripe Readers." 31 May 1997. http://www.idt-net.com/3800.htm Accessed: 7/15/97 4:08 PM.

Impediment, "Disk Drive Geometry Information." Impediment,1996. http://www.impediment.com/disk_parameters.html#0662-s12 Accessed: 7/11/97 10:28 AM.

Impediment, "Hewlett-Packard Disk and Tape Technical Information." Impediment, 1996. http://www.impediment.com/hp/hp_technical.html Accessed 7/11/97 10:27 AM.

Impediment, "Seagate Disk Data." Impediment, 1996. http://www.impediment.com/seagate/seagate_disk_data.html Accessed 7/11/97 10:27 AM.

Insignia Solutions, "Welcome to Insignia Solutions." Insignia Solutions Inc, 8 July 1997. http://www.insignia.com/ Accessed: 7/8/97 11:17 AM.

ISSCC, "Disk Drive Electronics." ISSCC Advanced Program, SSCS. http://www.sscs.org/isscc/1996/ap/tp4.htm Accessed: 7/18/97 4:57 PM.

Jaap, M. "Emulators." 2 June 1997. http://www.hh.schule.de/hhs/computer/english/emulator.htm Accessed: 6/14/97 7:19 AM.

Jaap, M. "Emulators. for PC DOS/Win." 2 June 1997. http://www.hh.schule.de/hhs/computer/english/emuepc.htm Accessed: 6/14/97 7:20 AM.

Johnston, R.L. and Julik, A.M. "Magnetic Disk Drives Evaluation (Amended)." NML Test Report TR0032A, National Technology Alliance, August 1996. http://www.nml.org/Publications/Te…EvalsAndSystemTools/MDDEvaluation/ Accessed: 7/17/97 4:49 PM.

Jones, D.W. "Emulated Punched Cards." University of Iowa Department of Computer Science. http://www.cs.uiowa.edu/~jones/cards/format.html Accessed: 6/14/97 11:29 AM.

Jones, D.W. "Making New Battery packs for the HP-35 Calculator." University of Iowa Department of Computer Science. http://www.cs.uiowa.edu/~jones/hp/batt.html Accessed: 6/14/97 6:29.

King, J. and Post, R. "Magnetic Tape Continues Vital Role at NSSDC." NSSDC, NASA. Volume 11, Number 3, September 1995. http://nssdc.gsfc.nasa.gov/nssdc_news/sept95/02_j_king_0995.html Accessed: 7/3/97 12:32 PM.

Kirk, M.B., Marks, M.P. and Robinson, S.G. "Binary Translation." Digital Technical Journal Vol 4. No.4. Special Issue 1992. http://www.uruk.org/~erich/emu/Binary_Translation_01apr1993DTJ809sc.txt Accessed 7/8/97 11:35 AM.

Kodak, "CD Permanence in Perspective." Eastman Kodak Company, 30 April 1997. http://www.kodak.com/daiHome/techInfo/permanence9.shtml Accessed: 7/4/97 9:44 AM.

Kodak, "Digital Scans Bring Smithsonian Images Closer to American Public." Eastman Kodak Company, 30 April 1997. http://kodak.com/aboutKodak/b…useumArchivePCD/smithsonian.shtml Accessed: 8/8/97 11:55 AM.

Kodak, "Do Not Fold, Spindle, or Mutilate: Safe Handling of CDs" Eastman Kodak Company, 30 April 1997. http://www.kodak.com/daiHome/techInfo/permanence7.shtml Accessed: 7/4/97 9:41 AM.

Kodak, "Kodak Unveils 25 Gigabyte Optical Drive." Eastman Kodak Company, 30 April 1997. http://www.kodak.com/aboutKodak/corpInfo/pressReleases/pr960401-07.shtml Accessed: 7/15/97.

Kodak, "The Nature of CD-ROM Discs." Eastman Kodak Company, 30 April 1997. http://www.kodak.com:80/daiHome/techInfo/permanence3.shtml Accessed: 7/4/97 9:45 AM.

Kodak, "The Nature of Writable CDs." Eastman Kodak Company, 30 April 1997. http://www.kodak.com/daiHome/techInfo/permanence6.shtml Accessed: 7/4/97 9:40 AM.

Kodak, "Permanence, Care, and Handling of CDs, References." Eastman Kodak Company, 1995. http://www.kodak.com:80/daiHome/techInfo/permanence10.shtml Accessed: 7/4/97 9:45 AM.

Kodak, "Permanence, Care, and Handling of CDs, Introduction." Eastman Kodak Company, 1995. http://www.kodak.com:80/daiHome/techInfo/permanence1.shtml Accessed: 7/4/97 9:34 AM.

Kodak, "Permanence of Kodak Photo CD and Writable CD Media with Infoguard Protection System." Eastman Kodak Company, June 1993. http://palimpsest.stanford.edu/byt…tronic-storage-media/kodakpho.html Accessed: 7/4/97 9:47 AM.

Kodak, "Readability, or When is a CD's Life Really Over?" Eastman Kodak Company, 30 April 1995. http://www.kodak.com:80/daiHome/techInfo/permanence4.shtml Accessed: 7/4/97 9:45 AM.

Kodak, "So, How Long Can CD's last?" Eastman Kodak Company, 30 April 1997. http://www.kodak.com:80/daiHome/techInfo/permanence5.shtml Accessed: 7/4/97 9:39 AM.

Kodak, "Storage Conditions for CDs" Eastman Kodak Company, 30 April 1997. http://www.kodak.com:80/daiHome/techInfo/permanence8.shtml Accessed: 7/4/97 9:43 AM.

Lindner, J. "Confessions of a Videotape Restorer or How Come These Tapes All Need to Be Cleaned Differently?" VidiPaxi, in AMIA Newsletter, 5 June 1997. http://palimpsest.stanford.edu/byauth/lindner1.html Accessed: 7/7/97 9:30 AM.

Lindner, J. "Magnetic Tape Deterioration: Tidal wave at Our Shores." 5 June 1997. Vidipax. in Video Magazine, February 1996. http://palimpsest.stanford.edu/byauth/lindner/tidal.html Accessed: 7/7/97 9:31 AM.

Lindner, J. "Setting Priorities for Videotape Recovery." VidiPax, National Technology Alliance. http://www.nta.org/Publications/NMLBits/September94/SeptemberArticle2/ Accessed: 7/7/97 9:47 AM.

Lindner, J. "Videotape Restoration – Where Do I Start?" Vidipax. 5 June 1997. http://palimpsest.stanford.edu/byauth/lindner/lindner2.html Accessed: 7/7/97 9:31 AM.

McCrady, E. "NARA Conference on Preserving Tapes and Disks, March 1996. Facts and Advice from the Speakers." Abbey Newsletter, Volume 20, Number 6, November 1996. http://palimpsest.stanford.edu/byorg/abbey/an/an20/an20-6/an20-614.html Accessed: 7/3/97 5:06 PM.

Madigan, S. "The College Papers, Magnetic Tape." Scott Madigan's Vidiot's Guide to the Galaxy. http://w3.one.net/~smadigan/vidiot/magnetic.htm Accessed: 7/3/97 12:15 PM.

Mailbase, "Engineering and Technology Lists." Mailbase. http://www.mailbase.ac.uk/category/H.html Accessed: 7/17/97 11:14 AM.

Mainstar, “ABARS: Solving Today’s Recovery Challenges.” From Disaster Recovery Journal. http://www.sisinfo.com/ABARSarticle.htm Accessed: 7/25/97 10:39 AM.

Mainstar, “ABARS Tip: Restoring data at D/R Sites Using Different Volsers.” From Systems Report, Mainstar Technical Newsletter. http://www.sisinfo.com/ABARStip1.htm Accessed: 7/25/97 10:36 AM.

Merz, J.P. “NML Storage Technology Assessment Final Report. Section 6:Rigid Disk Systems.” National Media Laboratory, National Technology Alliance, July 1994. http://www.nml.org/Publications/Te...nalReport1994/6_rigid_disk_syst.html Accessed: 7/4/97 10:10 AM.

Micropolis, “Drive Handling Instructions.” 28 February !997. http://www.microp.com/Drive_Handling.html Accessed: 6/14/97 2:04.

Microsoft Research, “Microsoft Research.” Microsoft Corporation, 1997. http://www.research.microsoft.com/home.htm Accessed: 7/17/97 10:49 AM.

Mini Disc “Mini Disc Frequently Asked Questions.” Mini Disc, http://www.connact.com/~eaw/minidisc/minidisc_faq.html Accessed: 9/10/97 16:31.

MINT, “Research.” The Center for Micromagnetics and Information Technologies (MINT) 1997. http://www.ee.umn.edu/groups/mint/research.html Accessed: 7/18/97 12:22 PM.

MoHPC “HP 9100A/B.” The Museum of HP Calculators. http://www.teleport.com/~dgh/hp9100.htm Accessed: 6/14/97 6:26.

MoHPC “HP 9100 Technology and Packaging.” The Museum of HP Calculators. http://www.teleport.com/~dgh/tech9100.htm Accessed: 6/14/97 6:26.

MoHPC “The Museum FAQ.” The Museum of HP Calculators. http://www.teleport.com/~dgh/faq.htm Accessed: 6/14/97 6:30.

Molitor, D. “Cleaning Methods for Helical Scan Recorders.” National Media Library, National Technological Alliance. http://www.nml.org/Publications/Te…OperationsSupport/CleaningMethods/ Accessed: 7/7/97 9:46 AM.

Mooney, J. “Developing Portable Software.” Proposed Textbook Outline. 1995. Department of Statistics and Computer Science, West Virginia University. http://www.cs.wvu.edu/~jdm/research/portability/book/outline.html Accessed: 7/24/97 3:07 PM.

Motorola, “Industry’s fastest PRML Read Channel IC.” Motorola Inc, 1997. http://motserv.indirect.com/home2/press/html/PR951204A.html Accessed: 7/18/97 5:04 PM.

Mountain Optech, Inc. “5.25” Optical Disk Drives Technical Specifications.” 1996. http://www.mt-optec.com/525specs.htm Accessed: 7/15/97 9:42 AM.

National Archives and Records Administration/ Long-Term Usability of Optical Media, “The National Archives and Records Administration and the Long-Term Usability of Optical Media for Federal Records: Three Critical Areas.” University of Stanford. http://palimpsest.stanford.edu/byt…ctronic-storage-media/critiss.html Accessed: 7/4/97 9:48 AM.

National Archives and Records Administration Technological Research Staff, “Development of a Testing Methodology to Predict Optical Disk Life Expectancy Values.” Summary of Report by Podio, F.L. NIST Special Publication. 27 January 1997. http://palimpsest.stanford.edu/byorg/nara/nitsum.html Accessed: 7/4/97 9:50 AM.

Nevola, J.E. “Hurricane Bertha. July 1996.” Disaster Recovery Journal. http://www.drj.com/articles/DRJezine/nevola.html Accessed: 8/4/97 12:09.

NTA, “About NTA.” National Technological Alliance. http://www.nml.org/AboutNTA/UsageRights Accessed: 7/7/97 2:50 PM.

NTA, “Recommended Storage Conditions for Magnetic Tape (1995).” National Technological Alliance. http://www.nml.org/MediaStability/...ndling/TapeStorageRecommendations/ Accessed: 7/7/97 2:50 PM.

NTA, “Questions and Answers.” National Media Library, National Technological Alliance. http://www.nta.org/MediaStability/QuestionsAndAnswers/#floppy_le Accessed: 7/11/97 9:33 AM.

Ontrack “Ontack Contact Information.” Ontrack, 1997. http://www.ontrack.com/London.html Accessed: 7/2/97 4:03 PM.

Ohrberg, M. “Project VAX .” Digital, 3 March 1995. http://www.medio.mh.se/projvax.html Accessed: 6/14/97 7:28 AM.

Peripheral Computer Solutions, “Tape Drive Sales and Service.” 1996. http://www.tapesales.com/ Accessed: 7/3/97 10:00 AM.

Platinum Technology, “White Paper, Enterprise-wide Backup and Recovery.” Platinum Technology Inc, 9 May 1997. http://www.platinum.com/products/entb_r.htm Accessed: 7/23/97 3:35 PM.

Polsson, K. “Chronology of Events in the History of Microcomputers. 1947-1970 The Early Years.” 16 January 1997. http://www.islandnet.com/~kpolsson/comphist.htm Accessed: 7/8/97 12:07 PM.

Polsson, K. “Chronology of Events in the History of Microcomputers. 1971-1976 The Birth of the Microcomputer.” 16 January 1997. http://www.islandnet.com/~kpolsson/comp1971.htm Accessed: 7/8/97 12:08 PM.

Polsson, K. “Chronology of Events in the History of Microcomputers. 1977-1980 Home Computers.” 16 January 1997. http://www.islandnet.com/~kpolsson/comp1977.htm Accessed: 7/8/97 12:09 PM.

Ptasienski, L.J. “NML Storage Technology Assessment Final Report. Section5: Movable Head Tape Systems Review.” National Media Laboratory, National Technology Alliance, July 1994. http://www.nml.org/Publications/Te...nalReport1994/5_movable_head_tape.html Accessed:7/4/97 10:09 AM.

Precision Research. “Precision Research: Client List.” Precision Research, Inc. http://www.netvisions.com/prco/170025.htm Accessed: 9/10/97 13:01:34.

Precision Research. “Designed by Precision Research: Other Technology Assignments.” Precision Research, Inc. http://www.netvisions.com/prco/170019.htm Accessed: 9/10/97 13:00:21.

QIC, “Reference Guide to QIC Tape Technology.” QIC 1997. http://www2.qic.org/html/qicgloss.html Accessed: 6/15/97 12:02.

Quantum, “General Description, Empire 1400/2100s Product Manual.” Quantum Corporation, 1997. http://www.quantum.com/products/manuals/empire+/chp2.html Accessed: 7/18/97 5:07 PM.

Quantum, “Technology Information Papers, Technology and Time-to Market: the Two Go Hand-in-Hand. Page 1. ” Quantum Corporation, 1997. http://www.quantum.com/products/whitepapers/techno1.html Accessed: 7/18/97 5:07 PM.

Quantum, “Technology Information Papers, Technology and Time-to Market: the Two Go Hand-in-Hand. Page 2. ” Quantum Corporation, 1997. http://www.quantum.com/products/whitepapers/techno2.html Accessed: 7/18/97 5:07 PM.

Ramsey, N. “Research Activities” http://www.cs.virginia.edu/~nr/activities.html Accessed: 7/8/97 11:32 AM, 7/24/97 3:01 PM.

The Ref™, “Controllers.” http://theref.c3d.rl.af.mil/controllers/mc_main.html Accessed: 6/14/97 1:58 PM.

The Ref™, “Hard Drives.” http://theref.c3d.rl.af.mil/hard_drives/mh_main.html Accessed: 6/14/97 1:58PM.

The Ref™, “The Ref™ Homepage.” 27 May 1997. http://theref.c3d.rl.af.mil/theref.html Accessed: 6/14/97 2:00 PM.

The Ref™, “Tech Talk ,Table of Contents.” http://theref.c3d.rl.af.mil/tech_talk_contents.html Accessed: 6/14/97 2:00 PM.

Roach, A. “Comp.Emulators.Misc Frequently Asked Questions.” 1997. http://www.why.net/home/adam/cem/toc.html Accessed: 7/16/97 12:24

Robenali, S. A., Sharnoft, D,M,. “Concurrent, Parallel and Simulation Languages.” Idiom Consulting, 1996. http://www.idiom.com/free-compilers/ECATEGORY/concurre-1.html Accessed: 7/8/97 11:39 AM.

Safetynet, “Safetynet PLC.” Safetynet PLC. http://www.safetynet.co.uk/index.htm 7/9/97 9:42 AM.

Sanyo-Verbatim, “Glossary.” Sanyo-Verbatim CD Company. http://www.sanyo-verbatim.com:80/glossary.html Accessed: 7/4/97 9:54 AM.

Sanyo-Verbatim, “Pit and Byte Guide.” Sanyo-Verbatim CD Company. http://www.sanyo-verbatim.com:80/pitbyte.html Accessed: 7/4/97 9:54 AM.

Schamber, L. “Optical Disk Formats: A Briefing. ERIC Digest.” May 1988. Eric Digest, University of Stanford. 27 January 1997. http://palimpsest.stanford.edu/byt…tronic-storage-media/ed303176.html Accessed 7/4/97 10:01 AM.

Schmidt, B. “UAE, the Ubiquitous Amiga Emulator.” http://www.schokola.de/~stepan/uae/uae.html Accessed: 7/8/97 3:59 PM.

Schwarz, T. “NML Storage Technology Assessment Final Report. Section 4:Linear Tape Systems Review.” National Media Laboratory, National Technology Alliance, July 1994. http://www.nml.org/Publications/Te...nalReport1994/4_linear_tape.html Accessed:7/4/97 10:09 AM.

Seagate Technology Inc, “Technology Papers.” 1997. http://www.seagate.com/support/papers.shtml Accessed: 7/3/97 10:30 AM.

Sony, “Sony Research and Development Labs.” Sony Electronics Inc, 1997. http://www.sel.sony.com/HR/about/bus/i.html Accessed: 7/17/97 10:53 AM.

Stanford University, “Embra, Overview.”. http://www-flash.stanford.edu/Embra/ Accessed: 7/23/97 12:35 PM

Step Engineering, “Metastep Plus.” http://www.stepeng.com/pages/metastep.htm Accessed: 7/8/97 11:37 AM.

Strategic Profile, “Demystifying Tape Performance.” Strategic Profile, Strategic Research Corporation, 1996. http://www.sresearch.com/search/105420 Accessed: 6/15/97 12:19.

Strategic Profile, “Demystifying Tape Reliability.” Strategic Profile, Strategic Research Corporation, 1996. http://www.sresearch.com/search/105435 Accessed: 6/15/97 12:19.

Sun Microsystems, “Wabi™ 2.2 Product Overview.” Solaris Products, Sun Microsystems. http://www.sun.com/software/Products/PC-Integration-products/index.html Accessed: 7/23/97 3:48 PM.

Syracuse University Library Preservation Dept. “Syracuse University Library Disaster Manual. Procedures for Recovering Audio and Sound Recording Materials.” 8/95. http://web.syr.edu/~libweb/aboutsul/depts/preserve/audio.htm Accessed: 7/7/97 10:01AM.

Tao Systems, “Elate’s Supported Processors.” May 1997. http://www.tao.co.uk/taointro/rangeof.htm Accessed: 7/8/97 11:55 AM.

Tao Systems, “Elate’s Translation .” May 1997. http://www.tao.co.uk/taointro/trandtal.htm Accessed: 7/8/97 11:55 AM.

Tao Systems, “Elate’s Translation for Optimisation.” May 1997. http://www.tao.co.uk/taointro/optimise.htm Accessed: 7/8/97 11:55 AM.

Tao Systems, “Elate’s Translation Process.” May 1997. http://www.tao.co.uk/taointro/translat.htm Accessed: 7/8/97 11:55 AM.

Tao Systems, “Elate’s VP2 Faster to Load than Native.” May 1997. http://www.tao.co.uk/taointro/vpcompct.htm Accessed: 7/8/97 11:55 AM.

Tao Systems, “Model for an Interpreted System.” May 1997. http://www.tao.co.uk/taointro/interprt.htm Accessed: 7/8/97 11:56 AM.

Taratorin’s A. “Introduction to PRML.” Chapter Nine from ‘Characterization of Magnetic Recording Systems: A Practical Approach.’ Guzik Technical Enterprises, 16 September 1996. http://www.guzik.com/Chapter9.htm Accessed: 7/18/97 11:55 AM.

Thompson, S.J. “NML Storage Technology Assessment Final Report. Section 9: Mass Storage Technologies.” National Media Laboratory, National Technology Alliance, July 1994. http://www.nml.org/Publications/Te…inalReport1994/9_mass-storage.html Accessed:7/4/97 10:14 AM.

The Tibbit Project. “Timing Insensitive Binary to Binary Translation.” Carnegie Mellon University and the University of Oregon. January 1997. http://www.cs.uoregon.edu/~cogswell/tibbit/ Accessed 7/24/97 3:03 PM.

Toomey, W. “PDP Unix Preservation Society Home Page.” PUPS. http://minnie.cs.adfa.oz.au/PU

Toray Inc, “Past, Present and Future of Optical Data Storage.” 1996. http://www.toray.com/html/dvd_migration.html Accessed: 7/15/97 10:07 AM.

University of Washington, “Shade.” http://www.cs.washington.edu/research/compiler/papers.d/shade.html Accessed: 7/8/97 11:18 AM, 7/23/97 3:30 PM.

University of Virginia, “Computer Museum.” Department of Computer Science, School of Engineering, University of Virginia. http://www.cs.virginia.edu/brochure/museum.html Accessed: 6/14/97 7:07 PM.

Van Bogart, J.W.C. “Magnetic Tape Storage. How Long Will Tape Last?” Presented at the NARA 11th Annual preservation Conference 14 March 1996. National Media Laboratory, National Technology Alliance. http://www.nta.org/Publications/Presentations/MagneticTapeStorage/nara_mag_tape_storage_3.html Accessed: 7/4/97 9:26 AM.

Van Bogart, J.W.C. “Magnetic Tape Storage. Introduction.” Presented at the NARA 11th Annual preservation Conference 14 March 1996. National Media Laboratory, National Technology Alliance. http://www.nta.org/Publications/Presentations/MagneticTapeStorage/nara_mag_tape_storage_1.html Accessed: 7/4/97 9:24 AM.

Van Bogart, J.W.C. “Magnetic Tape Storage. The Future of Tape.” Presented at the NARA 11th Annual preservation Conference 14 March 1996. National Media Laboratory, National Technology Alliance. http://www.nta.org/Publications/Presentations/MagneticTapeStorage/nara_mag_tape_storage_5.html Accessed: 7/4/97 9:24 AM.

Van Bogart, J.W.C. “Magnetic Tape Storage. What Can Be Done to Increase Longevity.” Presented at the NARA 11th Annual preservation Conference 14 March 1996. National Media Laboratory, National Technology Alliance. http://www.nta.org/Publications/Presentations/MagneticTapeStorage/nara_mag_tape_storage_4.html Accessed: 7/3/97 5:14 PM.

Van Bogart, J.W.C. “Magnetic Tape Storage. What Can Go Wrong with Magnetic Tape?” Presented at the NARA 11th Annual preservation Conference 14 March 1996. National Media Laboratory, National Technology Alliance. http://www.nta.org/Publications/Presentations/MagneticTapeStorage/nara_mag_tape_storage_2.html Accessed: 7/4/97 9:24 AM.

Van Bogart, J.W.C. “NML Storage Technology Assessment Final Report. Section 11: Archival Stability of Digital Storage Media.” National Media Laboratory, July 1994. National Technology Alliance. http://www.nml.org/Publications/Te…1Reort1994/11_arch_stability.html Accessed: 7/4/97 10:15 AM.

Van Bogart, J.W.C. “Recovery of Damaged Magnetic Tape and Optical Disc Media.” Paper presented at Emergency Preparedness and Disaster Recovery of Audio, Film, and Video Materials Library of Congress Symposium, 21 September 1995. http://www.nml.org/Publications/Presentations/DisasterRecov Accessed: 7/3/97 5:22.

VidiPax™, Inc. “The Last 40 Years.” 1996. http://www.panix.com/~vidipax/brochure.html 7/7/97 9:34 AM.

VidiPax™, Inc. “More Info, Formats Currently Handled by VidiPax.” http://www.panix.com/~vidipax/moreinfo.html Accessed: 7/7/97 9:35 AM.

Vigor, M. “Apple 2 Emulator.” 25 January 1995. http://www.ecnet.net/users/mumbv/pages/apple2.shtml Accessed: 7/8/97 4:07 PM.

VTC Inc, “Product Summary.” VTC Inc, 5/1/97. http://www.vtc.com/prod.html Accessed: 7/18/97 12:02 PM.

Wald, L.D. “NML Storage Technology Assessment Final Report. Section 7:Optical Disc Drives.” National Media Laboratory, National Technology Alliance, July 1994. http://www.nml.org/Publications/Te…inalReport1994/7_optical_disk.html Accessed:7/4/97 10:13 AM.

Wald, L.D. “NML Storage Technology Assessment Final Report. Section 8:Optical Tape and Cards.” National Media Laboratory, National Technology Alliance, July 1994. http://www.nml.org/Publications/Te…inalReport1994/8_optical_tape.html Accessed:7/4/97 10:14 AM.

Western Digital Corporation. “Hard Drive Products.” WDC,1997. http://www.wdc.com/products/ Accessed: &/25/97 10:11 AM.

Wheeler, J. “The Do’s and Don’ts of Videotape Care.” 5 June 1997. http://palimpsest.stanford.edu/byauth/wheeler/wheeler3.html Accessed: 7/7/97 9:33 AM.

Wheeler, J. “Unscientific American, Letter to Editor.” Letter to Editor of Scientific American, 30 January 1995. http://palimpsest.stanford.edu/byauth/wheeler/wheeler1.html Accessed: 7/7/97 9:50 AM.

Wheeler, J. “Videotape Preservation.” November 1994. http://palimpsest.stanford.edu/byauth/wheeler/wheeler2.html Accessed: 7/7/97 9:33AM.

Williams, B. “6809 Flex Emulators for Win95 and AmigaDOS 2.04+.” Black Belt Systems Inc. http://ww.blackbelt.com/blackbelt/flexem.html Accessed: 6/14/97 7:22 AM.

WRL, “WRL Papers on Binary-Code Modification.” http://www.research.digital.com/wrl/projects/om/wrlpapers.html Accessed: 7/23/97 3:43 PM.

Websites used

Site last visited on date listed.

Valtron Technologies - Billion Drive Story
http://www.valtron.com/billion/billion.html
04/09/97

FlashPix Home Page
http://www.kodak.com/daiHome/flashPix/flashPixHome.shtml
03/09/97

The Computer Conservation Society (UK)
ftp://ftp.cs.man.ac.uk/pub/CCS-Archive/public_html/ccs_info.htm#menu
03/09/97

CCS - Projects Being Undertaken
ftp://ftp.cs.man.ac.uk/pub/CCS-Archive/public_html/ccs_proj.htm
14/06/97

American Computer Museum, Ltd.
http://www.compustory.com/index.htm
01/09/97

Historic Computer Images
http://ftp.arl.mil/ftp/historic-computers/
01/09/97

CHAC History Pages
http://www.chac.org/chac/chhistpg.html#HistPg_CompHist
01/09/97

Information Age: People, Information & Technology
http://photo2.si.edu/infoage.html
14/06/97

Computer History and Emulation Homepage
http://www.freeflight.com/fms/comp/
16/07/97

The Retrocomputing Museum
http://www.ccil.org/retro/retromuseum.html
01/09/97

National Archive for the History of Computing
http://www.man.ac.uk/Sc...ring/CHSTM/contents.htm
04/09/97

Blasts from the Past
http://www.biostat.washington.edu/past.html
01/09/97

The Classic Computers List Web Page
http://weber.u.washington.edu/~bcw/ccl.html
04/09/97

Classic Computer Links
http://weber.u.washington.edu/~bcw/links.html
01/09/97

IEEE Annals of the History of Computing
http://computer.org/pubs/annals/annals.htm
14/06/97

Pdp's et autres antiques
http://perso.curie.fr/slt/pdp.html
08/09/97

IBM 7090/94 Architecture Home Page
http://www.bs2000.com/talos/7090.htm
14/06/97

History of Microprocessors
http://ourworld.compuserve.com/homepages/computer_museum/mikroprz.htm
14/06/97

Das Computer Museum in Aachen
http://wwwi5.informatik.rwthaachen.de/ComputerMuseum/
DasComputerMuseum.html
01/09/97

A Virtual Tour Through "Generations"
http://www.dg.com/about/html/generations.html
14/06/97

National Technology Alliance
http://www.nta.org/
12/09/97

Recovery of Tapes and Disks from Damage by Disasters
http://www.nta.org/Publications/Presentations/DisasterRecovery/
lc_disaster_recovery_slides_2.html
08/07/97

Disaster Recovery
http://www.nta.org/MediaStability/DisasterRecovery/
12/09/97

Data Recovery Services from the original - Nick Majors' Data Recovery Labs - When only the BEST will do!
http://www.datarec.com/infokit.html#choices
02/07/97

Total Recall - Data Recovery Service
http://sourcedata.com/500/000192.htm
02/07/97

Solutions By Design Home Page
http://www.solbydes.com.au/
06/08/97

Storage Products
http://ww1.systems.digital.com/Ddic.nsf/HWStorageProducts?OpenView
03/07/97

RS/6000-based Storage Products
http://www.rs6000.ibm.com/hardware/peripherals/storage/index.html
03/07/97

3490 Magnetic Tape Subsystem Enhanced Capability Models C10/C11/C22
http://www.almaden.ibm.com/storage/hardsoft/tape/3490c.htm
03/07/97

magnetic tape - PC Webopaedia Definition and Links
http://www.sandybay.com/pc-web/magnetic_tape.htm
03/07/97

tape - PC Webopaedia Definition and Links
http://www.sandybay.com/pc-web/tape.htm
03/07/97

The Alberta Hail Project Meteorological Archive
http://datalib.library.ualberta.ca:80/AHParchive/
03/07/97

Preserving Digital Information
http://lyra.rlg.org/ArchTF/tfadi.execsum.htm
03/07/97

Conservation OnLine
http://palimpsest.stanford.edu/
07/07/97

Electronic Storage Media
http://palimpsest.stanford.edu/bytopic/electronic-records/electronic-storage-media/
07/07/97

Psaltis Group Home Page
http://sunoptics.caltech.edu/Welcome.html
03/07/97

Media Stability Studies 1994—Executive Summary
http://www.nml.org/Publications/TechnicalReports/MediaStability/
04/07/97

VidiPax - the Magnetic Media Restoration CompanyMediaStabilityFinalReport1994/
http://www.panix.com/~vidipax/
07/07/97

Media Stability Technical Reports
http://www.nta.org/MediaStability/MSSTechnicalReports/
07/07/97

Aviation Safety Web Pages - Other sites
http://web.inter.nl.net/users/H.Ranter/safe.htm#invest
07/07/97

TIBBIT Home Page (Timing Insensitive Binary to Binary Translation)
http://www.cs.uoregon.edu/~cogswell/tibbit/index.html
08/07/97

Catalog of compilers: concurrent, parellel, and simulation languages expanded
http://www.idiom.com/free-compilers/ECATEGORY/concurre-1.html
08/07/97

1996 International Conference on Parallel and Distributed Systems (ICPADS '96)
http://www.takilab.k.dendai.ac.jp/conf/icpads96/
24/07/97

STonX Homepage (Atari ST Emulator for Unix/X)
http://www.complang.tuwien.ac.at/nino/stonx.html
08/07/97

Unisys History Newsletter
http://www.cc.gatech.edu/services/unisys-folklore/
08/07/97

COMP.EMULATORS.MISC Frequently Asked Questions List
http://www.why.net/home/adam/cem/
16/07/97

CPC++ - Core Page
http://www.worldnet.fr/~brice/cpc/cpcpp.core.shtml
08/09/97

Emmarc Ltd Home Page
http://ourworld.compuserve.com/homepages/emmarc/

tagish UK UNIVERSITIES ENGINEERING
http://www.tagish.co.uk/tagish/links/engineer.htm

DSSC Home Page
http://www.ece.cmu.edu/afs/ece/www/httpd_doc/research/dssc.html

CPA Home Page
http://palimpsest.stanford.edu/cpa/

Cornell Theory Center
http://www.tc.cornell.edu/ctc.html

EE Times on the Web
http://techweb.cmp.com/eet/823/

The Institute for Information Storage Technology
http://www-iist.scu.edu/

Research of Information Storage Technology Group
http://www.el.utwente.nl/tdm/istg/research/research.htm

CENTER FOR MAGNETIC RECORDING RESEARCH
http://www-physics.ucsd.edu/~chacker/

Liftime of Imation CD-ROMS
http://www.imation.com/dsp/cdrom/lifetime/index.html

Backcoating Technology
http://www.imation.com/dsp/blackwatch/tech.html

Storage Products
http://www.sresearch.com/search/105008.htm

Thomas Hammel´s Emulation Zone
http://www.datacomm.ch/~camelot/

DISK/TREND, Inc. home page
http://www.disktrend.com/dthompag.htm

Links to rigid, flexible and optical disk drive manufacturers
http://www.disktrend.com/lndrive.htm

Welcome to Nikkei Electronics Asia
http://www.nikkeibp.com/nea/october/index.html

Data Storage Systems Center Carnegie Mellon UniversityDescription and Proposal to Industry
http://www.ece.cmu.edu/afs/ece/usr/meg/www/DesPro.html

Caltech: Division of Engineering and Applied Science
http://www.caltech.edu/caltech/EandAS.html

eLib: Electronic Libraries Programme
http://www.ukoln.ac.uk/services/elib/

Norpak Corporation - Test Encoder
http://www.norpak.ca/test.htm

Series 3800 Magnetic Stripe Readers
http://www.idt-net.com/3800.htm

Raster Graphic Interchange Standards
http://www.pdsimage.com/html/news/jbig/raster.htm

OII - Video Interchange Standards
http://www2.echo.lu/oii/en/video.html

Information Market Europe Home page
http://www2.echo.lu/home.html

The School of Engineering and Applied Science (Princeton)
http://www.princeton.edu:80/~seasweb/

About NOLA (Networking of Literary Archives)
http://gonzo.hd.uib.no/Nola/Nolainfo.html

The Universal Library
http://m5.vi.ri.cmu.edu/ulplans/technical.htm

National Technology Alliance Home Page
http://www.nta.org/

NTA Home Page
http://www.nta.org/ntahome.html

Retargetable Binary Translation
http://www.cs.uq.edu.au/groups/csm/bintrans.html

NML Bits: Newsletter of the National Media Lab
http://www.nml.org/Publications/NMLBits/

NTA Technical Reports
http://www.nml.org/Publications/TechnicalReports/#ProductEvals

ready to ware: “Der Bingle Technology”
http://www.tir.com/~rtw/bing.htm

Work on Binary Translation
http://www.cs.uq.edu.au/groups/csm/otherbin.html

Ampex Corporation
http://www.ampex.com/

PRML Training
http://www.guzik.com/BOOK.HTM

Publications - Hard-Disk Drive PRML Read-Channel Optimized for Magneto Resistive Heads, Processor is First in a Family [ADRS120]
http://www.analog.com/publications/press/products/ADRS120_090695.html

IEEE JOURNAL OF SOLID-STATE CIRCUITS
http://www.sscs.org/jssc/indices/apr97.htm

Formatted Publications - UCLA
http://icsl.ucla.edu/aagroup/pubs.html

Secure Deletion of Data from Magnetic and Solid-State Memory
http://www.cs.auckland.ac.nz/~pgut001/secure_del.html

Empire 1400/2100S Product Manual - Chapter 4
http://www.quantum.com/products/manuals/empire+/chp4.html

UCLA Distributed MicroSystems Research Group: Student Research
http://www.janet.ucla.edu/stdnt.rsrch/stdnt.summs/ppai.html

Research in signal processing and electronics - IBM
http://www.almaden.ibm.com/sst/signalp.html

Senior Lab Project EEE at Oklahoma
http://www.ecn.uoknor.edu/~jspatric/srlab.html

MINT Research Areas (Centre for Micromagnetics and Information Technologies)
http://www.ee.umn.edu/groups/mint/research.html

3.5-Inch Ultrastar2 10.8 GB High Capacity Disk Drive
http://www1.ibmlink.ibm.com/HTML/SPEC/goem7058.html

CDSLab - Communications and Data Storage Lab
http://www.ee.umn.edu/groups/cds/

A 50MHz Eight-Tap Adaptive Equalizer for Partial-Response Channels
http://kabuki.eecs.berkeley.edu/~jrudell/papers/jssc/

AAGroup Disk Drive Signal Paper Order Form
http://icsl.ucla.edu/aagroup/ddsplibr.html

Maxcom - IBM No-ID sector format
http://www.maxcom.nl/ibm/noid.html

PR951204A - INDUSTRY’S FASTEST PRML READ CHANNEL IC
http://motserv.indirect.com/home2/press/html/PR951204A.html

TECHNOLOGY AND TIME-TO-MARKET
http://www.quantum.com/products/whitepapers/techno1.html

r-Drive 1002
http://www.robdata.com/r1002.htm

A List of Email Mailing List Listserver Lists
http://www.cuenet.com/ml.html

Data Recovery Group
http://www.datarecoverygroup.com/

Binary Translation Page
http://www.ece.cmu.edu/afs/ece/usr/newburn/www/bin-xlate.html

Miscelleneous Documents, Index - Digital Journal
http://www.digital.com/info/misc/

Translation Research Group - TTT.org
http://www.ttt.org/

Embra
http://www-flash.stanford.edu/Embra/

The SimOS Home Page
http://www-flash.stanford.edu:80/SimOS/

Binary Translation and Software Emulation
http://www.digital.com/info/misc/techno/techno.html

Digital Technical Journal, Back Issues
http://www.digital.com/info/DTJ/dtj-back-issues.htm

DIAMONDS
http://www.ifi.unizh.ch/groups/richter/projects/diamonds.html

Center for Reliable and High Performance Computing
http://www.crhc.uiuc.edu/index.html

Department of Electrical Engineering and Computer Science University of Tasmania
http://www.eecs.utas.edu.au/research/concurrent_index.shtml

Research Groups, Computer Science
http://www.cs.utas.edu.au/Research/Crrg.html

Shade
http://www.cs.washington.edu/research/compiler/papers.d/shade.html

PLATINUM technology, inc. Homepage
http://www.platinum.com/

Enterprise-Wide Backup and Recovery
http://www.platinum.com/products/entb_r.htm#purpose

The OM Project
http://www.research.digital.com/wrl/projects/om/om.html

WRL papers on binary-code modification
http://www.research.digital.com/wrl/projects/om/wrlpapers.html

Wabi 2.2 Product Overview
http://www.sun.com/software/Products/PC-Integration-products/index.html

Welcome to Hewlett-Packard
http://hpcc920.external.hp.com/

Case Study: Moving the Applications
http://www.hp.com/gsy/mfa/unplugged/how3.html

CiscoMgmt Variables
http://www.hp.com/rnd/support/techpub/inetp/j3138a/mibqref/mcisco.htm

Hewlett-Packard Journal
http://www.hp.com/hpj/journal.html

Norman Ramsey - Research and Publications
http://www.cs.virginia.edu/~nr/activities.html#retargetability

TIBBIT Home Page
http://www.cs.uoregon.edu/~cogswell/tibbit/

Software Portability Home Page
http://www.cs.wvu.edu/~jdm/research/portability/

Portability Book Outline
http://www.cs.wvu.edu/~jdm/research/portability/book/outline.html

Archelon's User Retargetable Development Tools
http://www.archelon.com/retarg.html

CHIPS - 9138
http://cabernet.esprit.ec.org/esp-syn/text/9138.html

1996 International Conference on Parallel and Distributed Systems (ICPADS '96)
http://www.takilab.k.dendai.ac.jp/conf/icpads96/

IEEE Transactions on Software Engineering (TSE), Volume 14
http://sunsite.ust.hk/dblp/db/journals/tse/tse14.html

Welcome to RealMedia !
http://www.real.com/

Hard Drive Data Recovery and Repair Center
http://fox.nstn.ca/~nstn2879/repair.html

Highpoint Technologies Home Page
http://www.hptech.com/

The Tech Page from Mainstar (formerly SIS)
http://www.mainstar.com/techpage.htm

Disaster Recovery Journal's Homepage
http://www.drj.com/

Disaster Recovery Directory
http://www.drj.com/vendor/drj5alt.html

HP: Business Recovery Services
http://www.hp.com/wcso-support/10cCPEnterpriseBRS.html

IBM Business Recovery Services Home Page
http://www.brs.ibm.com/

SunGard Recovery Services, the Disaster Recovery Experts
http://recovery.sungard.com/

Europe and the global information society - Bangemann report
http://www2.echo.lu/eudocs/en/bangemann.html

RLG's Home Page - Research Libraries Group
http://www.rlg.org/toc.html

IBM Almaden Web Farm
http://www.almaden.ibm.com/

Hard Drive Basics - Technicians' Guide to PC Hard Disk Subsystems
http://www.datarec.com/hdtech2.html

Selection Page (Hard Disk)
http://www.fujitsu-europe.com/disk/index.htm

WEAR
http://bulb.mit.edu/bulb/journals/00431648/EA920027.html

Welcome to InfoSys Corp.—Top Page
http://infosys.co.kr/

Adam Associates Home Page
http://www.adam.co.uk/

Emmarc Ltd Home Page
http://ourworld.compuserve.com/homepages/emmarc/

National Technology Alliance Home Page
http://www.nta.org/

Department of Electrical Engineering & Electronics - Brunel
http://www.brunel.ac.uk/depts/ee/EEHome.html

UH Home Page - Faculties - Hertfordshire
http://www.herts.ac.uk/uh/faculties.html

Kodak:FPC Inc.
http://www.kodak.com/aboutKodak/bu/mptvi/fpc/fpc.shtml

Media Stability Technical Reports
http://www.nta.org/MediaStability/MSSTechnicalReports/

IBM Technical Journals
http://www.almaden.ibm.com/journal/

FEDERAL AVIATION ADMINISTRATION
http://www.dot.gov/general/directory/faaphone.html

ARMA Metro NYC - the Records Management Listserv
http://www.mdyadvtech.com/armanyc/listinfo.html

Phillips Publishing International, Inc.
http://www.phillips.com/

Forensic Computer and Data Investigations
http://home.earthlink.net/~jmellon/

Computer Forensics Inc
http://www.forensics.com/

Storage Systems and Technology at the Alamaden Research Center
http://www.almaden.ibm.com/sst/

Kodak: Smithsonian Case History
http://www.kodak.com/aboutKodak/bu/ppi/museumArchivePCD/smithsonian.shtml

Verbatim Corporation
http://www.verbatimcorp.com/

High Technology Crime Investigation Association
http://htcia.org/

Charles Babbage Institute
http://www.cbi.umn.edu/

UVa Computer Museum
http://www.cs.virginia.edu/brochure/museum.html

The Computer Museum Network: Registration Page
http://www.net.org/

Obsolete Computer Museum
http://www.ncsc.dni.us/fun/user/tcc/cmuseum/cmuseum.htm

The Virtual Museum of Computing
http://www.comlab.ox.ac.uk/archive/other/museums/computing.html#museums

NanoTheater
http://www.di.com/cgi-bin/DIgallery.exe/HrdDiskTrcks.gif

TappingMode for Semiconductor Applications
http://www.di.com/AppNotes/Semi/Main.html

Intel Museum Home Page
http://www.intel.com/intel/intelis/museum/index.htm

Computer History Association of California (CHAC)
http://www.chac.org/chac/

Computer Museum of America
http://www.computer-museum.org/about_cma.html

Kevan's Computer Bits... Collection List - Computers
http://staff.motiv.co.uk/~kevan/old_collection/items_computers.html

KODAK:Digital Systems Design Engineers — Rochester, NY
http://www.kodak.com/aboutKodak/corpInfo/employmentOps/jobs/te970827-01.shtml

VOGON INTERNATIONAL
http://www.vogon-international.com/

Exabyte Home Page
http://www.exabyte.com/home/products.html

Welcome to M4 Data - High Performance Data Storage Solutions
http://www.m4data-usa.com/index.html

Hard Drive Data Recovery and Repair Labs
http://fox.nstn.ca/~nstn2879/repair.html

DPT Technology
http://www.dpt.com/techno.html

Welcome to DTC
http://www.datatechnology.com/

Valtron Technologies - Hard Disk Hospital
http://www.valtron.com/hospital/hospital.html

Western Digital Hard Drives/Enterprise 2.1 & 4.3 GB Drives
http://www.wdc.com/new/esg/entrprise2_4.html

WELCOME TO NEC ONLINE
http://www.nec.com/

The Museum of HP Calculators
http://www.teleport.com/~dgh/hpmuseum.html

ECMA information centre
http://www.ecma.ch/

British Petroleum Company Home Page
http://www.bp.com/

Waste Minimization in the Magnetic Tape Industry: Waterborne Coating Formulations for Magnetic Tape Manufacture
http://pprc.pnl.gov/pprc/rpd/statefnd/gulfcoas/wastemin.html

finishing.com — anodizing, electroplating, plating, powder coating
http://www.finishing.com/

ASTM Technical Committees (American Society for Testing and Materials)
http://www.astm.org/COMMIT/tcom.htm#Paints

Tape, Inc. - Coating
http://www.tapeinc.com/coating.html

Precision Research, Inc.
http://www.netvisions.com/prco/170019.htm

Computer Technology Research Corp. (CTR) Publisher of IT Reports and Newsletters
http://www.ctrcorp.com/getthis.cgi?url=ctrhome.htm

Anacomp - Magnetics
http://www.anacomp.com/page3-3.html

EMTEC Magnetics GmbH
http://www.emtec-magnetics.com/

Magnetic Tape and Digital Media Life Expectancies
http://www.phlab.missouri.edu/~ccgreg/tapes.html

Magnetic Recording - an introduction
http://www.ee.washington.edu/conselec/CE/kuhn/magtape/95x1.htm

Magnetic Media
http://www.pc-currents.com/drives.htm

ITA Focus Group - Magnetic Storage
http://www.daileyint.com/3magstor.htm

Magnetic Force Microscopy
http://www.di.com/AppNotes/MFM/Main.html

MiniDisc FAQ
http://www.connact.com/~eaw/minidisc/minidisc_faq.html

Bonding Still A Sticky Issue For DVD
http://www.kipinet.com/tdb/tdb_sep96/feat_bonding.html

IDEMA (International Disk Drive Equipment and Materials Association)
http://www.idema.org/

Preserving Digital Information
http://lyra.rlg.org/ArchTF/tfadi.members.htm

National Historical Publications and Records Commission (NHPRC) Home Page
http://www.nara.gov/nara/nhprc/nhprc.html

Preservation & Integrity - Introduction
http://www.slais.ubc.ca/users/duranti/intro.htm

Appendix 1: Proposal to investigate the post hoc rescue of digital material

Backdrop

This proposal responds to an invitation to tender issued by the British Library Research and Innovation Centre (BLRIC) on 3 April 1997. It is intended to investigate the post hoc rescue of digital materials.

Purpose of the study

The study will aim to examine the approaches to accessing digital materials where the media has become damaged (through disaster or age) or where the hardware and software is either no longer available or unknown. The summary of the problem given in the request for tender document under the Aim of the Study provides a good sketch of the issue. Other examples might have included the rescue of the Stasii tapes by the German Archives where the format of the information on the tapes was not readily known, the documentation was limited, and the hardware and software had to be identified (or constructed). The numerous examples of rescue from media in post-crisis situations (after fires, flooding) provide us with evidence as to the how the process of rescue needs to be managed and some of the obstacles that are encountered during a rescue. They also provide an indicate of the labour investment, financial costs, and methods of working.

The project will examine the issues included among the objectives listed in the request for tender in detail. It will:

- survey current activities, identify significant (both in terms of information value, complexity of rescue, and quantity of information recovered) rescue projects and describe how the rescue issues were approached and what lessons were learned during the rescue activities;

- examine the kinds of data formats and types that can be rescued from the vantage of hardware and software;

- examine the issues rescue from media whose format is unknown, where the hardware and software for reading the media no longer exist and where the media has become damaged;

- identify the technology preservation (e.g. museums, commercial retroconversion firms) and disaster recovery (or digital rescue) (e.g. public sector and commercial) services and companies;

- description kinds of operation (technical and organisational) which is necessary to carry out this work and to address the question as to whether it can be done on an ad hoc basis or whether it can only be done by an established institution in an effective manner;

- identify the issues that make the need to rescue inevitable and which increase the likelihood that rescue will not be successful;

- identify any guidelines which might help us to avoid having to turn to the rescue path; and,
- investigate the kinds of possible pilots that might be undertaken, if sufficient examples of rescue activities cannot be identified.

Method of approaching the problem

The project will begin with a literature review (including both online and print resources, and where possible the grey-literature) and a review of marketing literature from disaster recovery companies, major storage vendors, and what limited information comes from companies which provide these kinds of services the intelligence and law enforcement communities. This will be complimented by face-to-face discussions, telephone interviews, and written exchanges with selected representatives from these sectors.

Deliverables

The primary deliverable will be the report itself. The report will:

- review the published technical literature;
- review of example activities along with ‘war stories’ (e.g. rescue of black box tapes from crashed fighter jets—post hoc rescue, rescue in criminal investigations);
- description of the process of rescue in several target areas. These include (but will not be limited to) rescue (a) from damaged media, (b) from media containing material in an unknown format, (c) from obsolete software environments and applications, and (d) from obsolete hardware environments;
- outline the types of problems encountered discussed, the rescue methods in common use will be described, and describe promising new solutions;
- describe the minimal documentation practices to enhance rescue; and,
- conclude with a list of commercial and public sector institutions and individuals in the UK, Europe, and North America which could provide assistance in this area.

Appendix 2:
List of preservation institutes and emulation software sites

Computer History and Emulation Homepage
http://www.freeflight.com/fms/comp/

The Retrocomputing Museum
http://www.ccil.org/retro/retromuseum.html

National Archive for the History of Computing
http://www.man.ac.uk/Sc...ring/CHSTM/contents.htm

Blasts from the Past
http://www.biostat.washington.edu/past.html

The Classic Computers List Web Page
http://weber.u.washington.edu/~bcw/ccl.html

Charles Babbage Institute
http://www.cbi.umn.edu/

UVa Computer Museum
http://www.cs.virginia.edu/brochure/museum.html

The Computer Museum Network: Registration Page
http://www.net.org/

Obsolete Computer Museum
http://www.ncsc.dni.us/fun/user/tcc/cmuseum/cmuseum.htm

The Virtual Museum of Computing
http://www.comlab.ox.ac.uk/archive/other/museums/computing.html#museums

Intel Museum Home Page
http://www.intel.com/intel/intelis/museum/index.htm

Computer History Association of California (CHAC)
http://www.chac.org/chac/

Computer Museum of America
http://www.computer-museum.org/about_cma.html

COMP.EMULATORS.MISC Frequently Asked Questions List
http://www.why.net/home/adam/cem/

EMULATOR ZoNE
http://www.geocities.com/SiliconValley/Park/2912/

Emulator Showcase Main Menu
http://www.unicate.com/marc/mainemu.htm

EMU Express
http://home2.swipnet.se/~w-28929/

Video Game / Computer EMULATOR PAGE
http://www.netaxis.com/~petebuilt/videogames/emulate.html

.coNsOle .wORlD
http://www.cm.cf.ac.uk:80/Games/

STonX Homepage (Atari ST Emulator for Unix/X)
http://www.complang.tuwien.ac.at/nino/stonx.html

Thomas Hammel´s Emulation Zone
http://www.datacomm.ch/~camelot/

Appendix 3: Data Recovery companies

(those starred * = visited.)

UK

Adam Associates *
137 New GreenhamPark
Greenham Common
Thatcham
Berkshire
RG19 6HN

Guardian dr Ltd *
Head Office
Benchmark House
St. Georges Business Centre
203 Brooklands Road
Weybridge
Surrey KT13 ORN

Safetynet PLC
12-13 Bracknell Beeches
Bracknell
Berkshire
RG12 7BW

Emmarc Ltd *
5 Wymondley Close
Hitchin
Hertfordshire
SG4 9PW

Convar Systems
10 Overcliffe
Gravesend
Kent DA11 0EF

Ontrack Data Recovery Europe Ltd *
The Pavillions
1 Weston Road
Kiln Lane
Epsom
Surrey KT17 1JG

Vogon *
7-8 Forest Court
Oaklands
Fishponds Road
Wokingham
Berkshire
RG14 2FD

USA

Advanced Data Recovery Inc.
3487 Greystone Ct.
Medford
OR 97504

Advanced Data Solutions
2605 Hoover Ave. Suite “F&G”
National City
California 91950

Arcus, Inc
Corporate Office
7031 Koll Center Parkway, Suite 100
Pleasanton CA 94566

Computer Conversions, Inc
9580 Black Mountain Road, Suite J
San Diego, CA 92126

Computer Forensics Inc
501 East Pine Street
Third Floor
Seattle, WA 98122

Data Recovery Group
1821 Marina Blvd
San Leandro
CA 94577

Data Recovery and Reconstruction
P.O. Box 35993
Tucson AZ 85740 - 5993

Drive Savers
400 Bel Marin Keys Boulevard
Novato CA 94949

Excalibur Data Recovery Inc.
101 Billerica Avenue, Bldg #5
N. Billerica, MA 01862-1256

Healy & Associates
P.O. Box 2143
Asheboro, NC 27204

Independent Technology Service, Inc
4495 Runway Street
Simi Valley
CA 93063

MDS Disk Service
11750 Sterling Avenue
Riverside
CA 92503

Peripheral Repair Company
9233 Eton Avenus
Chatsworth
CA 91311

Total Recall
2462 Waynoka Road
Colo Springs
CO 80915

TS4
15011 S. Forsythe Road
Oregon City
OR 97045-9494

Vantage Technologies. Inc.
Data Recovery and Restoration
P.O. Box 1570
Merrimack
NH 03054-1570

33330 8th Avenue South
Mail Stop: PC2-150
Federal Way
WA 98003

CANADA

Accurate Data Recovery Services
429 Danforth Ave Unit 409
Toronto,Ontario
Canada M4K 1P1

CBL
590 Alden Road
Unit 105
Markham
Ontario
Canada L3R 8N2

Data Recovery Labs
1315 Lawrence Avenue East
Unit 502 -503
Din Mills
Ontario
Canada M3A 3R3

AUSTRALIA

Encom Technology
Level 2, 118 Alfred Street
Milsons Point
NSW 2061
Australia

Appendix 4: Outline of issues to be discussed with data recovery firms

What follows is the background material provided to the data recovery firms before Ann Gow and Richard Alexander carried out the visits.

Outline provided:

Thank you for agreeing to meet us and to discuss the main areas that we are researching.

The main aims of the project are to survey current activities, identify significant (both in terms of information value, complexity of rescue, and quantity of information recovered) rescue projects and describe how the rescue issues were approached and what lessons were learned during the rescue activities; to examine the kinds of data formats and types that can be rescued from the vantage of hardware and software. Also to examine the issues rescue from media whose format is unknown, where the hardware and software for reading the media no longer exist and where the media has become damaged.

We are therefore investigating a wide range of issues concerned with the recovery of data under varying circumstances. During our meeting we would be interested to discuss those broad issues with you and we would also be particularly interested to discuss the following specific areas:

1. Which operating systems and hardware platforms is recovery support available for? Are the supported platforms driven by market demands, technical feasibility, or some combination of both?
2. Does your company deal exclusively with “disaster” recovery or do you also provide recovery services for instances in which the hardware environment for the storage device and/or the operating system environment are unavailable due to obsolescence?
3. What levels of investment in terms of staff, facilities, spare parts and so on are involved in providing the various elements of your recovery services portfolio? Commercial sensitivities will be respected.
4. What are the typical recovery costs for a range of scenarios? This information will be non-attributable and will be used simply to provide broad costing information showing the relationship between data value and recovery costs.
5. Do you have any experience with recovery from non-oxide storage devices, e.g. CD ROM?
6. Do you currently use operating system emulation during recovery projects or is the originating operating system always available?
7. Do you have any specific future plans to provide obsolescence recovery using operating system emulation and/or other techniques?
8. What precautions and processes should data users observe to ensure the highest possible chance of successful recovery either following disaster or equipment obsolescence?
9. We would like to identify exemplar recovery projects which we could mention in the report. This would imply that either the project was not “commercial in confidence” or that the project could be described (with the client’s agreement) without risk of identifying the client.

Appendix 5: Letter sent to online discussion lists and lists contacted

Apologies for cross posting

We are part of a group conducting research into the issues surrounding the post hoc rescue of digital materials and we would appreciate any help and information. Our study aims to examine the approaches to accessing digital materials where the media has become damaged (through disaster or age) or where the hardware and software is either no longer available or unknown.

The mains aims of the report are to survey current activities, identify significant (both in terms of information value, complexity of rescue, and quantity of information recovered) rescue projects and describe how the rescue issues were approached and what lessons were learned during the rescue activities; to examine the kinds of data formats and types that can be rescued from the vantage of hardware and software; to examine the issues rescue from media whose format is unknown, where the hardware and software for reading the media no longer exist and where the media has become damaged.

We would be particularly grateful for examples of rescue projects that have issues relevant to our study as well as any technical information, whether established procedures or new and emerging techniques.

Discussion lists mailed

CYBERIA-L:	Law & Policy of Computer Communications
INTLAW-L:	Internet and Computer Law Association
LAWOBSERVER:	Computer Law Observer
DRP-L:	Disaster Recovery Plan for Computing Services
ENGLIB-L:	Engineering, Library Discussion List
CECS-L:	MU Computer Engineering and Computer Science
SMETDIAL:	SMETDIAL - Science/ Math/ Engineering/ Technology Dialog
IEEE:	“Eventos en Ingenieria Electrica e Informatica”
IEEE-CS:	Meeting Announcements for the Boston IEEE Computer Society
IEEE-EGE:	IEEE Ege Student Branch Discussion and Announcements List
IEEE-L:	List for all EE students
IEEE-L:	IEEE Discussion List
IEEE-L:	UTA IEEE Student Branch
IEEE-SB:	IEEE Student Branch Discussion and Announcements List
IEEE-TCPC:	IEEE Technical Committee on Personal Communications
IEEE-VMS:	IEEE Virginia Mountain Section
CHEME-L:	Chemical Engineering List
ERECS-L:	Management & Preservation of Electronic Records
LIBRES:	Library and Information Science Research Electronic Journal
ICA-L:	International Council of Archives Listserv
AUS-ARCHIVISTS! :	A Listserv for Australian Archivists
RECMGMT list:	Records Management Program

Respondents to queries and requests

Dr Cristina Cifuentes, Department of Computer Science, The University of Queensland, Australia

Clive Jenkins, EMMARC, Hertfordshire

Dr Michael Wettengel, Electronic Records, Bundesarchiv (Federal Archives), Germany

P C Hariharan, NASA, chm_zpch@jhunix.hcf.jhu.edu

Doron Swade, Senior Curator (Computing and Information Technology), Science Museum, London

Andrew Prescott, British Library

Alan Essam, Marketing Director, Anacomp, Brynmawr. Wales

Jim Suderman, Senior Archivist, Political Legislative Portfolio, Archives of Ontario

Philip Bouvier and J.J. Wanegue, DIGIPRESS, France

Philip Nevitt, Director (Information Technology), INTERPOL, Lyon, France

Jerry George, National Historical Publications and Records Commission, National Archives and Records Administration, Washington, DC

Luciana Duranti, School of Library, Archival & Information Studies, University of British Columbia, Vancouver, B.C.

Carlos Medeiros , The Jacques Delors Information Centre, Lisboa

Peter Gutterman, Documents Services Information & Technology Services, The World Bank (Washington DC)

Sarah Tyacke, PUBLIC RECORD OFFICE

Michael J.D. Sutton, FMP/Flaman Management Partners Ltd., Ottawa, Ontario, CANADA,

Professor Michael Moss (University Archivist), Archives & Business Records Centre, University of Glasgow

Greg O'Shea, Australian Archives National Office

Richard E. Barry, Barry Associates

Vera Sayzew, MIT

Susan L. Burkett, Department of Electrical Engineering, University of Alabama

Cock Lodder, Information Storage Technology Group, University of Twente, The Netherlands

Margaret Hedstrom, School of Information, University of Michigan

Meg Papa, Outreach and Publications Coordinator, Data Storage Systems Center, Carnegie Mellon University

James A. Bain, Dept. of ECE, Carnegie Mellon University

Alan Murdock, Central Research Pfizer Ltd. Sandwich, Kent

Stephen M. Fochuk, fochuk@gcpo0.geocan.NRCan.gc.ca

Alan S. Zaben, Albuquerque, New Mexico

Bob Arnold, Disaster Recovery Journal

Tom Ruller, Associate Archivist, New York State Archives and Records Administration.

Barbara Reed, FCIT Monash University (Clayton)

Bob Stock, Law & Policy of Computer Communications

Martha McConaghy

Richard Laurie Vlamynck., Applied Customer Engineering Services, Microtec

Simon Muir, Bristol, United Kingdom

Enrico Luparini, luparini@stat.ds.UNIFI.IT

JSinBACA@aol.com

A Bensalem, Napier University,Department of Civil & Transp. Enging

Michael Bittle, 8th World Conference on Disaster Management, June 14-17, 1998 Hamilton (Ontario) Canada

Karen A. Shaw, Senior Information and Records Manager, Fort Leavenworth, Kansas

Patricia Palmer, Head, Preservation Services, Virginia Commonwealth University, University Libraries, Richmond, VA 23284-2033

Lorraine Horton, College of Business Administration, University of Rhode Island

Thomas Brown, National Archives and Records Administration

Tom Wayman, LaserFiche Document Imaging

Alex Trott, Shell International Website, Shell Centre, London SE1 7NA

Appendix 6: Letter sent to universities specialising in areas covered by the study and departments contacted

I am part of a group conducting research into the issues surrounding the post hoc rescue of digital materials at Glasgow University and we would appreciate any help and advice you could offer us. Our study aims to examine the approaches to accessing digital materials where the media has become damaged (through disaster or age) or where the hardware and software is either no longer available or unknown.

The mains aims of the research are to survey current activities, identify significant (both in terms of information value, complexity of rescue, and quantity of information recovered) rescue projects and describe how the rescue issues were approached and what lessons were learned during the rescue activities; to examine the kinds of data formats and types that can be rescued from the vantage of hardware and software. Also to examine the issues rescue from media whose format is unknown, where the hardware and software for reading the media no longer exist and where the media has become damaged.

We are aware that your department has research interests in this area and would be very grateful for any assistance you can give yourself. We would appreciate any information on technical papers or articles that your department has been involved in. We are particularly keen to explore more fully the technical processes in recording media and the structure of magnetic tape.

We also hope to build up a collection of case studies looking at particular projects, either successful or unsuccessful, to gain information on the whole recovery process. We would appreciate it if you passed on any experiences you have in this area.

Please feel free to contact me if you want any further details of the project.

Specific universities identified and contacted

MIT - Department of Electrical Engineering and Computer Science
Princeton - Department of Electrical Engineering
Brown - Engineering Faculty - Electrical Science
University of Pennsylvania - Department of Electrical Engineering
UCLA - Electrical Engineering Department
Harvard - Computer Science and Electrical Computer and Sytems Engineering
New Jersey Institute of Technology - Newark College of Engineering: Electrical and Computer Engineering
Carnegie Mellon - Data Storage Systems Centre
Stanford - Department of Material Science and Engineering
University of Twente (Netherlands) - Information Storage Technology Group
University of Alabama - MINT (Center for Materials for Information Technology)
University of Newcastle- Upon - Tyne - Department of Electrical and Electroniic Engineering
University of Plymouth - Centre for Research in Information Storage Technology
Brunel University
University of Hertfordshire

Appendix 7: International organisation contacts

Contact was made with Interpol, Police Organisations, the FBI, the CIA, and FAA (unfortunately we have only had a response from Interpol.)

I am part of a group conducting research into the issues surrounding the post hoc rescue of digital materials at Glasgow University and we would appreciate any help and advice you could offer us. Our study aims to examine the approaches to accessing digital materials where the media has become damaged (through disaster or age) or where the hardware and software is either no longer available or unknown.

The mains aims of the report are to survey current activities, identify significant (both in terms of information value, complexity of rescue, and quantity of information recovered) rescue projects and describe how the rescue issues were approached and what lessons were learned during the rescue activities. To examine the kinds of data formats and types that can be rescued from the vantage of hardware and software. Also to examine the issues rescue from media whose format is unknown, where the hardware and software for reading the media no longer exist and where the media has become damaged.

Some of the examples of work we are looking at in this area include the rescue of the Stasii tapes by the German Archives (Koblenz) where the format of the information on the tapes was not readily known, the documentation was limited, and the hardware and software had to be identified (or constructed). Other examples might include the rescue of data (in either analogue or digital form) from media in post-crisis situations (after fires, flooding).

We are aware that your organization will have experience in specialist data recovery in the growing field of forensic computing and we would be very grateful for any information you could give us. We are particularly keen to collect reports from previous data recovery projects and hoped you could identify some of your most interesting successes. We are very aware that much of your methods and projects will be highly confidential, but we would be grateful for whatever information you feel appropriate to send.