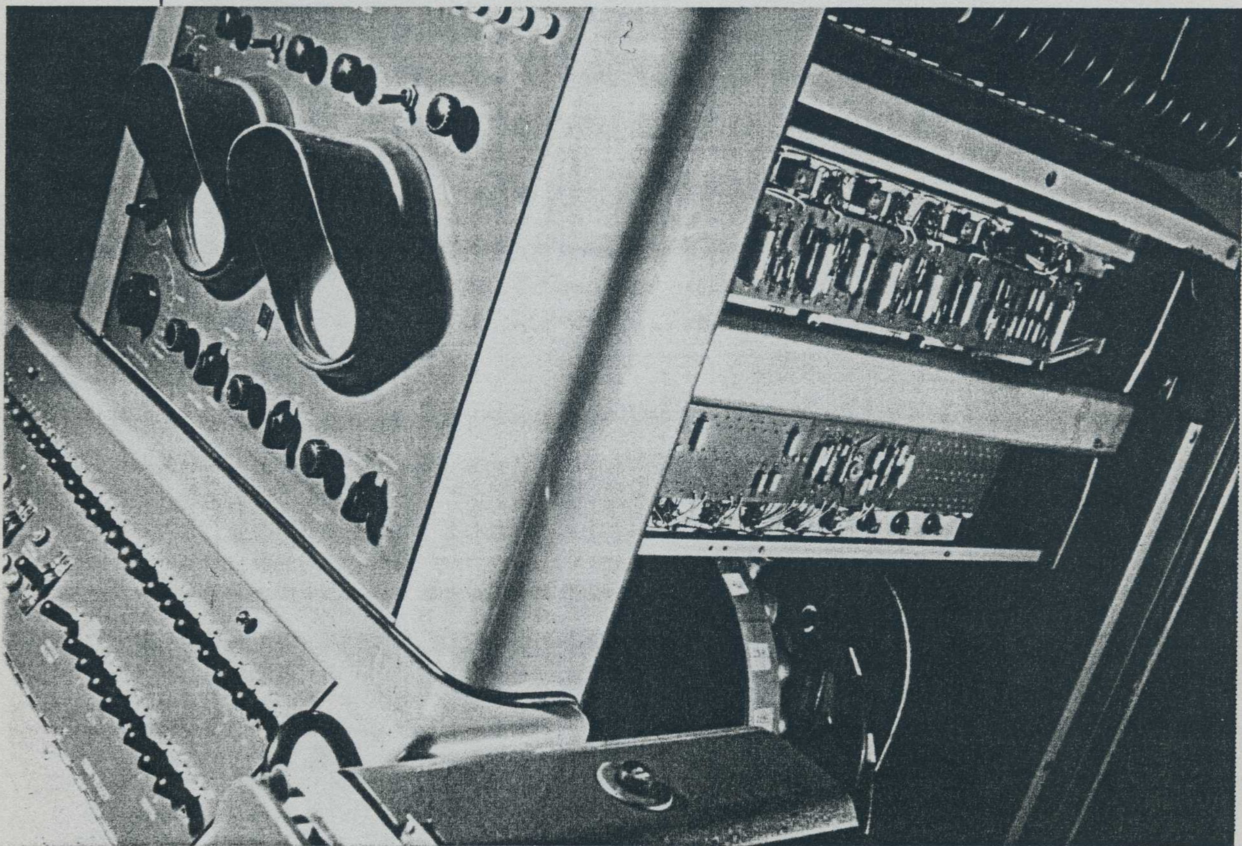
The National Museum of Science & Industry

COLLECTING and CONSERVING COMPUTERS



CONFERENCE PAPERS

COLLECTING AND CONSERVING COMPUTERS

Conference Papers

Compiled by

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The National Museum of Science & Industry

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Scope

This collection of papers was prepared for a conference/workshop on collecting and conserving computers.

The material covers practical, philosophical and ethical issues associated with the restoration and conservation of electronic computing machines.

This volume will be of interest to conservators, industrial archaeologists, curators, restorers and collectors.

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Preface

The restoration of historic computers at the Science Museum began in 1989 with the founding of the Computer Conservation Society, a joint venture between the Science Museum and the British Computer Society. Restoring historic computers to working order raises a host of museological issues. There are issues of working practice, of conservation ethics, and, inevitably, of the proprieties of physical intervention in a conservation culture that properly regards the physical integrity of the object as sacrosanct.

Computer restoration draws on the efforts and expertise of diverse groups of people both inside and outside the museum profession. In 1992 a pilot project was designed to explore and integrate the roles of those involved – conservators, curators, engineers and archivists. As well as bringing together museum professionals from different disciplines the project allowed the collective body of museum professionals to develop and formalise working relationships with experts outside the official chain of curatorial accountability – computer pioneers, engineers and technical experts of various kinds.

The programme to date has met with signal success. Since 1989 the volunteer efforts of the working parties of the Computer Conservation Society and the efforts of Science Museum staff have resulted in the successful restoration to working order of an Elliott 803 (discrete component transistor minicomputer dating from 1963), a Ferranti Pegasus (vacuum-tube machine dating from 1958), several Digital Equipment Corporation machines as well as a unique exploration of software simulators that capture the operational personae of early machines. Significant advances have also been made in documentation practice: replicating original circuit diagrams on fiche and print as well as indexing a rich archive of historic papers, many of them contributed by pioneers and users of the machines being restored.

The papers in this collection mark the completion of the pilot project and were prepared as contributions to a conference/workshop on 'Collecting and Conserving Computers' which was to have been held in June 1993 at the Science Museum. Interest in the conference was heartening but the community of people to whom it appealed was geographically too dispersed to justify a live workshop. This volume has been compiled in response to the many who expressed interest in the venture and serves as a record of the findings and accomplishments of the project.

The papers in this collection do not belong to any one genre. Some are in the form of lecture notes, others are fully referenced articles. Some treat ethical and philosophical issues, others detailed practice and technique. Some are closely argued, others polemical. The absence of any attempt at editorial uniformity is deliberate: it reflects the diversity of thought and the rich variety of approach in those who contributed to the project. This is reflected quite intentionally by presenting the papers in the original format in which they were prepared by the authors.

The collection opens with the article 'Computer Conservation and Curatorship' written for the inaugural issue of *Resurrection: Bulletin of the Computer Conservation Society,* May 1990. This paper identifies some of the curatorial dilemmas of a restoration programme that had yet to begin. Roger Bridgman's paper 'What's in a Computer?' breaks new ground. It provides an invaluable record of the material constituents of computers and the conservation hazards that these entail. The detailed appendix will allow conservators and materials specialists to extend their expertise to computers and electronic devices in an unprecedented way. Suzanne Keene's paper 'Conserving the Information Machine' considers issues of conservation ethics and locates the overall activity in the context of existing conservation practice. Doron Swade's paper 'Collecting Software: Preserving Information in an Object-Centred Culture' raises some of the museological issues associated with the principles and practice of software preservation. Helen Kingsley gives a conservator's view of the restoration of the Elliott 401, a unique early vacuum-tube computer presently being restored, and Jane Kirk considers the organisation, indexing and cataloguing of computer-related documentation. As well as paper-based material, the evidentiary 'record' here includes video as well as software. Anne Moncrieff considers a daunting variety of agents hostile to the physical integrity of historic artefacts and offers invaluable advice on practical preventative measures. Tony Sale provides a case-study account of the restoration of Pegasus from the standpoint of a seasoned electronics and computer engineer who played a leading role in the technical restoration of this machine. Christopher Burton, who developed the simulator for Pegasus, reflects on software simulation and emulation.

The collection represents the differing views of groups of people from the standpoint of their own experiences and professional discipline. The unifying theme of the volume is each contributor's concern and interest in the capture and preservation of our computing past.

Doron Swade
Suzanne Keene
20 October 1993

Cover illustration

Console of Ferranti Pegasus, vacuum-tube computer, 1958. Restored to working order at the Science Museum, London, by the Computer Conservation Society.

Cover design: Marc Foden

Computer Conservation and Curatorship

Doron Swade

[This article was written for the inaugural issue of 'Resurrection: Bulletin of the Computer Conservation Society', Vol. 1, No.1, May 1990]

The activities of the Computer Conservation Society at once overlap, complement and extend those of the Science Museum. The purpose of this piece is to explore and, where possible, clarify the relationship between the two organisations.

The aims of the Society are to restore to working order early computers, preserve working practices and the operational culture of the communities that built and serviced early machines. The spirit of the Society's conception is fresh in the minds of its founders and its aims are explicitly formulated in its charter – that of a specialist group of the British Computer Society. The aims of the Science Museum, on the other hand, have been formulated differently at different times. In the last century the founding ideal was to promote the values of industrial society by displaying the best examples of the 'industrial arts'. Since then, science education, material culture and, more recently, 'public understanding of science', have featured variously in the formulation of corporate intent. We can sense a general harmony of purpose between the fledgling Society and its cultural host. But the overlap is diffuse. Where, in practical terms, do these two ventures combine, differ or even conflict?

The Museum has many identities – temple, warehouse, fairground. In whatever way museums are perceived they are essentially about people and things. The 'things' that presently concern us are the machines in the Computer Collection; the 'people' are curators and museum staff on one hand, and the members of the Society – its working parties and support groups – on the other. The two groups have different relationships and attitudes to computers. How do they compare?

'Inventoried objects' occupy a special place in the Museum's landscape and their role and status is frequently not well understood outside the museum profession. An inventoried object is one that has been formally admitted into the Museum's care by an inventory procedure which transfers the 'title' of the object from the donor/lender/vendor to the Museum. Each inventoried object is the direct responsibility of a named curator, the collecting officer, who signs a formal declaration of responsibility for the object when it is acquired. Such objects are subject to formidable safeguards against disposal and unqualified alteration and the curator is legally and professionally responsible, via a chain of accountability – line management, the Director and the Trustees – to the Arts Minister. A forbidding tale. A consequence of particular interest to the Society is that in ordinary circumstances the curator, as collecting officer, is the only person empowered to authorise physical access to an inventoried object in his or her care.

The curator's brief, and the object of these fearful procedures, is to preserve the object for posterity – a period conveniently not quantified but taken to extend beyond the professional span of any given incumbent. Ordinarily preserving the object amounts to securing benign storage conditions to prevent, or at least retard, physical deterioration. The assumption throughout is that the object remains unaltered in an essentially passive environment. The Society, however, proposes to restore machines to working order. Restoring a computer, as distinct from conserving it, more often than not requires physical intervention. The process may well involve recabling, reconfiguring, repair, renewal of parts, or modification. Operating the machine runs the inevitable risk of physical damage through accident, and entails gradual destruction of moving parts through use.

The traditional culture of museums is essentially conservative and protective. Its safeguards, procedures and formalised chain of responsibilities are designed to protect the physical integrity of objects and thereby their historical authenticity. How do we reconcile the aspirations of the Society (and those of its Curator of Computing) with the 'sacred relic' tradition that renders objects inviolate? First we must examine the desirability of restoring computers and then address the issue of how we can responsibly extend rights of access to the Society's members who, though outside the formal chain of curatorial accountability, often have more expert knowledge of specific machines than the official custodians.

The internal model of curatorship is essentially archaeological – the reconstruction of circumstance and context from limited physical evidence. The physical residue of earlier cultures provides limited clues to the past. The antiquity, incompleteness and relative rarity of relics afford them a certain reverence. However, the earliest electronic computers are still within living memory. Most are well documented and their creators and implementors are still hearty if not hale. The antique past of electronic computing is not yet inaccessibly distant. We remain sufficiently close to the technology and its culture for early electronic machines to invite amused and sometimes wry nostalgia rather than the awed reverence accorded to relics from an unrecoverable past. My argument is that these machines are not yet the fragile sacred relics of the archaeological model which presupposes separation by an unbridgeable gulf of time. Electronic computers occupy a window of recency roughly one professional lifetime wide and it is both proper and responsible to review the appropriateness of existing practice and attitudes to these artefacts.

The Curator of Road Transport recently observed that there is already an element of ambiguity in curators' behaviour towards their machines – that their actions are often closer to vandalism than hands-off reverence: sectioning engines and pumps for the purpose of education and display, accelerating the deterioration through wear of vintage cars by running them, placing them at risk by taking them on public roads, renewing parts with non-original components manufactured using modern materials and methods, and restoring them to pristine external condition (paintwork, upholstery), thereby tampering with the historical 'evidence' and altering aspects of provenance. It seems then that not only is the archaeological model not the best fit for electronic computers on the grounds of recency, but the archaeological model is not universally subscribed to even in the museum world.

Why is it desirable to restore an early computer? The first stage of operational restoration is physical reassembly. It hardly needs arguing that the datum of physical integrity should be as close to the operational state of the machine as possible. However, large and medium-sized computers are invariably uncabled and dismantled into manageable units for purposes of transport from donor's site to store. Machines treated in this way include the Ferranti Pegasus, the Harringay, Wembley and Ipswich Totalisators, the Elliott 401 and 803, and ERNIE I and II. Paradoxically the act of acquisition is the most traumatically destructive process in the life of the supposedly prized machine. Physical reassembly after acquisition can be seen as a healing process – an attempt to restore something of what is lost in rupturing the machine from its operational habitat. It is part of rehabilitation for retirement – a bona fide episode in the natural life of the machine. Physical reassembly, the first stage of restoration, is not therefore an anti-historical intervention hostile to preservation that degrades a machine sanctified by the inventory procedure. Quite the reverse – it establishes a datum of greater historical probity than would otherwise be the case.

A reasonable guardian of procedural sanctity would, I believe, find physical reassembly unobjectionable and even desirable. However, restoring an assembled machine to working order will often involve radically controversial action – reconfiguring the system, recabling, and replacement of damaged parts. It is here that we face real issues of judgement and potential conflict that send traditionalists, brows furrowed, reaching for the museum professional's handbook of approved practice.

The serious 'archaeological' purpose of the Museum's activities is to preserve machines for future generations of curators, historians and scholars. The lessons and messages these machines embody for our successors, and the line and focus of their enquiries, are unforeseeable. If we replaced rubber-sleeved or fabric-wound cable with PVC on the grounds of availability or safety might we not mislead some future enquirer researching, say, the introduction and use of plastics in electrical insulation? Original spares (cable terminators, lugs, capacitors, selenium rectifiers ...) may not be available. Is posterity better served by a machine that works (or has worked) using non-original parts, or by a machine that is intact but in an uncertain state of completeness with respect to electrical detail? These are more than merely rhetorical issues. There are no universal solutions on offer. We are breaking new ground.

My purpose in dwelling on curatorial issues is twofold: to sensitise the Society's membership to the considerations of historical authenticity that apply to computers in the Museum's collections – considerations that do not ordinarily apply to machines in commercial, scientific or engineering environments; secondly, to reassure my colleagues in the museum profession that we are acutely aware of the museological issues agitated by these activities and that clearance procedures and working practices have been devised to safeguard curatorial responsibility.

The pioneers, engineers and technicians who built and serviced these grand old machines are those best qualified to restore them. The venture provides us with a unique opportunity to capture know-how, expertise and narrative history. The activities of the Society allow us to explore, for the first time, a range of technical, historical and museological issues. We have only just begun. I, for one, relish the prospect of what is to come.

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What's in a Computer?

Roger Bridgman

FROM THE CONSERVATOR'S VIEWPOINT, a computer is not a mighty number cruncher, a dream machine that changed the world, but just an assemblage of metals, glass and plastics that can interact in a bewildering variety of ways. Computers are mortal. What prevents them living for ever is a catalogue of changes brought about by interactions between their environment, their components and the components of their components.

Seen purely as an object, then, what does a computer look like? The disinterested view of the scrap merchant is useful here. To his eye, the typical mainframe is 75 per cent low-value materials: the iron, steel and aluminium that form the structure of its frame and the cores of its transformers. Copper conductors — wire and printed circuit tracks — weigh in at only around 5 per cent. Precious metals, mostly the gold flashing on connectors, form a negligible percentage by weight but may be worth a pound or two. The remaining 20 per cent is what the dealer regards as rubbish — plastics which, because non-recyclable, are worthless.

While this macroeconomic perspective may engender a proper disrespect for the once-exalted computer, it is only a starting point. Intelligent conservation also demands detailed engineering knowledge. All electronic equipment is built by assembling standard components into some sort of framework and connecting them together. Components can be divided into two classes: active and passive. Active components are those that are able to transform raw electrical power into signals representing information — transistors are the most familiar example. Passive components can change the relationship between voltage and current, but are unable to impose a pattern where none existed before. Emerging from the electrical technology that preceded the birth of electronics, their nature has changed only gradually over the half-century or so that computers have been in existence. Active components, on the other hand, starting with the devices that initiated the electronic revolution in the first years of this century, have undergone dramatic development. In less than 90 years they have changed from evacuated glass envelopes filled with spidery metalwork ('valves' in Britain, 'electron tubes' in the USA) to compact, ceramic-encapsulated chips containing the transistor equivalent of a roomful of valves.

One result of the demise of the valve has been a reduction in the power requirements of computers. This has affected the size of passive components: components handling the large currents and voltages demanded by valve technology are necessarily bigger than those associated with transistors. Thus conservators dealing with an early valve computer may find themselves immersed in heavy power technology, with sausage-sized resistors and transformers that require lifting equipment, not to mention 15 kilowatt rotary inverters like the one that supplies power for the 1956 Ferranti Pegasus. The arrival of practical transistors in the late 1950s reduced the voltages in electronic circuits, but not the currents. So large transformers, and in particular very large electrolytic capacitors, are found in the power supply units of early transistor machines. Electrolytic capacitors (see Appendix) present particularly intractable conservation problems; to this extent the initial impact of the transistor was negative.

Restoration or conservation?

Before embarking on a catalogue of computer components and the conservation problems they may present, we must face up to a fundamental difficulty. Antique computers are the target of at least two groups of people, whose needs and wishes may not coincide. I apologise for caricaturing their positions, but a caricature can be clearer than a photograph. Computer *restorers* believe that what is important about a machine is its operating behaviour — that the soul of the machine emerges only when the power is switched on and a program is loaded and run. Any means that achieve this end are justified: substituting modern, unrelated components, re-wiring circuits that don't quite fit with what is available now, cutting out the rusty bits and bolting on new metalwork. Of course, the appearance of the machine matters too, so the new components are hidden inside the shells of the old ones and the new metal carefully painted to conceal its presence. Computer *conservators* believe that the original hardware is all-important as a material record of a vanished technology, and strive to prevent the corruption of this record. Thoughts of turning back the clock with a coat of paint or altering the very body of the machine to a state that could not possibly have existed when it was made, let alone covering one's tracks with outright deception, are anathema. If the price is an unattractive, functionless machine, so be it.

Of course these positions have been described in black and white: the two groups can and have co-operated effectively. In any case, it is not my task to adjudicate between them. But in what follows, it is worth remembering that restorers and conservators may view quite differently the changes that occur in computer components as time passes. For the restorer, deterioration that does not affect function — progressive flaking of paint on a resistor, for example — is unimportant. The conservator, on the other hand, is relatively indifferent to changes which, having occurred, remain stable — loss of vacuum in a valve, for instance — even if they bring about a total loss of function. Happily, the needs of the two groups usually coincide: a battery that is corroded and leaking is a threat to both the functional and the physical integrity of the machine and must be excised.

Computers, subsystems and components

So, what's in a computer? Most of the internal material, even in a machine as old as Pegasus, is plastics of some kind — circuit boards and insulation. Externally, there are heavy cabinets and frames. The actual working parts form only a fraction of the bulk. Already the different viewpoints of restorer and conservator are beginning to show, but I propose to stick to this hierarchy of bulk down to the component level, and then deal in turn with passive and active components.

The outer casings of all computers except the earliest prototypes were finished with care: this was what first struck the prospective customer. Unfortunately it is also what first strikes the outside world in the event of mishandling during the machine's working life or when it has come to rest in a museum, so stains, dents and scratches are normal. The structure is often a modular system with sheet metal panels slotting into an extruded section frame. The finish may be paint (many luxurious coats on Pegasus) or the metal may be PVC-laminated. In addition, there will be mechanical components such as wheels, hinges and fasteners. There are many opportunities for damage here, though few of the changes will be progressive. Exceptions to this are loss of paint adhesion, particularly on aluminium which may not have been properly primed, and the unstable nature of PVC coatings, which can become sticky through plasticiser migration.

Inside the casing, most older mainframe computers will be divided up into a number of well-defined subsystems such as power supply, magnetic stores (drum, disk or tape), memory and central processing unit (CPU). This division is needed because of the very different physical forms of these subsystems, reflecting their underlying technologies. Power supply units usually account for most of the bulk. Early machines had linear power supplies operating at mains frequency (modern computers use 'switched-mode' supplies operating at tens of kilohertz). Since transformer size for a given power handling capability falls with frequency, operating at only 50Hz means heavy transformers containing lots of iron and copper. Linear regulation means dumping surplus power, which must be removed by the cooling system; and filtering out 50Hz ripple from high-current supplies demands huge capacitors and chokes.

Drum, disk or tape stores in early machines can also be bulky, and are the only functional subsystems to contain moving parts, usually operated by stepping motors and linear magnetic actuators (solenoids). These suffer all the problems of wear, instability of lubricants, and distortion of wheels and bearings through lack of use. Memory technology has changed greatly during the history of the computer: early 'core store' memories contained thousands of minute ferrite (magnetic ceramic) beads threaded on to copper wires which, although not nearly as delicate as they look, are nonetheless vulnerable, while more modern memories are fully electronic and so do not appear as a separate subsystem.

Finally, the electronics proper: CPU, control and (electronic) memory. This forms a substantial part of valve machines and is conspicuous in discrete transistor machines, but forms only a small part of integrated-circuit computers. However, these subsystems make up in complexity what they lack in bulk, containing a range of component types each of which may appear in several forms. The rest of the paper will be taken up with reviewing these.

Passive components

Passive components include resistors, inductors, transformers and capacitors. Diodes (two-electrode valves or semiconductor devices) are strictly passive at low frequencies but, since they share the technology of active devices, are usually considered with them.

All conductors have resistance, but resistors specialise in it, having well-defined resistances which may range from less than one to over a million ohms. A resistor generates heat when it operates, and its power-handling capacity is the basic parameter determining its size and construction. The bulk of resistors in electronic circuits handle only a fraction of a watt: typical construction is a small cylinder of plastic heavily loaded with carbon to render it conductive or, in more modern circuits, a ceramic tube coated with a thin film of carbon or metal. High-power resistors more often consist of a coil of resistance wire wound on a ceramic tube. Resistors are susceptible to moisture, which can change their value temporarily, or permanently if it initiates corrosion; they are usually painted to inhibit such processes but, particularly on large wire-wound resistors, the paint film often fails owing to repeated heating and cooling.

An inductor is simply a coil of wire (almost always copper), usually wound on a plastic bobbin through which may pass a core of magnetic material – iron or ferrite. Very early inductors may dispense with the bobbin and have the windings applied directly to the core, protected electrically by a layer of oiled paper or cloth. The whole thing is frequently covered in resin or varnish. You will not find many inductors in a typical computer: their function is basically to introduce time delays in analogue circuits, and where such delays are needed (to isolate high frequency circuits from each other, for example), expensive inductors can generally be replaced by cheaper capacitors. An exception is in the power supply unit, where large inductors capable of carrying heavy currents form part of the filters that remove 50Hz ripple from the supply.

Transformers and electric motors are related to inductors, differing from them in having more than one winding on the core, which is often supported in a cast or sheet metal frame. In the transformer, electrical power in one winding is transferred to the other with the ratio of voltage to current transformed. An electric motor is a form of transformer in which one winding is free to move, allowing electrical power to be transformed into mechanical power. The conservation problems of all these devices are similar, and arise from the possible interactions of their three basic materials: iron, copper and plastics. Faults are comparatively rare, but include winding and insulation damage caused by overheating, and rusting of frame or core after encapsulation failure. Motors, of course, suffer all the ills of moving machinery as well.

Capacitors consist of one or more insulated conducting plates (almost always of aluminium), stacked or rolled together inside some sort of outer covering. The insulation is known as the 'dielectric'. The function of capacitors is to accumulate charge on their plates, causing a voltage to appear across them and storing electrical energy as strain in the dielectric; as these processes take time, capacitors, like inductors, introduce time delay into circuits, governing the frequency of oscillators, for example. There are two major classes of dielectric, and hence of capacitor. The largest class consists of capacitors having a dielectric made from a permanent insulator such as paper, plastics, mica or ceramics. The most commonly used plastics are polystyrene and, more recently, polyethyleneterephthalate (PET) and polytetrafluoroethylene (PTFE). All these materials are highly stable and such capacitors present few problems. Capacitors found in machines built before about 1960, particularly for use at high voltages, may have oiled paper dielectrics which are less stable and possibly present toxicity hazards from polychlorinated biphenyls (PCBs). These oily compounds were used because of their high dielectric strength, but are now known to be carcinogenic. However, any risk here is slight compared with that from the real PCB villains — large, oil-filled transformers, not usually found in computers.

The other, smaller but highly significant class of capacitor uses as a dielectric the thin layer of non-conducting oxide that forms on the surface of aluminium when in contact with an electrolyte and subject to a sustained voltage. These 'electrolytic' capacitors consist of a fibrous layer soaked in an electrolyte and sandwiched between two sheets of aluminium foil, the whole being rolled up and sealed into an aluminium can, possibly with an outer heat-shrunk plastic jacket. Because the dielectric is very thin (yet often able to withstand hundreds of volts), and capacitance is inversely proportional to dielectric thickness, electrolytic capacitors have a much higher capacitance/volume ratio than other types, so are found wherever high capacitance values are required. However, because they depend both on retained liquid and on the maintenance of the 'forming' voltage across them, they present considerable conservation problems. Typical failure modes are resorption of the oxide film if the capacitor is left unused for several years, causing the capacitance to fall and the electrical leakage to rise; and loss of moisture through imperfect seals, causing total failure. Capacitors that have not lost their moisture can usually be re-formed by applying a voltage well below their working maximum for a few hours before putting them back into service.

Active components

Active devices include valves, transistors and integrated circuits. Computers used valves until the late 1950s, thereafter discrete transistors and, from the late 1960s onwards, integrated circuits incorporating many transistors on one chip of silicon. Valves use electric and magnetic fields to manipulate streams of electrons moving through a vacuum from a heated cathode to an electrode held at a higher electrical potential — the anode. They contain a complex assemblage of metal plates and wires inside a glass envelope which is evacuated to an extremely low pressure. Contact with the outside world is via wires which are sealed through the glass and connect to pins which can be inserted in a socket, allowing easy replacement of these relatively short-lived components. As long as the vacuum remains intact, the electrodes of a valve live in an ideal world from the point of view of conservation. Only the external pins, with possibly a plastic valve base, are exposed to the elements. Once the vacuum seal is penetrated, however, either by failure of a metal/glass interface or, more commonly, by physical damage to the envelope, the valve not only ceases to work but becomes a metal-containing object like any other. Some valve types used in 1950s computers are still available, but how long this situation will survive the breakdown of the Soviet Union, the prime market for and producer of such antique devices, is uncertain.

Although transistor action was observed in a laboratory device in 1947, it was another ten years before satisfactory commercial transistors were available.[1] Early transistors used germanium, at first duplicating the cat's whisker-like 'point-contact' construction of the laboratory prototype, soon afterwards adopting a more reliable 'alloyed junction' form. All these devices suffered from the fact that the active region of the transistor was more or less exposed to the elements, in spite of manufacturers' attempts to surround them with grease or seal them in cans or glass envelopes. It was not until the development of the planar process in 1962 that the transistor became a really rugged structure with all its working parts safely buried under a layer of silicon dioxide. So transistors from machines built before about 1965 may have died of old age, their delicate junctions poisoned by contaminants from the atmosphere or, more probably, from their packaging. This process is almost certainly irreversible and, apart from the problem that it presents to restorers, raises the question: to what level of detail are we seeking to conserve? The changes here are progressive, but on the atomic scale, and they are more significant than the easily-stabilised macroscopic processes occurring elsewhere in the machine. Perhaps one day we may see the evolution of a new breed of nanoconservators.

The planar process not only made cheap, reliable silicon transistors available to designers, it also provided a technology that could make integrated circuits, at first containing tens of transistors, latterly over a million on one chip. Computers currently in conservation will probably contain at the most some small-scale integration (SSI) chips, typically logic devices of the 7400 series (employing bipolar transistors) or 4000 series (formed from metal-oxide-silicon (MOS) transistors). In spite of their rather primitive plastics packaging, the inherent stability of the planar process has ensured in most cases that these chips still work. Indeed, early 7400 series logic chips are remarkably rugged, surviving static discharges that would kill their faster, more sophisticated descendants. The 4000 series devices can, however, be damaged by static electricity, and circuit boards containing them should not be handled without ensuring that tools and hands are earthed. Where devices have failed, there is generally a modern equivalent available. But should this be used, or should an exact replacement be cannibalized from another machine?

This section would not be complete without reference to the various forms of 'integrated circuit' that preceded the monolithic silicon types. These were in fact miniature circuit boards assembled from discrete components, sometimes using 'thick film' technology (screen-printed passive components and naked transistors on a plastics or ceramic substrate). After assembly, the circuits were sealed into a plastics case with epoxy resin to form a self-contained plug-in 'module'. These modules saved space but proved highly unreliable. Once sealed, the unpredictable brew of metals, resins and silicon, all with different coefficients of thermal expansion, often stopped working or, worse still, became intermittent. The solution, during the lifetime of the machine, was simple replacement of the whole module; this is now impossible.

Batteries

Many computers, especially microcomputers, contain batteries. They are normally there to power volatile memory containing system parameters or to run a clock. Larger systems may contain batteries that help the power supply unit maintain a highly stable, noise-free voltage to ensure that the logic circuitry works without error in the presence of mains voltage disturbances. Batteries are a conservator's nightmare. They are basically containers of metals and metal oxides immersed in highly corrosive electrolytes.[2] They may fail in many ways, some of more interest to restorers than conservators. One might label as a 'benign' failure the loss of water that results when hermetic seals fail: the battery stops working, but the corrosive ions are immobilised. 'Catastrophic' failures range from breaching of the battery casing, leading to corrosion of the battery compartment (a familiar domestic disaster) to explosion of lithium batteries when reverse polarised.

At least nine basic types of battery may be found in computers (see Appendix). These do not usually include the lead/acid battery used in cars, whose sulphurous fumes are tolerated only because of its good energy/weight ratio, although the uninterruptible power supplies (UPS) sometimes used to protect more modern computers may contain these.[3] The best advice one can give about batteries is to take them out of the equipment and store them elsewhere, well out of the way of other objects. If you need to use them, look after them properly: keep primary (non-rechargeable) batteries cool and dry; check secondary batteries periodically but don't recharge nickel/cadmium batteries unless you have to, or their capacity may be reduced by the 'top-up' effect (in which you get back only what you last put in). Finally, batteries that have been in equipment for years with no signs of corrosion have almost certainly dried out; they won't work, but they present no threat.

References

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(2) Vincent, C A, *Modern batteries* (London: Edward Arnold, 1984), pp 16–18

(3) Barak, M (ed), *Electrochemical power sources* (London: Peter Peregrinus, 1980), pp 288–9

Appendix: computer components and failure modes

Component	Construction	Materials	Failure modes
Frame	Cast or sheet metal with metal or plastics infill; plastics handles, castors or feet; flexible gasketing; painted, PVC laminated, nylon dipped, plated	Iron, steel, aluminium; melamine or phenolic laminates; rubber, PVC, nylon; chromium, zinc or cadmium passivated plating	Corrosion leading to jamming of hinges, catches and fasteners; failure of gaskets and castors; loss of paint adhesion; softening or embrittlement of PVC or nylon coatings; dents and scratches
Chassis	Sheet metal, plated	Steel, aluminium, zinc or cadmium passivated plating	Corrosion; dents and scratches
Printed circuit board	Phenolic/paper or epoxy/glass fibre board with conductors etched from laminated copper foil, solder coated; solder resist lacquer overall; edge connector pads gold flashed; early double-sided boards may have 'griplet' thru-connectors, later boards have plated-through holes	Phenolic and epoxy resins; paper; glass fibre; copper; foil adhesive; tin/lead solder; plasticised heat-resistant lacquer; gold; plating substrate for plated-through holes	Generally stable but very long-term stability of this complex sandwich unknown; 'griplet' connections crack with repeated flexing or temperature cycling
Connector	Ceramic or plastics moulding with inset pins or contacts plated with precious metals; may be enclosed in a cast or sheet metal housing, usually plated, sometimes painted	Glazed porcelain, phenol-formaldehyde, urea-formaldehyde, nylon, ABS, rubber; copper, brass, phosphor-bronze, nickel, chromium; platinum, rhodium, silver, gold; paints	Embrittlement of rubber; corrosion of contact surfaces; contact bending and misalignment due to poor handling or failure of supporting structures; loss of gold flashing due to repeated insertion
Wire	Copper or tinned copper solid or stranded wires insulated with rubber or plastics	Copper, tin; rubber (natural, synthetic or silicone); PVC, polyethylene, PTFE	Embrittlement of rubber; softening of PVC; internal fractures due to repeated flexing
Resistor (wire wound)	Resistance wire on ceramic former with metal end connectors, painted overall	Ceramic tube; nichrome wire; tinned copper connectors; paint	Fracture of ceramic former; corrosion of wire leading to open circuit, esp. at junction with end connectors; paint failure
Resistor (carbon composition)	Thermosetting plastic filled with carbon powder moulded over connecting wires, painted overall	Carbon; phenol-formaldehyde or other thermosetting plastics; copper, tin	Cracking of body due to stress or temperature cycling leading to increased resistance
Resistor (carbon or metal film)	Ceramic or glass tube coated with thin film of carbon or metal, with connecting metal end caps and wires; painted overall	Glass or ceramic; carbon or chromium film; copper/tin end caps and wires; paint	Generally stable; high value resistors have very thin films and are more vulnerable to corrosion after paint failure
Inductor (ferrite cored)	Ferrite core or pot; plastic bobbin; lacquered copper winding; soldered connecting pins	Ferrites; carbon-filled polystyrene; lacquered copper wire; copper/tin pins; tin/lead solder	Stress cracking of ferrite, esp. where 2-part core is mechanically compressed; may suffer failure of solder joints due to metallic leaching
Inductor (air cored)	Phenolic/paper or epoxy/glass fibre former; lacquered copper winding; soldered connecting pins	Phenolic or epoxy resins; paper or glass fibre; lacquered copper wire; copper/tin pins; tin/lead solder	Generally stable, but may suffer failure of solder joints due to metallic leaching

Transformer (power)	Laminated iron core with lacquered copper windings separated by plastic or oiled paper; foil screens; phenolic/paper tag strips with tinned copper tags; pressed steel shrouds, zinc or cadmium plated or painted	Iron, steel; lacquered copper wire; PVC, polyethylene, PET or PTFE; paper; oils including polychlorinated biphenyls; aluminium foil; phenol-formaldehyde resins; copper, tin, lead, zinc, cadmium; paints	Generally stable, but may suffer failure of soldered joints or loss of insulation resistance in oiled paper or plastics layers; note PCB hazard
Transformer (signal)	As for inductors (ferrite cored), but core may be painted	As for inductors (ferrite cored), plus paint	As for inductors (ferrite cored), plus possible paint failure (no electrical effect)
Capacitor (film-foil)	Aluminium foil rolled up with plastics film and plastic encapsulated with axial connecting wires	Aluminium; polystyrene, polypropylene, polycarbonate, PET; possibly PVC outer; tinned copper wire	Generally stable
Capacitor (metallised film)	Vacuum coated plastic films, rolled or layered together and plastic encapsulated with axial or radial connecting wires	Aluminium on PET; range of plastic outers including epoxy dip and injection moulded polystyrene; tinned copper wire	Generally stable
Capacitor (silvered mica)	Natural mica, silver plated and layered, with riveted silver plated connecting leads, coated with paint-like composition	Mica; silver, copper; resin composition	Generally stable; riveted connections may fail under mechanical stress
Capacitor (paper)	Aluminium foil rolled or layered with oiled paper; tinned copper connecting wires or tags; plastics or sheet steel case	Aluminium; paper; oils including PCBs; copper, tin; phenol-formaldehyde resins; steel; paints	Loss of oil through imperfectly sealed casing; corrosion of steel casing
Capacitor (ceramic)	Aluminium layers fused within ceramic stack; tinned copper wires; plastics encapsulation	Ceramics; aluminium, copper, tin; epoxy or other outer dip	Generally stable
Capacitor (electrolytic)	Aluminium foil rolled up with paste electrolyte or electrolyte-soaked paper in aluminium can, sometimes with plastic outer; hermetically sealed with rubber bung; tinned copper wires or tags	Aluminium; paper; corrosive electrolyte; plastics shrink-film outer; rubber; copper, tin	Drying or leakage of electrolyte due to imperfect seal; loss of electrolytically formed dielectric coating on positive foil, leading to high leakage / low capacitance (can be restored by re-forming with applied voltage)
Capacitor (variable)	One set fixed, one set rotatable metal plates with air or plastic dielectric, in metal or plastic frame; connecting screws, tags or pins	Aluminium, brass, copper, phosphor bronze, tin; ebonite, PET, polystyrene	Generally stable
Valve	Evacuated glass tube with plated metal electrodes and cathode coated with high-emission compound; connecting wires/pins of special alloy with thermal expansion matched to glass; earlier types have phenol-formaldehyde base glued to glass and sprung plated copper pins	Glass; copper and other metals used for plating; thorium compounds on cathode; alloy connecting wires	Loss of vacuum due to cracking or failure of seal where connecting wires emerge through glass; detachment of base due to adhesive failure, with possible breakage of connecting wires
Diode (point contact)	Germanium crystal sealed in glass envelope with contact wire and external connecting leads	Germanium; copper and other (unknown) platings / probe wire; glass; alloy connecting wires	Vulnerable to mechanical stress where connecting lead is sealed through glass — crystal contamination will cause failure if seal broken

Diode (Schottky barrier)	Silicon crystal sealed in glass envelope with metal electrode in contact and external connecting leads	Silicon plus trace dopant; glass; alloy connecting wires	Generally stable; small size makes them mechanically rugged
Diode (junction)	Silicon junction sealed in glass envelope with connecting leads	Silicon plus trace dopants; glass; alloy connecting wires	Generally stable; mechanical stress may destroy metal / glass seal
Transistor (point contact)	Germanium crystal with two probe wires, three connecting wires, sealed in metal case, possibly with grease as moisture barrier	Germanium; copper and other (unknown) platings / probe wires; aluminium case; tinned copper wire; grease	Failure due to contamination of germanium surface is normal; leakage of grease
Transistor (other germanium types)	Germanium crystal with transistor structure formed by alloy junction or surface barrier process; tinned copper connecting wires; sealed in metal case	Germanium, indium and other metals; aluminium case; tinned copper wire	Failure due to contamination is common
Transistor (silicon bipolar)	Silicon crystal with or without epitaxial layer, with transistor structure formed by junction, surface barrier, mesa or planar process; gold internal, tinned or gold plated copper external connecting wires; encapsulated in plated metal or plastic package	Silicon plus trace dopants; gold, copper, tin; nickel or cadmium plated brass or steel case; thermoplastic package	Generally stable (post-1962 planar process most stable); any failures, apart from mechanical damage, due to contamination of exposed junctions
Transistor (FET)	Silicon crystal with epitaxial layer, with field effect transistor structure formed by planar process; gold internal, tinned or gold plated external connecting wires; encapsulated in plated metal or plastic package	Silicon plus trace dopants and aluminium metallisation; gold, copper, tin; nickel or cadmium plated brass or steel case; thermoplastic package	Generally stable, but functionality will be destroyed by electrostatic effects if handled without shorting or grounding
Transistor (BeO power)	As other bipolar types but includes high thermal, low electrical conductivity layer to aid heat dissipation	As other bipolar types, plus beryllium oxide	As other bipolar types, but beryllium oxide is strongly carcinogenic — damage to outer package indicates health hazard
Hybrid circuit	Small circuit board containing discrete components encapsulated in plastics case filled with epoxy resin	All constituents of included components; polystyrene outer case; epoxy resin potting compound	Inaccessible internal component or connection failures leading to loss of function; gross cracking of outer case due to incompatible thermal / hygroscopic properties of plastics
Integrated circuit (bipolar, metal case)	Single silicon chip processed to form complete circuit, mounted on metal header with internal gold connecting wires, in plated metal can with plated wire external connections	Silicon plus trace dopants; aluminium track metallisation; gold; nickel or cadmium plated brass or steel case; copper leadout wires, usually gold plated	Generally stable
Integrated circuit (bipolar, plastic or ceramic package)	Single silicon chip processed to form complete circuit, mounted in plated sheet metal lead frame with internal gold bond wires, in injection moulded plastic or glued two-part ceramic package with plated sheet metal PCB pins	Silicon plus trace dopants; aluminium track metallisation; gold; plated brass lead frame and pins; thermoplastics, e.g. ABS; ceramics with epoxy sealant	Generally stable; recent types with sub-micron features may suffer electrostatic damage if handled without grounding

Integrated circuit (EPROM)	As other bipolar silicon integrated circuits, but in ceramic package with quartz window for UV erasure	As other bipolar silicon integrated circuits plus quartz	Any stored data vulnerable to long-term UV exposure and will be erased quickly at high intensities (e.g. sunlight); dark life uncertain
Integrated circuit (FET)	As for integrated circuit (bipolar)	As for integrated circuit (bipolar)	Generally stable, but functionality will be destroyed by electrostatic effects if handled without grounding or shorting
Tape drive	Induction, DC and stepper motors driving tape via solenoid clutches, brakes, pinch wheel and capstan or sprocket drive; reels of plastics tape with magnetic coating; in painted or coated steel cabinet with glass front	Zinc alloy motor frames with iron armatures and lacquered copper windings, cloth or PVC tape wrapped, solenoids similar; steel moving parts on steel or zinc alloy chassis; organic friction pads and drive belts; lubricants; cellulose triacetate or PET tape coated with ferrous oxide in organic binder; electronics contain all materials listed under separate components; case painted or plastics-coated steel with plated catches etc, glass, rubber gasketing	Corrosion of steel parts; solidification of lubricants; seizure of bearings due to both of these; reaction of PVC tape with wire lacquer; stiffening of friction pads and drive belts; loss of tape coating adhesion; softening of coating lacquer; loss of information on low coercivity tapes possible if exposed to strong magnetic fields
Disk or drum drive	Induction or DC motor rotating drum or disk with stepper motors operating track selector; control electronics; all in metal case	Zinc alloy motor frames with iron armatures and lacquered copper windings, cloth or PVC tape wrapped; steel moving parts on steel or zinc alloy chassis; lubricants; aluminium drum or disk coated with ferrous oxide in organic binder; electronics contain all materials listed under separate components; case painted or plastics-coated steel with plated catches etc, rubber gasketing	Corrosion of steel parts; solidification of lubricants; seizure of bearings due to both of these; reaction of PVC tape with wire lacquer; loss of drum or disk coating adhesion; softening of coating lacquer; loss of information on low coercivity drums or disks possible if exposed to strong magnetic fields
Battery (vented nickel-cadmium)	Pocketed nickel plated steel or sintered nickel plates filled with cadmium / iron (negative) or nickel / cobalt hydroxides (positive), immersed in 25% potassium hydroxide electrolyte solution in plastics container with plastics spacers / separators and metal connectors	Cadmium, iron, nickel, graphite; nickel / cobalt / barium hydroxides; water; potassium / lithium hydroxides; brass; nylon, polystyrene, polyethylene, polypropylene	Leakage of caustic electrolyte; swelling and loss of filling from plates; loss of electrolyte by evaporation; mechanical and electrochemical damage due to excessive rates of charge / discharge; deterioration through normal repeated charge / discharge cycle (deterioration in storage, in any state of charge, is slow)
Battery (sealed nickel-cadmium)	Similar to vented type, but with excess cadmium hydroxide in both electrodes to prevent gassing and with high permeability separators for good oxygen diffusion; button (disc electrodes) or cylindrical (wound electrodes) construction in nickel plated steel case; buttons may be stacked in plastic outer for higher voltage	As for vented type, but with lower plastics content	Loss of electrolyte through safety vent due to gross overcharging; charge / discharge and storage deterioration as for vented type, although some evidence of 'topping up' effect in which premature charging leads to loss of capacity; early types suffered from dendritic cadmium growth during charging, leading to short circuits

Battery (Cylindrical Leclanché)	Powdered manganese dioxide and carbon positive electrode with carbon current collector; ammonium chloride paste electrolyte; amalgamated zinc container (negative electrode); paper, fabric or plastics separator; plastics or bitumen seal; paper or plated steel outer	Manganese dioxide, carbon; ammonium / zinc chlorides; water; starch, polyvinyl or cellulose alkyl ethers (gelling agents); zinc, lead, cadmium, mercury; brass, steel; paper (porous for immobilising electrolyte or light board for packaging); bitumen, plastics	Corrosion of anode (zinc container) due to oxygen ingress, direct attack by electrolyte or electrochemical effects of impurities; water loss by evaporation or formation of hydrates; damaging leakage after heavy discharge caused by corrosive rise in pH at zinc and pressure of trapped hydrogen; race between drying and leakage can occur: if battery dries before it leaks, it remains stable
Battery (stacked Leclanché)	Flat cake of powdered manganese dioxide and carbon forming positive electrode; paper, fabric or plastics separator; paper impregnated with ammonium chloride electrolyte; carbon coated zinc duplex electrode (negative of one cell, current collector of next); each cell has plastic retaining band, with wax seal round stack of cells in plated steel outer; insulated wire connects bottom electrode to top connector	As for cylindrical type, but higher plastics content	Generally as for cylindrical type, but note that the sealing method (plastic and wax) is quite different; leakage can occur without corrosion of zinc electrode
Battery (zinc chloride)	Similar to cylindrical Leclanché type, but electrolyte contains no ammonium chloride, zinc container is plastic jacketed and elaborate seals reduce leakage; recognisable by 'High Power' designation	As for cylindrical Leclanché type, but without ammonium chloride and with a higher plastics content	As for cylindrical Leclanché type, but with improved leakage performance due to lack of hydrogen build up and better seals
Battery (alkaline)	A form of the cylindrical Leclanché in which a hollow powdered amalgamated zinc negative electrode is placed at the centre of a plastic sleeve: the electrolyte, gelled concentrated potassium hydroxide, fills this electrode and also impregnates a fabric separator between the zinc and the manganese dioxide positive electrode; an insulated metal base cap connects to the zinc via a brass collector; the plated steel jacket forms the positive connector	As for cylindrical Leclanché, but chlorides replaced by 30% potassium hydroxide solution with some zinc oxide and immobilised using carboxymethyl-cellulose	The vulnerable zinc electrode plays no part in sealing, which is achieved by elaborate design of steel and plastic outer, so leakage is rare, but catastrophic when it does occur (perhaps through mechanical damage), owing to the highly caustic nature of the electrolyte; undischarged shelf life is good — typically 80% capacity after 4 years
Battery (mercury)	Cellulose absorber, soaked in concentrated potassium hydroxide electrolyte solution, sandwiched between compressed pellets of amalgamated zinc powder mixed with electrolyte (negative electrode) and mercuric oxide / carbon (positive), inside two-part plated steel 'button', sealed and insulated by plastic gasket; zinc foil / paper coil is sometimes used instead of zinc pellet	Zinc, mercury; potassium (sometimes sodium) hydroxide, zinc oxide; mercuric oxide, carbon; cellulose; steel, nickel; plastics	Designed with excess mercuric oxide, so that exhausted cells have no zinc left which could give rise to hydrogen evolution and bursting. Stable unless mechanically damaged or plastic gasket deteriorates

Battery (silver zinc)	Similar to mercury type but using silver oxide instead of mercuric oxide for the positive electrode	As for mercury type, but with mercuric oxide replaced by silver oxide	As for mercury type
Battery (lithium)	Lithium negative electrode used with a wide range of solid, liquid and gaseous positive electrodes and non-aqueous electrolytes; construction in button, flat, and bobbin and wound cylindrical forms, plus larger types for military use; most common commercial type uses thionyl chloride liquid cathode with a dissolved salt providing conductivity	Only thionyl chloride type dealt with here: lithium; thionyl chloride, lithium aluminium chloride; teflon / carbon; nickel plated steel	Extended shelf life; hermetically sealed, but thionyl chloride is very aggressive; misuse, e.g. inadvertent charging due to failure of protection diodes in back-up circuits, can lead to high sulphur dioxide pressure and explosion

Collecting Software:
Preserving Information in an Object-Centred Culture[1]

Doron Swade

Abstract:

Computer software is not yet an explicit part of the custodial mandate of the museum establishment and there is growing alarm at the historical implications of this exclusion. The nature of software is philosophically problematic. In practical terms, a programme of acquisition and conservation is technically forbidding as well as resource intensive. This article attempts to locate software as an artefact in the material culture of museums and explores some of our preconceptions and expectations for a software preservation programme. It examines some respects in which software is both like and unlike traditional museum objects. It briefly considers the prospects for extending the operational life of obsolete systems through physical restoration as well as logical simulation.

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Museums are part of an object-centred culture. Their essential justification is the acquisition, preservation and study of physical artefacts. Physical objects, their meaning, significance and their care, dominate a curator's professional psyche. One of the first tasks, then, is to locate computer software in the artefactual landscape. Computer hardware, as a category of object, is seemingly unproblematic. It is the physical stuff of computer systems and falls painlessly into the custodial universe of conventional object-centred curatorship. Software, a term in general use by the early 1960s, is usually defined negatively, that is to say, a component of computer systems distinct from hardware. The *Oxford Dictionary of Computing* (1986) defines software as 'a generic term for those components of a computer system that are intangible rather than physical'. Prentice Hall's *Illustrated Dictionary of Computing* (1992) irreversibly severs the material link by noting that 'software is independent of the carrier used for transport'. The non-material features of software have ominous implications. The Science Museum's Corporate Plan for 1992–1997 states that one of its core objectives is to 'acquire the most significant objects as physical evidence of science worldwide'. Physical objects are explicitly identified as the evidentiary medium. We have a *prima facie* conflict. If what distinguishes software is something non-physical, and software is in some sense irreducibly abstract, then it falls outside the mandate of material culture and a conscientious museum curator might have qualms about mobilising resources to acquire and preserve it. The dilemma may seem pedantic. But there is a real issue: in whose custodial territory does software fall? Is it the responsibility of the archivist, librarian, or museum curator? Some software is already bespoke: archivists and librarians have 'owned' certain categories of electronic 'document' – digitised source material, catalogues, indexes and dictionaries, for example. But what are the responsibilities of a museum curator? Unless existing custodial protection can be extended to include software, the first step towards systematic acquisition will have faltered, and a justification for special provision will need to be articulated *ab initio* in much the same way as film and sound archives emerged as distinct organisational entities outside the object-centred museum establishment.[2]

The distinction between hardware and software is not absolute. 'Firmware' (programs held in read-only memory (ROM)) defies categorisation as exclusively one or the other. The ROM-chip itself clearly belongs to the universe of hardware. Yet insofar as the chip embodies a symbolic record of a program it is apparently also software. If forced to answer the question 'is firmware hardware or software?', you would be excused for responding with a helpless 'yes'.

One way of by-passing philosophical misgivings about the materiality of software is to appeal to the broader mandate of science museums to maintain a material record of technological change. Software represents a substantial human endeavour, and the intellectual, economic and material resources involved in its production and distribution represent a major technological movement. Its importance is not in dispute. So perhaps we can bluff it out and collect software by day leaving philosophical disquiet to the troubled night. In practical curatorial terms the abstraction of software is, in any event, something of a pseudo-problem. We do not collect prime numbers or polynomials. We collect instead physical models, mathematical instruments and the written deliberations of mathematicians. In much the same way our curatorial concern for software centres on the external physical record of programs and data – coding sheets, punched paper tape, punched cards, flowcharts, manuals, magnetic discs, publicity literature, i.e. the distinct physical media of creation, representation, distribution and storage. So we could perhaps make a case for offering curatorial protection to artefactual software by regarding it as part of the contextual and functional extension of hardware without which technical history would be incomplete.

But the lump under the carpet is still visible. Once we grant ourselves the licence to collect the physical artefacts of software, there remain, at least at first sight, respects in which software is both like, and unlike, traditional museum objects. At the centre of curatorial practice is something called an inventory procedure. This procedure formally transfers the 'title' of the object from the donor/lender/vendor to the Museum. Each inventoried object is the direct responsibility of a named curator, the collecting officer, who signs a formal declaration of responsibility for each object when it is acquired. "I hereby take responsibility for the objects described overleaf" is the forbidding form. An object once inventoried is subject to formidable safeguards against disposal and unqualified alteration. In museum culture the physical integrity of an inventoried object is sacrosanct and the act of inventorying marks its transition into protective custody. However, objects decay despite our best efforts to conserve them. Yet, when we acquire a brass telescope, it remains a brass telescope despite inevitable deterioration. We refer to a rusted telescope as a 'rusted telescope' or more impressively, 'telescope, condition poor'. The time-scale of its degeneration does not seem to threaten its identity as a telescope, that is to say, its physical deterioration is sufficiently slow to support the illusion of permanence. That it is a telescope seems not to be at risk. Ultimately when time reduces our prized telescope to some orphaned lenses adrift in a little heap of metallic oxide we sadly shake our heads over the debris and say 'this was a telescope', or, in Pythonesque terms, 'this is an ex-telescope'.

This acquisition model for conventional physical objects poses two curatorial conundrums for any potential software acquisition programme. There is the issue of permanence, and the related issue of artefactual identity. Magnetic media, the most common means of information storage for machine-readable software and data, are notoriously impermanent. Banks, required to retain computer records for audit purposes, were advised in the US in the early 1980s that no archived magnetic medium over three years old should be regarded as reliable. Posterity stretches ahead without limit whereas disc and tape manufacturers, when they are prepared to commit at all, are reluctant to do so for more than a few years. In what sense can a curator responsibly sign the acquisition declaration knowing full well that there is no guarantee that a floppy disc or tape will be readable in a few years even if pampered with executive class conservation treatment – acid-free packing, humidity- and temperature-controlled environment, and low ambient light levels? While magnetic media are in general demonstrably more robust than worst-case fears indicate, it is only worst-case life-expectancy figures that can responsibly be adopted in the context of systematised software archiving.[3]

The acknowledged impermanence of the medium leads to the question of artefactual identity. Is a set of floppy discs for Windows 1.0, say, like the telescope with an identity that transcends its state of repair? If the information content, represented by the magnetic configuration of the disc coating, is what makes a set of discs Windows, then does 'Windows 1.0, condition poor' mean anything? In more practical terms, does meaningful collection of software imply a functionally intact copy with the promise or potential of running it? If so then we have at least one clear respect in which artefactual software, acquired in accordance with the canons of conventional museology, differs from software acquired for archival purposes.[4] We do not ask 'functional intactness' of the telescope. 'Telescope, broken' does the job.

We can perhaps draw a useful analogy with pharmaceutical products. I learn from my medical sciences colleagues that the Science Museum has recently placed some proprietary drugs on inventory. Panadol, say, is now an inventoried object. There is valuable cultural information in the physical artefact: tablet form, bubble-pack press-through dispenser, advertising imagery used in the logo and packaging, and information about consumer appeal. But we can be reasonably sure that the drug company will not guarantee the potency of the sample beyond its sell-by date. We are clearly acquiring Panadol at least partly as a cultural artefact on the understanding that its chemical infrastructure and therefore its potency is ephemeral. In museological terms Panadol does not cease to be Panadol when it is no longer chemically potent. Similarly, the centuries-old 'poison-tipped arrow' remains so-called though the likelihood of any residual toxin is remote. Is the Windows disc like Panadol? Apart from the facetious difference that the one gives headaches which the other alleviates, there are strong similarities. 'Potency' in both cases is not visually meaningful. Function is not manifest in external form. Further, the Windows discs are no less a vehicle for contextual and technical messages than the Panadol pack: symbolism and imagery in brand logos and packaging, quality of label print, physical size, soft or hard sectored, whether or not factory write-protected, presence of reinforcing ring and so on. The discs are informative as generic objects (media) as well as conveying product-specific information about Windows. However, the richness as a cultural object of a deteriorated Windows 1.0 disc pack is cold comfort to an archivist or historian preoccupied with preserving or regenerating the operational environment of the product. So we return to the question of functional intactness.

Software we know is 'brittle'. It degrades ungracefully. We are all familiar with the awful consequences of what in information terms may be a trivially small corruption. One bit wrong and the system crashes. There are however situations in which the value of magnetically stored information is not bit-critical. Discs used as storage media for textual data as distinct from programs provide one example. Parchment deteriorates leaving us with partial or fragmentary records. A progressively corrupt magnetic record is simply a partial record but a usable record nonetheless. The residual data are not deprived of meaning or access by partial corruption. The 'all or nothing' fears do not in this case apply and we may be encouraged to re-examine whether there is some give in the apparently uncompromising need for bit-perfect records of program software.

If we look at the effects of corruption on program performance we can identify three broad categories. Non-critical corruption covers situations in which unused portions of the program are compromised – unused print drivers, irrelevant utilities or subroutines, for example. If we use a steam engine, say, as an example of a conventional museum object, 'non-critical corruption' would correspond to the damage to an unused or non-critical part – a nut dropping off, a dented panel. Damage in this case does not compromise the primary function, that of producing traction. Critical corruption leading to evident malfunction is a second category – the system hangs, the cursor freezes, the operating system fails to boot, or the program produces obvious gibberish. In our steam locomotive comparison, the engine loses traction, or makes an expensive noise and stops. So far the comparison with physical machines works. The third and most worrying category is critical corruption that produces non-evident errors – a maths program that produces an incorrect numerical result, a data-base manager that cross-labels data records, for example. Comparison with the stalled steam engine is not obvious. Perhaps a closer analogy would be with a telescope that misrepresented what we were looking at. The distant unsighted object is a church steeple. But observed through our telescope (condition, good) we see the image of a mosque. It seems reasonable to conclude that if archived program-software is to be run, the need for bit-perfect records is uncompromising.

If the medium of issue is magnetic then the indefinite maintenance of bit-perfect records commits us to an active program of periodic renewal and integrity checking, or a one-off transfer to a more permanent medium.[5] Engineering instinct favours retaining the medium and format of issue to ensure compatibility with the original hardware. Transferring software to a more permanent storage medium, optical disc, for example, offers a tempting liberation from the fate of perpetual periodic renewal. However, the interdependence of hardware and software poses formidable technical difficulties to running programs so transferred. Machine-independent software is frequently anything but. Correct operation of applications software relies more often than not on particular revisions of system software, program patches, hardware upgrades, firmware revisions and machine dependent interfacing to peripherals. Transferring to an alternative medium requires new data formats yet to be standardised and dependence on a new generation of hardware to read or download stored information. Interfacing to these devices and executing code so stored is not straightforward. Transfer to a more permanent medium is not without penalty despite its promise of releasing Sisyphus from his fate in the copying room.

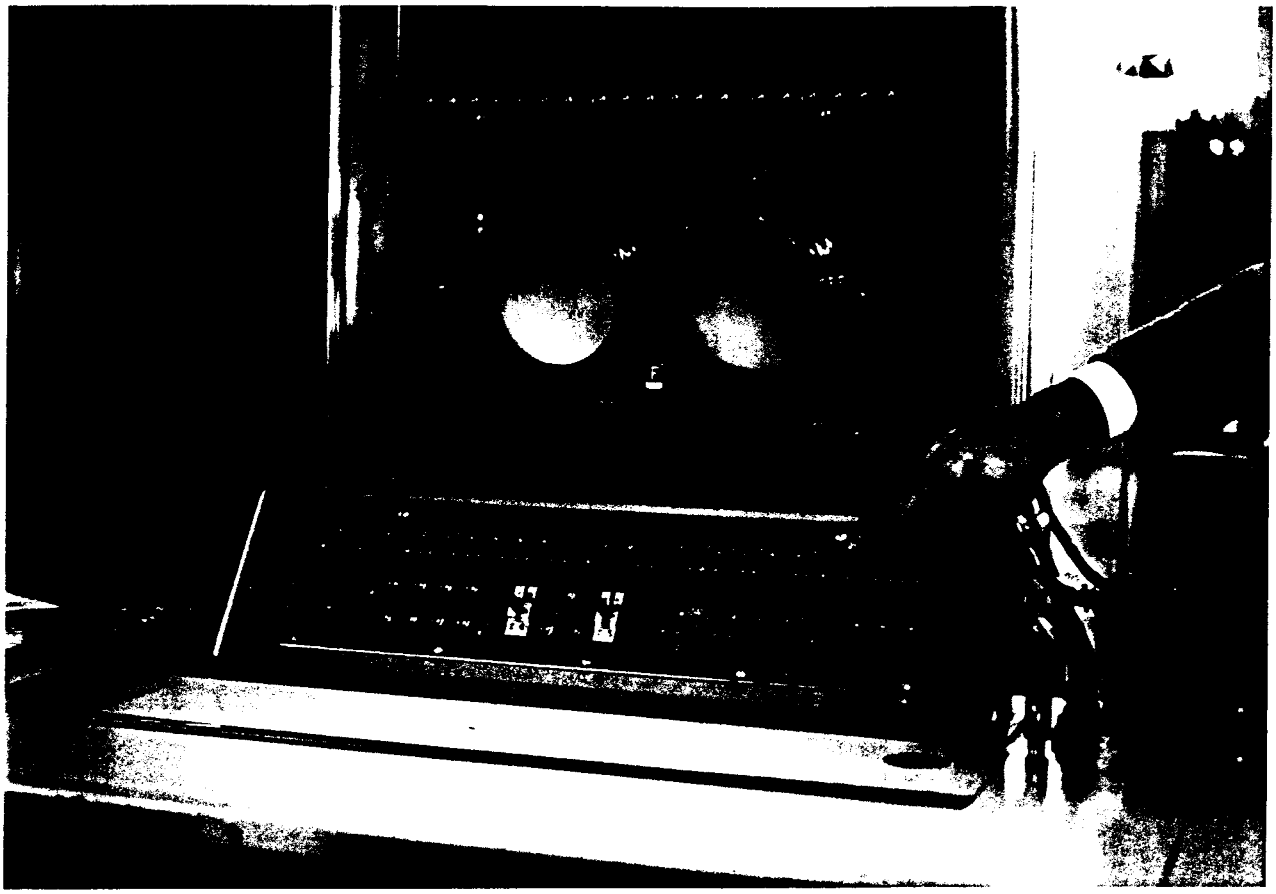
The requirement for functional intactness of software not only entails the maintenance of bit-perfect records but also implies the provision at some time of operational contemporary hardware or a functional equivalent. Neither the provision of contemporary hardware or a functional equivalent is trivial. In 1989 the Science Museum, with the British Computer Society, founded the Computer Conservation Society dedicated to the restoration and preservation of historic computers and to the capture of operational know-how of computing machines. The Society has had signal success in restoring to working order a Ferranti Pegasus, a large vacuum-tube machine dating from 1958, and an Elliott 803, a discrete component germanium transistor machine dating from 1963. At best such ventures can extend the operational life of obsolete systems. The life expectancy of the Pegasus, for example, has been extended by an estimated 5–10 years. But however successful these endeavours, we have to accept the eventual demise of such systems. The intractable fact of the matter is that in terms of archaeological time-scales the operational continuity of contemporary hardware cannot be assured even when suitable specimens are available to begin with. What meaning, then, does an archive of bit-perfect program software have if the material cannot be run?

One way forward presently being explored by the Computer Conservation Society is to simulate early hardware on present-generation computers using the restored original as a benchmark. Two simulations are well advanced, one for the Pegasus, the other for a German Enigma cypher machine. In the case of the Pegasus, console switches, console oscilloscope traces, input/output peripherals (paper tape, teletype-style printers) are visually simulated in facsimile and animated on-screen. The operator can write, run and debug programs by 'driving' the simulated controls and the simulator responds appropriately even to the extent of execution times. Since the original storage medium for software is paper tape, surviving data and software libraries can be captured and preserved on modern hardware by interfacing to contemporary optical tape readers and storing the programs in a form that can executed by the simulator.

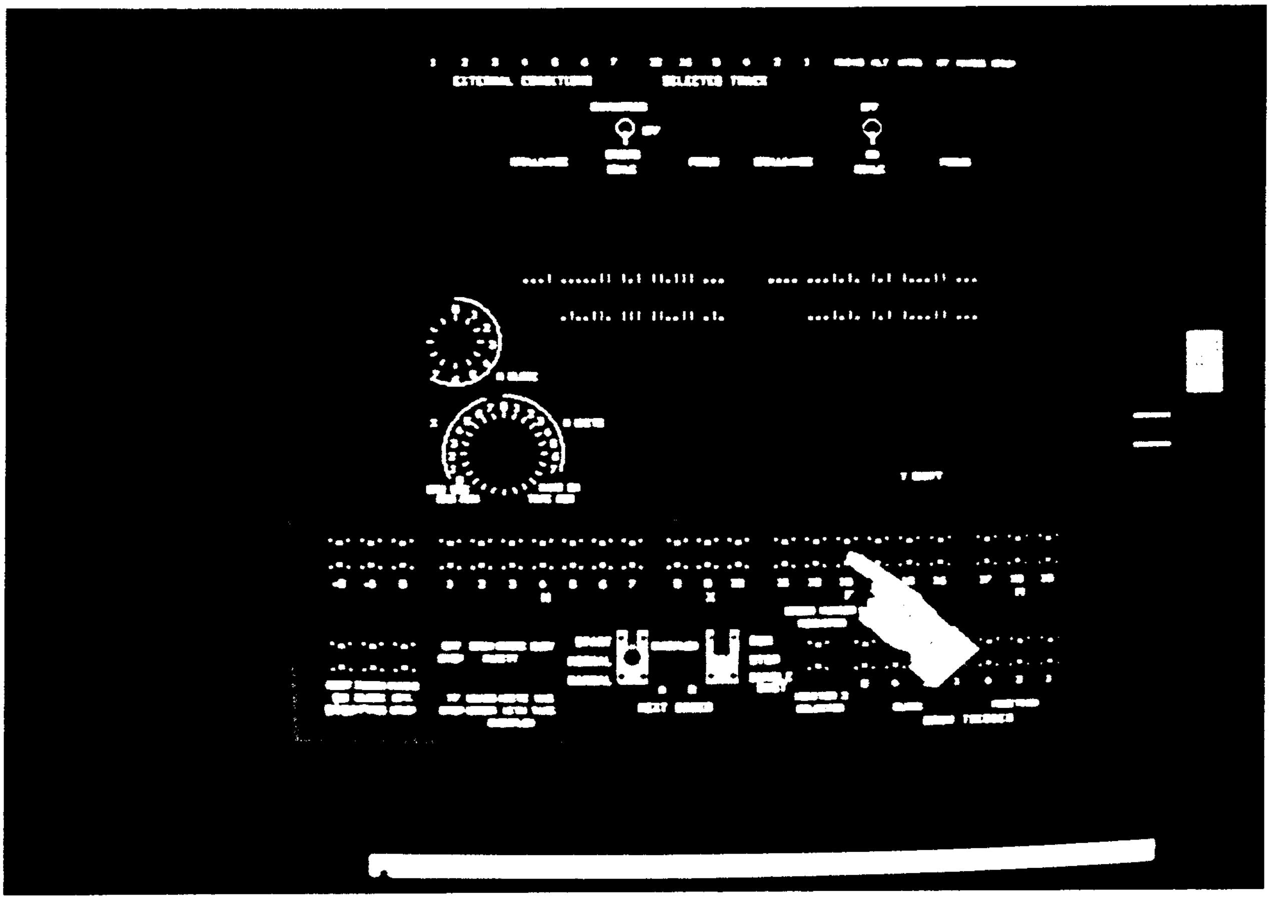
The museological implications of such simulations are intriguing. An implicit tenet of museum life is that the original object is the ultimate historical source. In museum culture

Ferranti Pegasus, 1958

The restored machine pictured in the Old Canteen, Science Museum, South Kensington



Ferranti Pegasus, Engineer's Console



Ferranti Pegasus, Modern simulation of engineer's console and peripherals the original physical artefact is venerated at the expense of a replica, duplicate, reconstruction or hologram. However, physical replicas can only incorporate features and characteristics perceived to be significant at the time of replication and part of the justification for preserving original objects in preference to a copy is that the original can be interrogated in an open-ended way in the light of unforeseen enquiry.[6] If we wished to test a new theory about Napoleon's allergy to snuff, say, it would not make sense to examine look-alikes of Napoleon's clothing. Prior to the snuff-allergy hypothesis, snuff-content would not be a consideration in the making of garment replicas. Only the original artefact with authenticated provenance would suffice for this forensic purpose. However, logical replication as distinct from physical replication seems to offer more. Capturing the operational persona of an early machine on a later machine promises possibilities for open-ended analysis of the kind formerly offered only by a working original. The technique seems to offer a form of logical immortality as computer languages used for the simulations become increasingly machine-independent.

The resource implications of a meaningful software acquisition programme are formidable. However persuasively we argue to include software in the existing fold of custodial protection, the need for the special provision of resources cannot be evaded. The maintenance of bit-perfect records requires an open-ended commitment to periodic copying and checking. This requires staff and equipment. The transfer of program-software to optical media invokes a raft of technical issues of operational compatibility that would require prohibitively large (for a museum with a conventional mandate) engineering and hardware design investment to solve. The restoration and maintenance of contemporary hardware on an indefinite basis demands vast financial resources and the opportunity cost is likely to be politically indefensible. The development of simulations and emulations is technically promising but the skills-levels are high and the financial implications of programming, development and verification are substantial. The progress made in this field at the Science Museum would have been unaffordable without the voluntary efforts and expertise of Computer Conservation Society members. In custodial terms, even a successful simulation exercise does no more than transfer the operational persona of an historic early machine to a currently supportable platform (typically a 486-based PC) which will itself be duly subject to generational obsolescence: the potential of the technique lies not in the immortality of current hardware but in the prospect of machine-independent software. But the Utopia of machine-independence may not ultimately appear on the custodial atlas of the future. In the meanwhile, simulation buys time and allows us to pass the baton to the next generation which may well have to face similar problems.

Despite the formidable obstacles that face a fully-fledged software preservation programme there is at least one modest but significant programme of software acquisition that is technically achievable and that has affordable resource implications, namely, software for personal computers – 'shrink-wrapped' consumer software as well as custom-written special applications software. It remains a realistic objective to acquire working specimens of significant volume-production post-1977 personal computers and their variant upgrades. The technical skills required to recommission, repair and maintain such machines are still available. The complementary task is to identify and acquire significant examples of contemporary consumer software, from VisiCalc (an early spreadsheet package for the Apple II, available in 1979) and Electric Pencil (a word-processing package for the Tandy Model I, 1978), through to DOS 6.0 and Windows 3.1 for presentday PCs. The acquisition of these products can be accomplished with existing resources at the Science Museum. The recommissioning of the hardware, copying onto fresh stock, and documenting the operational quirks of the systems would require additional but affordable technical support. Once established, the 'archive' will be relatively easy to keep updated – this by purchasing off-the-shelf current software products and contemporary hardware. In the absence of an independently resourced organisation with a specific brief to preserve systems and applications software, this programme represents one practical step we can take. In overall archival terms the venture is no more than a holding operation. Perhaps the cavalry will still arrive in time.

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Notes and References

1. This paper is an edited and expanded version of an article published under the same title in *History and Computing*, Vol.4, No.3, 1992. The version reprinted here appeared in *Electronic Information Resources and Historians: European Perspectives*, Seamus Ross & Edward Higgs (eds), St. Katharinen: Scripta Mercaturae Verlag, 1993.

2. The National Sound Archive (NSA) opened in 1955 as the British Institute of Recorded Sound. The NSA became part of the British Library in 1983. See Day, T., 'Sound Archives and the Development of the BIRS', *Recorded Sound: The Journal of the BIRS*, No.80, July 1981. The National Film Archive was founded in 1935. See Butler, I., *"To Encourage the Art of the Film": The Story of the British Film Institute*, London: Robert Hale, 1971.

3. Thirty-year old magnetic tapes have been successfully read at the Science Museum, London. The 35mm tapes were created on an Elliott 803 discrete component germanium transistor computer dating from 1963. This computer was restored to working order and original tape stock read on the original hardware. The tapes, stored in metal canisters, were stowed in an unregulated garage environment for many years without any special conservation measures taken. In the PC context, material written to floppy discs over ten years ago is commonly still usable.

4. Aspects of these issues are treated in 'Collecting Software: A New Challenge for Archives and Museums', *Archival Informatics Newsletter and Technical Report*, Vol.1, Part 2, David Bearman, Pittsburgh, PA: Archives and Museum Informatics, August 1987.

5. Gunnar Thorvaldsen, formerly with the Norwegian National Archives, reports on integrity checks on archived tapes being carried out every two years and routine transfer to new tape stock every five years. See 'The Preservation of Computer Readable Records in Nordic Countries', *History and Computing*, Vol.4, No.3, 1992.

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Conserving the Information Machine

Suzanne Keene

The objective of this paper is to examine the thinking that has been taking place on conserving computer systems from the perspective of 'conventional' conservation ethics and professional practice, and to see if useful parallels can be drawn with approaches to the conservation and use of other types of object.

Conservation ethics

At the foundation of the conservation ethic lies the precept 'thou shalt not change the nature of the object'[1]. Ethics are necessary in conservation because the processes which take place can drastically alter the object. It is not possible to specify and supervise such complex work in sufficient detail for total control: therefore it is necessary to indoctrinate the practitioners with general values which will determine, or at least influence, how they act. Once people have been inculcated with a value system, they cannot be expected to violate it to order. You would not, for example, be able to find a surgeon in the UK who would amputate your leg if there was nothing wrong with it; medical ethics would preclude it.

In the precepts generally adopted in conservation ethics, conservation is seen as the perpetuation of the object-as-evidence about past technology, values, or use. Alterations to the object are more and more being kept to a minimum. This is in order that museums can meet their obligations to maintain collections as the basis for study and research, and to show users and visitors, as far as possible, 'the real thing': objects from which they can draw their own conclusions, rather than objects altered to conform to a particular viewpoint or passing taste[2]. Minimising conservation is also an acknowledgement that conservation treatments have often failed in the past, and that many heavily altered objects have been devalued because of changes in taste or display fashion.

The roles of objects in museums

MacDonald and Alsford[3] discuss the foundation for preserving the object-as-evidence from the museological point of view. The importance of original objects is now, they point out, being challenged by, for example, science centres, children's museums, and ecomuseums in which the emphasis is on demonstrating the processes of science rather than objects. They go on to argue that, on the other hand, the fundamental product of museums is information: 'museums are (at the most fundamental level) concerned with information ... and ultimately the wisdom acquired from extensive and experience-enriched knowledge'; 'preservation of heritage objects is not an end in itself, but serves to maximise (over time) the access to the information encoded in them'.

Objects in museums, then, are sources of information and of evidence (ideally, primary evidence in the historian's sense), but they are also vehicles for conveying it. Because display or demonstration often affects the value of the object-as-evidence, these functions are sometimes mutually incompatible. In striking a balance, we should bear in mind that conveying information is usually a short-term requirement (indeed, the duration may be self-limiting if the object wears out), whereas maintaining the evidential value of the object keeps options open and serves the museum in the long term. But in science and technology museums the point of the object is often what it does, or did [4]. Still, we should show 'how this machine was used by people to make widgets in 1888 ...', not 'how we have made this machine make much better widgets than it used to'.

Conservation and demonstration

In 'conventional' museum conservation, then, efforts are made to restrict work on objects to:

- what is needed to remove or counter factors causing deterioration, plus the minimum work necessary to repair past damage;
- making new parts or adding material if needed to hold the object together or to make it mechanically stable;
- necessary additions to make the object understandable.

All work is documented in order to preserve the evidential value of the object as far as possible. New work is clearly identified but not necessarily obvious. Old parts are only replaced if they constitute a danger to the object. Even then, the original part would be kept as part of the object-as-evidence.

The case against running museum objects

The implications of running objects have been interestingly explored by Mann [4],[5]. The conservator's objection to running an object will be that this compromises it as primary evidence. Conservators are usually the people called on to do the work to make objects functional: the objective itself of the work thus conflicts with the values by which their actions are normally determined. Returning an object to operational order will often mean that work with more profound effects has to be carried out on the object than would be the case if it were preserved without running it. Also, the work has to be done in the knowledge that the aim is then to do something with the object that will endanger it as a true record of the past.

These apparently incontrovertible ethics are in practice compromised all the time. For example, displaying pictures is closely analogous to running an object, because light causes colour changes, yet dozens of conservators prepare pictures for display in the course of their normal work.

Conserving computers

Computer conservation has until very recently been undertaken by highly skilled computer engineers and technicians, working with curators, rather than by people with specific conservation training [6]. There is a difference in approach, partly of course a matter of skills and knowledge. Computer engineers can restore the function of the object: conservators are more knowledgeable about the chemistry of deterioration and how to remedy or prevent this. To a great extent, the knowledge of each is a closed book to the other. A third dimension is the way in which the objective of the exercise is understood and interpreted: whether or not the ethics of conservation are understood or observed. This awareness can be supplied by the curator or by the conservator. What we really need are electronics conservators, knowledgeable about electronics, chemistry and conservation, and ethics.

To preserve a computer, possible conservation measures fall into three main categories (computer conservation is described by Kingsley and Moncrieff in their papers in this volume):

- Preservation actions: e.g. removing oil and grime that is likely to promote corrosion and breakdown of plastic insulation; providing mechanical support or joining loose parts; removing potentially damaging components such as batteries for separate storage because they have the potential to damage the main object.

- Remedial and pro-active measures: for example, applying antioxidant to insulation.

- Restoration actions such as replacing wiring in part or in whole; resoldering; replacing blown valves: in general, replacing original parts with new ones.

Replacing 'consumable' parts or parts with a known short lifetime, e.g. valves, can only be somewhat ethically dubious for a museum, as it uses up the finite historic stock of such objects. Can original, historic parts be excluded from the conservation ethic? At least, the original part that came with the object should be kept and clearly identified. The alternative would be to replace the dysfunctional part with a modern component, as often happens with other sorts of working object.

Running computers

What are the implications of running computers themselves? Especially in older and large computers, the act of collecting them itself may well have entailed traumatic intervention: for instance, cutting through all the main cables. But returning a computer to working condition will sometimes entail replacing parts or components, or in extreme cases resoldering and rewiring it.

Unlike mechanical objects, electronic components do not wear out, although most computers have mechanical parts which do: disk drives, keyboards, etc. Not running such machines may itself be detrimental to them, however: after a period of inaction they often will not function when switched on. This may simply be because of deterioration over time, or it may be some effect such as that the heat involved in regular running prevents corrosion films forming. If true, it could be argued that regulated use is part of the conservation process. But when a computer is in operation, heat is generated, and this will certainly hasten the deterioration of synthetic materials such as plastic and rubber.

The information gain from running computers

There is undoubtedly a large information gain from running computers - probably more than from most mechanical objects (and see papers by Sale and Burton in this publication). This possibly arises because computers are much more complex than most mechanical objects - maybe orders of magnitude more complex. If software is included, a computer could have millions of working parts. The actual operation cannot be deduced or envisaged by examining the physical non-running object. This may be true also of complex machines.

Information is also gained because information in documentation and manuals is often incomplete. It is not unusual for the culminating developments for a technology not to be fully documented. If surviving expertise can be used in the resurrection process, the information on how the machine is maintained and operated can be made more complete, provided that the work is properly captured and documented, using video, photographs, records, etc. The existence of the 'virtual object' part of other objects (i.e. software) may depend on the computer running, if it is the only one available, and no software emulation of it exists.

As with other working objects, once the operational characteristics of the original machine can be studied it can, if required, be reproduced as a replica. In the case of computers, this can be in the form of a software emulation, which can more or less exactly represent the operation, and to some extent the nature, of the original on a modern machine.

Information loss

To set against the information gain, there is likely to be a loss, if the physical nature of the object is altered. The physical characteristics of computers are an important determinant for their design and for the efficiency of their operation. Many important developments in computer design and technology have come about through changes in the physical nature of their component parts - the superseding of valves by electronic components being a striking instance of this. In turn, the physical operating characteristics and requirements of computers have determined the design of a whole generation of office buildings. Huge amounts of space between floors to accommodate cabling, cooling and ventilation ducting have been needed only since the spread of information technology in the late 1980s, and this feature will be rendered obsolete if the technology of networking by means of radio or other non-physical means of transmission develops sufficiently.

Apart from information on the history of computing technology to be gained from studying the physical evidence of the object itself, the appearance of the object both inside and out has a powerful impact on the viewer. It is absolutely obvious even to the inexpert that Pegasus, for example, is completely different from a modern PC in many fundamental ways - much more different than is a horse-drawn carriage from a Vauxhall Astra. So the physical characteristics of computers are important to museums.

Conserving software

As a museum object, software can be thought of as having physical parts: the box, the disk, etc., and a distinct 'virtual' part which comes into existence when it runs [2],[7]. The sole function of a computer is to run software: i.e. to cause the software 'virtual' object to exist. In terms of conservation ethics, software conservation is much less problematic than hardware, although it raises many intriguing questions of analogy.

The physical parts of the software - the box, the shrink wrapping, the disks, etc. - will have exactly the same kind of information value as does any other physical object and will be subject to the same ethical constraints if they are required to be treated or 'used'. Software media (disks, tapes, etc.) are likely to be very difficult to preserve physically in perpetuity, but this is not a problem we need to address here. The code, the 'virtual' object, can be held to be a separable 'object part'. This part is an ideal subject for conservation because (a) it has no physical existence; (b) it can easily be replicated. If the replicas are exact - bit-perfect - then the 'original' embodiment of the code has no more information value than does any subsequent replica. Printing the code out onto a stable physical medium such as acid-free paper could greatly assist its later remedial conservation (see below). This would be equivalent to a highly detailed physical record, such as a hologram, of a physical object. While written code would not operate, it could be drawn on if the current replica of the actual code was defective and had to be 'treated'.

The conservation treatment of software code will consist of:

Preventive conservation:

- storing the code on a physical medium selected to be as stable as possible so as to minimise subsequent copying;

- if necessary, copying the code onto a new medium at intervals before the shelf life of the existing medium is exceeded;

- ensuring that a computer, whether the original or an emulation, exists on which the 'virtual' object can run.

Remedial conservation:

- If a copy of the code turns out to have developed a fault (e.g. copying it has not resulted in a perfect replica of the original) then repairing this fault by replacing the faulty code with code that will run will constitute conservation. An analogy would be to retype a sentence in a document if it had become garbled during copying. The same procedures should be followed as are used in documenting normal conservation work: the replacement code should be marked as such, preferably by means of code in the program (REMs, etc.), and the exact work done should be recorded. In fact, the same conservation record forms as are used for physical conservation can probably be employed.

- If the original code has a mistake in it, i.e. it has a bug, then removing or repairing this bug would constitute restoration. The great advantage is that copies of software code may be restored without compromising the original - as long as the original is identified, retained, and preserved unrestored, and the restoration on the restored version is identified as such.

Therefore, there is no unique ethical problem about conserving software; questions of the instability of the physical medium are no more problematic than for other objects made of non-stable materials and need not affect the preservation of the 'virtual' object. However, Swade, in his papers in this volume, and Johnstone [7] rightly identify the large requirements for person-hours and skills if software and hardware are to be 'conserved'.

Preserving systems

Museums which collect modern technology will have to come to terms with the systemic nature of objects which include electronic components and programs. Computers and software cannot be treated separately, although each can be identified as a separate type of object. The particular problem is that the sole purpose of the computer or hardware is to run the software: and the software cannot meaningfully exist unless the hardware works. This does not only apply to computers, but also to the multitude of machines with electronic components - especially those with built-in hardware and software, for example, analytical instruments or electron microscopes. To an extent, at least for computer systems, it is possible to treat the two components of the system independently, by creating a software emulation of the original hardware that will enable the program to run on a newer machine. Burton and Sale discuss this in the papers in this volume. However, this solution is so expensive as to be impractical for all but a few very important machines.

Conclusions

Many types of object are conserved, or restored, in order to subject them to 'use' that will probably be detrimental, including for instance buildings, musical instruments and paintings. Computers are just another type of object to take their place in this list. Musical instrument historians, curators and musicians have engaged in a very similar debate for some time [8],[9], and it would be worth studying their codes of practice [10]. In these, the older, rarer and less modified the instrument, the less the justification for restoring it in order to use it. If the instrument is brought to working order, then the maximum information should be gained if and when it is played. For example, performances of historic instruments are made available to as many people as possible by making recordings for sale; technical drawings of them are produced so that exact replicas can be made for the historic music business. These guidelines are very similar to those proposed by Mann for historic vehicles [4]. The case for restoring and running an historic computer may be somewhat strengthened by the argument that only by doing so can software 'virtual' objects exist.

The argument for restoring and running a computer is that this enriches the information dimension of it as a museum object. The conflict between archival and demonstration functions may best be resolved by separating the two requirements: one computer is conserved, frozen in time, as physical evidence, while evidence of function is maintained either by restoring a machine to working order or by creating a replica or emulation. Particularly valuable information may be gained if the process of restoration captures the technical skills and knowledge of the original operators. In this event, there is an obligation to record permanently such information, since eventually the object will cease to work. These considerations are common to many types of object. Unique to computers may be that they are components in a system, in that their sole purpose is to run software, which can only be said to exist if it can be run on a computer. In a sense, perhaps the system has an equally strong claim to be an object.

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Abstract

The conservation of computers and software, and their restoration to running order, is examined in the light of conventional conservation ethics, to maintain the original object in as nearly its original form as possible. This is interpreted as being to maintain the information embodied in the object as a source of primary evidence. Restoring a computer and running it will usually compromise the physical evidence it embodies. However, a considerable gain in information may be achieved in the process of restoration. Also, the very existence of a second class of objects, software, may depend on a suitable computer being in running order. The conservation of software is explored. These issues are by no means unique to computer conservation: musical instruments as well as other functional objects such as vehicles or even buildings provide good parallels. It is concluded that the conflicting objectives of preservation of evidence and preservation of function may best be served by preserving separate computers or by creating a simulation. What is unique to computers is that they are a component of a system, the other major component of which is software, and the system itself may have a claim to preservation as an object.

How can we Tackle Conservation? Prevention of Damage

Anne Moncrieff

Prevention of damage and deterioration is the ideal of conservation. Total prevention of deterioration is not possible in practice, but measures can be taken to slow down decay and reduce damage, thus enabling the historic material and evidence of the original manufacture, present in the historic computer, to be preserved for study now and in the future. This paper will consider the main factors that may cause the deterioration of a historic computer and suggest how they can be controlled.

Helen Kingsley's paper (see pp 51-8) gives a case history of this and other aspects of conservation in the treatment of the Elliott 401 at the Science Museum.

Conservators cannot yet quantify the damage caused to artefacts by not taking protective measures. This means that a risk analysis or cost benefit analysis, comparing the cost of protection with the cost of damage, deterioration and repair, cannot be carried out. The lack of precise knowledge is frustrating. The owner, curator and conservator have to feel their way towards a balance, between the cost of care and the loss of historic material and evidence, if protection is not provided.

Fire could destroy most of the fabric of a historic computer, and put the operator and observers at risk as well. Prevention requires attention to the design of the building used to store and exhibit computers, so that it is built and furnished with fire resistant materials wherever possible. Fire escape routes must be provided, kept clear and signposted. Regular maintenance and testing for safety of gas and electric supplies and appliances, including the computers, is important. Smoke detectors will give people time to tackle the fire and more importantly escape themselves, but these and fire alarms are of no use in protecting the computer if ringing in a deserted building, and if people who hear them have not been trained in the action to be taken to protect people and property. A means of contacting help is essential, perhaps by fixed telephone line, or mobile phone or radio if this is more appropriate to a storage building. Fire extinguishers need to be of the correct type and adequate size and people in the building must know how to use them. Training people, and regular practical testing of their knowledge, is by far the most important conservation measure that can be taken to protect and preserve historic computers, or any other artefact, whatever the source of risk may be.

It is essential that people working with the computer, or in the same building, know what risks there are, what to look for and what action to take if they see signs of any problem. Catching fire is a possibility for a working computer; everyone around it must know what they can safely do themselves, when and how to get help and most importantly how to protect themselves and other people. Officers from local fire brigades are usually willing to advise on ways to prevent fires, on fire extinguishers and on training. The Fire Protection Association provides advice and has some relevant publications (1).

Theft and vandalism. Small computers are attractive to thieves; and vandals can do a lot of damage in a short time. Insurance will not bring back a rare or badly damaged computer, so attention to security is worthwhile. Brian Dovey writing in the Manual of Curatorship (2) sets out the measures to be considered.

Environmental conditions

Heat will reduce the viscosity of oils, waxes and some resins, in transformers etc. and in working parts. The improved flow may make these materials more effective as insulants or lubrication or may cause them to run, or leak out of their proper place, reducing their effectiveness.

Heat will accelerate the deterioration of chemically active components e.g. batteries and electrolytic capacitors, rubber, gutta-percha, plastics and the paper and magnetic tape etc. of software (3)(4)(5)(6). With the rate of deterioration of some materials known to double for every 10°C rise in temperature, investing in roof insulation, double glazing, shutters or blinds on windows to keep summer heat out, and turning heating down low in winter, is recommended. It will also save on winter heating bills. The cost of cooling plant for the whole room is probably too high for the protection that it would give, but a working computer may be fitted with, or need, localised cooling to prevent damage due to overheating.

It is important that the fans or airconditioning fitted by the manufacturer be maintained and work properly whenever a computer is in use; a lot of heat can be produced by some computers and be detrimental to their life expectancy and efficiency if not removed. Ducting the heat out of the building might be necessary and will provide more comfortable conditions for people, as well as protecting the computer.

Cold is less of a problem than heat in storage. Low temperatures are recommended for the preservation of plastics, paper and photographic film; most conservators would suggest 10 or 15°C but temperatures as low as 5°C are sometimes used provided that condensation can be avoided (4)(6). Storage buildings should either be dehumidified or heated sufficiently to prevent condensation on the casing or components of the computer. On display, temperatures must be acceptable to visitors, but many museums are uncomfortably hot in winter; this energy and the damage that it causes could be saved by installing effective temperature controls and maintaining 15-18°C.

Cycles of temperature may cause damage due to the stresses set up in thermal expansion and contraction, especially where dissimilar materials are joined together; there are a lot of these in computers, e.g. glass and metal joins in valves, soldered connections in wiring.

Water. A computer would survive a flood in better condition than many other historic artefacts, but paper (e.g. punched tape and cards, manuals, wiring diagrams etc.) would suffer. Sue Cackett gives advice on how to avoid such disasters and on how to cope with and clean up after them should they occur (7).

High humidity will promote corrosion of metals and mould growth on organic materials. Measures such as dehumidification of store rooms and packing crates can be taken, as described by Sarah Staniforth (8).

A relative humidity of 50%, or lower if the store is likely to get very cold, will avoid condensation, and so reduce the damage and hard work involved in removing corrosion from contacts, rust from steel frames and cabinets etc. and mould from paper, paint and plastics.

Conditioned silica gel can be used to keep the humidity low to reduce corrosion of computers stored in heat sealed, barrier film, packaging (8). Total desiccation might be harmful to paints and plastics (9). It is important that wood and other materials which give off corrosive vapours in confined spaces are not sealed in with vulnerable materials (10). Commercial vapour phase inhibitors (VPI), also called volatile corrosion inhibitors (VCI), should not be used; they are unnecessary in dry conditions, may cause deterioration or staining of painted surfaces and plastics and are toxic, a hazard to people unpacking and handling them immediately afterwards.

Where damp conditions in storage are unavoidable corrosion can be prevented by coating bare metal parts with oil, grease, wax, lacquers, silicones, conformal coatings etc. Some of these materials are likely to have been applied to parts of the computer in manufacture (or working life) and it may then be appropriate to maintain these by adding to them or replacing them as they deteriorate. Conservation advice would be not to add any material to the historic computer unless there is no other way to prevent deterioration and only then if it is certain that the material will protect all the components that it will cover. Solvents used in application of lacquers may soften or craze paints, rubber and plastics (11). Oils and waxes may swell or stain these same vulnerable materials (5) and be difficult to remove when they have picked up dirt, are no longer protective and need to be replaced. At worst, coatings may not only fail to protect but may themselves deteriorate, forming acidic or other products which corrode or discolour other parts of the computer. Because these problems have occurred in the conservation of historic artefacts, conservators now recommend non-intervention, i.e. protection by environmental control.

Light provides the energy for chemical reactions with oxygen, which are likely to cause deterioration. This may start with colour changes, fading or yellowing and progress to crazing, cracking, embrittlement, loss of strength of paper, plastics, paints, rubber and gutta-percha. Ultraviolet light is the most damaging, but visible light will also cause some damage: the greater the dose, i.e. higher light intensity and longer exposure, the greater the damage (8)(12). This is not a great risk for many components of a computer which are kept away from light by the casing, except where this is removed for display (but the casing material itself may be harmed). In storage, lights should be switched off when no-one is working in the area and windows should have blinds down, or the computer should be covered with an opaque dustsheet. On display, any source of ultraviolet light should have filters fitted and the light level should be kept below 200 lux (8).

Pollution

Dust. Apart from detracting from the appearance of the computer, dust may cause damage by blocking cooling vents or by holding moisture and salts which increase the risk of corrosion and encourage mould growth. Removing it may cause scratches on painted or plastic cases and covers. Dustsheets can be used in stores and showcases in galleries to protect static exhibits. Working computers, and their operators, need ventilation for cooling, even if this does bring some dust with it!

Acidic gases corrode metals and degrade paper, and ozone accelerates the deterioration of rubber, plastics, paint and paper (12). The information needed to calculate the cost of providing clean air vs. the benefit in increased durability, less remedial treatment, is not available. Probably the balance lies against full air conditioning, but in favour of providing acid-free storage materials for software, wiring diagrams and other records on paper.

Research is being done on the protection of rubber and plastics against the deterioration caused by reaction with oxygen, by packaging with an oxygen absorber, 'Ageless' (13)(14). This technique might have an application in the storage of some computers in the future.

Vermin. Most people would want to keep exhibition galleries and stores free from rates, mice and even birds. Their faeces and urine are unpleasant and may be a health hazard for people. The mess also acts as a paint remover and can damage plastics and corrode metals. It has been known for rodents to damage electric wiring by chewing it and their paper and cloth nests could be a fire risk inside a computer. Keeping them out is not easy. Looking out for signs and taking action immediately keeps the numbers and damage to a minimum, as does good hygiene and keeping the area free from rubbish, especially food residues and dirt. The tougher measure of trapping may work in some cases, but the advice of a pest control expert should be sought before starting this and must always be obtained before using poison: there is a risk to people, domestic animals and to the general environment in the use of these chemicals and there are legal requirements to be met (15).

Elements of the computer itself. Roger Bridgman (see pp 7-18), mentions that corrosion can be caused by leaking components, especially batteries. These and other reactive components should be inspected regularly and removed if seen to be swollen or leaking. Computers in storage and on static display should have these components removed and stored separately. Dummies, empty cases, can be fitted filling the gap where the appearance of a battery is needed. It is unlikely that a method of stabilising these parts will be found. Cold storage would probably prolong their life but might be harmful to some. Not enough is known about them to recommend this yet.

Other interactions between materials that have been found to cause problems are: sulphur from ageing vulcanised rubber, tarnishing metals and discolouring paints and plastics; plasticisers exuding from one plastic, softening other plastics and paints nearby; cellulosic plastics and vinylchloride based plastics giving off acidic vapours when they themselves deteriorate, which tarnish or corrode metals and accelerate the deterioration of other paints and plastics (5)(10). It is sometimes necessary to separate and remove some components from a complex object, such as a computer, in order to protect other parts.

People can be the best protectors of the computer, but also are potentially harmful. Knowledge, training and discipline are needed for everyone who is going to handle, or work with a computer, especially a historic one. More damage can be done by dropping a computer than almost anything else! If it is large its own weight will cause damage to it and the person if he or she is underneath; smaller computers are lighter but often less robust. Cracked plastic cases and broken circuit boards cannot be perfectly repaired and there may be no spares left in the world for replacement. Handling needs care. Gwyn Miles (16) gives advice on handling and moving objects and training for the people who are involved in this work. Visitors just touching surfaces can wear away the paint coating even when they do not intend to do any harm. Ecklund and Richwine in the paper on their conservation work on ENIAC describe the protection needed (17).

Use. Dismantling can cause breakage and loss of components and lead to failure if reassembly is done wrongly, perhaps because the arrangement of parts and wiring was not carefully observed and recorded. Training for inexperienced people and discipline in everyone concerned is necessary in order to be able to plan ahead, work slowly and methodically, and to reassemble the computer within a reasonable time scale (18). While dismantled, a computer is at risk of damage to fragile components, such as valves, falling from a table, being stepped on or kicked on the floor, crushed by heavier parts etc. There is some risk of parts being lost or fitted to a different machine. Parts are at less risk when fully assembled in the computer.

In operation, especially during testing, there is a risk of fire and of electrical damage. Ideally people should not work alone with the computer switched on. Tony Sale (19) talks of working with one hand to avoid the worst damage from electric shock, but what if the engineer trips and falls against live wiring? Isolator switches should be fitted within reach and workers should be taught how to switch off and close down quickly to protect people whilst causing the minimum damage to the computer.

Moving parts such as keyboards, tape and disc drives, printers, cooling fans etc. will be subjected to some wear in use. Good maintenance - keeping parts clean and greased where necessary (and not where not!) - will help to protect working parts, but eventually they will wear out and have to be replaced. This may lead to a progressive loss of 'authenticity', a distortion of the historic evidence (see Suzanne Keene's paper, pp 30-39).

Emulation can be of value in preventative conservation for the following reasons:-

It protects the fabric of the historic computer by reducing is use. This avoids the risk of damage and the wear and tear and replacement of parts that prolonged use inevitably involves.
It can be used to train users, to some extent, so reducing the risk of accidental misuse.

It can be used by many more people than can have access to the historical machine. This is likely to have the effect of arousing interest in the preservation of computers. In general, as with other historic artefacts, the more people there are with an interest in and enthusiasm for them, the greater the chance of their survival and preservation. To some extent the more people there are interested, involved and wanting to try out their programming on the real thing, the greater the use and risk of damage; but without that interest and involvement, there is a real risk of historic computers not surviving beyond the lifetime of the present group of enthusiasts.

However, in the enthusiasm for the undoubted advantages and attraction of emulation, no one should lose sight of the fact that it is **not** the original. Emulation can contain only what its designer puts into it at the time. It cannot be interrogated, researched in depth, for information not collected and used by the emulation designer. The importance of the original fabric with its store of known and as yet undiscovered evidence remains, together with our responsibility to protect and preserve it for the future, not to let it be destroyed by neglect or used up, consumed in our time.

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How can we Tackle Conservation?

Helen Kingsley

In the summer of 1992 the Conservation Department at the Science Museum was faced with an innovative project which involved the conservation of a computer that would be presented to the public as a working exhibit. The model chosen for treatment was the Elliott 401 Mark 1, a general purpose electronic digital computer used for mathematical, engineering and scientific calculations. It was developed and constructed by the Research Laboratories of Elliott Brothers in London for the National Research Development Corporation. The 401 Mark I was constructed in 1952 and was in use until 1965 when it was acquired by the Science Museum and placed in our storage facility at Hayes. In 1990 it was brought to the Museum's main site at South Kensington.

This paper describes the ethical considerations and approaches to determine conservation procedures in treating a complex composite object with a view to facilitate the conservation and/or restoration of the computer to working condition. Fortunately we will be able to draw on the expertise and assistance of the Computer Conservation Society who set up a restoration working party consisting of people who designed or worked on the 401 during its operational life.

The Elliott-NRDC 401 Mark I

The computer consists of 13 units:

1) The top duct, divided into two sections.

2) The base plinth, divided into two sections.

3) Two end panels.

4) The control desk which consists of the input tape reader and the output Olivetti typewriter.

5) The monitor and test equipment unit which provides monitor oscilloscopes and facilities for setting up numbers and orders manually.

6) The cooling system cabinet which houses a fan to draw air up from the base plinth which is then taken from each chassis in the cabinet into vertical ducts

running up each side of the cabinet to the top duct.

7) & 8) Two power supply cabinets. Alternating current from the mains is transformed to direct current for the valves.

9), 10) & 11) Three plug-in circuit board cabinets where the arithmetic and control circuits are housed with interpackage wiring at the rear with up to fifty-six packages plugged into each cabinet section.

12) The drum unit with the driving motor which houses the magnetic disc store and its associated amplifiers which are of plug-in form. The disc was coated on both sides with a red magnetic oxide about 0.001" thick and carries only two heads, the 'clock' and 'address' heads, in addition to the eight store tracks.

13) The alternator control unit which was used to prevent the effects of transient power surges from the mains power supply.

All the cabinets are interconnected by leads between tag boards.

The units contain many of the same components including resistors, capacitors, transformers, relays, valves, stabilisers, rectifiers and condensers, which comprise many different materials, for example copper alloy, aluminium, steel, ceramic, plastics, glass, chromium plated brass and steel, nickel alloy, enamel, Mylar etc.

The Condition and Preliminary Treatment Procedures

The conservation of the 401 computer posed a number of problems. The first was the requirement for the computer to be conserved and/or restored to working condition. The consequence of exhibiting a working computer is wear and tear leading to the deterioration of original parts. These will then have to be replaced from our limited resources of spares and, in some cases, we do not have original parts to use as replacements. Ethically we must recognise that it is important for us to keep material evidence of technology for future generations.

The second problem involved the potential danger of deteriorating parts causing internal damage, for example the electrolytic capacitors which are visibly swollen and could possibly explode when a current passes through them.

Another important issue was evaluating the appropriate conservation treatment for each material, most of which would have to be treated in situ.

The first step was to carry out a comprehensive condition report on the Elliott 401 Mark I computer to assess the deterioration and conservation needs. The conclusion from the report indicated seven main problems which are listed below, together with preliminary treatment procedures:

1) Surface damage. In some areas the painted layer was lifting away from the metal surface.

The computer units consist of green painted steel and aluminium doors, panels, frames, and internal support racking. Small areas of surface damage to the paint coating by way of abrasions and scratches were identified with the paint layer lifting exposing metal surfaces. Rather than remove any of the original painted surface it was decided to adhere the lifting paint flakes back onto the surface consolidating the edges to prevent further loss.

2) Chemical deterioration of plastic and rubber coated wires, rubber leads, grommets and sleeves.

The plastic or rubber coating on many of the wires had deteriorated, becoming brittle and cracked exposing bare metal. This occurred most frequently at the point where the wires were connected to the tag boards. It was thought that disconnecting, replacing and resoldering many wires would be extremely time consuming, with a risk of further damage and disturbance of other parts. Therefore it was proposed, where feasible, to introduce an inert silicone rubber material into the cracks of the original covering to act as an insulator.

3) Chemical deterioration of the foam rubber sealing material.

The rubber sealing strip around many of the door panels appeared to be in good condition. However the foam rubber sealing in other areas was found to be deteriorating i.e. embrittlement causing cracking and splitting of the material, or shrinkage causing distortion. In some areas the foam rubber was tacky to the touch, appearing to have liquefied. This is an indication of the first effect of deterioration caused from attack by oxygen, ozone and oils, and is accelerated by exposure to heat and light. As the oxidation process continues this sticky substance becomes brittle. At this point we pose the question 'should we preserve or replace?' It was agreed that deteriorating foam rubber performing an important function in the running of the computer should be replaced, and that this should be done with a material that has been as closely matched to the original as possible. To prevent further oxidation of other rubber materials the application of an antioxidant was considered. An antioxidant retards the atmospheric oxidation of the polymer chain by preferentially reacting with oxygen. However this is not a long-term solution as it acts as a sacrificial additive which is eventually depleted.

4) Tarnished silver plating.
The sockets and plugs consist of a Bakelite casing with tarnished silver plated brass pins and contacts encased in a coated copper alloy holder.
The tarnished surfaces can be cleaned manually with acetone or alcohol and/or a glass bristle brush.

5) Corroding steel and chromium plated brass and steel.
Connecting several of the plugs and sockets to the plastic coated copper wires are steel support clips with a transparent plastic sleeve. In most cases the steel screws holding the copper alloy holder to the Bakelite case are corroding, as are many of the support clips. Also many of the chromium plated brass and steel attachments, and such steel attachments as hinges, screws, nuts, bolts, etc., have pitted corroded surfaces. Where possible these will be removed to be cleaned, stabilised and inhibited, otherwise treatment will be carried out in situ.

6) Corroding aluminium.
The top unit has applied aluminium letters, numbers and punctuation, many of which had a thin surface layer of aluminium oxide corrosion. It was also noted that several of the black painted aluminium covers for the glass valves had white crystalline deposits which were lifting the painted surface. Manual or chemical removal of the corroding layer will be carried out where possible.
A number of the letters etc. are missing, leaving a black adhesive residue, which is soluble in acetone. After consultation with the curator it was decided that new letters should be made to replace the missing ones so that the computer

should be returned to its 'original' appearance for exhibition. To denote the replacement, each new letter, number or punctuation would be stamped with the Science Museum identification mark.

7) Accretions in the form of dust, dirt and oil deposits.
Dust, dirt and oil deposits are present over all surfaces. These are readily removed with 50:50 deionised water and alcohol mixture or alcohol to which a non-ionic detergent is added when necessary to 'wet' the surface.

Documentation/recording of treatment

All treatment procedures will be documented for future information.
When it is essential to replace or resolder parts, information is to be put onto computer disc and where possible replaced parts are to be kept for future reference.

Associated materials

In conjunction with the conservation of the computer an examination of the associated materials such as the manuals, circuit diagrams, paper tapes and other parts was carried out to assess the condition and recommend future storage requirements.
A paper conservator was approached to carry out a preliminary survey on the computer archive material, i.e. manuals, computer publications, as well as printout rolls, punched paper tapes and computer tracings. The vast bulk of the material was found to be in good condition, requiring little attention other than good storage. Some had been damaged through mishandling and required remedial attention. Only a few items had seriously deteriorated and needed full conservation treatment before storage.
The computer tracings consist of circuit diagrams drawn on tracing paper which have deteriorated becoming brittle with tears and creases around the edges. During the restoration and maintenance project many of the diagrams will be in continuous use, therefore it was imperative to obtain copies. A decision was made to microfiche each diagram, allowing copies to be taken from high quality negatives. This will reduce the amount of handling of the originals and prevent

exposure to high UV light and heat levels by photocopying them.
After microfiching, the diagrams will be stored in Melinex (a polyethylene terephthalate film) sleeves, placed into acid-free folders and stored in a metal plan chest.
For storage of smaller items, i.e. punched paper tape, spare valves etc., metal cupboards were recommended as they are easy to keep clean and dust free. The objects will be cushioned and supported where necessary with Plastazote (inert polyethylene foam) and packed in acid-free boxes or perspex containers.
The control of the relative humidity and temperature is of prime importance, especially with the lower quality papers. The storage conditions should be in accordance with the British Standards BS5454, which states that the environments for paper and parchment material should be at a constant temperature within the range of 13°C to 18°C and with a constant relative humidity of 55% to 65%, although a lower RH of 40% is acceptable for paper which is not bound.

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The Information Archive:
Collection-Related Documentation for the Historic Computers.

Jane Kirk

This paper discusses the collection-related documentation associated with the historic computers. It describes how the paper records have been catalogued, the method proposed for cataloguing the video tapes, and some thoughts about the documentation issues of collecting software.

The objective in managing the collection-related documentation is to enable access to relevant material by either staff or public now and in the future. In order to do this it needs to be preserved and catalogued appropriately. The better the cataloguing, the less need there will be for repeated handling and this will aid long-term preservation.

Paper records

The paper records held with the historic computers fall into three categories.

The first is acquisition documentation. This is a file containing papers concerning the acquisition - typically letters to and from the former owner together with an acquisition form signed by the Museum and the owner which constitutes evidence of legal title to the object.

The second category of material is technical or other support information about the object itself. This will include technical manuals, users' manuals, technical drawings, reports and trade literature and is described as technical file material.

The third category is material similar in nature to the previous category but which does not relate to specific objects in the Museum's ownership. It includes also other technical material about computers and information relating to companies that manufacture computers. It is described as subject-related material.

Paper tapes are considered as objects in their own right and fall outside the scope of this paper.

These three categories of material are not unique to the historic computers collection and will be found for all collections held in the Science Museum. Material in the first category is filed and preserved in exactly the same way for these objects as for any other object in the Museum collections. For the second and third categories, whilst the material is similar in nature to that for other collections, there is a much greater volume. For twelve inventoried historic computers the Museum holds 22 linear metres of documentation. For other collections in the Museum there is a total of some 500 linear metres. On average the Museum has several hundred times as much information per computer as for any other object (though there is a considerable variation in amount per object throughout the collections).

This project has been considered as a pilot project and the work carried out will be assessed as a model for documenting the information archives associated with other collections in the Museum.

The first step in the project was to consider how the documentation would be stored. Having taken advice from the Museum's conservation staff it was decided to store all material in acid-free boxes with individual items in inert polyester sleeves as appropriate. The large technical drawings will also be stored in such sleeves. In addition the drawings have been copied onto microfiche and prints made for use as working copies. As the material was catalogued, a note of any specific conservation needs was made, though in fact the majority of the material was found to be in good condition. All the records will be kept in the new Documentation Centre.

For cataloguing the archive, each item was recorded on a database with the following information: number, title, name, address, cross references, keywords and notes.

The cataloguer, Sue Julian-Ottie, worked from an initial listing of the archive produced by Harold Gearing of the Computer Conservation Society. This was particularly helpful as, having worked in the industry for many years, he was able to identify the material and advise on the appropriate categories for it. The quality of the result is a tribute to the meticulous work done by Sue in ensuring the data input conformed to the standards set. Below is an extract from the term list used for keywords.

Applications: Accounting
Applications: Aircraft Industry
Applications: Astronautics

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Computer graphics
Conversion code
Cost
Creed
Data processing

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Programming language: Algol
Programming language: Basic
Programming language: Cobol

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System analysis
System design

A distinction is made between the technical files and subject-related material. For the former the prefix T (for Technical file) is followed by the inventory number and then a consecutive number for each item. For the subject-related material the subject classification COM (for computer) is followed by the year of cataloguing followed by a consecutive number.

There are some 800 documents in the T series, and 2400 in the COM series. The database is the Museum's Records database, used also for recording Museum files. This was designed in house using Adlib software and is run on a Prime mini-computer. Retrieval is by free text indexing - any word in the entry for each record can be searched for and refined by selecting on another word. All documents relating to any specific object can be listed.

For example selecting on the terms 'user' and 'guide' there are 27 matching records, of which 23 are in the T series and four in the COM series. Some examples are listed below.

T/1989/0544/050

TITLE: Elliott 803 - Computer Handbook : Text / Elliott Bros Ltd - London Elliott Bros Ltd, 1961 - 1962, vol. 3

NOTES: Contains different information from T/1989/544/49

XREFS: T/1989/544/49; T/1989/544/43 - 48

KEYWORDS: Engineering manual; User's guide

T/1989/0550/063

TITLE: PDP-12 - Software package and Services / Digital Equipment Corp - Maynard, Massachusetts : Digital Equipment Corp, June 1972

NAME: Rosen, S. (DR)

ADDRESS: University of London, University College, Phonetics Department

NOTES:

KEYWORDS: User's guide; Programming

T/1980/0382/004

TITLE: TRW-130 - AN/UYK-1 (TRW-130) Digital computer Set Technical manual: Programming - TRW-140 Input/Output controller Reference manual / Thompson Ramo Wooldridge Inc, RW Division - Conoga Park, California

NOTES:

XREFS: T/1980/382/1; T/1980/392/2

KEYWORDS: Applications: Military; User's guide; U.S. Navy

COM/1993/0033

TITLE: The Ferranti high speed printer / Bennett, J.M., AUG. 1953

NAME: Ross, H.McG

ADDRESS: Ferranti Ltd

NOTES: Authors were employees of Ferranti Ltd

KEYWORDS: Input/Output terminals; User's guide; Manchester Mark 1

COM/1993/1569

TITLE: Teach yourself Electronic computers / Westwater, F.L. - London: The English Universities Press Ltd, 1962 - 151p

NAME: Gearing, H.W.G.

NOTES:

KEYWORDS: Training; User's guide; Applications; Logical Design; ICT/ICL

Having carried out this pilot project, there are a number of points to be considered. The first is whether this detailed cataloguing is really improving access for the staff and the public and, if so, what level of usage is there likely to be? If the index is little used it may be that the existence of the material is not known or that the material is not of sufficient interest. Even if the material is used well, the value of the detailed cataloguing must be considered - a less detailed listing might be perfectly adequate.

The costs of the cataloguing must be considered also. The cost to catalogue the 2000 items was about £5000, of which 90 per cent was staff costs. This does not include the 60 or so days spent voluntarily by Harold Gearing in listing the items which, had it been paid for, would have raised the total cost to around £7000.

Thirdly, would a similar method be appropriate to other collections? The amount of supporting documentation for other objects is much less but there would be a benefit from reduced handling of the material. Also for subject-related material there is no standard system within the Museum for cataloguing, indexing, organising or storing it. The curator for each collection maintains it to suit her or his needs and access to it must be made via the curator. Adopting the historic computers model would enable any other staff or, in time, the public to see exactly what we have.

A more general point for discussion which emerges from this work is the extent to which the Museum should acquire collections-related documentation, both that which is related to specific objects and that which is not.

Video tapes

The historic computers collection has some 70/80 video tapes with about the same number of hours of actual recording. The subject matter covers three things. One is the rebuilding of the historic computers, the second is interviews with people involved as either builders or users of the computers and the third is the building of the Babbage Difference Engine No. 2 by the Science Museum.

The tapes are S VHS, i.e. high-quality VHS. The majority were taken with a large Panasonic camera. More recently the Museum has purchased a smaller compact camera which uses S VHS C tapes.

All of the tapes have been taken by Tony Sale and they were taken to ensure as complete a record as possible of what has been done in restoring the historic computers. Unlike the paper records the Museum does not have a large volume of videos for other Science Museum collections but this will be a developing trend and so in cataloguing the tapes a system which would be more widely applicable was sought.

Tony Sale has devised a system for cataloguing and retrieval of the tapes. The system has two elements. The first stage is to put a time code on each tape. These codes are known as VIT C codes and code each tape to frame level. A copy tape will hold these codes on the tape itself.

Once the tape is coded the cataloguer runs through each, noting the start and finish times of each scene. The scenes are then listed on a database together with the start and finish times. Retrieval is by search for any word appearing in the description of each scene. A refinement that could be considered is to use a database with an image capture facility so that when a record is on the screen there is also a typical image from it. Currently there is no commercially available software to do this but it is likely that there will be in the near future. An alternative is to print off a selection of frames from each tape and keep them in paper form in a file.

To access a tape, the database is searched using one or more keywords. This identifies the relevant tape and time code. The tape is retrieved and put in the video player and can be run directly to the relevant time code. For most purposes, this would be the copy tape with visible time codes. For exhibition or television it would be necessary to go back to the master tape for a clean copy.

This cataloguing work will be carried out when resources become available. In the first instance it is proposed to use the same database as for the paper records and to maintain paper copies of an image from each scene. This approach will be evaluated before deciding whether to continue or to pursue the use of a database with image capture facility.

Software

At present the Museum has not determined the policy and practice of documenting software but is beginning to consider some of the issues. Two important areas are licensing and copyright, and cataloguing.

Most software is protected by an explicit licence agreement between the supplier and the user and this licence lapses when the software is passed to a third party (the Museum) which then needs to renegotiate the licence with the supplier. This may be a particular problem if the supplier no longer exists.

Software is also protected by copyright which persists for 50 years after the author's death. Clearly most software will still be covered by copyright. The copying of software should be negotiated with the original supplier. If the supplier no longer exists this can pose considerable difficulty as it will be difficult or impossible to track down the copyright holder.

When acquiring new software the Museum should obtain an explicit agreement with the supplier both concerning the licence agreement and copyright issues. It seems likely that, provided it is maintained and preserved (either in virtual or physical form) as a museum object, a satisfactory agreement will be obtained.

When software is already in the collections - generally when it has been obtained together with hardware - the Museum should try to track down the supplier and copyright holder and obtain an explicit agreement. By analogy with other situations in which owners of objects need to be traced, the important thing to demonstrate is that 'reasonable' efforts have been made to do so. However the material should be used only for activities associated with preserving it and maintaining it as a museum object and not as a working tool.

A second area of concern on legal issues related to data held on software is the data that may be acquired on software which has been used. The issue for consideration is the Data Protection Act. Any organisation holding personal data on computer must be registered under the Data Protection Act stating what they hold and what use they will make of it. Both the Museum and the donor will need to be aware of the nature of any transfer of data.

Another documentation-related issue for software is how it can be catalogued. Software may exist in any or all of the following forms:

- packaged off the shelf software
- software codes put on another medium [e.g. acid-free] with further copies to extend shelf life
- a link to an appropriate hardware platform - either original or an emulation
- emulation of all or part of a system

What is held in any particular case will depend on a number of factors but mainly on whether it was acquired primarily as software or incidentally with hardware. One solution would be to regard the virtual element of the software as the museum object with any and all of the other physical versions as parts of it. Should any become redundant because, for instance, there is no longer a hardware platform on which to run a particular software version, it could be written off through the formal write-off procedure.

Summary

In this paper the documentation issues that have arisen in the course of the historic computers project have been described and discussed. There has been more progress in some areas than in others. The work on the paper documentation is complete; there is a proposed method of documenting the video tapes and some of the documentation issues of collecting software have been considered. The work has been immensely useful as a pilot study and potential model for how the documentation of all the Science Museum collections could be managed.

The Pegasus Restoration and Simulation Project

Tony Sale

Introduction

This project involves the restoration to full working order of a Ferranti Pegasus electronic valve computer built in 1958 and in the care of the Science Museum of London, by members of the Computer Conservation Society (CCS).

The work took two years and was co-ordinated by the author, Manager of the Computer Restoration Project at the Science Museum.

A Working Party of the CCS chaired by Mr John Cooper (now deceased) brought Pegasus back to life. The vice-chairman, Mr Chris Burton, has written a simulator of Pegasus using VGA graphics on a 386 IBM PC. This simulator has a remarkable degree of realism and really has captured the 'persona' of Pegasus.

The Pegasus simulator exactly models Pegasus and runs all the original engineers' test programs and library routines. It has even found a previously unknown 'bug' in some Pegasus routines written in the late 1950s.

This is thought to be a world first in restoring such an early computer and in providing such a detailed simulation of it running on a modern PC. It is a major step forward in interpreting early computers to the wider public.

1. Aims

1.1. To restore to full working order a Ferranti Pegasus electronic valve computer built in 1958.

1.2. To construct a bit level emulation of the functioning of Pegasus running on a modern Personal Computer (PC).

1.3. To construct a realistic interactive computer graphics simulation of Pegasus as a 'front end' to the emulation.

1.4. To capture from original sources examples of the uses of Pegasus by running or recreating original programs.

2. Method

2.1. To establish a working relationship between The National Museum of Science & Industry, Science Museum, London, which has the Pegasus computer in its collections, and the designers, builders, maintainers and programmers of Pegasus by setting up the Computer Conservation Society (CCS) as a joint venture between the Science Museum and the British Computer Society (BCS).

2.2. For the Science Museum to employ a senior computer professional both to manage the project for the Science Museum and to set up the CCS and act as its secretary and coordinator.

2.3. To establish procedures and controls which would enable non-Museum personnel to work on Museum objects but still satisfy the Museum's responsibilities towards objects placed in its care.

2.4. To set up a Working Party of CCS members for the Pegasus project.

2.5. To produce an agreed 'script' for the reassembly, testing and commissioning of Pegasus, including a risk analysis of each operation.

2.6. To set up a Software Working Party of the CCS to look at the problems of collecting, preserving and maintaining software.

2.7. To form a sub-committee of the Pegasus Working Party to look at emulation and simulation of Pegasus on a modern PC.

3. Resources

3.1. Personnel.

3.1.1. One senior Science Museum staff member (Curator grade C), to manage the project and to act as secretary and coordinator for the CCS. The Curator of Computing is responsible for the objects in the Science Museum's computer collection.

3.1.2. Volunteer unpaid effort from CCS members.

3.2. Facilities.

3.2.1. Provided by the Science Museum.

3.2.1.1. A workroom for Pegasus and a CCS committee meeting room.

3.2.1.2. Basic hand tools, oscilloscopes etc.

3.2.1.3. Support to the CCS secretary for photocopying, mailing etc.

3.2.2. Provided by the CCS.

3.2.2.1. Funding to pay CCS members' travel and subsistence expenses when attending Working Parties. These funds raised from computer companies being Corporate Members of the CCS at £1,000.

3.2.2.2. The corporate body of knowledge from over 300 CCS members.

3.2.3. Provided by the British Computer Society (BCS).

3.2.3.1. The constitutional framework for the CCS as a Specialist Group of the BCS.

3.2.3.2. An annual grant from the BCS as for other Specialist Groups.

3.2.3.3. Mailing and printing facilities available from BCS HQ.

3.3. The Pegasus computer.

3.3.1. History.

Pegasus Number 18, built in 1958, started life as a Mk 1 but was converted to Mk 2 and exported to Skania in Sweden. Was returned to UK in 1961 and donated to University College London Chemistry Dept in 1963. Used by Dr Judith Milledge for X-ray crystallography analysis until 1983. Went to ICL West Gorton and was put on display. Was dismantled in 1988 and put into store at the Science Museum.

3.3.2. Technical description.

42 bit word length with two 19 bit instructions per word.

Internal computing store 56 words held in nickel delay lines.
Drum store 8,000 words.
Power consumption 15 KWatt.
1,800 valves, 10,000 germanium diodes.
Paper tape I/O, plotter table interface.
Order code designed by Christopher Strachey.

4. Project description

The project manager (the author) was appointed on 1st August 1989. Pegasus was surveyed in store and found to be in good condition. A workroom was identified in the Old Canteen building in the car park at the west end of the Science Museum and Pegasus was moved in on Tuesday 19th September 1989.

Work on Pegasus was then delayed by three months whilst some building alterations were done to the interior of the Old Canteen. During this period the Computer Conservation Society held its inaugural meeting in October and was formally launched in November 1989. Mr John Cooper was chosen as chairman of the Pegasus Working Party and Mr Chris Burton chosen as vice-chairman. The Working Party was formed and methods of working discussed and agreed with the Science Museum. Chris Burton then started preparing a script for reassembling, testing and commissioning Pegasus. This was most appropriate since Chris was the ICL engineer who had decommissioned Pegasus before its move from West Gorton to the Science Museum. After discussion with the Working Party this script was agreed and broken down into a series of tasks. The risk level was agreed on each task. It ranged from very high risk tasks such as first power switch on, to low level tasks like checking indicator lamps. Because Pegasus consumes over 12 KWatt of power great care had to be taken at switch on. This task required the highest 'sign off' level, that of the Curator of Computing and the Project Manager. Lower sign off levels could be delegated to Working Party members.

Our Pegasus had been modified to include a closed air cooling system via intercoolers. This had to be reconnected and recommissioned.

The heavy engineering phase of the restoration took place over a period of about two months. This involved placing all the components in their correct positions and connecting up all the interbay cabling. Chris Burton had done an excellent job in labelling all the wiring and this was a straightforward if tedious job.

All the wiring was then checked by at least two Working Party members. Outside contractors were used to rewire the motor alternator set and the cooling system.

By March 1990 all the preliminary work had been done and switch on could commence. One tense moment was the first time the motor alternator set was activated. It was vital that it rotated in the correct direction. It did and all was well. The excitation currents to the alternator are valve controlled and these had to be checked out. One of the large 12E1 valves had gone soft. The rest were OK.

All the valve heaters on Pegasus are brought up slowly from zero to full voltage. This is to avoid thermal shock when switching on, a notorious cause of valve failure. This gradual buildup involves a large number of delay switches and potentiometers. These all had to be checked.

The High Tension (HT) voltages are +300v, +200v and -150v, all shunt stabilised by power valves. Some of the backplane wiring can have large voltage differences over short physical distances. Various small piles of dust ignited when the HT was first switched on. Spectacular effects, but no damage apart from blown fuses. After considerable discussion it had been decided not to remove all the packages and thoroughly clean the insides. The consensus was that this would cause more faults than a small amount of dust; events proved this to have been a correct decision.

At last the HT supplies were staying on and real testing could begin. The first problem was the cathode ray tube displays on the operator's console which are vital to seeing what is going on. A long shafted multi contact switch had seized up and needed stripping out and cleaning. Once this was done, the displays began to work and the contents of registers could be seen. The computer was then slowly brought to life by entering and obeying instructions from the operator's keyswitches. A major step forward was to get a counting loop running and to see bits counting up on the operator's display.

All this initial testing had been done using the internal crystal controlled clock. The drum had not yet been switched on. When the drum is running, the clock is taken from the drum's clock track and this was tested next. The drum ran up and stabilised correctly and data could now be written to and read from the drum. Eventually the drum system was fully working and the engineers' test programs could be run. This revealed a surprisingly small number of packages needing changing. In all only six packages had to be changed before the engineers' test programs ran. That implies that only 18 valves were possibly dud out of 1,800. A remarkable testimony to the sound engineering design of Pegasus and to the professional expertise of the removal firms that handled it.

By September 1990 Pegasus was running, still not 100% and not every time it was switched on but enough for it to be demonstrated at the CCS Open Day in November 1990. The high point was the 'playing of the tunes' – of no computing importance but giving immense pleasure to all who heard them. Pegasus, like all early computers, has a large loudspeaker driven by pulses tapped off a point in the internal circuitry. It was an irresistible challenge to any mathematician to devise programs which caused various notes to be played on the loudspeaker, hence the tunes.

After the Open Day demonstrations work reverted to making Pegasus more reliable so that the programmers could get some useful work done. The cause of the unreliability was eventually traced to faulty plugs and sockets connecting to the drum clock track. Once these had been rectified Pegasus reverted to the high reliability levels for which it was justly famous in its prime.

The package tester was restored and faulty packages repaired.

By spring of 1991 Pegasus was working well enough for the software libraries to be retested and installed and for the Autocode system to be set up. A number of original programs had turned up and these all ran successfully.

5. The emulator

By early 1991 it was clear that Pegasus was going to run again and thoughts turned to software emulation as a means of preserving Pegasus in the long term.

It is not difficult to construct a functionally correct emulator given the specification of the order code of a computer. It is far more difficult to construct a bit level emulator which exactly matches a working machine. The CCS had from the outset recognised the importance of this and the Software Working Party had been giving it some consideration. The Chairman of the Software Working Party, Dr Martin Campbell-Kelly, had already written emulators for some early computers including EDSAC, but this had been done entirely from published specifications since the actual machines no longer exist.

A number of people then started to write emulators for Pegasus and the Elliott 803, another computer being restored. An excellent bit level emulator already existed, written by Mr Colin Smith, for the DEC PDP-8, also being restored.

Chris Burton, the vice-chairman of the Pegasus Working Party, was also persuaded to have a go. He had an inside track, because of his knowledge of the Pegasus hardware.

6. The simulator

6.1. Design concepts.

When thinking about how to tackle the emulator, Chris Burton had the idea of constructing a realistic and functionally correct interactive graphics front end to the emulator. The widespread availability of VGA graphics and relatively cheap, fast 386 PCs made this possible. Using Turbo Pascal, work started in May 1991 and in eight man days most of the interactive graphics were working, as well as the emulated Pegasus ADD instruction. By June 1991 the first prototype had been demonstrated to the Pegasus Working Party to great enthusiasm. Chris Burton then spent 25–30 man days through till November 1991 refining the graphics interface and completing the emulator. He was assisted in this by Mr Derek Milledge who wrote a large amount of the original Pegasus software. Between them the emulator was enhanced and tested so that by November all the engineers' test programs were running on the emulator together with most of the Pegasus library routines.

It was during this latter phase that the importance of having a real working machine became apparent. There were a number of ambiguities in the Pegasus order code specification which could only be resolved by running identical test programs on the emulator and the real machine. This also revealed the power of the simulator graphics interface; the simulated cathode ray tubes showed exactly the same bit patterns as the real thing. This greatly simplified comparative testing and debugging.

The degree of realism achieved and the detail shown is impressive. All the switches on Pegasus are operated by a realistic finger and hand protruding from a red striped shirt cuff with button. Both cathode ray tubes show the correct bit patterns *in real time* and punched paper tape has the correct holes in it for each character. When a reel of paper tape is loaded into the reader the diameter of the reel relates to the size of tape and decreases as the tape is read in. The teleprinter head moves across the printed page with the jerky motion so characteristic of those devices. All this adds up to the complete feeling of being at the operator's console of a real Pegasus. As with any first-class computer interface, after a few minutes the illusion is complete and to all intents and purposes this really is Pegasus.

6.2. Performance.

On a 20Mhz 386 PC with VGA graphics card the combined simulator and emulator runs at the same speed as the real Pegasus. The loudspeaker in the PC has been connected to the same point in the emulator as the real loudspeaker in Pegasus. The music programs run at nearly the same pitch depending on the precise 386 configuration and speed.

Part of the work of the CCS Software Working Party was to suggest standards for paper tape to PC file format transfers. This work has been slightly adapted for the Pegasus simulator so that real paper tape programs and data can be imported and exported via a PC fitted with paper tape peripherals. It is thus possible to transfer programs and data between Pegasus and the simulator. This was essential for the detailed testing of the simulator.

Over the period from November 1991 to January 1992 the simulator was further polished until now there are no known discrepancies between it and the real Pegasus.

In its present form it has been given a restricted release to CCS members who are using it to re-develop their original software for Pegasus, particularly application software. One CCS member, Mr Doug Brewster, is recreating a suite of programs that he developed in the early 1960s for the Institute of Structural Engineers. He is doing this using the simulator on a PC and then bringing the programs for final demonstration on Pegasus.

7. The implications of the project

The project has demonstrated both the feasibility of restoring an early electronic valve computer back to full running order and the possibilities of capturing the 'persona' of an early computer on a modern PC thus preserving it long after the real computer has ceased to function.

The project has also highlighted the necessary conditions for restoration. Firstly there must be adequate documentation to establish a complete list of parts necessary to assemble a working computer. Secondly all these parts must exist and be in restorable condition. Thirdly there must exist an accessible corporate body of maintenance knowledge about the computer, together with maintenance manuals.

Finally it has demonstrated that given a Museum and a professional body with sufficient vision, it can be made to happen.

8. Acknowledgements

The Project Manager would like to pay tribute to the Director of the Science Museum, Dr Neil Cossons, to the Head of CMD, Dr Tom Wright, to the Curator of Computing, Doron Swade, who had the initial ideas for it all, to Dr Roger Johnson, the Vice-President (Technical & Specialist Groups) of the BCS, and to Ewart Willey, the Chairman of the CCS. Also to all the Committee and members of the CCS including the Corporate members, Allied Business Systems, Bull, DEC, ICL, UNISYS & Vaughan Systems, without whose financial support this would not have been possible.

9. The Pegasus Working Party

Chairman	John Cooper (since deceased)
Vice-Chairman	Chris Burton
Members	Doug Brewster
	Beryl Cooper
	Roy Crabbe
	Len Hewitt
	Peter Holland
	Derek Milledge
	David Mitchell
	Bob Rhodes (since deceased)
	Robin Shirley
	Pat Woodroffe

Historic Machine Simulation in Practice

Christopher P Burton

The Computer Conservation Society has encouraged the modelling of old computers, using modern software running on modern personal computers. The paper introduces some of the work done by individuals in this context. A simple distinction between emulation and simulation is suggested, and practical examples of both are described. Some similarities and differences among examples are mentioned.

Introduction

From the inception of the Computer Conservation Society (the CCS), emulation of early computers had been considered important in conservation work; indeed one of the original Working Parties was devoted to the topic. This paper describes some of the work done by members of the Society to write computer programs which emulate the operation of historic, sometimes non-existent, computers. Other similar work outside the Society exists but no published information has been located.

Emulation of **new** machine designs hosted on earlier systems is a common technique in the computer industry. Modern hardware products can only be produced correctly if their design has been extensively modelled (usually using large-scale software tools), to enable realistic testing and validation. In some cases a newly designed computer may be modelled not in software but in hardware. For example, the ICL 2900 series design was quickly implemented in old, conservative technology to create two hardware systems for use as software and system test-beds.

The justification for emulating an **old** computer design on a modern system, in a museum context, is to :-

- Assist training of operators and maintainers of those artefacts which have limited accessibility or availability;

- Assist conservators and restorers to understand the functional behaviour of a computer prior to physical intervention, in order to limit unexpected contingencies;

- Preserve the behaviour and functionality of an artefact, irrespective of its fate.

This last point is somewhat novel. Where the physical description might have been recorded, say, as a series of photographs, we can now record not only an abstract description, but interact with that abstraction in a similar way as with the original object.

In our discussions in the Working Party, our definition of the word 'emulation' focused on this wish to represent and manipulate the abstract functionality of a computer system. The next section of this paper mentions two examples of emulators produced by CCS members.

During 1991, an extension to this approach was demonstrated where the abstract emulation was embedded in a quite realistic graphical representation of the 'look and feel' of the control panels of a Ferranti Pegasus. For users, the emulator is very much easier to operate and comprehend because no mental jumps are needed between the representation and the abstraction. We now refer to this sort of program as a simulator, analogous to a flight simulator for aircraft.

We can now add further benefits due to simulation:-

- In addition to preserving the behaviour and functionality of an artefact, preserve its 'persona' so that it is easier to capture what it is like to sit at the console of the old machine;

- Provide an environment for former and new programmers of an old machine to develop and test old and new programs prior to use on the real machine;

- Provide a 'portable' historic artefact, suitable for demonstration to audiences to illustrate computer conservation activities, and for distribution to interested parties.

A later section of this paper describes some aspects of some of the simulators we have produced.

Emulators

The emulation programs produced by members of the CCS have been individual efforts. The standard approach is to provide on the screen of a personal computer (the host) a representation of the value of the contents of the various registers of the emulated machine (the target), and to allow the user to adjust those values. The user then starts the emulation process which manipulates the contents of the registers in the same way that the original target machine would, leaving new register values for the user to inspect. The paper tapes, cards etc. on the input and output devices in the target machine would be represented by access to files of data in the host. Some external software tool is required to convert old data, or create new.

Edsac

This emulator was written by Campbell-Kelly[1,2] at the University of Warwick in the early 1980s, many years before the existence of the CCS. It emulates EDSAC, the pioneering computer which was working at the University of Cambridge in 1949. Campbell-Kelly's work involves research in and teaching of the history of computing, and, as he points out, writing an emulator program is an excellent self-contained student project. It has been enhanced many times since the original Unix-based version, in particular to be more interactive and graphical.

Edsac (the program) is hosted on an Apple Macintosh, and consequently has been rather inaccessible to other CCS members. It does carry some aspects of the simulators to be described later. On the rather crowded screen (a problem with all these programs is to get a human-scale object into a 9"x7" view) are separate windows showing an image of a cathode ray tube display, a representation of values in internal registers, push-buttons, the output teleprinter and so on. Numbers in registers are shown as bright and dark dots directly mapping the binary representation. While the program is emulating EDSAC executing an EDSAC program, the displays on the screen are kept up to date with the values they would have had in EDSAC itself. In addition to the emulator proper, the user is provided with an editing tool to enable the preparation and correction of program and data 'tapes'. The editor presents the user with an image similar to the original EDSAC coding sheets.

The graphical display, for example of the cathode ray tube screen of the target, does make the program more like the simulators to be described later, but the similarities are accidental since the programs evolved independently, but with a common goal to be reasonably realistic.

Elliott 803

The first emulator for the Elliott 803, a very early transistorised mini-computer, was written by Onion in 1990 to run on an industry-compatible personal computer. It was a traditional emulator with the contents of target machine registers displayed as numbers in boxes on the screen of the host, and operation was controlled by suitable keyboard commands. No attempt was made to represent the physical characteristics of an Elliott 803 console. The program was very fast, and inspired other people to attempt to write emulation programs.

Simulators

As was mentioned in the introduction, when the soft model of the target computer includes a realistic representation of its physical aspects, particularly of the components with which a user typically interacts, then the model is a simulator. Where the user formerly would manipulate data in registers, now he operates simulated switches and paper tapes, and observes animated displays. With the new graphical interactive approach, simulators now exist in various stages of completeness for Ferranti Pegasus, Elliott 803, Ferranti Mercury and the Enigma ciphering machine, and others are planned.

Although the focus has been on fully software programs which emulate and simulate historic machines, there are opportunities to connect real contemporary peripherals and control panels to a modern host computer, thus creating a hybrid old/modern, hardware/software system. The amount of work for an individual is somewhat daunting, and no firm proposals are known to be in progress.

Ferranti Pegasus

There had been some activity by members of the CCS to produce an emulator of Pegasus, but Burton[3] demonstrated a simulator approach in 1991. This attempted to present a realistic view of the control panels and peripherals. By operating the keyboard of the host personal computer, the user was only allowed to move the image of a pointing finger on the screen. In turn, the finger could then be used to operate the simulated control switches, paper tapes etc, as if it was an extension of the user's own arm. A Pegasus has two cathode ray tube displays, over thirty lamps, forty switches, several rotary switches, as well as two paper tape readers, a tape punch and teleprinter. The moving paper tapes are represented such that the image of the punched holes is visible, making the characters interpretable by eye, as in the real thing.

As mentioned earlier, there is the benefit of a real feeling that one is operating the Pegasus directly. This 'man-machine-interface' was developed first, and the subsequent details of the logical functionality of Pegasus added later, very much as the commissioning of a real machine was done. During this phase, stages of development could be checked and diagnosed by an experienced Pegasus programmer colleague, greatly speeding-up the validation of the simulation. The speed of running of a target program on a typical personal computer is about the same as the speed of Pegasus.

Elliott 803

With the Pegasus simulator as an example, Onion was able to rewrite his earlier emulator program to add simulator graphical features[4]. He took the approach of allowing the user to switch his point-of-view, for example from the console, to the tape reader, then to the paper tape library. This permits quite detailed images of items, possibly at the expense of a slight loss of context. One of the views is of the tape editing station, where the user may prepare and edit paper tapes in the traditional way.

Ferranti Mercury

Perhaps encouraged by the activities in the CCS, Mitchell produced a simulator of the Ferranti Mercury as part of a final year student project[5]. This is interesting because, like the EDSAC, no machine remains extant, and technical documentation regarding the design is limited. Validation depends on careful checking of the results of running a sufficient number of original Mercury programs.

Enigma

Though not a computer system, the Enigma ciphering machine[6] used in World War II has been simulated by Sale as a vehicle to develop general toolkit techniques for creating simulators of large complex historic objects. The work is not complete, and is not readily portable because currently it is hosted on an Amiga personal computer, but nevertheless the operation of an Enigma can be simulated, including opening the cover and changing the code wheels.

Lessons learned

A few characteristics of the development work leading to the various emulators and simulators mentioned above should be mentioned.

Prior familiarity with the details of the design of the target machine is apparently not a pre-requisite for the simulator designer, nor is operating experience on the target machine. However, such experience does help to give confidence in the correctness of the simulation. The final arbiter of the correctness is whether the simulator successfully runs the original target machine programs. In the case of Pegasus, great benefit was obtained by having a Pegasus programming expert independently check the correctness of the evolving simulator.

Again, the programming language used for the simulator does not appear to be important – Pascal, C, C++, assembler and Modula2 have all been used. The nature of simulator programs seems to favour object-oriented design methods.

An interesting consideration is the level of documentation which is to be supplied with the simulators. Ideally, a very brief explanation of how to load the simulator program, together with the basic manipulations of the keyboard and mouse, is all that is required, along with copies of the relevant original target machine documents. In practice it has been found that many users quite unfamiliar with the target machine (and its contemporary context) want to use the simulators, and they need additional tutorial material about the target. Perhaps this is a substitute for the extensive training courses which were provided for users of those machines.

Many different principles of approach to the design of simulators are possible and have been used. In the examples mentioned earlier, at least the following differentiators can be found:-

- Mixed physical realism and abstraction representation on the screen *versus* all physical *versus* all abstract;
- Modelling of individual target machine gates and wiring *versus* modelling of higher level functions;
- Single point of view *versus* multiple point of view;
- Displayed pictures *versus* real-time interpretation of geometric descriptions.

It seems likely that simulation of historic computers in the future will naturally take advantage of what is currently called 'Virtual Reality' technology. It would be fitting that the ancestors of the very-high-performance computers which are required for that technology are revived again in their own descendants.

Acknowledgments

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