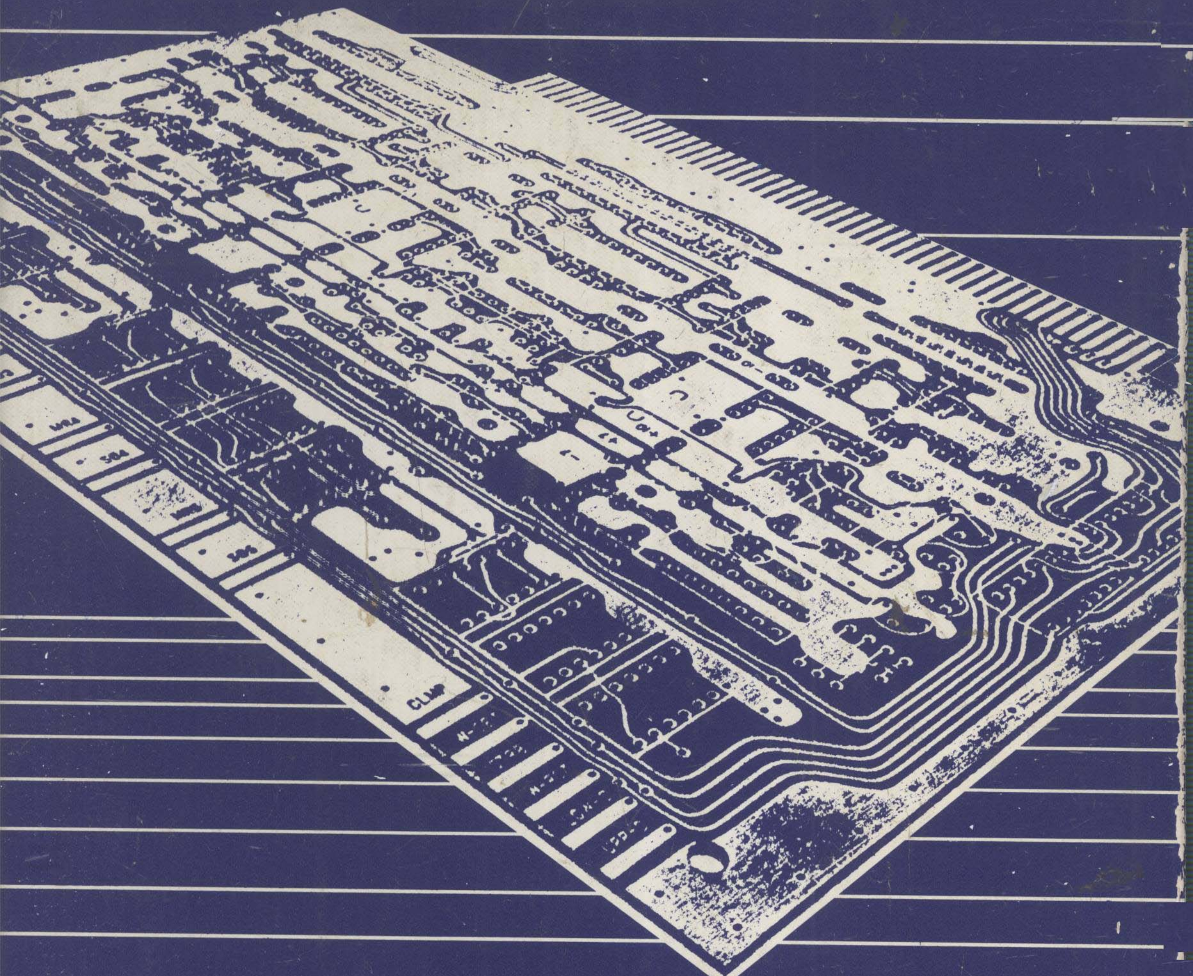
David J. Malcolme-Lawes



MICROCOMPUTERS AND LABORATORY INSTRUMENTATION

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PREFACE

The invention of the microcomputer in the mid-1970s and its subsequent low-cost proliferation has opened up a new world for the laboratory scientist. Tedious data collection can now be automated relatively cheaply and with an enormous increase in reliability. New techniques of measurement are accessible with the "intelligent" instrumentation made possible by these programmable devices, and the ease of use of even standard measurement techniques may be improved by the data processing capabilities of the humblest micro. The latest items of commercial laboratory instrumentation are invariably "computer controlled", although this is more likely to mean that a microprocessor is involved than that a versatile microcomputer is provided along with the instrument.

It is clear that all scientists of the future will need some knowledge of computers, if only to aid them in mastering the button pushing associated with gleaming new instruments. However, to be able to exploit this newly accessible computing power to the full the practising laboratory scientist must gain sufficient understanding to utilise the communication channels between apparatus on the laboratory bench and program within the computer. This book attempts to provide an introduction to those communication channels in a manner which is understandable for scientists who do not specialise in electronics or computers.

The contents are based on courses given to undergraduate and postgraduate science students at King's College London. The objective of those courses was to provide students with an understanding of how modern microcomputers can communicate with laboratory apparatus for measurement and control purposes. It was not expected that all the students would have to design and build interfaces to achieve their ends, but rather that they should understand the principles on which interfaces operate and the capabilities and limitations of practical devices, so that they could design experiments in their own fields with a foundation knowledge of how a microcomputer could be employed.

The courses were closely associated with practical experience gained on microcomputers and a variety of items of standard laboratory instrumentation. Of course that element is not included in the present text, but the fact remains that this book is intended to be of assistance to the practical scientist. While not designed as a do-it-yourself guide to building particular electronic circuits, a number of interfacing circuits are discussed in some detail and the readers may well be able to develop these to suit their own needs. The circuits described are derived from the author's own experience, which is limited to systems associated with PET, Apple, BBC and Spectrum microcomputers. The devices available for use in signal handling continue to increase rapidly. Even over the last year a number of new devices have appeared (particularly opto-isolated devices and LSI circuits), which would be useful for a number of the tasks discussed. However, the principles of communication between microcomputers and laboratory systems are not changing quite so rapidly, and it is hoped that the examples will be found useful.

I wish to express my thanks to Drs. Allwood, Blatchford and Overill of King's College London for their helpful advice and criticism during the preparation of this manuscript, to the research students who have suffered changes in the apparatus while circuits were tested, and to my family for their patience during my long sessions with the WORDPET word processor.

King's College London
October 1983

D. J. Malcolme-Lawes

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CHAPTER 1

INTRODUCTION

One of the consequences of a major change in technology is that a large number of familiar ideas, procedures and equipment quickly become replaced by less familiar devices and ways of doing things. The world has recently embarked on one such revolutionary upheaval and, although it will be many years before the full impact of computers is felt, it is now that we should prepare ourselves to understand the nature of the massive changes which lie ahead. The scale of the technological changes to come will undoubtedly be enormous, just as was the case during the first industrial revolution, and go well beyond the perceptions of those who think that "it" has already happened. These changes will eventually effect almost every aspect of our lives, from education to leisure, from housekeeping to heavy industry. In this book we are concerned with the beginings of this change in one small area of activity - the laboratory, and in particular with the electronic instrumentation used in the laboratory for measurement and control purposes.

Let us start by making quite clear the aim of this book. The objective is to provide scientists who do not specialise in electronics or computers with an introduction to the basic aspects of the use of low cost, mass produced microcomputers for communicating with and controlling experimental equipment. It is not part of the objective to discuss robotics, the mathematical procedures of data handling or sophisticated electronic signal processing techniques. Neither is the use of microprocessors in laboratory instrumentation to be discussed and it is not assumed that the reader has any special knowledge of these devices - other than that a microprocessor is one of the component parts of a microcomputer. In this chapter we discuss briefly some general aspects of microcomputers and their relation to laboratory instrumentation, and outline the level of knowledge required to appreciate subsequent chapters. In chapter 2 we examine the basics of the electrical signals commonly encountered in laboratory systems, and in chapters 3 and 4 we discuss the major elements of the electronic circuits used for handling analog and digital signals respectively. In chapter 5 we look at the modern microcomputer, some of its peripherals which are of value in the laboratory, and a few of the details of its internal organisation and

Table 1.1 Examples of Measurement and Control functions of commonly used laboratory instruments

Instrument	Measured property
thermometer	temperature
manometer	pressure
photometer	light intenstity
pH meter	hydrogen ion activity
GM counter	radioactivity
Multimeter	voltage, current, resistance
clock	time

Instrument	Controlled property
thermostat	temperature
manostat	pressure
potentiostat	applied voltage
monochromator	wavelength transmitted
timer	time interval
flostat	flow rate

function - where these are related to communication with external equipment. Chapters 6 and 7 are devoted to some of the techniques which can be used for communication between a microcomputer and other items of analog or digital signal handling equipment - a subject known almost universally as interfacing. In chapter 8 we consider how to approach the problem of designing an instrumentation system which uses a microcomputer as its control centre, looking at both the hardware and software aspects of the problem.

It must be pointed out that the subject matter of the book is intended to overlap with a number of traditional fields, and that the topics discussed are covered solely for their relevance to the application of microcomputers in practical laboratories. The coverage can undoubtedly be criticised for its omission of topics necessary for a wider understanding of electronics or computers, and could equally be regarded as unnecessary for the man who just wants to connect a computer to an instrument to collect some data. However, the nature of laboratories will change as a result of the technological reorientation that computers are bringing, and in this author's view many scientists, whatever their specialist field, will require a quantity of knowledge in these areas.

Table 1.2 Examples of low cost microcomputers

Models	Manufacturer
BBC model A & B	Acorn Computers
Electron	Acorn Computers
Apple II and III	Apple Computers
CBM, PET, VIC & 64	Commodore
Dragon	Dragon
HX-20	Epson
Newbrain	Grundy Business Machines
HP85, HP125	Hewlett Packard
380Z, 480Z	Research Machines
ZX81 and Spectrum	Sinclair Research
Oric	Tangerine Computers
TRS80 and model 3	Tandy

1.1 Laboratory instrumentation and microcomputers

Laboratory instrumentation assists the scientist by enabling him to make measurements of a wide range of physical, chemical and biological parameters, and by automating the control of measurements, processes and recording functions. Examples of just a few of the measurement and control functions of widely used laboratory instrumentation are listed in table 1.1.

Modern instrumentation allows sophisticated combinations of many of the basic measurement and control functions to provide systems capable of the direct and highly automated measurement of complex quantities. Examples include systems such as thermal luminescent dosimeters, automatic liquid scintillation counters, materials testing equipment, magnetic resonance spectrometers, infra red and ultra violet absorption spectrometers and gradient elution chromatographs. However, although well established instrumental techniques have benefitted from recent developments in electronics, the situation for laboratories with limited resources and for research groups working in new areas of measurement and control is less favourable if commercial systems which meet their specifications are not available.

The dramatic growth in the availability of low cost microcomputers over the last few years has initiated significant changes in the development of laboratory instrumentation, not only by allowing simplification of the operation of many common instruments, but also by providing the means for the development of new instruments based on methods of measurement and control complexity which were relatively inaccessible to the previous generation, such as real-time

Table 1.3 Typical BASIC language instructions

```
1 REM Remarks for ease of reading

10 INPUT X              :REM input data and store in X
20 LET Y = 2+X/3        :REM calculate Y from expression
30 GOTO 100             :REM control transferred to 100
40 PRINT "Y= "; Y       :REM output message & Y,
50 IF X=0 THEN 100      :REM goto 100 if X is 0
70 STOP                 :REM stop execution of program

60 FOR I=1 TO 100       :REM instructions between FOR and
   ------               :REM NEXT repeated for values of
69 NEXT I               :REM I from 1 to 100 inclusive

80 GOSUB 5000           :REM control transferred to line
5000 Y=0                :REM 5000 then instructions obeyed
5999 RETURN             :REM until a RETURN is encountered
```

Fourier transform techniques and diode array detectors for spectroscopy. Some of the most popular microcomputers, available at costs ranging from less than $100 to over $2000, are listed in table 1.2. Any of these micros may be used for the moderately high speed measurement of signals, storing of measurements and data, controlling electrical and mechanical equipment, performing arithmetical and logical manipulations, and the displaying or recording of information.

Microcomputers offer the laboratory scientist a new dimension in instrumentation because they can be programmed to perform the tasks of complex electronic circuits, and the program can be modified until it does precisely what is wanted. Furthermore, when properly designed and tested, microcomputer based systems can offer fast and reliable operation over long periods of time and yet can be rapidly reconfigured to perform a totally different function when necessary. They offer the laboratory scientist the ability to control instumentation during long term unattended operation, to automate routine measurement functions for large numbers of samples, to record and process large amounts of data, and to present the result of a measurement based on many or different quantities.

The value of the modern microcomputer lies in the fact that it can be programmed. Almost anyone with a secondary school education can master the elements of programming a microcomputer in an afternoon using the most common language (BASIC). The principal instructions of the BASIC language are listed in table 1.3, although we are not going to cover the language further or discuss its normal use here. Indeed

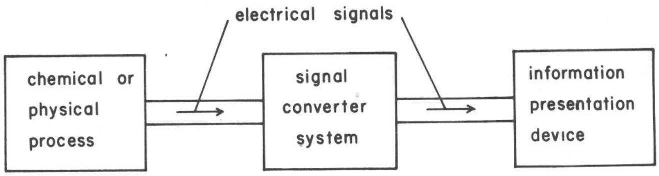

Fig 1.1 The basic components of a conventional measurement system.

we will assume that the reader is familiar with both the appearance of microcomputers and with the elements of BASIC (or any other BASIC-like language, such as FORTRAN) when we come to discuss the operation of micros and communication with them. (There is a large number of books available on the use of BASIC and it is to be highly recommended that the reader who is not already familiar with the language should study one of these before going beyond chapter 4 in this text.)

1.2 Measurement systems

Let us begin by examining the nature of a conventional laboratory measurement system as illustrated by the block diagram shown in fig 1.1. The system consists essentially of three components. The first is the physical or chemical process which is the basis of the measurement, and this can be almost anything from a mouse taking a piece of cheese to carbon-13 atoms absorbing radiofrequency energy at a specified frequency in the magnetic field of an NMR system. The last component is some kind of information presentation or display device which presents a feature of the quantity being measured in a form which can be noted by a human operator. This may be a simple chart recorder trace or a display showing a numerical value. Generally in between there is a second component which acts as a signal converter, converting the signal produced by the first component into the signal required by the third. In most cases the signals are of an electrical nature, and the signal converter is an electronic circuit.

As an example of a simple conventional measurement system consider the basic pH meter illustrated in fig 1.2. In this case the first component of the system is the pH electrode in contact with the solution being tested. The third component is a digital display, allowing readings of pH to be observed directly to two decimal places (eg. 7.04). The signal converter component in this case is an electronic circuit which converts the electrical signal generated by the pH electrode into the whatever signals are required to make the digits 7.04 appear on the display.

Let us now consider a computer based laboratory measurement system, using the simple example illustrated in fig 1.3. In this example the first component may be the same as the first component of

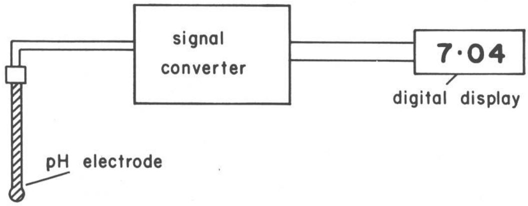

Fig 1.2 The basic components of a typical pH measurement system, incorporating an electrode, a signal converter and a display.

a conventional measurement system, thus it might be the pH electrode as used above. However, instead of just an information display device we now have a computer receiving the signals generated by the measurement process. We still require a signal converter system, to convert the signal produced by the first component into the types of signals which can be understood by the computer, and this will be a different kind of electronic circuit from that used in the conventional measurement system.

Now using the computer in a most elementary role we could program the computer (ie. use "software") to produce signals suitable for an information display, which may be just a display of numbers on a video screen, a fairly conventional chart record, or even an elaborate multicoloured diagram annotated with helpful details (such as a spectrum with peaks highlighted and axes labelled). In that case the computer based measurement system would provide a similar result to that obtainable from the conventional measurement system. For example, if the first component had been the pH electrode, the computer could be programmed to display the pH on a video screen and we would have an expensive pH meter.

However, the computer based system has a number of advantages to offer. Firstly a computer can be programmed to process data before displaying a result. Suppose that we use our computerised pH meter for a system in which a slow chemical reaction is occurring in the sample at a rate proportional to the concentration of a substance X and that one of the reaction products causes a change in the pH of the sample as the reaction proceeds. The computer could be programmed to monitor the pH variation over a period of time, calculate the rate of the reaction, and display the concentration of X. This is surely a big improvement over manually recording a series of pH readings and then sitting down with a calculator to calculate the quantity of interest. Secondly a computer may be programmed to store results for later use, or to compare a result with one obtained earlier. Thus a spectrum recorded on a computer may be filed away on, say, disk and at a later time retrieved and overlaid with the spectrum of another sample, to

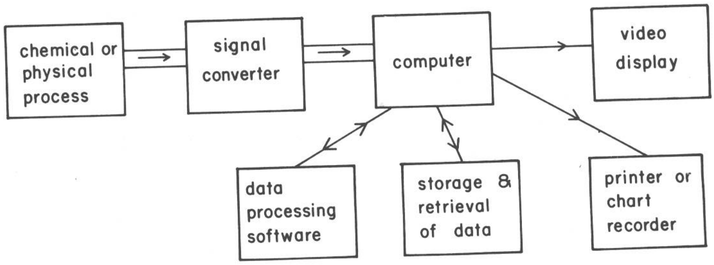

Fig 1.3 The elements of a computer based measurement system, including both hardware and software components.

aid perhaps in the identification of a sample. Thirdly the computer is a flexible device, its software may be changed at will. So our pH meter may be converted into a chloride ion monitor by changing the electrode to a chloride ion selective electrode and the computer's program so that it displays the chloride ion concentration. Similarly a single computer may be connected to several different measurement devices and with a suitable program may be used to monitor several different properties at once, such as pH, chloride concentration, temperature and uv absorbance at 280nm.

Finally a computer based measuring system may also be programmed to effect and control the conditions in the system on which measurements are being made. For example, fig 1.4 shows the computer producing electrical control signals which are then used by a device (say, a heater) to effect the experimental system in a specified manner (eg. by changing its temperature), and monitoring electrical signals produced by a measuring device (say, a thermometer), so that the computer is able to keep track of the effects of its control signals.

Each of these aspects of a computer based measuring system has been dependent on the hardware (ie. the electrical circuits) only to the extent that signal converters are required to translate the signals used or produced by various components into those which can be understood by the computer. But the versatility and power of the the system really comes from our ability to use software (ie. the computer's program) to manipulate these signals in an infinitely extendable variety of ways. This book is largely about the hardware aspects involved in connecting computers to other components. Although there will undoubtedly be developments in this field they will probably fall in the category of technical improvements rather than revolutionary changes. We discuss software in only a limited way, and from the much more restricting philosophy that major changes in this area still lie ahead.

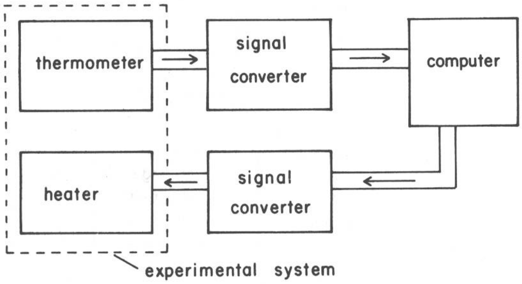

Fig 1.4 A computer based system with control and measurement functions.

1.3 Electronic black boxes

Throughout this book we will be discussing electronic circuits which form the basis for the hardware connection between a microcomputer and any external devices. In chapter 2 we examine the nature of the electrical signals most commonly encountered in the laboratory and discuss some important aspects of signal transmission. In chapters 3 & 4 we discuss the types of electronic circuits relevant to signal converter applications. In all cases it is assumed that the reader has a basic knowledge of electrical components and electricity, covering Ohm's law and elementary ac theory, although a detailed knowledge of electronics is not required. (The symbol R will be used to indicate resistance values in ohms, k for kilohms and M for megohms.) Our discussion will be almost entirely confined to integrated circuits (ICs), which can be regarded as "black box" electronic devices with precisely defined properties (ie. applying particular signals at certain connectors of the IC results in predictable signals appearing at other connectors).

Most of the ICs mentioned are readily available from a variety of manufacturers and suppliers, although the complete code numbers used to identify particular circuits may vary with the manufacturer. For example, the 709 operational amplifier (see chapter 3) may be identified by the codes SN72709N, MC1709G, LM709C or a variety of other codes. Where a device is available from many sources, circuit diagrams containing the device are labelled using only the device code (eg. 709) and not with the manufacturer or packaging codes. Where any ambiguity may result the code of the commercial quality device offered by National Semiconductor Corporation has been used (generally these begin with LH, LF or LM depending on whether the device is of hybrid, BIFET or monolithic construction respectively).

Many of the devices discussed are available in a variety of packages. Nearly all of the circuits shown in this book have been used

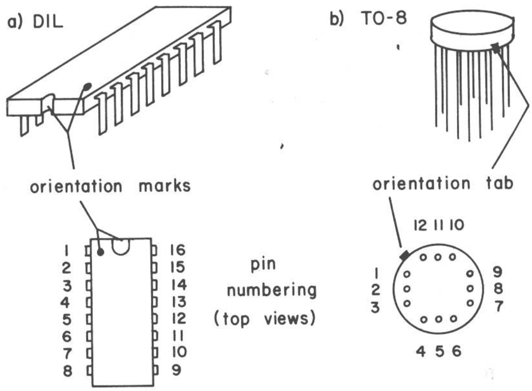

Fig 1.5 Two of the commonly encounter packages used for integrated circuits. a) the DIL package, and b) the TO-8 can.

in the author's laboratory, where the circuits were constructed using commercial quality plastic packages (these are usually black) of the dual-in-line (DIL) configuration illustrated in fig 1.5a. DIL packages have two rows of connection pins, each pin being 0.1 inch from its nearest neighbour and the two rows being 0.3 or 0.6 inches apart, and the number of pins varying from 4 to 40. At no time has the author found it necessary to use the more expensive ceramic DIL packages where the plastic packaged devices have been available (some importers only stock the ceramic packaged devices), nor has the author deliberately purchased any devices specified to higher than commercial quality (military and certain other quality devices are specified over wider operating temperature ranges and may have a tighter spread of characteristics than their commercial equivalents). A variety of other packages are available for many analog devices, the 12 pin TO-8 can shown in fig 1.5b being one of the most commonly encountered. Some of the devices discussed are only available in this form.

1.4 A practical footnote

This book was not conceived as a "do-it-yourself" guide to building computer interace systems, although hopefully some readers may find that the subject is not as complex as they may have thought and so be encouraged to do just that. For such readers the following brief practical comments may be of assistance. The majority of our circuits have been constructed on pre-drilled IC circuit boards (we use Eurocards) using "wire wrapping", a technique by which wires are wrapped without soldering around the pins of IC sockets to convey signals from one part of a circuit to another. This technique is to be highly recommended as only a couple of inexpensive tools are required and wiring errors can be easily rectified. Unless a considerable amount of test gear and expertise is available the "insulation displacement" form of wire wrapping (in which plastic covered wire is wrapped around the socket pins and the sharp edges of the pins cuts through the plastic to make contact with the wire) is not advised. The time wasted in finding a faulty joint can more than offset the time spent in conventional wire wrapping (where the insulation is removed from the wire before wrapping). For high speed (>10 MHz) and fast TTL (see chapter 4) we have preferred to rely on printed circuit boards.

Many of the systems described involve multiwire connections between a microcomputer and an auxilary electronic circuit such as an interface system. For such connections the author is a convinced advocate of "insulation displacement" connection systems (available at relatively low cost from most electronic hardware supply houses). In these the connection between the conductor wire and the connector pin is made by teeth (tines) on the connector which are forced through the plastic insulation around the wire, usually with the aid of a simple bench vice. The use of this technique almost forces a high degree of neatness as special soft plastic covered ribbon cables have to be used.

Most microcomputers are powered from the mains, so don't poke around inside with screwdrivers and bits of wire while the computer is still plugged in - the repair costs could be as much as a new computer. Many of the cheaper micros are low voltage devices powered from separate transformer/rectifier units. In either case be careful about taking power from the micro to drive external circuits like interfaces, some manufacturers have provided power supplies which are barely adequate to run the computer let alone any extra circuits. Although the Apple is an exception (it was obviously designed to have extra circuits plugged into its IO slots), with most micros it is usually wise to provide separate power supplies for interfaces using more than half a dozen TTL ICs or equivalent, and in such cases it is particularly important to ensure that the micro does not produce interference (see chapter 2) in any analog interface circuits. TVs and video monitors tend to radiate a fair amount of high frequency signal. The 0 V connections of the micro and the externally powered devices will need to be connected together but some care should be taken about whether the micro can be grounded - certainly check for any voltage between the micro's 0 V level and mains ground first, and if its more than a few millivolts be careful about connecting to ground. If a separate ground connection for the micro has to be provided then this should be done at the power supply circuit and not from a point in the middle of the logic circuits. And always be aware that dabbling inside the computer generally invalidates any warranty it had.