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SCOTTISH SCHOOLS SCIENCE EQUIPMENT RESEARCH CENTRE

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21st Birthday Edition

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FOREWORD

21st ANNIVERSARY EDITION

Double Celebration

The first Director of SSSERC, the late Joe Stewart, took up the post on the 1st of March, 1965. With luck the printing of this, the 150th issue of the "Bulletin", will more or less co-incide with the 21st anniversary of that event.

History is what you remember

Convention has it that anniversaries such as this be accompanied by chronological catalogues of, and anecdotes on, the events leading up to and beyond the foundation of the agency. To that end, I started looking through what must be one of the Centre's thinnest files. It is entitled "Publicity" and contains newspaper cuttings and copies of old press releases. I was struck by how relatively old was the material and by how little was filed.

I suppose that must reflect on how successive Centre staff members have always put publishing before publicity. This archiveal inadequacy may also reflect a group pre-occupation with looking forward rather than back.

Latter day Adrian Mole

I will be forty this Summer and have been trying, unsuccessfully, to set time aside for my mid-life crisis. Having reached the age when policemen and sixth-year students look about thirteen and even nostalgia isn't what it was, I feel justified in using a little Bulletin space in looking back.

Déjà-vu

Reading more closely some of the archived material, most of it written in the mid to late sixties, I was struck by a number of parallels with current educational issues. A few statements made then, with serious but light optimism, appear heavy with irony now.

Each generation sees its problems and pre-occupations as being unique. As recent examination of SED papers released under the 'thirty-year rule' has demonstrated, a lot of educational issues are not really new, merely re-cycled.

Educational changes occupy a much longer timescale than many folk realise. They also exhibit a curious oscillatory behaviour, rather like the proverbial drunkard trying to follow a white line. Sometimes it looks as though he might never arrive and he may retrace his steps.

A selection of quotes, all from press cuttings contemporary with the opening of the Centre and the first few years of its operation, will serve to further illustrate this principle. Readers are left, for the most part, to draw their own parallels and make up their own jokes.

Opening remarks

"The Centre has been established because of the rapid modernisation of science teaching which has resulted in Scotland through the guidance of the Scottish Education Department along with the enthusiastic co-operation of education authorities and teachers"[1].

(Readers should note that despite the impression given in a recent "TESS" article, by a bit of over-enthusiastic sub-editing, the Centre is at present wholly controlled by Scottish Regional and Islands Councils).

"...to ensure that the equipment going into Scottish schools is the best obtainable and that it performs the functions teachers want" [2].

"The real crux of the matter is that teachers are bewildered by the complexity of equipment being produced. They need advice and guidance, and that is what we will attempt to provide. At the same time we hope that teachers will pass onto us their own ideas and suggestions as to what can be done to improve or develop equipment" [3].

"Here's tae us..."?

"Scotland is at least three years ahead of England in the field of science in schools".

Mrs Judith Hart, then Joint Parliamentary Under-Secretary of State, at the 'official' opening of the SSSERC premises.[4].

"In this scientific and technological age, Scottish pupils are being taught to think in the same way as scientists. It is this approach which....has placed us almost three years ahead of England in the teaching of science in secondary schools" [5].

So MEP, SSCR, NCST, British [sic] School Technology et. al. ya, boo, sucks! We were first. Well, we were in 1965.

Round the back of the scrum

"In a few short months he (the late Donald McGill) had made a whirlwind tour of Scottish schools to find where the strengths and weaknesses lay, and had prepared the blueprint for the New Alternative Syllabus in Physics. By leaving it as an alternative to the existing syllabus he was able to short circuit the statutory five year period which otherwise would have been necessary before the syllabus could have been brought into force". [1].

An early TVEI type tactician? But then -

"After much soul-searching the SED had altered the physics syllabus...". [1].

Those were the days!

"How far away those halcyon days now seem! I can remember a one day conference devoted to the topic of how to measure the force on a current carrying conductor. Now we have a one day conference to "polish off" - I quote one of HMI - the work of a whole year!" [1].

Problems, problems!

Honeymoon period over, the really knotty problems began to appear. They have been with us ever since.

Safety

"School-children under the age of sixteeen have been banned from science experiments....in case their sex life is affected when they are fully grown. These experiments have been going on...for three years. They began after exhaustive safety tests by experts at the Scottish Schools Science Equipment Research Centre in Edinburgh". [6].

No, not some startling new piece of evidence from the anti-practical work faction of educational researchers. Yes, you guessed it! We once even made it into "The News of the World". The subject - the old Ionising Radiations Regulations and the Schools Exemption Order. A curious coincidence, or a measure of the real pace of change, is that we are currently assisting with the formulation of examplar local rules for new, amended regulations.

Demand and workload

"The success of the new syllabus outstripped all the hopes of its originators but landed them with a grave embarassment. How to ensure that all those schools got the tools which would do the job". [1].

"With the increase in the pace of developments in science teaching, there are developments we may never catch up with. There is a lot of stuff in schools we have not had the chance to check and report on". [7].

A proper sense of style

That last quote, of 1966 vintage, was attributed to Joe Stewart. Although he may have said something like that, he certainly did not write those words. Joe had a gift rare in scientific and technical fields. He could write.

There cannot be many of his contemporaries who could with him boast of being a double 'Dux', in Science and English. In Joe Stewart's SSSERC, that report would have served as an example of syntax up with which we would not put. I would hope that present day Bulletins still bear witness to that tradition which he established.

Hopes for the future

"The difficulty, he explained, was examinations. "We must find a new form of examination - we are all groping for what form this must take. A written paper may not be the best answer to this"". [7].

"On development, it would be a disaster leading to stagnation if teachers in schools stopped this work... Where SSSERC can help is in providing facilities, time and money in developing a worthwhile idea without losing faith with the teacher and without claiming credit where none would be due". [1].

Servants not masters

"In the final analysis, it is the teachers of Scotland who will decide the success or failure of SSSERC. Local Authorities are going to support this development only so long as they see benefits accruing to their schools, teachers and children. The decision on this rests with teachers present and future". [1].

True when written in 1966 and just as effective a motivation to Centre staff now. Closure of SSSERC has always been an option open every year to any large EA or a large enough grouping of smaller ones. There has only ever been the support of sufficient satisfied classroom clients to prevent their exercising that option. SSSERC will survive to celebrate Bulletin 200, only if the staff and our Governing Body keep those clients firmly in mind. The standard of service we provide to teachers is our only defence and the "Bulletin", the post and the 'phone literally are our lifelines.

References

1. "The Scottish Educational Journal", June, 1966.

2. "The Times Educational Supplement Scotland", 17th September, 1965.

3. "Aberdeen Press and Journal"(?), October, 1965.

4. "Daily Mail", 8th October, 1965.

5. "Daily Record", 12th February, 1968.

6. "News of the World", 31st March, 1968.

7. "Weekend Scotsman"(?), 10th November, 1966.

[Note: In one or two cases old cuttings could not be either dated or identified with absolute certainty. We apologise in advance for any errors].

*   *

INTRODUCTION

Special Edition

This bulletin is special in a number of respects. The occasion of our 21st birthday and our 150th issue dictated that we include some background on the Centre and its activities. We still meet many teachers and technicians who have the impression that we are some sort of central government adjunct, a miniscule lean-to on New St.Andrew's House.

The Director's foreword to this issue and the "History Notes" hopefully will correct those false impressions. We also hope they will provide some harmless entertainment for those with an interest in recent science education history.

Cover colour

No, the printer did not suddenly run out of what some SSSERC staff have christened "dirty orange" board. The new cover colour (would you believe "flying emerald"?) is to mark the beginning of a new batch of ten bulletin numbers. This change of colour every ten issues was requested by the Planning Committee. The idea is that the colour will change every two years or so. Particular back numbers should thus be easier to pick off the shelves. That assumes that they weren't, long ago put in the bucket!

Index

In case those past bulletins have not been bucketed, we include with this issue an index to the last ten.

Specialists' signposts

Physicobiomistry?

Desperately scratching around for section titles for this bulletin we half seriously coined this as a descriptor for a new scientific discipline. This issue has two 'families' of technical articles, each of which will probably be of major interest to one discipline yet should also have application in the others. Such strains in section titling are not new. We have before adopted the expedients of "Environmental", "Science" or "Instrumentation" in amplifying "Notes".

The first set of articles, which form a family of three, we have placed under "Environmental Notes". They deal with aspects of fieldwork involving measurements on natural waters. This, in our experience of advising on SYS projects, is as frequently a province of the sixth year chemistry student as it is of the biologist.

Another family of articles is placed in "Physics Notes". It deals with the background to, and some applications of, bridge circuits. Its main intent is the support of teaching on electrical bridges, a topic fairly new to engineering science and physics at 'H' grade. Little of the detail is likely to directly interest the biologist or the chemist.

Please note though that bridges are central to the design of a very wide range of instruments and that their usage looks set to increase at the school level. As well as a full treatment of design principles the article also contains a practical thermistor based circuit likely to find a range of uses in biology and chemistry.

RSC Offer

The Royal Society of Chemistry is offering schools an integrated publication service costing £30 per annum. Under this arrangement the school will receive six packages a year which will include the following regular publications:

- "Education in Chemistry", the RSC journal for teachers;

- "Chem Matters", published by the American Chemical Society on the practical applications of chemistry;

/cont.

-"Chem 13 News", from Canada with features, ideas and experiments for teachers and pupils; and

-"Chemistry in Action", a journal published for Irish chemistry teachers.

In addition, relevant papers, posters, booklets and careers information published by RSC and occasional publications of particular interest are included in the package. In illustration of the value offered by this package deal - the special interest publication added into the January pack was the new revised edition of the ASE's publication on "Chemical Nomenclature".

* * * * *

CLEAPSE Guides

We have recently received the following new or revised publications from our sister organisation CLEAPSE School Science Service:

L1 - "Index to Guides" (revised).

L22 - "Video Microscopes".

L151 - "Ammeters etc.".

Copies of the above documents are available on loan on application to the Director of SSSERC.

* * * * *

ENVIRONMENTAL NOTES

Section Outline

We deal first with the tricky business of pH measurements in natural waters. A second article is largely devoted to the description of a handy battery powered stirrer. The idea for this arose during fieldwork done by a school in investigating 'acid rain'. The original application was in pH measurement. The device however is of wide potential application both in field and laboratory. We end the section with notes on conductivity measurement and a summary of recent tests results for some commercial conductivity meters and probes.

Environmental parameters -in general & pH in particular

Even without current heavy coverage in the media, it is difficult not to feel concerned about the quality of the environment. However emotional reactions should not be substituted for assessment of the facts followed by appropriate remedies. It is thus gratifying to increasingly read about and see pupils monitoring the environment. In general the following parameters are most often of interest:

(i) conductivity;
(ii) pH;
(iii) light;
(iv) turbidity of waters;
(v) oxygen content of waters, BOD, COD;
(vi) concentrations of metal ions and various anions;
(viii) gases and particulates in air e.g. SO_2 or lead.
(ix) sound.

Natural Waters

In the examination of waters (i)-(vi) are relevant parameters. Measurement of some or all of these can often be backed up by the use of biological indices, i.e. the distribution of species with known levels of tolerance.

Practical difficulties

In our recent work with environmental equipment we have been concerned with what is practicable in the field at secondary school level. To that end staff have accompanied a school party on a short, local field trip. They have also had extensive discussions with staff from another school. They had been on an extended exercise involving an expedition in Norway. It emerges that a technique which looks straightforward in the instruction leaflets, and the other literature, may be far from easy in practice.

The interpretation of results is not the least of the difficulties. The monitoring of one parameter in isolation and over emphasis on its effects can be misleading. For example, two locations can have the same BOD but special factors in a particular location may keep the water sufficiently healthy for aquatic life. The local weather conditions and fetch of the wind may combine to produce waves, oxygenating the water at sufficiently regular intervals. The pH of a natural water may appear unusually low, yet high levels of certain ionic species may offset possible ill-effects from that source.

Some techniques may appear to 'work' satisfactorily in the lab, but are confusing when applied to extreme conditions such as fairly pure water of low ionic strength at one extreme or sea-water at the other. Pupils rushing out with a typical school pH meter to monitor the possible effects of acid rain may become rapidly disillusioned when they find the meter reading drifting considerably. Some will ask why indicator paper isn't being used instead!

pH in natural waters
Application problems

Natural waters not unusually are also low -conductivity waters. Standard pH probes of the type used in schools, whilst suitable for normal laboratory usage, are not ideal for measurements in such waters.

A demonstration of these difficulties is seen on measuring the pH of diluted acids, salts, or alkalis both with the solution stirred and unstirred. The effects of stirring are negligible even on a meter reading to 0.01 pH. If the same measurements are then repeated with water samples of very low ionic strength, e.g. de-ionised or distilled water, you will be wondering which stirring speed to employ or how long to wait before taking a reading. pH values over a range of 0.3 or more can be obtained depending on the speed of the stirrer.

With a pH probe placed in a burn, several minutes will pass before the read-out stabilises. These effects will appear to be less obvious and therefore less annoying, if an analogue meter is used.

Why should there be such difficulties when measurements are made in aqueous solutions of low ionic strength?

Sources of problems

-the liquid junction devices used in many standard pH probes inevitably allow a slight leakage of the potassium chloride (KCl) reference electrolyte into the sample under test. In natural waters this contamination may significantly alter both the conductivity and pH values of the sample.

-there may be back-diffusion of water from the sample through the junction into the KCl electrolyte. This may create large and variable liquid-junction potentials. These will cause instability in the pH readings.

-the large electrical resistance of a low-conductivity water sample added to the already high resistance of the pH glass membrane may present an unusual input signal to the meter. This may mean that the pH meter readings may become unstable due either to a mis-match in impedance or to capacitance effects from the hands or body of the operator.

Possible remedies

Freshwater research station workers and other professional environment watchers often use separate glass and reference electrodes in a special configuration rather than a combined probe. Additionally their meters will probably have a slightly higher input impedance than the typical school instrument. Impedance mis-match effects may now be less problematic with the advent of inexpensive, modern meters with input impedance as high as 10^{12} ohms. Recently, specialised combined probes have become available but these typically cost upwards of £65.

Unless their use will be fairly regular the purchase of specialised electrodes, either separate or combined, cannot be justified at school level. We shall continue to investigate less expensive ways of improving such aspects of performance in existing meters and probes.

In the meantime some advice is offered on ways of ameliorating some of the anomalous results which may otherwise occur when standard school pH probes and meters are used with low-conductivity waters.

(a) To overcome the effects caused by the high concentration gradient across the liquid junction, (i.e. a satd.solution of KCl & complexed AgCl on the inside and virtually pure water on the outside),

In order to ensure a good flow of electrolyte through the junction of the reference electrode:

-use a fast flowing junction. A ceramic, annular configuration is one of the faster flowing junctions found in combined probes. Fibre and wick types are slower.

-do not dip the probe deeply below the surface. Slightly increasing the pressure of the electrolyte by means of a syringe applied to the filler port will help.

(Another benefit of this is that the electrolyte on the reference will not be diluted by back-diffusion. Such dilution of the chloro-silver complex will cause precipitation of silver chloride in the junction.)

(b) The sample of water can be easily contaminated by the merest trace of a buffer solution used to standardise the probe.

-before measuring, wash the probe well with deionised water and preferably several times with some of the water which will also provide the actual sample.

(c) It is necessary to allow time for temperature equilibration. Streams and lochs are usually much colder than both the buffer solutions used for standardisation or calibration and the filling solutions inside the electrodes.

-before taking a reading allow sufficient time for heat transfer through two thicknesses of glass and two layers of solution.

-alternatively allow samples time to warm up to lab temperature if they have been brought 'home' and been stored in a fridge.

(d) Water of low ionic strength has a very low buffer capacity.

-where possible examine in bulk and on site. Even traces of Na^+ ions leached out of a glass sample bottle may have a significant effect.

[For further information on collecting samples from the field see the article on conductivity meters, page 11.]

(e) Where stirring is used:

-make all measurements at the same speed of stirring in order to obtain results that are at least comparable.

Provided that these precautions are taken and that young operators do not expect highly accurate results in absolute terms or complete absence of drift, then the humble school meter and its general purpose probe can be used satisfactorily for measurements on natural waters.

* *

Portable magnetic stirrers

The importance of controlled stirring has already been mentioned above in the context of environmental pH measurements. Measurements of conductivity and oxygen concentrations can also be improved by such stirring. It also finds a use in redox and pH titrations.

Edinburgh Academy Science Department recently showed us a battery powered, magnetic stirrer suitable for use both in field and laboratory.

Their original design was based on a minature model electric motor. This was mounted vertically, with a small strip of bar magnet mounted on the spindle. The stirrer assembly was constructed of wood and consisted essentially of a box sectioned 'tower' with two compartments. The lower one housed the motor and a potentiometer, used as a voltage divider to control the speed. The top held a beaker containing the sample solution under test. A raised support on one side carried two clips to hold probes (e.g. electrodes and dip cells) in the solution but clear of the stirrer bar or 'flea'. The external battery pack was held to the side of the 'ground floor' to give added stability. Most of the dimensions were not critical, but the base of the beaker needed to be within 2 mm of the top of the rotating magnet.

We were impressed both with the concept and the detailed design. Its robustness had been demonstrated by lengthy use, the same dry cell fitted throughout, on a field study expedition. The design is simple, the materials cheap and the instrument should prove versatile. Clearly many of these mini stirrers can be constructed for the price of a small commercial stirrer. Whilst they will be inadequate for large volumes or for viscous liquids or heavy suspensions, their 'stir-power' will satisfy many demands.

As an alternative to the wooden structure described, we tried out and offer a plastic one! It does look 'plastic' but, not requiring woodworking skills, is easily constructed.(see Fig. 1)

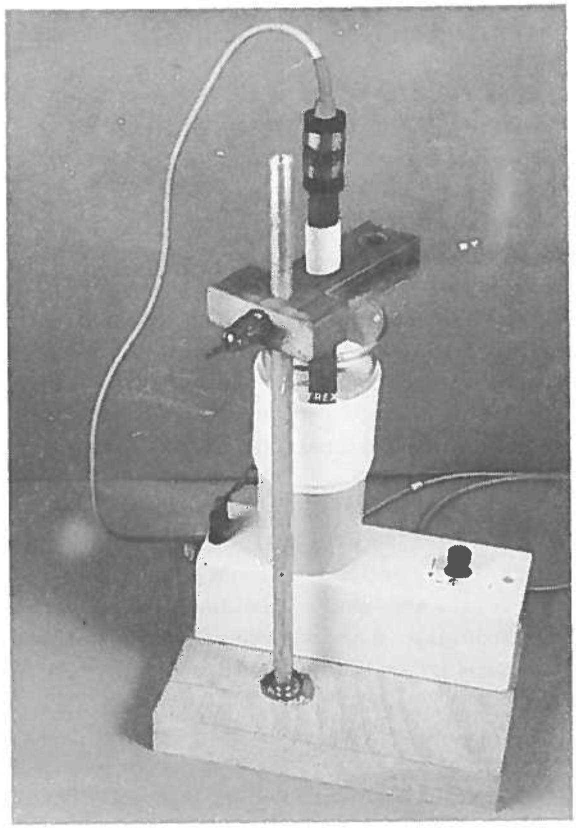


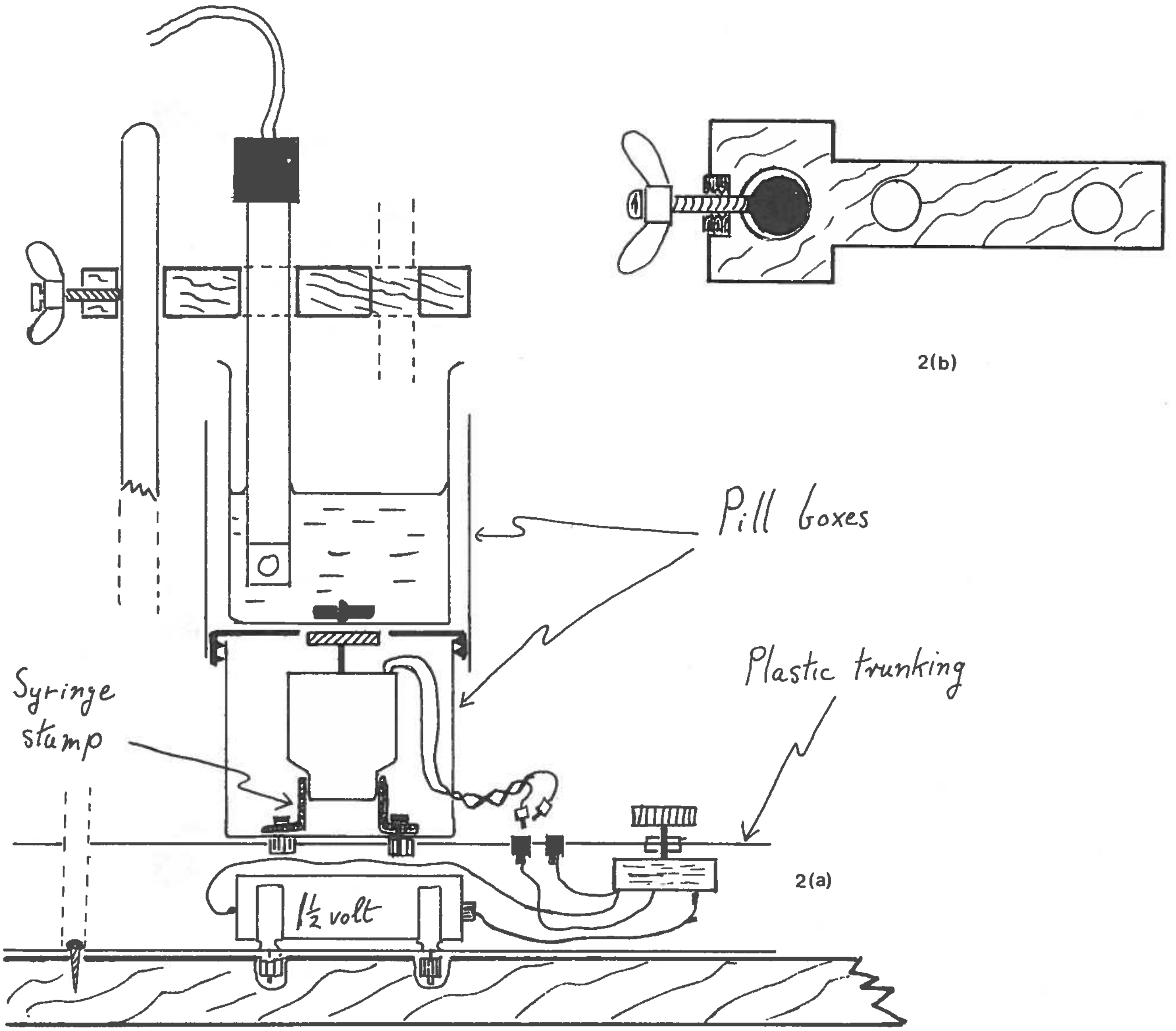
Fig.1

Two different sized cylindrical, plastic pill containers, easily obtained from the local pharmacist, can be push-fitted together to form a motor compartment and a beaker cradle. Again sizes are not critical. Those used by us were:

(i) 49 mm outer diameter by 58 mm high with a snap-on lid for the lower motor compartment and

(ii) a section of the next size up (54 mm i.d.) to act as a collar to hold a 100 cm^3 squat form beaker.

With the aid of a cork borer, previously gently heated, a hole of about 30 mm diameter should be cut out of the centre of the lid of the lower beaker. A BM6 3 volt motor available from SSSERC (price 40p, Item. 389) or from John Bull. This has no fittings for direct mounting but it slots very snugly into the 'sawn-off' barrel of a 20 cm Gillette disposable, plastic syringe. Acrylic syringes are brittle and best avoided.



2(b)

2(a)

Fig.2

The length of the syringe stump should be such that the magnet rotor is just about a millimetre below the top edge of the lid. (see Fig.2(a)) Each lug of the residual barrel is fastened to the base by a 4BA bolt.

An alternative trick here is to put a knurled nut on the outside of these bolts. These will grip the stirrer/motor assembly to the plastic base if the two holes in the latter are made about 1 mm closer together than the projecting knurled nuts. This arrangement permits the easy removal from and replacement of the motor/stirrer unit to the base.

Alternatively the two parts can be fastened permanently by having smaller holes in the base and the nuts on the underside of the 'roof' of the base compartment.

For a base we used a short length of plastic, electrical trunking. In it were housed an RS battery holder and a 15 ohm pot, used as a voltage divider to control the motor speed. The former could be dispensed with the leads soldered directly onto the battery which is simply supported on Terry clips.

The potentiometer is available from SSSERC for 20p(Item 328). Note also that square-sectioned, plastic drainpipe is an alternative to the trunking.

The whole plastic unit can now be screwed to a wooden base which gives it extra stability. A Whitworth 3/8" hex nut embedded into the blockboard base with Araldite will hold a short retort stand rod. Onto this an adjustable probe holder can be clamped at any vertical position. This holder was made from a piece of hardwood two holes slightly larger in diameter than the probes or electrodes used and,close to one end, a third hole just slightly larger in diameter than the retort rod.

A hole made horizontally with a 6 mm drill from the end to the larger hole for the retort rod will allow passage of an OBA bolt. See Fig.2(b) Enlarging this hole with a 12 mm drill to a sufficient depth to accomodate a brass OBA nut. This can be 'Araldited' in position and an OBA brass bolt fitted with a wing-nut can be tightened to grip onto the retort rod.

If you don't have any suitable, bar magnets the SSSERC bargain basement again can provide for 15p, small magnets pre-drilled with a small hole in the centre. These can be mounted on the motor spindle with Araldite.

The total costing for the parts as described above is approximately £2.50, the most expensive component being the retort rod at £1.50. A cheaper alternative is to substitute a length of wooden dowelling. However as anyone, who has ever struggled to adjust wooden clamp stands, will testify even a good wood like beech will alternatively swell and shrink indoors never mind out in the field. Two suitable alternative, rapidly constructed, forms of clamping onto a length of dowel are depicted in Figs 3(a) and (b).

Several other variations are possible. For example, the motor stirrer unit could be bolted straight onto the wooden base beside the 'power unit', making the instrument lower.

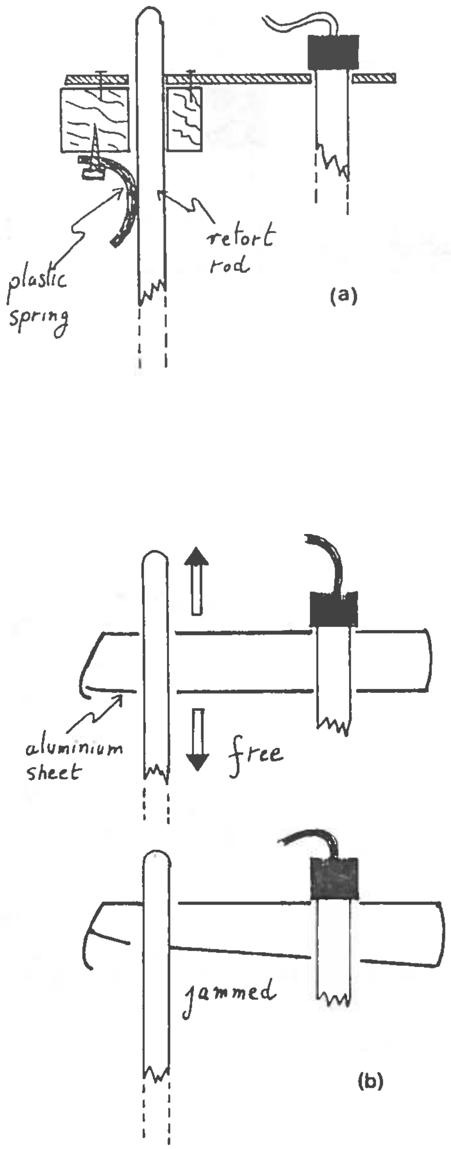


Fig.3

* * * * *

Conductivity Meters

Abstract

The theory of conductivity measurement is outlined briefly with advice on water sampling practice in the field. Three conductivity meters and four conductivity probes are evaluated.

Preamble

This article arises from recent work in evaluating equipment for field use in environmental measurement. Chemists will be familiar with the principles of operation of conductivity probes and meters, particularly in laboratory based activities. These would include analytical techniques such as conductimetric titrations as well as in a range of other illustrative applications.

Biologists may be less familiar with the basis of conductivity and its measurement. Therefore we begin with a brief explanation of relevant terminology and operational principles. Readers who are solely interested in our evaluation results should skip to Table 2.

What is conductivity?

The electrical conductivity of a water sample may be defined, in simple terms, as it's ability, through the presence of ions, to conduct electricity.

Resistance & conductance

How poorly a water sample conducts electricity may be inferred by measuring it's resistance (R) [units, ohms, Ω] to current flow (I) across a potential difference (V).

i.e. by Ohm's Law $R = \frac{V}{I}$

Conversely, or should it be said inversely, the conductance (G) [units, siemens, S or Ω^{-1}] of a water sample represents how well it conducts electricity.

Hence $G = \frac{I}{V}$ or $G = \frac{1}{R}$

'Conductivity meters' & cell constant

The conductivity meters in common use in schools are of a construction which allows direct measurement of the current flowing in a sample cell. A low alternating voltage (minimising the possibility of electrolysis) is applied to two platinum plates within the probe. Most conductivity meters actually measure conductance and it is only when the internal dimensions of a conductivity probe are taken into account, i.e. the cell constant, that conductivity units may be derived.

The cell constant (usually to ∓10% accuracy) is often marked on the side of the dip-type probes commonly used in schools. If the figure quoted is near 1, or the interest is in relative conductivities, then the meter may be read directly. However, to obtain an accurate measure of conductivity (k) [units, Sm^{-1}, $\Omega^{-1}m^{-1}$ or $\Omega^{-1}cm^{-1}$], the meter reading of conductance should be multiplied by the cell constant.

Hence k = G x cell constant

Furthermore, really accurate work necessitates that a cell constant is obtained experimentally for conductivities close to that of any sample tested. This is done by testing KCl solutions of known molarity (see Table 1), i.e.:

$$\text{cell constant} = \frac{\text{conductivity of KCl solution}}{\text{meter conductance reading}}$$

Molarity of KCl	**Conductivity @ 25°C ($S\ cm^{-1}$)**
0.2	2.48×10^{-2}
0.1	1.29×10^{-2}
0.05	6.67×10^{-3}
0.02	2.77×10^{-3}
0.01	1.41×10^{-3}
0.005	7.18×10^{-4}
0.001	1.47×10^{-4}
0.0005	7.40×10^{-5}

Table 1.

Probe care & maintenance

Conductivity probes should be kept immersed in distilled water when not in use. If the platinum black film on the electrodes deteriorates it may become necessary to re-platinise. Griffin & George supply a platinising solution @ £21.74, Cat. No. EKW-800-H. CLEAPSE School Science Service have described the details of d-i-y re-platinising. [1]. Meters and/or probes are usually supplied with similar re-platinising instructions.

Water sampling

When collecting water in, and preserving samples from, the field, the following points should be observed, or spurious readings may result:

- use polythene bottles only.
- do not use soda glass bottles.
- completely fill sample bottles.
- make sure sample bottles are tightly stoppered.
- ensure that no air bubbles or insoluble material such as oil or vegetation is attached to the electrodes when testing.
- filter or let any insoluble matter settle before sampling.
- carry out conductivity tests as soon as possible at 25°C.
- preserve samples in the dark at 4°C.
- conductivity varies with temperature changes by approx. 2% per degree Celsius (Kelvin).

Water collected from 'natural sources' may vary widely in conductivity and this is well illustrated by comparing sea and fresh water, or hard and soft water. A most instructive exercise is to investigate conductivities in samples from an area where a freshwater burn enters the sea.

Conductivity measurements will allow inferences about the total ionic species present in a sample, but not the type of ions present. Therefore it would be impossible to distinguish by conductivity measurement alone, a sample of burn water from a limestone rich area and a sample polluted by nitrate fertilizer.

The student of environmental science must therefore have at his/her disposal a meter and range of probes capable of giving accurate and reproducible results over a fairly wide spectrum of conductivities.

Table 2. is a summary of evaluation and test results carried out on three conductivity meters and four probes from major suppliers. The 'Accuracy with probe' figure quoted is the average accuracy of conductivity measurement for manufacturers' meter/probe combinations taken over the range of standard molarities of KCl solution shown in Table 1.

Reference

1. CLEAPSE Guide L94, "Conductivity Meters", March 1984.

Table 2. opposite/

Meter, Price & Cat. No.	Supplier	Probe, Price & Cat. No.	Cell const.	Scales (S or Ω^{-1})	Chart output?	Battery reqd.?	Accuracy with probe
WPA CM35 portable cond. meter £135.00 CRT-200-J	Griff. & George	plastic bodied £32.83 CRT-400-Q	1.63	analogue 10^{-2}-10^{-6} x1 & x3	yes 100 mV 4 mm sockets	yes PP3 not supplied mains adaptor available	±5-15%
Conductvy. Group * 421.004- Cndy. unit £21.67 423.003- Meter/battery box 24.20	Unilab	plastic bodied £16.54 424.005	1.06	analogue 10^{-1}-10^{-5} x1 & x3	yes 100 mV 4 mm sockets	yes PP3 supplied	±6-17%
S-range Conductvy. meter with cell included £109.00 C29950/1	Philip Harris	plastic bodied £47.73 (spare) C29980/9	1.46 1.3	analogue 1-10^{-5}	yes 1 V 4 mm sockets	yes PP9 not supplied	±5-23% ±5-16%

*Note:- One version of the Unilab Conductivity unit (not tested) is calibrated as a 'Salinity Meter' reading from 0-50 parts per thousand in water. Cat. Nos. 421.005 & 421.003

Table 2.

* * * * * * * * * * *

Bridge circuits

Abstract

Bridge networks are often used in out of balance conditions with resistive sensors. The basis of this practice is referencing the signal output and compensating for ambiance. Crucial to design work is the question of linearization, a property which is shown to be dependent on a careful choice of bridge.

The article begins with an examination of passive bridges, the problems of referencing and annulling environmental factors, and the means whereby the out of balance voltage can be linearized. It goes on to describe the use of operational amplifiers in active bridges as an alternative means at linearization. There is an outline of some common resistive bridge devices: a detailed look at thermistors and a sketchy one at platinum film resistors and strain gauges. It concludes with means of interfacing bridges to other systems.

For convenience the article has been split into four sections.

Section One	Bridge theory
Section Two	Active bridges
Section Three	Applications platinum film resistor strain gauge thermistors
Section Four	Interfacing to other devices

Section One - Bridge theory

Introduction

Both the revised Higher Engineering and Physics syllabuses include for the first time the Wheatstone bridge in out of balance condition.

Syllabus objective 02.15 in Physics states:

> 'Pupils should acquire the ability to perform and describe an experiment to show that, for an initially balanced bridge, as the value of one resistor is changed by a small amount, the galvanometer current is proportional to the change in resistance.'

There is a similar objective in Engineering.

The choice of current in both these courses is unfortunate; most applications make use of the out of balance voltage and we would recommend to teachers that they treat the topic as such.

Sensor plus series resistor

Before getting into bridge circuits themselves it is worth starting off with a simple potential divider arrangement (Fig.1) that is widely used. The downward pointing arrow marks the 0 V rail.

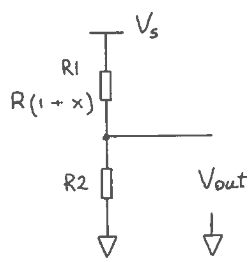


Fig. 1 - Resistive sensor with series resistor

An elementary way of producing a voltage output from a resistive sensor, R1, is to wire it in series with a fixed value resistor, R2, across a supply voltage, V_s. The voltage output, V_{out}, is a function of the measured variable, X.

The system has a transfer function, f(X), such that

$$V_{out} = f(X)$$

V_{out} is a non-linear function of R1, the relationship being

$$V_{out} = V_s \cdot \frac{R2}{R1 + R2} \qquad (1)$$

or

$$V_{out} = V_s \cdot \frac{1}{1 + R1/R2} \qquad (2)$$

R1 can be thought of as comprising two parts, a fixed part, R, and a variable, fractional part, x defined by

$$R1 = R(1 + x)$$

The system suffers from two major disadvantages which are explained by the following analysis.

To keep the algebra simple we will consider the special case in which R2 = R. From equation (1)

$$V_{out} = V_s \frac{R}{R(1 + x) + R}$$

$$\Rightarrow \quad V_{out} = V_s \frac{1}{2 + x}$$

$$\Rightarrow \quad V_{out} = \tfrac{1}{2}V_s \frac{1}{1 + \tfrac{1}{2}x}$$

by expressing as a power series we get

$$V_{out} = \tfrac{1}{2}V_s\,[1 - x/2 + x^2/4 - x^3/8 + \ldots]$$

and by changing the subject we obtain

$$\tfrac{1}{2}V_s - V_{out} = \tfrac{1}{2}V_s\,[x/2 - x^2/4 + x^3/8 - \ldots] \qquad (3)$$

Therefore V_{out} is in general a non-linear function of the fractional change in resistance, x, of the sensor. In particular we should note that the function is not referenced to ground, but to an offset signal, $\tfrac{1}{2}V_s$, the factor of $\tfrac{1}{2}$ arising out of the special condition whereby R2 = R.

In the case where x << 1, only the first order power of x is significant and the function is virtually linear, though offset. By putting in numbers to the first two terms of equation (3) we can appreciate the size in percentage terms of the associated off-linearity error (Table 1) (the effect of 3rd and subsequent order terms is small enough to ignore).

x	1st term	2nd term	% error off linearity at x
0.01	0.005	0.000025	0.5%
0.02	0.01	0.0001	1.0%

Table 1

Thus, provided that the fractional change in resistance is kept within an overall limit of 2%, the transfer function of this electrical system (Fig.1) is linear to within 1%.

A distinction should be made between the transfer function of the electrical circuit and the transfer function of the resistive sensor. For example, a combination of a linear electrical circuit and a non-linear resistive sensor will give a non-linear output. In many applications the achievement of an overall linearized system is an important design criterion.

There is another interesting special case. This occurs when R2 >> R1.

Suppose, by way of example, R2 = 100R, then from equation (1)

$$V_{out} = V_s \frac{100R}{R(1 + x) + 100R}$$

$$\Rightarrow \quad V_{out} = V_s \frac{100}{101 + x}$$

$$\Rightarrow \quad V_{out} = (100/101)V_s \frac{1}{1 + x/101}$$

$$\Rightarrow \quad V_{out} = (100/101)V_s[1 - x/101 + (x/101)^2 - \ldots]$$

by changing the subject

$$(100/101)V_s - V_{out} = (100/101)V_s\,[x/101 - (x/101)^2 + \ldots] \qquad (4)$$

Here the right hand side is an almost linear, but offset, function of x, even for large fractional changes. However the sensitivity is low.

One major defect of this elementary circuit is the offset dependence to which the output signal is subject. This defect is removed on using a bridge.

A further crucial concern is the effects of ambiance. Both the sensor and series resistor could well be sensitive to changes in temperature, light level, humidity, etc. Furthermore the output will fluctuate with shifts in the supply voltage. Our introductory system has no in-built mechanisms whereby the output signal is effectively isolated from the environment excepting that signal to which it is supposed to respond.

A sensor system should ideally behave like a narrow band-pass filter, accepting the signal it has been designed to detect, but rejecting all others.

Bridge circuits are employed because they have the mechanisms whereby they can counteract outside influences.

Bridges - why they are used

The basic bridge is drawn below (Fig.2). R1 to R4 are the four resistive elements, R1 being the sensor element and R2, R3 and R4 being fixed value resistors.

The supply voltage is designated V_s. The voltage developed across the bridge can be thought of as a Thevenin voltage source and is called the **Thevenin voltage**, E_{Th}.

The significance of these symbols holds throughout the article.

Some teachers may be reluctant to introduce the concept of Thevenin voltage sources. An alternative would be to use the term 'bridge output'. If taking this alternative, the symbol E_{Th} should be replaced by V_{out} in the equations which follow.

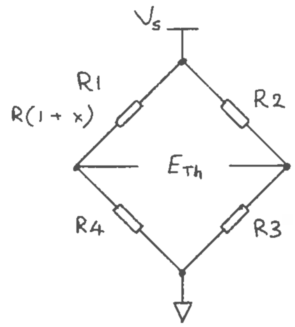


Fig.2 - Resistance bridge

It can be seen as an extension of equation (1) that the Thevenin voltage can be expressed as follows

$$E_{Th} = V_s \left[\frac{R1}{R1 + R4} - \frac{R2}{R2 + R3}\right] \qquad (5)$$

As before in order to simplify the algebra we shall analyse this function for the special case in which R2, R3 and R4 are all equal to R. Equation (5) becomes

$$E_{Th} = V_s \left[\frac{R}{R(1 + x) + R} - \frac{R}{R + R}\right]$$

$$\Rightarrow \quad E_{Th} = V_s \left[\frac{1}{2 + x} - \tfrac{1}{2}\right]$$

$$\Rightarrow \quad E_{Th} = \tfrac{1}{2}V_s \left[\frac{1}{1 + \frac{1}{2}x} - 1\right]$$

$$\Rightarrow \quad E_{Th} = \tfrac{1}{2}V_s \left[1 - \tfrac{1}{2}x + (\tfrac{1}{2}x)^2 - \dots -1\right]$$

$$\Rightarrow \quad E_{Th} = -\tfrac{1}{4}V_s x \quad \text{for } x << 1 \qquad (6)$$

If we extend from the particular to the general it can be shown that the Thevenin output is a function of x which does not have an offset component. This is partly what makes it more useful than the elementary case (Fig.1) of the sensor and series resistor.

Of greater import is the ability to annul the effects of ambiance, a significant factor in precision applications.

Consider the effect of power supply drift on the bridge output. The shifts in potential on both arms are of equal magnitude and cancel. Thus there wil be no corresponding d.c. drift in the Thevenin output. There will however be a change in sensitivity as indicated by equation **(6)**. For this reason the bridge supply should be kept stable.

There are tricks which can be employed to overcome unwanted responses of the sensor to other environmental changes. The resistance of a strain gauge is highly temperature dependent. By constructing a bridge with one strain sensing gauge in position G1 and a similar gauge acting as dummy in position G4 (Fig.3), the influence of temperature on G1 is balanced by the identical effect on G4. R2 and R3 are equal.

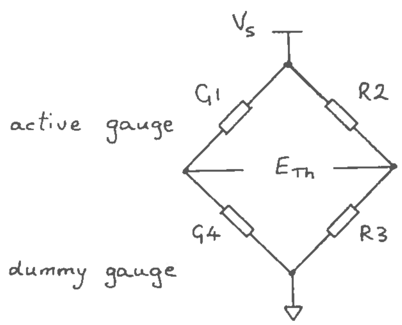


Fig.3 - Annulling environmental drift

Developing this idea, strain gauge bridges can have both sensors active if they are placed so that one experiences compression and the other extension, say on opposite sides of flexing plate. Temperature effects will still cancel while the effective signal is doubled.

Linearization

The analysis above also indicates mechanisms for achieving a linear output from a bridge. For a sensor with a linear transfer function either one keeps to very small values of fractional resistance, x, and operates around the balance point (equations **(3)** and **(6)**) or one operates with a very large resistance ratio (equation **(4)**). For a non-linear sensor one can use the non-linearity of a bridge to compensate, thereby achieving linearity.

Since the resistance ratio is one of the key parameters in the design of a bridge it is often found useful to work with the bridge equation **(5)** in which the resistors are expressed as ratios.

$$E_{Th} = V_s \left[\frac{1}{1 + R4/R1} - \frac{1}{1 + R3/R2}\right] \qquad \textbf{(7)}$$

Arising out of equation **(7)**, the relationship between the Thevenin voltage and R1 can be seen to depend on three parameters: V_s, R4 and the ratio (R3/R2). As has been shown their selection has a bearing on

bridge sensitivity
bridge linearity

These relationships can be checked by experiment. A digital voltmeter of input impedance 10 MΩ is used to measure the Thevenin voltage. In the graphs below (Fig.4), R2, R3 and R4 are all 1KO. Matching at this stage is critical; you can often obtain a matched set by using resistors from the same bandolier as issued by the manufacturer to the supplier. The supply voltage, V_s, is 10 V obtained from a voltage regulated source. It is important that V_s is stable.

A resistance box allowing variations in steps of 1, 10 and 100 Ω is used for R1. Careful matching between the balanced value, R, and the 1KO fixed value resistors is necessary.

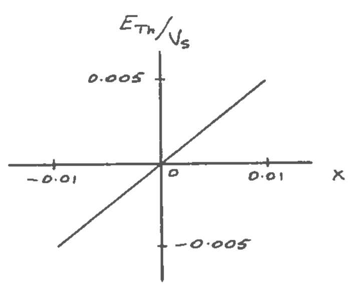


Fig.4a - Thevenin output, R3/R2 = 1, |x| < 0.01

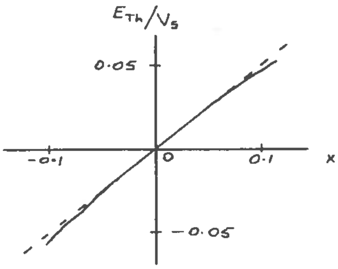


Fig.4b - Thevenin output, R3/R2 = 1, |x| < 0.1

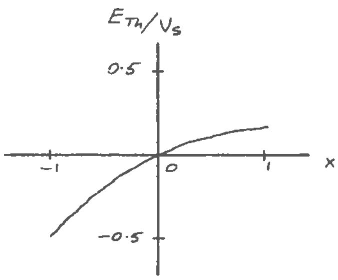


Fig.4c - Thevenin output, R3/R2 = 1, |x| < 1

These measurements show that linearity holds to better than 1% under the condition that the fractional change in resistance does not exceed 0.02 (that is, a percentage change of 2%).

The dependence on the ratio R3/R2 is shown by a similar set of measurements (Fig.5). Experimental particulars are given in Table 2, the supply voltage being 10 V throughout.

Figure	R	R2	R3	R4
5a	100R	100R	10K	10K
5b	100R	100R	1K0	1K0
5c	1K0	1K0	1K0	1K0
5d	1K0	1K0	100R	100R

Table 2

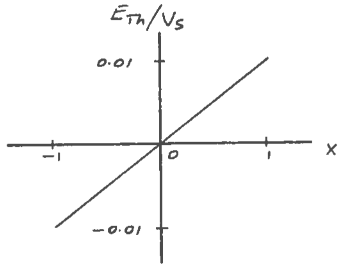


Fig.5a - Thevenin output, R3/R2 = 100

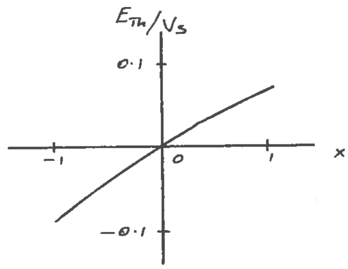


Fig.5b - Thevenin output, R3/R2 = 10

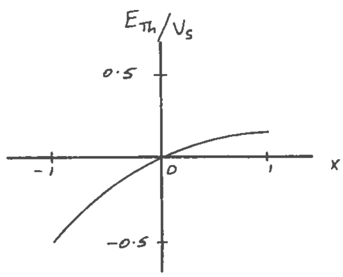


Fig.5c - Thevenin output, R3/R2 = 1

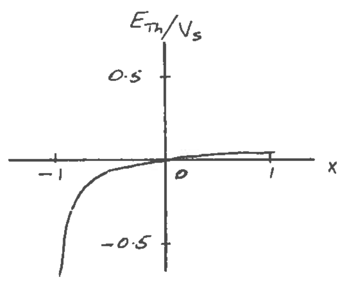


Fig.5d - Thevenin output, R3/R2 = 0.1

The value of the ratio R3/R2 clearly has an effect on bridge characteristics:

(1) Sensitivity is a maximum at R3/R2 = 1; however the performance is non-linear except for small deviations about the balance point.

(2) Linearity is good at high values of R3/R2; this is at the expense of sensitivity.

We thus have identified mechanisms whereby bridge systems can be designed so as to provide linearization.

The art of using bridges with resistive sensors depends on matching these features with the characteristics of the specific sensor. This point is developed in the Applications Section.

Power dissipation

Another factor to bear in mind in bridge design is the self heating effect of the resistors and, in particular, the sensor. This effect can be reckoned from a calculation of the power dissipated in R1.

$$P = V_s^2 \cdot \frac{R1}{(R1 + R4)^2} \qquad (8)$$

Technical data sheets should be consulted as to details of tolerable self heating margins. The parameter with the greatest influence on this is V_s. As general advice, resistors R2 to R4 should be chosen to set the linearity and sensitivity; V_s to control the power dissipation.

In the majority of applications the self heating effect should be minimized by careful design. However certain applications such as anemometry and katharometry exploit the self heating effect. Here one is interested in the rate of heat-loss from the sensor, this being dependent on rate of flow and thermal conductivity of the surrounding fluid.

Before going on to apply this theory to examples with specific sensors we shall examine another class of bridge circuit known as the "active bridge".

Section Two - Active bridge

There are some who consider the active bridge to be overlooked and undervalued. Two types are shown and some indication given of their usefulness.

Active bridge - type 1

An active bridge is one which is kept permanently in balance. The active component is an operational amplifier (Fig.6). In this first type the resistive sensor is connected in the negative feedback path, the design being such that the op amp maintains a constant current through the sensor. Therefore the change in p.d. across the sensor is directly proportional to the fractional change, x.

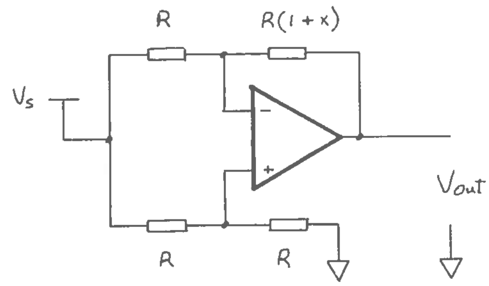


Fig.6 - Active bridge - type 1

The resistors marked R should be carefully matched and set to equal the 'zero' or 'reference' value of the sensor. The downward pointing arrow in the figure represents connection to the 0 V rail.

The theory is explained as follows.

The potential at the non-inverting input is set at $\frac{1}{2}V_s$ by the pair of series resistors, R. The operational amplifier therefore maintains the inverting input at this potential.

By potential division

$$\frac{V_s - V_{out}}{V_s - \frac{1}{2}V_s} = \frac{R + R(1 + x)}{R}$$

$$\Rightarrow \quad (V_s - V_{out})R = \tfrac{1}{2}V_s(2R + Rx)$$

$$\Rightarrow \quad V_sR - V_{out}R = V_sR + \tfrac{1}{2}V_sRx$$

$$\Rightarrow \quad V_{out} = -\tfrac{1}{2}V_sx \qquad (9)$$

Hence V_{out} is directly proportional to x.

In trials with this circuit R is 1KΩ, the feedback resistor is varied between 0 Ω and 2000 Ω such that x has values between -1 and +1, V_s is 12 V. Various operational amplifiers have been tried including a BIFET TL071 which, although it has a low common mode rejection ratio, performs satisfactorily; the output varies according to theory (Fig.7).

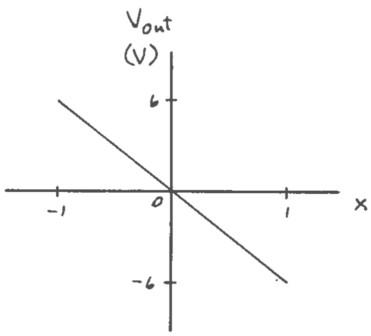


Fig.7 - Active bridge - type 1, output

This bridge can be recommended for any resistive sensor having a linear transfer function; the bridge output should be a linear function of the quantity being measured.

Active bridge - type 2

An alternative form of active bridge (Fig.8) maintains balance as follows.

As the resistance of the sensor in one arm changes, current is pumped automatically into the other arm to actively maintain the balance. This compensating current is monitored and, as can be shown, directly proportional to the change, x.

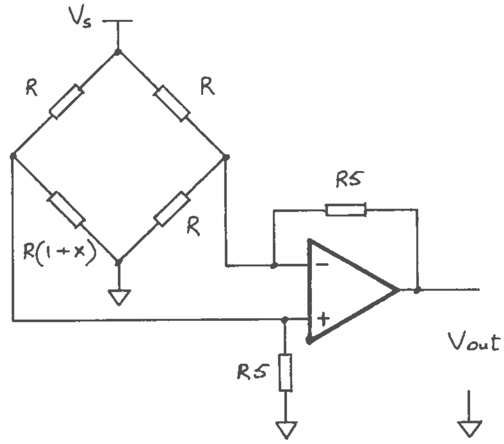


Fig.8 - Active bridge - type 2

Resistors, R, should be matched; similarly, R5, which are subject to the constraint

$$R5 > 20R.$$

There is unfortunately insufficient space to show the analysis of this circuit; it can be obtained on application to SSSERC.

The output is linear provided that x is small, but offset. Its transfer function, subject to approximation, is

$$V_{out} = \tfrac{1}{2}V_s + \tfrac{1}{2}V_s(R5/R).x \qquad (10)$$

Therefore performance is highly sensitive and the bridge appears to suit a linear transducer whose resistance varies by only a small amount.

Under test with a TL071 op amp, R is 1KΩ, R5 is 68K and V_s is 12 V. We obtain a linear output (Fig.9) having a measured gradient of 411 mV Ω^{-1}. This compares with the theoretical gradient of 408 mV Ω^{-1}.

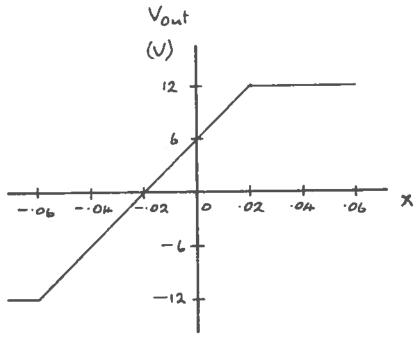


Fig.9 - Active bridge - type 2, output

Active bridges are neither as well known nor as widely used as they should. Passive bridges remain popular, perhaps because of their seeming, four resistor simplicity, apparent, but a property which does not stand up to analysis. Compare their transfer functions; that of the passive bridge is non-linear except for special cases; that of the active is linear. Comparisons of this feature and of others mentioned in the final Section place the advantages firmly on active bridges.

These bridges deserve to be understood and used.

Section Three - Applications

There is a very wide range of uses to which bridges are put in instrumentation. These include

anemometry with thermistors or hot wires

force measurement with strain gauges

katharometry in gas chromatography with either thermistors or hot wires

pyrometry with either radiation detecting thermistors or thermopiles

thermometry with either platinum film resistors or thermistors

Moreover there are capacitive and inductive sensors which, like their resistive brothers and sisters, are also widely used in bridge circuits. They are mentioned in passing. No more, no less.

Resistive sensor review

Hitherto the discussion has been kept general. It now develops into applications with actual sensors. Three are dealt with:

platinum film resistor,
strain gauge,
thermistor,

The first two in principle (they will possibly be dealt with fully in future articles), the last in detail.

The discussion will centre on the problem of linearization: how this can be achieved in each of the three cases. This is with reference to the passive bridge, the section forming a basis to applications related to both the Higher Engineering and Physics topics.

Characteristics of the sensors are summarized in Table 4 together with the outlined solutions (see overleaf).

Platinum film resistors

Platinum film resistors have a wide operating range which extends from -250°C to +850°C. An RS sensor, stock number 158-238, can be used across a range of 550°C. Resistance values of this device are shown below (Table 3).

temperature (°C)	resistance (Ω)
-50.00	80.31
0.00	100.00
100.00	138.50
200.00	175.84
300.00	212.02
400.00	247.04
500.00	280.90

Table 3

sensor	sensor transfer function	solution - type of bridge	R3/R2
platinum film resistor	almost linear fairly high sensitivity typical values T = 0°C R(T) = 100 Ω T = 100°C R(T) = 138 Ω	linear bridge of low sensitivity	R3/R2 = 100
strain gauge	virtually linear low sensitivity maximum range of x is 0.03-0.04	make the sensitivity as high as possible exploit linearity at small values of x	R3/R2 = 1
thermistor	exponential high sensitivity T = 0°C R(T) = 10^4 Ω T = 50°C R(T) = 10^3 Ω	use a non-linear bridge such that it complements the sensor's own non-linearity	R3/R2 to lie between 0.1 and 1

Table 4 - sensor characteristics & outlined solutions

Platinum film resistors (continued)

Two features are apparent: (1) the temperature coefficient is fairly linear within this range and is about +0.385 Ω per °C around 0-100°C; (2) from one end of the range to the other, resistance values change by over 100%. The sensitivity can therefore be expressed as about 0.4%/°C of the resistance value at 0°C.

The passive bridge which best matches these particulars is the one with the ratio R3/R2 of 100; it is linear for a wide variation in x (Fig.5a) and the drawback of its low sensitivity is to a certain extent overcome by the high sensitivity of the platinum film device.

It can be shown that the Thevenin output from such a bridge with V_s of 10 V is 0.385 mV per °C, quite a low sensitivity and one which would require amplification before processing or display.

This need to amplify imposes operational difficulties for, with a lowish signal such as this, electrical noise and drift can be troublesome; special low noise, low drift amplifiers and compensated bridges are often employed.

The problem of low sensitivity is not encountered if one uses the active bridge, type 1.

Strain gauge

The strain gauge by way of contrast operates with very small shifts in resistance. At the limit the maximum value of x is typically 0.03 to 0.04. In practice one may be operating with shifts not exceeding 0.1% over the whole range. Thus the inherent sensitivity is extremely low.

There are trade-offs. One is that the device is virtually linear, it being the case that both strain and resistance are directly proportional to change in length, a precise relationship that holds for small changes. Another is that we can use the most sensitive kind of bridge, that in which the ratio R3/R2 is 1 (Figs.4 & 5c). We are able to use this bridge in spite of its overall non-linearity only because we are working with small changes in resistance.

The Thevenin output from such a bridge can be expected to be of the order of a few millivolts. Amplification is required bringing the problems associated with drift and noise.

One technique employed to boost the sensitivity is to have multiple gauges in two or four arms of the bridge.

A second technique is the raising of the supply voltage. By doubling V_s one can double the sensitivity. The penalty is the quadrupling of the self heating effect. As gauges are highly sensitive to temperature a pulsed supply is sometimes used at a high enough amplitude to boost the sensitivity but with a sufficient mark-space ratio to limit the self heating effect.

Thermistors

Thermistors are semiconductor devices with either a negative temperature coefficient (n.t.c.), the usual kind, employed for temperature measurement, or positive temperature coefficient (p.t.c.), used for over-current protection, but not described below.

When they first became available thermistors acquired a reputation for being unpredictable and unstable devices due to problems in manufacture and in usage (e.g. self heating effects). With better manufacturing techniques and appreciation of their application one ought nowadays to be able to use the devices with confidence.

Because of their high sensitivity they are often the best choice of sensor in high resolution situations. Therefore they are better suited as monitors of minor fluctuations in temperature covering a small span than in covering a large range such as 0°C to 100°C.

Thermistors are manufactured in a number of forms. These include the following.

The **rod** type is physically large, about 22 mm in length, and is used for current limiting and circuit protection.

The **bead** type is physically small, in one version 5 mm long by 1.5 mm diameter, the bead usually being encased in a glass envelope, but may be naked for very rapid response. They are frequently used for temperature measurement and because of their smallness are suited to microclimatological studies and quick response physiological applications. A further use is in katharometry and anemometry where the self heating effect of the thermistor is exploited as a means of detecting the rate of heat dissipation.

R-T curve matched thermistors are also of the small bead type, having a diameter of 2.4 mm. These epoxy encapsulated devices are manufactured with precise characteristics so that one may be replaced by another without the need for the system being redesigned or recalibrated. Working details of such a device are given below.

The resistance of the n.t.c. thermistor decreases with rise in temperature in a non-linear, but predictable, way and can be described by the following equation

$$R_1 = R_o.\exp(\beta/T_1 - \beta/T_o)$$

where
β = characteristic temperature constant (units - kelvin)
T = thermistor temperature (units - kelvin)
R_o = resistance at T_o (units - Ω)
R_1 = resistance at T_1 (units - Ω)

Values for an R-T curve matched n.t.c. thermistor (RS stock number 151-215) are shown below (Table 5). This list is a restricted version of that in RS data sheet 1867 covering the range -80°C to + 150°C in steps of 10°.

temperature (°C)	resistance (Ω)
0	9795.0
20	3747.0
25	3000.0
30	2417.1
40	1598.1
60	746.40
80	376.40
100	203.49

Table 5

At 25°C the sensitivity is 5%/°C of the resistance value at that temperature.

Relating the theory of bridges described in Section One to these characteristics it is possible to insert a thermistor into one arm of a bridge and linearize the output. The mechanism involves compensating for the non-linearity of the sensor by choosing a non-linear bridge set-up, the transfer function of the one complementing that of the other. Typically R3/R2 will lie between 0.1 and 1.

In designing for such a response and in setting the sensitivity one has to select values for V_s, R4 and the ratio R3/R2. This is done by calculation.

One bases the calculation on the requirement that the function for the Thevenin voltage (equation **(7)**) is linear. By solving as a set of linear simultaneous equations the three unknowns can be calculated and the design accomplished.

First the temperature range and sensitivity have to be chosen. Then a suitable thermistor. Set values of resistance covering the required range are taken from the data sheet, the data applied to the equations and solutions obtained. An example covering a range useful to physiological work is given.

range +20°C to +40°C

sensitivity 10 mV/°C
with -100 mV at 20°C
0 mV at 30°C
+100 mV at 40°C

thermistor R-T curve matched device
RS stock number 151-215

From Table 5, R1(20°C) = 3747.0 Ω
R2(30°C) = 2417.1 Ω
R3(40°C) = 1598.1 Ω

Substituting into equation **(7)**

$$-0.1 = V_s\left[\frac{1}{1 + R4/3747} - \frac{1}{1 + R3/R2}\right]$$

$$0 = V_s\left[\frac{1}{1 + R4/2417.1} - \frac{1}{1 + R3/R2}\right]$$

$$0.1 = V_s\left[\frac{1}{1 + R4/1598.1} - \frac{1}{1 + R3/R2}\right]$$

By solving these equations one gets

$R3/R2 = 0.764$, $R4 = 1846\ \Omega$, $V_s = -0.971$ V

The self heating effect should be considered. Using the mid-range value of 2417 Ω this can be calculated from equation **(8)**.

$$P = V_s^2 \cdot \frac{R1}{(R1 + R4)^2}$$

$$\Rightarrow \quad P = 0.971^2 \cdot \frac{2417}{(2417 + 1800)^2}$$

$$\Rightarrow \quad P = 0.13 \text{ mW}$$

From the thermistor data sheet the dissipation constant, defined as the amount of power required to raise the temperature of the thermistor 1°C above its ambient temperature, is 1 mW.

With our designed supply voltage of 0.971 V we can therefore expect our probe to warm up by about 0.1°C due to the current activating it. This falls within the specified tolerance of ±0.2°C and is regarded as being insignificant.

Should a smaller self heating effect be required one remedy is to reduce the supply voltage; a reduction by two reduces the heating effect by a factor of four, but halves the sensitivity.

The data sheet, incidentally, does not specify the medium in which the figure for the self heating effect is quoted. If still air, the figure for a conducting solid or liquid would be much lower. The corollary also applies.

Returning to our design, from the ratio R3/R2 = 0.764 we have made R3 equal to 1800 Ω, that is the preferred value, 1K8, and R2, 2356 Ω, made up from two preferred values in series, 2K2 and 150R. The other unusual value, R4, 1846 Ω, becomes the preferred values 1K8 and 47R in series. By careful selection using a digital resistance meter, resistors are chosen to be as near as possible to the required values. The bridge is shown in Figure 10.

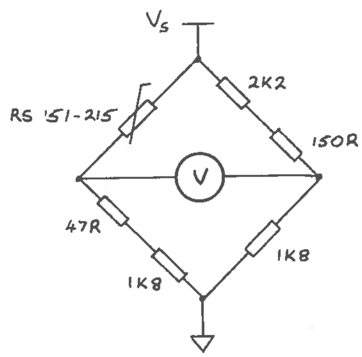


Fig.10 - Linearized thermistor bridge

Voltage measurements are made with a digital multimeter on its 300 mV range.

A stabilized supply voltage (Fig.11) has been devised by tapping off a signal from a band gap reference i.c., ZN423, being nominally 1.26 V. By potential division, the required 971 mV is obtained. This signal is driven by a voltage follower to power the bridge.

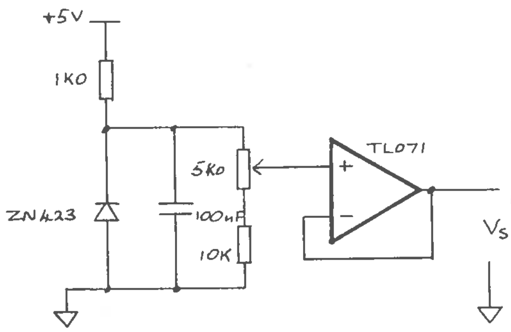


Fig.11 - Stabilized voltage supply

The system has been tested by direct comparison with a commercial thermocouple probe linked to a digital readout having a resolution of 0.1°C, but not, alas, holding a calibration certificate.

In the comparison, both sensors were immersed in a large water bath which was continually agitated. The thermistor leads were electrically insulated by means of miniature sleeving. A larger diameter heat-shrinkable sleeving was slipped over the entire thermistor body (Fig.12), to prevent contact with water.

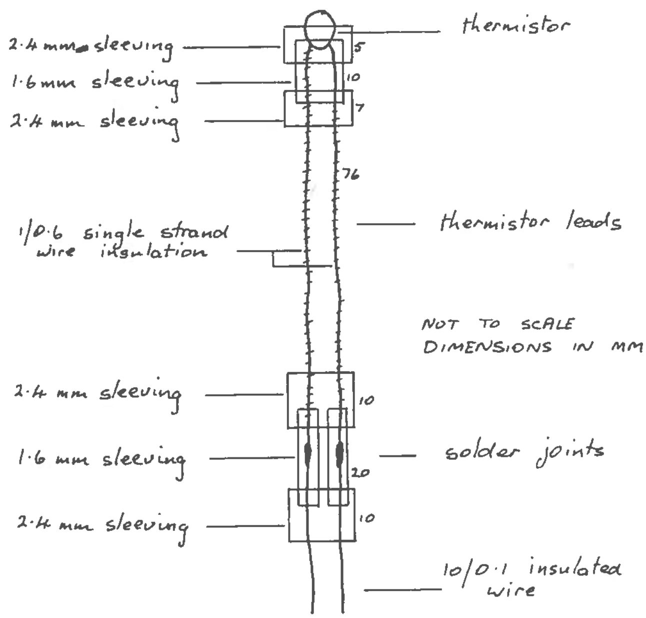


Fig.12 - Protection against water

The Thevenin output (Fig.13) shows good linearity between the limits +10°C and +42°C, thus including the specified range of 20-40°C. Statistical analysis based on drawing the line of regression shows

$$\text{gradient} = 10.04 \pm 0.02 \text{ mV/°C}$$

$$\text{offset at 30°C} = 6.0 \pm 0.1 \text{ mV}$$

where the uncertainties are the standard errors of the values.

The systematic error of 6 mV may be largely due to the incorrect calibration of the thermocouple probe; it lies outwith the tolerance of the thermistor.

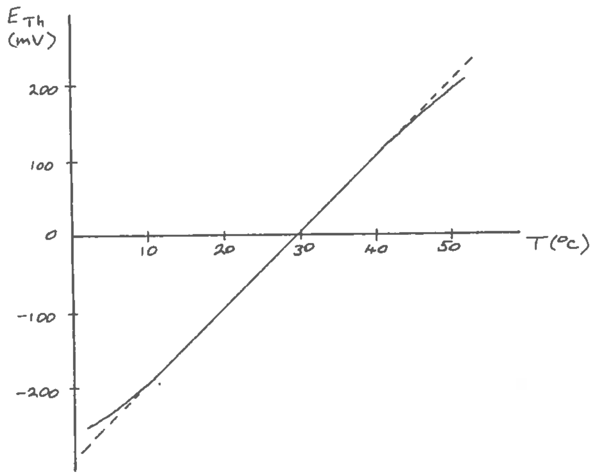


Fig.13 - Linearized output

Section Four - Interfacing to other devices

This field is technically demanding and will not be explored in detail.

Of the many problems which beset the designer that of common mode voltage will be discussed. This problem arises out of the requirement to reference the potential levels on the bridge with the ground rail of the device to which the bridge is being linked.

Suppose the bridge supply, V_s, is referenced to ground as shown (Fig.14). Then with the thermistor bridge above in which the ratio R3/R2 = 0.764, we have a d.c. signal of $0.433V_s$ at points A and B. The Thevenin voltage across AB therefore sits on a d.c. signal of about 420 mV.

We call this common potential at points A and B the **common mode voltage.**

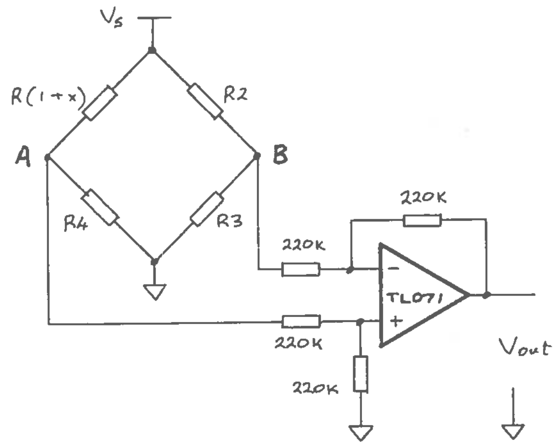


Fig.14 - Common mode voltage

A differential amplifier is connected across the bridge output. This is the means whereby one retains the Thevenin signal, but rejects the common mode voltage. In practice this rejection is never quite complete; the ability of an amplifier to perform in this respect is called its **common mode rejection (CMR)**, expressed in decibels. An example will explain its meaning.

Using the case of the thermistor bridge

common mode voltage	=	420 mV
required resolution of Thevenin signal	=	0.1 mV
⇒ rejection gain	=	0.1/420
	=	1/4200

let the gain of the differential amplifier be 1, then

$$\text{common mode rejection ratio (CMRR)} = \frac{\text{signal gain}}{\text{rejection gain}}$$

$$\Rightarrow \quad CMRR = \frac{1}{1/4200}$$

$$\Rightarrow \quad CMRR = 4200$$

$$\Rightarrow \quad \text{common mode rejection (CMR)} = 20 \log_{10}(CMRR)$$

$$\Rightarrow \quad CMR = 20 \log_{10}(4200)$$

$$\Rightarrow \quad CMR = 37 \text{ dB}$$

The required common mode rejection of 37 dB can be met by the BIFET operational amplifier, TL071, which has a CMR of 76 dB. This case is rather an anomaly because with bridge amplifiers one often requires a common mode rejection of the order of 100-140 dB.

The amplifier gain has been kept at 1 in order to minimize the common mode rejection.

A further means of reducing the common mode voltage is by use of a dual rail supply to the bridge with the centre rail grounded (Fig.15). This would only apply to a bridge with a ratio R3/R2 = 1.

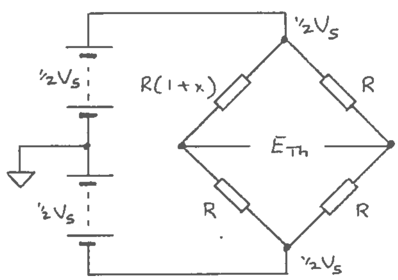


Fig.15 - Use of grounded dual rail supply to minimize common mode voltage

Other desirable properties of a bridge amplifier include high input impedance, low drift and good stability. The first cannot be adequately met by the elementary differential amplifier shown (Fig.14). Its input impedance is governed by the input resistance values. To meet these properties and that of high common mode rejection, one should employ a specialist amplifier such as the classic, three op amp, instrumentation amplifier. These refinements are beyond the scope of this article.

Let it suffice to provide a cheap and cheerful interface (Fig.16) for the Analogue Port of the BBC computer. It is based on the quad op amp package, TL074. Op amp 1 supplies the bridge with a stable voltage, V_s; op amp 2 is the differential amplifier across the bridge; op amp 3 provides an offset voltage of 600 mV so that the signal at the Analogue Port is mid scale; and op amp 4 adds this offset to the Thevenin signal.

Fig.16/ over

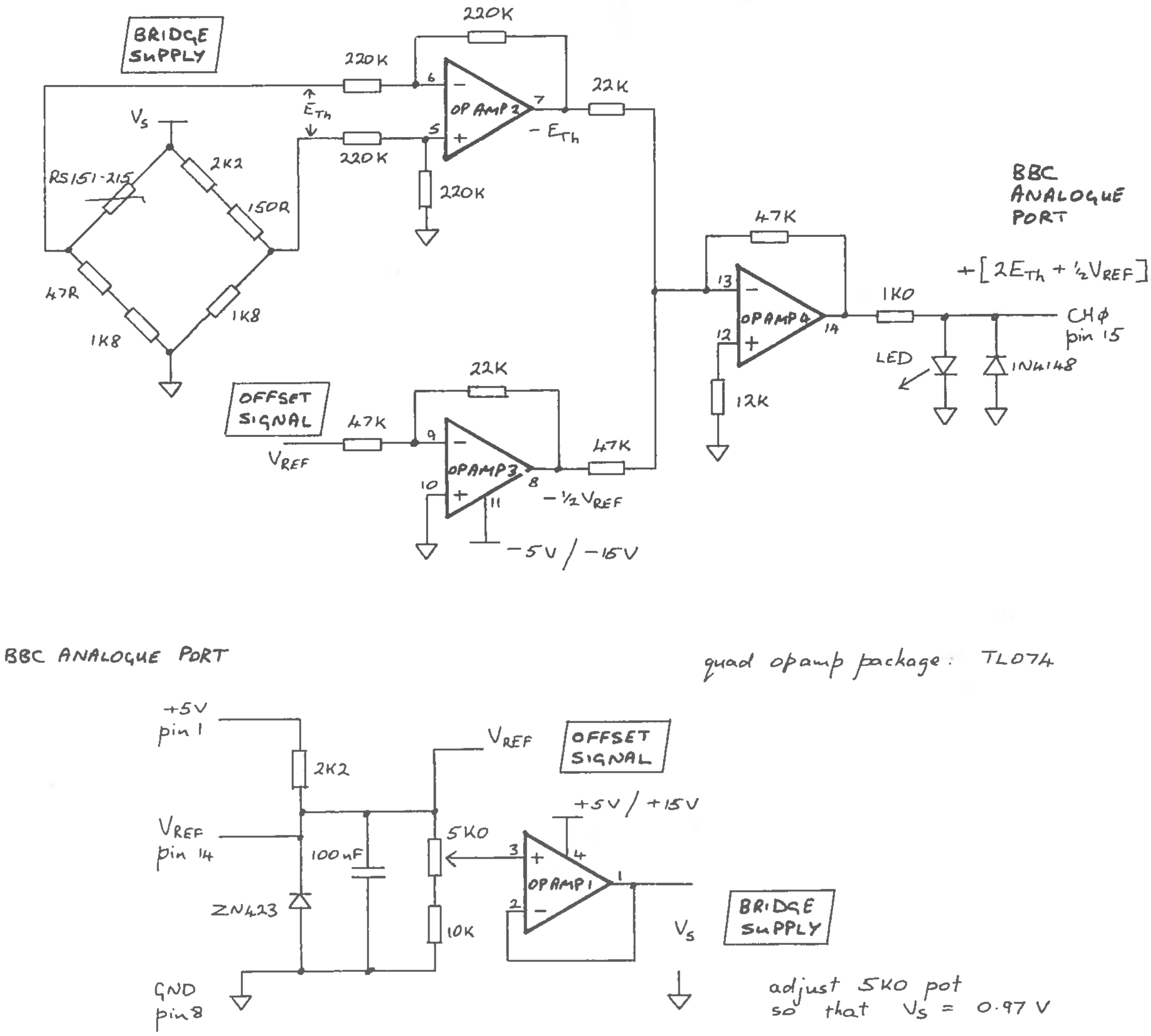


Fig.16 - Interface to BBC Analogue Port

The voltage reference diode, ZN423, serves three functions. It provides a stable reference for (1) the computer's A to D converter, (2) the bridge supply and (3) the offset signal.

One final point, the problems just mentioned of referencing the bridge output to ground disappear if one uses an active bridge.

A telling reason for their adoption.

Conclusion

This article has first of all been written to provide a background to a new area of the Higher syllabuses which, we suspect, lies outwith the training and experience of most teachers. We hope the treatment is appreciated.

There is a second reason, the general requirement by teachers of all science and technical subjects for an understanding of instrumentation and sensors. To this end we hope we have provided the basis for an informed use of properly designed and reliable devices.

Acknowledgements

Two books which have been a source of inspiration and assistance in the preparation of this article are

(1) Bentley, J.P., "Principles of measurement systems", Longman, 1983, ISBN 0 582 30506 3

(2) Sheingold, D.H., "Transducer interfacing handbook", Analog Devices, 1980, ISBN 0 916550 05 2

To Dr. Peter Williams, Director, Microelectronics Educational Development Centre, the author is in several ways grateful: for my introduction to active bridges, for general advice in the preparation of this article, for an overview of the text.

Components

item	supplier	cat.no.	price
thermistor			
R-T curve matched	RS	151-215	3.78
platinum film detector			
flat element	RS	158-238	2.48
	Farnell	146-884	5.98
rod	Farnell	146-883	5.98
strain gauge type 11	RS	308-102	2.40
	Farnell	143-012	2.13
type 23	RS	308-118	2.40
	Farnell	143-014	2.13
single op amp TL071	RS	304-245	0.43
	Farnell	TL071CP	0.41
quad op amp TL074	RS	302-621	1.35
	Farnell	TL074CN	1.28
voltage reference ZN423	RS	283-233	1.00
	Farnell	ZN423T	0.95
15-way 'D' plug	RS	466-185	1.81
	Farnell	DAF15P	2.57
heat shrink sleeving			
1.6 mm	RS	397-988	3.55
	Farnell	143-717	0.60
2.4 mm	RS	397-994	3.62
	Farnell	143-718	0.63

*   *   *   *   *

S U R P L U S   E Q U I P M E N T   O F F E R

In general this offer is subject to the conditions laid down in Bulletin 116. However all of the entries in this issue are **subject to our ballot** procedures. Entries should preferably be submitted on a postcard and in an order of prority. Items marked "**OO**" will be only sold against an official order. Please do not send this unless and until requested, it should not accompany the original ballot entry.

Item 430	Digital timer (made for British telecom?), 4 digits 3 ranges -10 s to 9.999 s triggering on both edge and level sensitivities. Separate controls start & stop. Auto or manual reset. 12 V d.c. or 240 V a.c., 50 Hz. Modern design.	£15
Item 431	Natural gas Bunsen burners by Flamefast, as new.	50p
Item 432	Slide projector,by Gnome 'Supreme de-luxe', with circ. magazine for 122 slides.[**OO**].	£20
Item 433	Linear expansion apparatus by Harris (P 24552/0).	£5
Item 434	Electrothermal "Red Rod" immersion heater.	£1
Item 435	Alga stereo amplifier, 240 V a.c. 50 Hz. 36 Watt.[**OO**]	£2
Item 436	Glass reagent bottles, 250 ml etched labels, asstd. common reagents. Details on request.	5p
Item 437	Lens, apochromat, f 2.5 by Kinoptik of Paris. Overall size 105 x 74mm.	£2
Item 438	Lens, by Isco-Gallington, f 3.1, 120 x 70mm.	£2
Item 439	Lens, apochromat, f 2 by Kinoptic, Paris, 62 x 45mm	£2
Item 440	Lens, zoom, 0.75 - 1. by Sankor, Japan, 50 x 66mm.	£1
Item 441	Eyepiece lens by Wray of London, overall 48 x 30mm, lens dia. 22 x 12mm.	50p
Item 442	Viewfinder lens, '2 inch' for Bell and Howell cine camera. Mount 28 x 10mm, lens 5 mm by 4 mm.	50p
Item 443	Automatic sampler by Newton contains tally counters, motors switches etc.	£2.50
Item 444	Unicam SP40p automatic sample changer, in working order.	£2.50
Item 445	Mettler, top-pan balance P1200, 1200 g by 0.1 g.	£10
Item 446	Spot or mirror galvonometer by E.E.L., Type 20.	£5
Item 447	Galvonometer, scale expansion unit. (Works as galvo.).	£5

End of ballot

Please note: A large range of components (pots, resistors etc.) many as advertised in more recent issues are still available. Consult for example, Bulletins 143, 145 and 147.

*   *   *   *   *

"A few gadgets"

"We have a few gadgets which we think are of value to the schools"

Joe Stewart, newspaper interview, November 1966.

The first Director of SSSERC was given to under-statement. The records show that even in the early days, indeed before the Centre had been opened, a lot of excellent development work was already under the belts of Scottish teachers.

Development and testing

A twin tradition

SSSERC really grew out of the work of the Advisory Committee on Physics set up in 1961 to advise the Secretary of State on all matters affecting the teaching of physics. Early in its life this spawned a Technical Sub-committee. The function of this sub-committee was to assess apparatus for its suitability for the modernised, alternative physics syllabus. Testing of apparatus was carried out by teachers in their spare time in their own schools and in what was then Heriot Watt college with the help of the late Professor W.H.J.Childs.

Meanwhile, in England and Wales the Nuffield Foundation Science Project had begun. Scotland was designated a "Region" (twas ever thus!) and a team set up under the leadership of W.R. Ritchie, then of Kirkcaldy High now an HMSCI at SED. Development work was done in schools and in the Apprentices' School of Ferranti Ltd.

With the untimely death of Donald McGill (of the parent Nuffield project) much of the impetus of the Scottish effort fell away. Nevertheless the success of the Scots team can be gauged from some of their products: the linear air track, magnetic pucks for frictionless motion and the Venner stopclock. Revolutionary then, these devices have become familiar to several generations of students. Some have now themselves been superseded and that is how it should be.

By the Summer of 1963, Technical Sub-committee members were fully occupied testing equipment for the alternative syllabus. The Scottish Nuffield team were developing new equipment much of which was in turn finding application in the Scottish syllabus, by then fully launched. For some who were members of both groups, like W.R. Ritchie, Jim Jardine and the late John Emery of Glenalmond, the burden of work was overwhelming. Not only had the workload in testing and development put unacceptable demands on the spare-time of already hard-pressed teachers, but there was no means of communicating results to the majority of their colleagues. On the horizon was the possibility of radically new syllabuses in biology and chemistry.

With the backing of the SED and the Advisory Committee on Physics local authorities were asked to co-operate to form a National Science Centre. With no guarantees that the scheme would find general favour with all Education Authorities, Edinburgh and Glasgow and one or two others of the old City and County Councils co-operated in laying the legal and administrative foundations for the new centre. Only when these initial stages were complete and premises found was the scheme offered to all the Scottish EAs. Only one County Council opted out. SSSERC was born.

Design and Development

In their development work, almost by definition, Centre staff have to be ahead of the game. The trick seems to lie in not being too far ahead as well as in travelling in the right general direction. That has usually been ensured by the Centre's Planning Committeee with its majority membership of practising teachers. It has also helped to have had active co-operation over the years, with Joint Working Parties. The generally hidden SSSERC exports of work commissioned by Central Committees and SCDS have kept us to close to the established curricula.

It has also to be admitted that some of our work has turned out to have been wholly speculative and largely unrewarding in the sense that it was never widely taken up. Other work that once we worried over as luxurious speculation eventually neatly filled a previously unidentified curricular need.

Most frustrating for staff has been the proselytising technical development work which would be highly relevant and would meet an important curricular need if only the curriculum wasn't so very far behind! The curriculum may eventually catch up. Suddenly, our old hobby horse has been stolen out from under us - commandeered by our erstwhile critics and hitched up to their new bandwagon.

SSSERC staff learn to live with that sort of thing. For example SSSERC's first electronics article appeared in Bulletin No.3. (February, 1966). It dealt with a valve application! The Centre has thus been active in the field of electronics in schools for twenty years. For teens of years doubts were expressed about the relevance of such involvement. If microelectronics means work with 'chips' then our record in such work for Scottish schools is, by some standards, verging on the venerable.

Bulletin 'snippets'

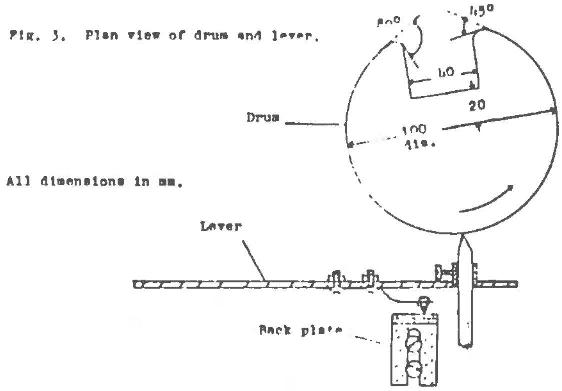
One of the less tedious ways of illustrating such a curious mix of development work over 21 years, is through an eccentric selection of items from earlier bulletins. Reproductions, some necessarily reduced, of illustrations and diagrams from back issues will also show how the presentation has improved (though we hope it still appears reasonably homely). The ideas remain the important ingredients. For some of those we have to thank staff members past and present, in particular the late Joe Stewart and Hugh Medine, Dennis Belford and Colin Weatherley both now back teaching in Scottish schools. Even greater is our gratitude to the large numbers of Scottish teachers, technicians and science advisers who have sent us so many excellent ideas during those 21 years.

Keep them coming!

*   *

Acknowledgement

We are grateful to Philip Harris Ltd. for permission to reproduce three illustrations from their 1974 catalogue.



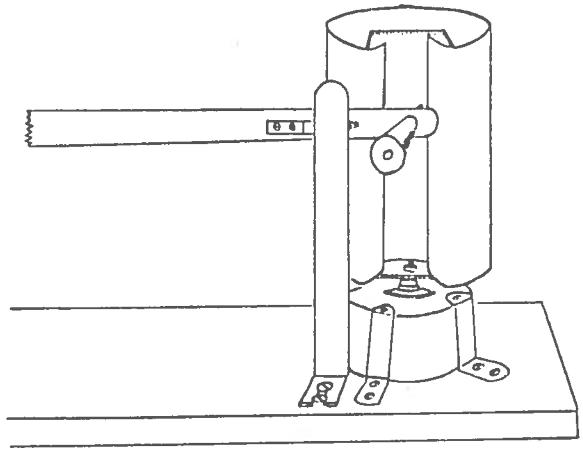
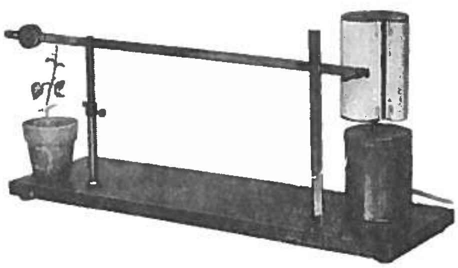


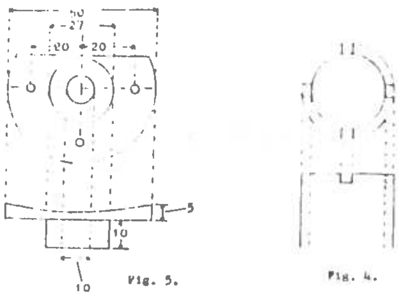
Fig. A. - Auxonometer

Above is the original design - Bulletin 12, March 1967, below a commercial version.



B5129

B5129 AUXANOMETER ROTATING DRUM, S.S.S.E.R.C. PATTERN (PATENT No. 1155107)



Dimensions in mm.

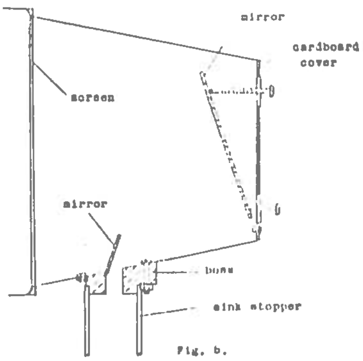
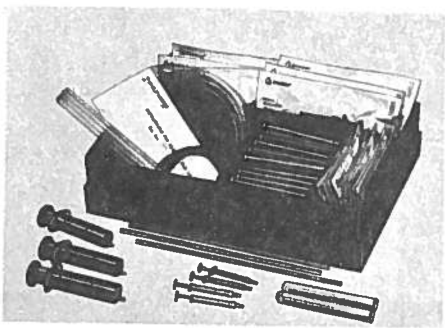


Fig.B.

Microprojection - viewing head from a flowerpot.

Bulletin 67, December 1973.



B5073

B5073 GAS ANALYSIS KIT, S.S.S.E.R.C. PATTERN

For the determination of CO_2 and O_2 in expired gas from Man, Insects, Water Plants, Land Leaves, Seeds, Yeast in Sugar solution etc.

Fig.C.

SSSERC gas analysis - commercial version.

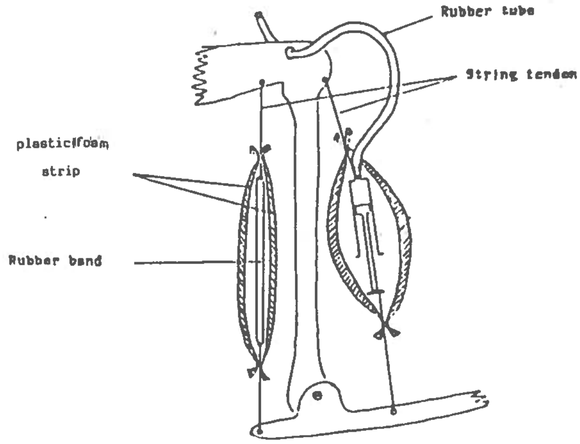


Fig.D.

Early version of model arm.
Bulletin 24, August 1968.

In The Workshop

In the majority of cases when a liquid is to be dispensed from a bottle an exact measure of the quantity is not needed, and this makes the commercial fixed-volume dispensers expensive. Also from the safety viewpoint it may be an advantage to dispense the most commonly used reagents, e.g. dilute acids and alkalis from two or three Winchesters placed on side benches in preference to 500ml reagent bottles. There is less risk of spillage, and no risk of contamination through careless handling of stoppers.

The dispenser uses the ubiquitous plastic bottle. Detergent bottles are suitable, but probably too large and unwieldy, and bottles of hair lotion, bubble bath etc. are more convenient. A hole which can be covered with the thumb, is made in the side of the bottle, which is then fitted up as in the diagram. The dispensing tube passes almost to the bottom of the liquid container, and the upturned end prevents any sediment, e.g. from lime water, from being delivered. To dispense the liquid the user requires to squeeze the plastic bottle while keeping the hole covered by the thumb.

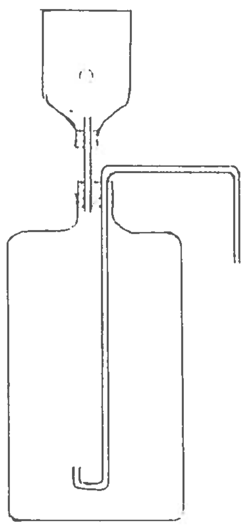
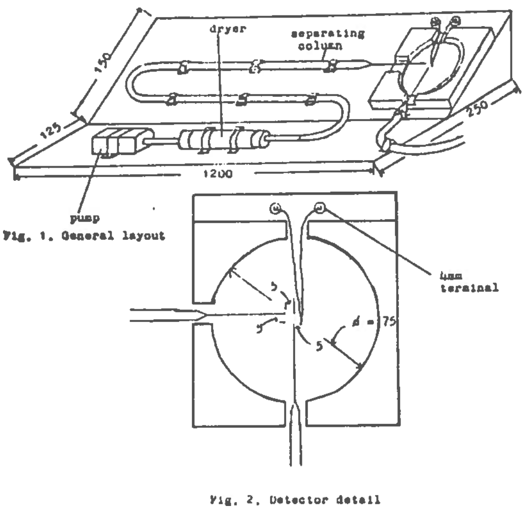


Fig.E.

Liquid dispenser from bulk & basis of burette filler. Bulletin 29, March 1969.



Dimensions in mm. Not to scale

Fig.F.

Simple gas chromatograph.
Bulletin 69, February 1974.

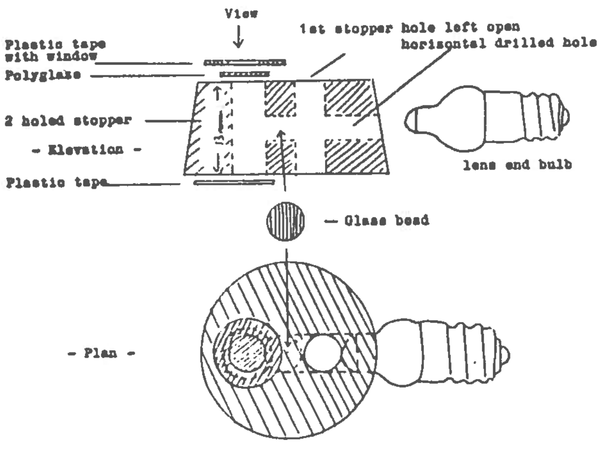


Fig.G.
'Musselburgh' smoke cell from a rubber stopper.
Bulletin 4, March 1966.

P8845

P8845 SPECTROSCOPE, STUDENT PATTERN
This simple instrument (suggested by S.S.S.E.R.C.)

Fig.H.
Spectroscope - commercial version.

While illustrating energy conversion at an elementary level, the motor should promote discussion with senior pupils when asked to explain why the maximum motor speed is not obtainable in the strongest magnetic field, i.e. with the motor between the poles.

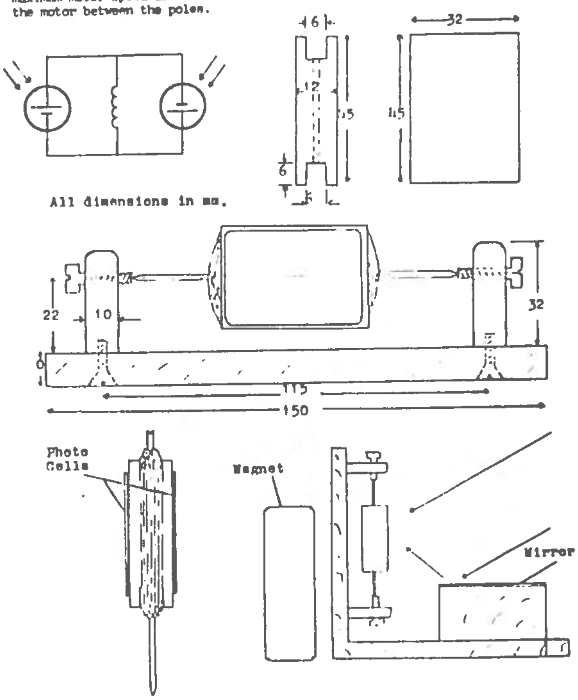


Fig.I.
Solar motor. Bulletin 8, Sept. 1966.

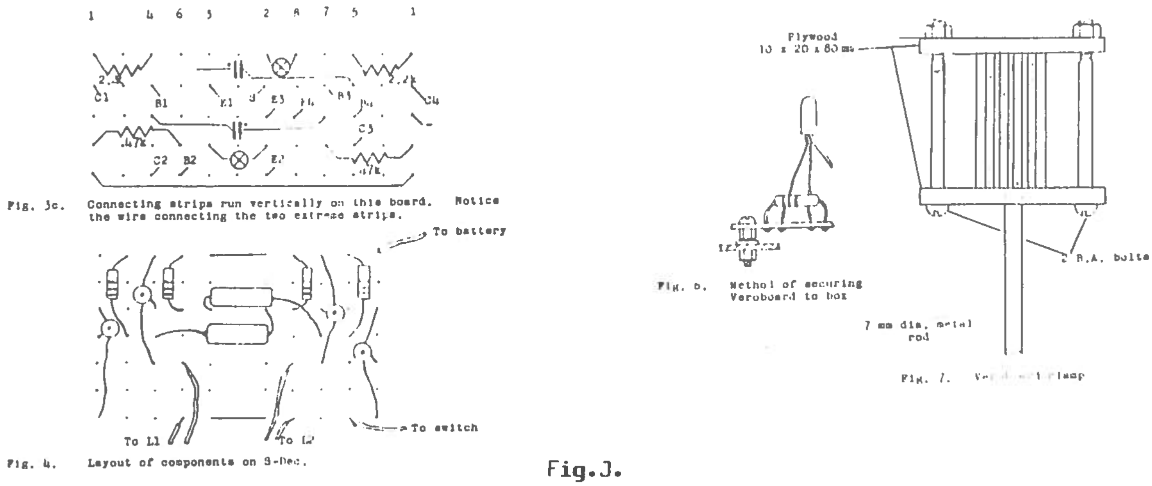
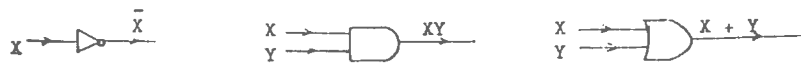


Fig.J.

Early electronics. Above - Fig.J. - conversion of circuit diagrams to working versions on Veroboard. Bulletin 18, November 1968. Below - Fig.K. - basic logic functions and TTL circuitry for a 'Pelican' crossing. Bulletin 72, June 1974.

For the benefit of those who are unfamiliar with logic circuits, an explanation of the functions of the various units will be given. Some account of Boolean algebra under which these gates function will be found in Bulletin 34 in connection with a Nim playing machine.



(a) Inverter. (b) Dual-input AND. (c) Dual-input OR.

Fig. 1. Logic symbols.

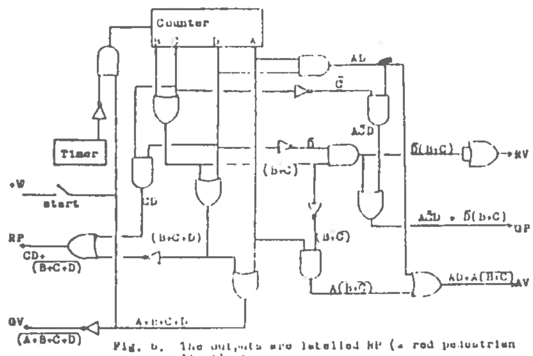


Fig. 6. The outputs are labelled RP (= red pedestrian light) etc.

This arrangement for initiating the sequence works well enough, although it means that the pedestrian must hold the push button until the first pulse from the timer has gone through, which may be up to one second. It is possible, and fairly simple, to include a pulse-lengthening device between the switch and the AND gate, but this means another integrated circuit - SN74121 monostable multivibrator - and consequently greater expense.

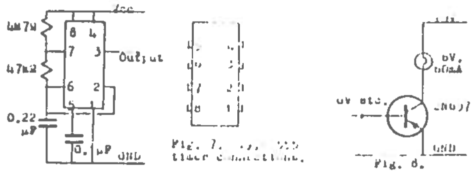


Fig.K.

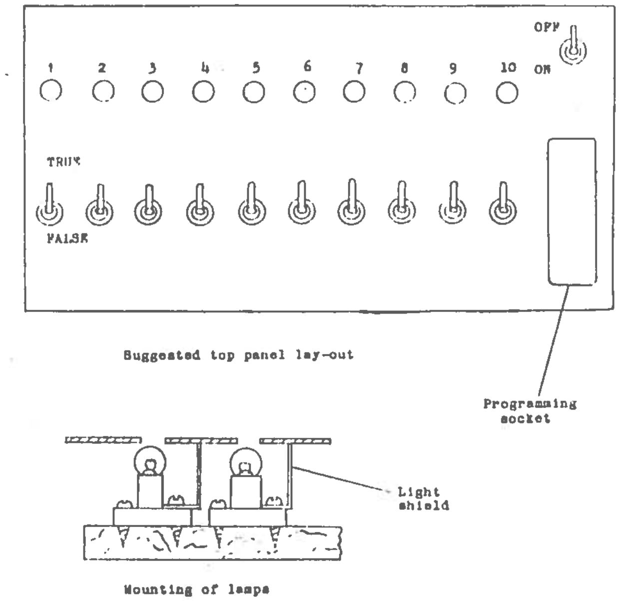


Fig.L.

Early computing? A self-test machine. Bulletin 27, December 1968.

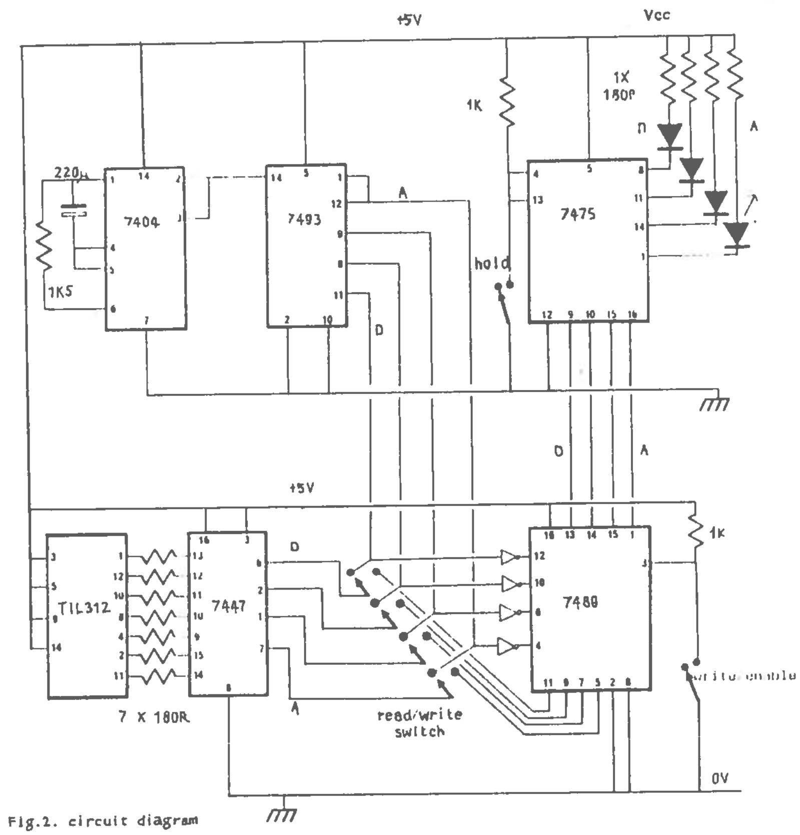


Fig.M.

Model RAM (random access memory) device. Bulletin 127, April 1981.

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