UCL DEPARTMENT OF PHYSICS AND ASTRONOMY
Gower Street Teaching Laboratories

Course PHAS3440:
Experiment E5

Development of a Digital Thermometer

Experiment Objectives:

To build a thermometer with digital readout to operate in the range 0^0C to 80^0C using a thermistor as transducer

This experiment is designed to give the student a feel for current technology that is employed in electronics. It is split into four separate projects, each with its own set of objectives, which when combined form a simple electronic thermometer with a digital display that operates in the temperature range 0 to **80^0C**. The experiment introduces the student to transducers, operational amplifiers, A-D converters, memories and digital integrated circuits.

Relevant Lecture Courses:

PHAS2201 ELECTRICITY AND MAGNETISM

Department Physics and Astronomy Risk Assessment Form

WORK/PROJECT TITLE : 3c40 experiments E8 (Linear Power Supplies) and E5 (Development of a Digital Thermometer)

LOCATION(S): Gower Street Teaching Laboratory III

DESCRIPTION OF WORK: A short digital electronics project

PERSONS INVOLVED: Undergraduate students, technical staff, demonstrators and members of academic staff

HAZARD IDENTIFICATION *(state the hazards involved in the work)* Use of laboratory equipment, hot water.

RISK ASSESSMENT *(make an assessment of the risks involved in the work and where possible state high, medium or low risk)*

Low Risk - use of office equipment and computers

Low Risk – use of hot water

CONTROL MEASURES *(state the control measures that are in place to protect staff and others from the above risks. Put in place adequate control measures for any risks that have been identified as uncontrolled.)*

Departmental safety procedures will be followed

Kettle will be used with caution, and hot water not carried around the lab, except to work bench. Quantities of water to be kept to a minimum.

DECLARATION: I the undersigned have assessed the work, titled above, and declare that there is no significant risk / the risks will be controlled by the methods stated on this form (delete as applicable) and that the work will be carried out in accordance with Departmental codes of practice.

Name: Neal Skipper Signed: NSkipper Date: 08 Aug 2008

The four compulsory sections to the experiment are 5-1 to 5-4. Section 5-5 is an optional section:

E5-1. Introduction to the use of a thermistor as a temperature sensor. Here the change of voltage with temperature of a thermistor included in a resistor divider network is measured.

E5-2. Design of operational amplifier circuits. The output of the thermistor circuit in E5-1 is amplified and any bias voltage subtracted to provide the correct input voltage range to the A-D converter. This part of the experiment familiarises the student with the gain and differential input characteristics of an operational amplifier.

E5-3. Operation of an A-D converter. The analogue output voltage from the amplifier needs to be converted into a digital form for display of the temperature. This is accomplished using an A-D converter. In this part of the experiment the student (a) familiarises himself/herself with the operation of such a converter and designs the digital sampling circuit for the converter.

E5-4. Design of a binary to Binary Coded Decimal (BCD) converter.

E5-5. Optional further experiments.

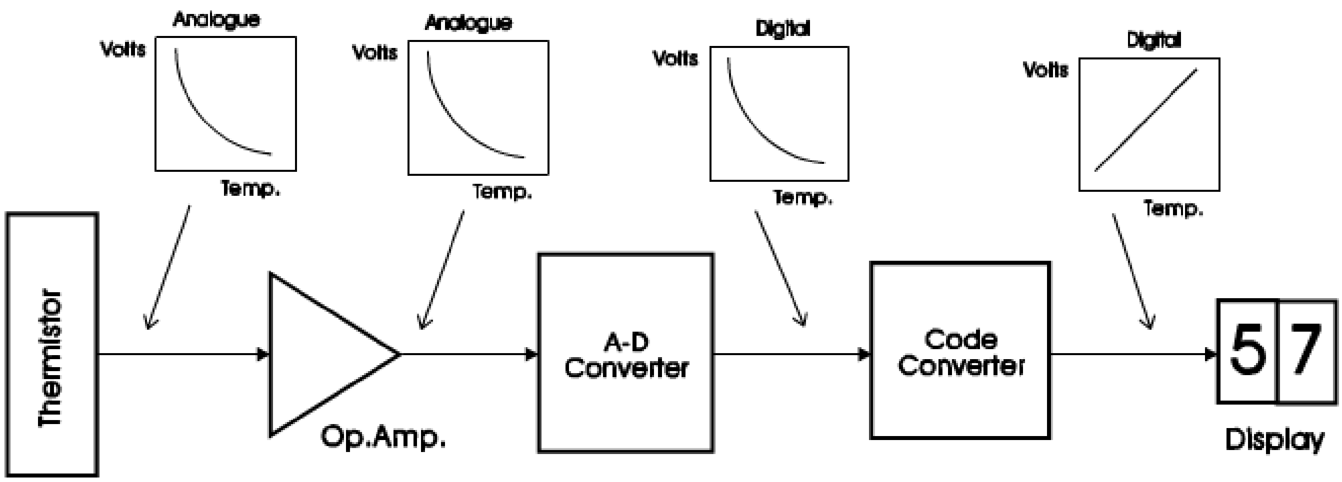


Figure 1. Development of a digital thermometer.

A printed circuit board (PCB) is provided on which the circuit that eventually becomes the digital thermometer is built up. This PCB contains the following components:

- Power input connectors - to be connected to +12 V, -12 V and +5 V supplies
- Thermistor input connectors
- Integrated circuit sockets
- Fixed passive components - resistors, capacitors and potentiometers

- Individual sockets for connecting passive components
- Test points for monitoring voltages

Keep a complete and concise record of your progress through the experiments in your Laboratory Notebook, and attempt to answer **all** questions that are posed in this script.

Although this type of experiment does not lend itself readily to a "Conclusion", please comment on your success (or failure) and on the suitability of the lab exercise itself.

E5-1 Calibration of a Thermistor

1.1 Introduction

In many scientific experiments the initial requirement is to convert some physical quantity, such as temperature or light, into an electrical signal so that it can then be measured. Devices that perform this task are called *transducers* of which a large variety exists for the many applications that are present in a laboratory.

This experiment is concerned with the measurement of temperature and for this specific application transducers such as thermocouples, thermistors and integrated circuit sensors are available. Here we will be, in this experiment, looking at the characteristics of the *thermistor*.

The thermistor is a semiconductor device that has a negative coefficient of resistance with temperature - i.e., as the temperature rises the resistance gets less. What makes it a good choice for general temperature measurement is its large change in resistance with temperature. The manufacturers' table of resistance v temperature for the device to be used in this experiment is shown in Table 1.

A standard method for measuring the resistance change is to include the thermistor in a simple voltage divider network such as that shown in Figure 2. Here the voltage at the Measurement Point changes in direct proportion to the resistance of the thermistor. The resistor in parallel with the thermistor is used for providing a more linear voltage/temperature curve.

(For a justification of this statement, see "The Art of Electronics", Horowitz & Hill, 2nd edition, p992, copies of which are in the Lab III library)

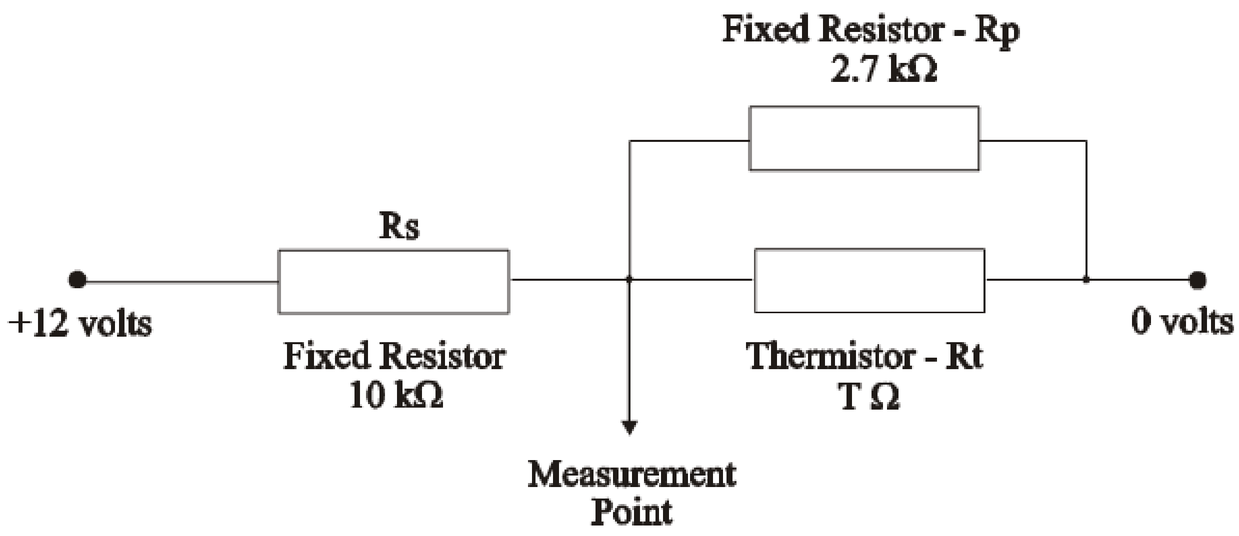


Figure 2 – Including a thermistor in a Voltage Divider network.

1.2 Experimental technique to be employed

The following are required for carrying out the experiment:

Thermistor type RS 151-215
Printed Circuit Board with 10 kΩ (Rs) and 2.7 kΩ (Rp) Fixed Resistors incorporated
±12 volt Power Supply
500 ml Pyrex beaker
Thermos of crushed ice
Digital Thermometer
Digital Voltmeter (DVM)

To connect the circuit together:

1. Connect the power supply to the connectors (colour coded) on the PCB.
2. Connect the Thermistor to the thermistor inputs on the PCB (colour coded). This connects the Thermistor to the power supply as is shown in Figure 2. The voltage at the Measurement Point is available on Test Point T1 on the PCB.

3. Connect the positive terminal of the DVM (DC voltage range selected) to T1. Connect the negative terminal to the 0 V output of the power supply.
4. Fill the Pyrex beaker half full with hot water from a kettle.
5. Place the thermistor in the water along with the digital thermometer probe. Note the readings on the thermometer and the DVM.
6. Place some ice in the water to start lowering the temperature (about one hand full). Allow time for all the ice to melt, agitating the water with the thermometer. Note new readings on thermometer and DVM.
7. Repeat 6 until a low temperature of approximately 5 C is reached.

1.3 Results

1. Plot a graph of *voltage v temperature* using *Excel*, *Sigmaplot* or *EASYPLOT* on the PC computer. Fit a curve to this data using a fitting routine (a 4^{th} or 5^{th} order polynomial is probably best – but try both and explain which you choose). Note down the equation associated with this curve, and calculate the χ^2 using the methods described in your data analysis sheets. It will be needed in experiment E5-4. Extrapolate from the curve the voltages associated with 0 C and 80 C.
2. From the theoretical data on the thermistor shown in Appendix 1 derive a theoretical curve for *voltage v temperature* when the thermistor is placed in the circuit shown in Figure 2.

Voltage = 12 × (Rt in parallel with Rp)/((Rt in parallel with Rp) + Rs)

1. Compare this curve with the actual curve and comment on any errors.

- *Comment on the advantages and disadvantages of using a thermistor for temperature measurement.*

- *Explain the physical origins of the voltage vs. temperature curve that you have measured for your thermistor: why does the voltage decrease with increasing temperature ?*

- *What sort of voltage vs. resistance curve would you expect to measure if you had used a metallic, rather than semiconducting, material ?*

- *Comment on the value of a suitable choice of fixed resistor Rs - what happens if it is too large or too small ?*

E5-2 The Operational Amplifier

2.1 Introduction

The operational amplifier (or op-amp) is used in almost all analogue electronic amplifiers nowadays, superseding in the majority of designs the use of discrete transistors. The circuit symbol for the op-amp is shown in Figure 3a. There are two basic characteristics associated: (1) the amplifier provides gain and (2) there are two signal inputs - non-inverting and inverting - that allows operation in a differential mode, the gain being applied to the difference between the two inputs.

Op-amps can be used in many applications of which three are shown in Figures 3b, 3c and 3d. Common to these circuit diagrams is a resistor, Rb, that connects the output to the inverting input. This provides *negative feedback* that is essential in amplifier applications that require stable gain.

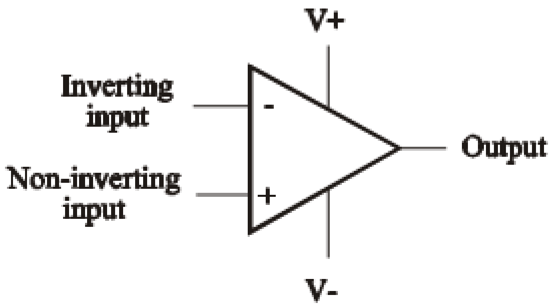


Fig 3a. Circuit symbol for an op-amp.

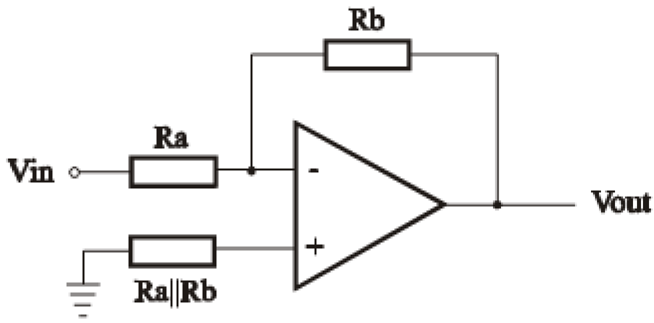


Fig 3b. Inverting amplifier

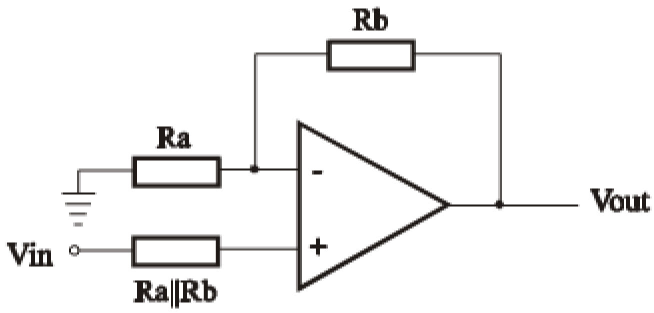


Fig 3c. Non-inverting amplifier

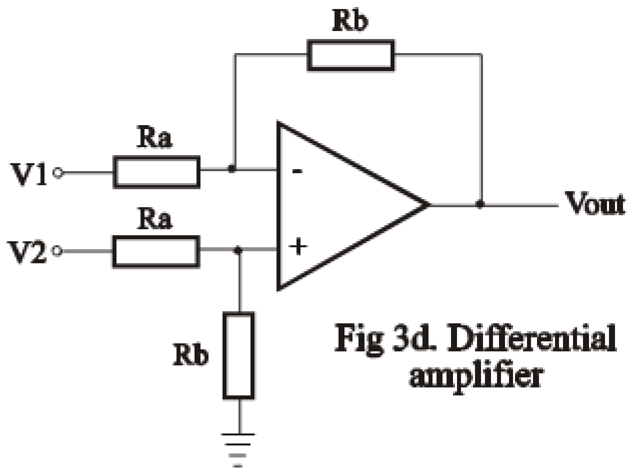


Fig 3d. Differential amplifier

Inverting amplifier (Fig. 3b)
The input voltage (V_{in}) is applied to the inverting input. The gain associated is:

$$G = \frac{Vout}{Vin} = \frac{Rb}{Ra} \qquad [1]$$

It can readily be seen that if the feedback resistor is left out then the gain becomes infinite and, in this case, saturation occurs where the output is limited by the power supply levels applied to the op-amp (+12 V and –12 V).

The resistor on the non-inverting input is used to balance the two inputs. Assume that Vin = 0 V. No current, in principle, should flow and the output equals 0 V. In practice a very small current is present and a non-zero output obtained. To overcome this the same current is applied to the non-inverting input by making the associated resistor equal to Ra in parallel with Rb.

Non-inverting amplifier (Fig. 3c)
The input voltage (V_{in}) is applied to the non-inverting input. The gain associated is:

$$G = \frac{Vout}{Vin} = 1 + \frac{Rb}{Ra} \qquad [2]$$

Differential amplifier (Fig. 3d)
The input voltages V1 & V2 are applied to the inverting and non-inverting inputs respectively, and the gain is applied to the difference between the two. The gain associated is:

$$G = \frac{Vout}{(V2 - V1)} = \frac{Rb}{Ra} \qquad [3]$$

2.2 Object of the experiment

To set an appropriate amplifier gain and bias so that an input in the range 0 C to 80 C provides an output in the range 0 V to 4.00 V. The output of E5-1 will look something like Figure 4a. What is required for the next part of the experiment (E5-3) is shown in Figure 4b. V_{80} needs to be set to 0 V and (V_0 - V_{80}) needs to be set to 4.00 volts.

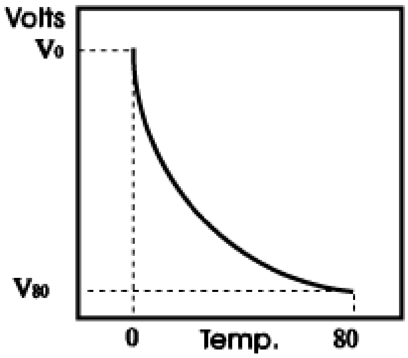


Fig 4a. Typical thermistor curve

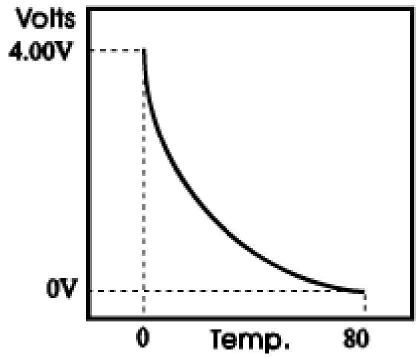


Fig 4b. Required voltage curve

The circuit for carrying this out is shown in Figure 5. There are two op-amps in the circuit.

1. The first op-amp (U1) is a non-inverting amplifier (see Fig. 3c) which amplifies the signal from the thermistor circuit, the gain being set by (R2 in series with VR1)/100 kΩ as shown in Equation 2 above, to achieve the 4.00 V required for (V_0 - V_{80}).
2. The second op-amp (U2) is a unity gain amplifier, nominally set by R_{f2} (100 kΩ) and R_{g2} (100 kΩ), that operates in a differential mode (see Fig. 3d). By adjusting the voltage on the inverting input via VR2, a voltage equal to V_{80} (multiplied by the gain of U1) can be subtracted from the output of U1, so that V_{80} will appear as 0V at the output of U2.

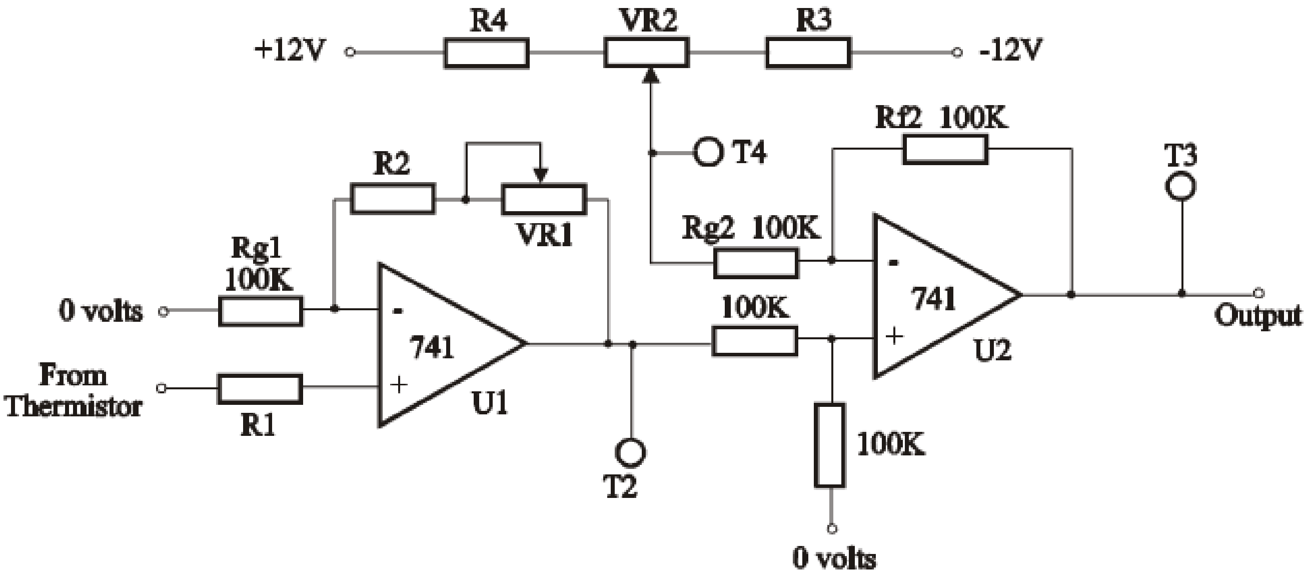


Figure 5. Circuit diagram for the operational amplifier experiment

2.3 Experimental technique to be employed.

1. Insert a 741 op-amp into position U1 on the PCB, and another into position U2. These are general purpose op-amps used in a wide variety of applications. The power supply must be switched off whilst this is carried out. *Care must be taken plugging the op-amps into their sockets in the correct orientation - the notch on one end of the op-amp aligns with the notch in the socket.*
2. From your thermistor curve derive the value of (V_0 - V_{80}).
3. Work out the gain required to convert (V_0 - V_{80}) to 4.00 volts.
4. From Equation 2 derive a value for R2 to achieve this gain. Assume that VR1 equals 100 kΩ (mid-point of 200 kΩ potentiometer). Choose the nearest available standard resistor (see Appendix 2) and insert this in the PCB in position R2.
5. Work out the ideal value for R1 (see note under Non-Inverting amplifier section above) and, from Appendix 2, select the nearest available resistor. Insert this in position R1 on the PCB.
6. With a DVM, measure the voltage on T1 (the input to the op-amp) and T2 (the output of the op-amp). Is the gain correct? If not, set correctly by altering VR1.
7. From your thermistor curve note the voltage for V_{80}. Multiply this value by the gain derived above as this offset will be amplified by U1. This is the value that must be subtracted from the output of U1 so that 80 C ≡ 0 V.

8. The resistor/potentiometer network R3, VR2 and R4 in Figure 5 provide the voltage to be subtracted. Derive values for R3 and R4 so that (a) when the potentiometer is at its central position the output is the desired value, (b) at either end of the potentiometer the output should be approximately 2 V from the desired value. Assume VR2 = 500 Ω. Connect into the PCB the nearest available standard resistor values for R3 and R4.

➢ *Why should the values of R3 and R4 be low when compared against the 100 kΩ R_g2 resistor?*

9. Measure the voltage range available from the potentiometer on test point T4. Set the voltage to the bias value desired. Check with a DVM that the output of U2 is (input - Bias voltage). The input is available on T2 and the output on T3.

E5-3 The Analogue to Digital Converter

3.1 Introduction

Unlike analogue circuits, where a voltage or current defines the input and output signals, digital circuits have inputs or outputs which have just two voltage levels associated, commonly represented by a "1" and a "0". Computers, for example, are all based on digital circuits and for a computer to read an analogue voltage an Analogue to Digital Converter, or ADC, must be employed. A schematic of a typical ADC is shown in Figure 6.

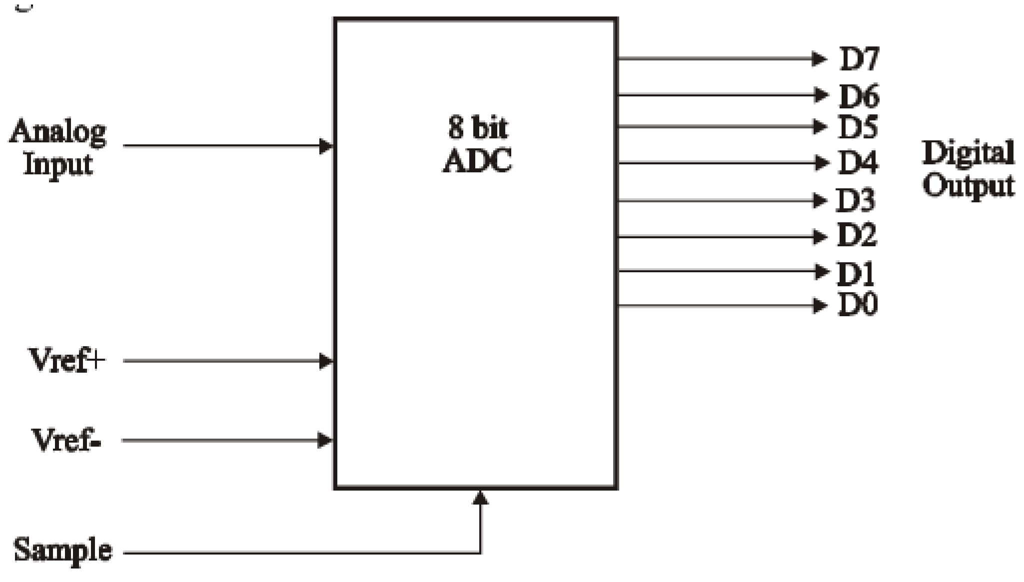


Figure 6. Schematic diagram of a typical ADC.

This is a diagram of an 8 bit ADC. The 8 bit binary output has 256 separate values associated - 00000000, 00000001, 00000010 .... 11111110, 11111111. The range of the analogue input is defined by Vref+ and Vref- which are fixed values. Vref- defines the input voltage that is equivalent to an output of 00000000 and the difference between Vref+ and Vref- defines the voltage range over which the 256 binary values apply. For example, if (Vref+ - Vref-) = 4.3 V then each step in the binary output is equivalent to 4.3/255 = 16.8 mV. If a 10 bit ADC were employed then 1024 binary values are associated and each step would be equivalent to 4.3/1023 = 4.2 mV. Thus the more output bits to the ADC the greater the resolution. The typical error on an ADC is $\pm 1/2$ of the least significant bit (LSB) or, in our example, ± 8.4 mV with an 8 bit ADC, ± 2.1 mV with a 10 bit ADC.

A conversion in the ADC only takes place when a sample signal is applied. This is a digital control input. Typically, as is shown in Figure 7, the conversion takes place during the "0" period of the sample signal and the digital data placed on the outputs on the "0" to "1" transition.

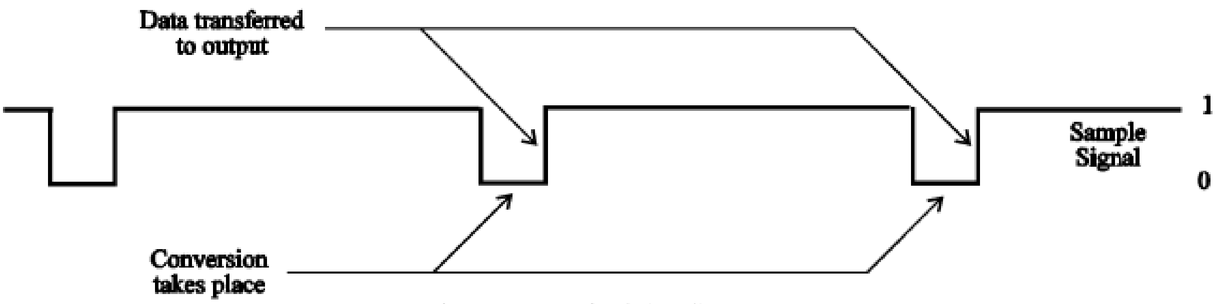


Figure 7. Typical ADC cycle.

A simple way of generating the sample signal is using a digital integrated circuit called a monostable multivibrator. As will be discussed in E5-4, there are many different types of digital integrated circuit of which the monostable is an example. It is activated by either a +ve to -ve or -ve to +ve (designer selectable) transition in an input digital signal and produces a pulse whose width is defined by an associated resistor/capacitor combination.

$$\text{Output Pulse width} = 0.7 \times C \times R \qquad [4]$$

This output pulse can be either a "1" pulse (obtained from a Q output) or "0" pulse (obtained from a $\overline{Q}$ output). By using two of these monostables, as is shown in Figure 8, a sample signal generator can be designed. In this example, the $\overline{Q}$ output is used and -ve to +ve edge triggering. The combination of two monostables like this is called a bistable multivibrator.

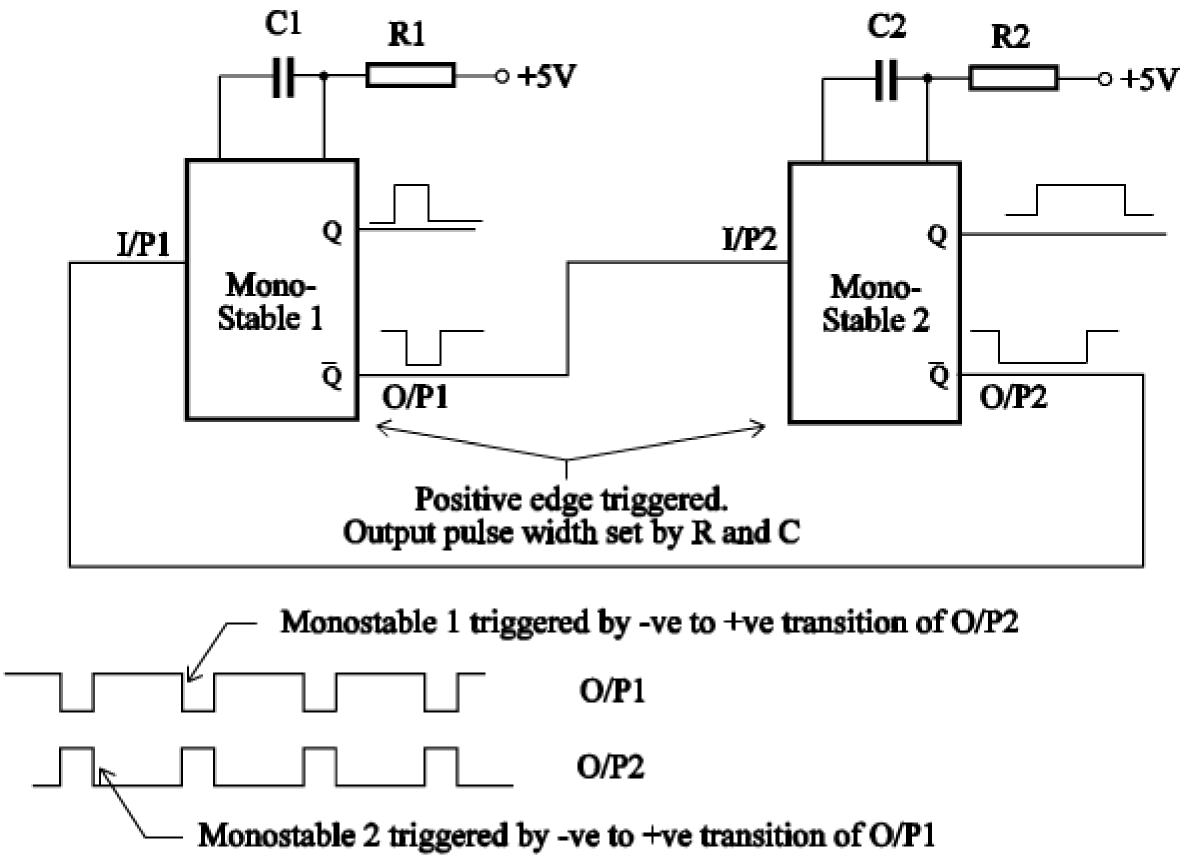


Figure 8. Sample pulse generation circuit

3.2 Object of the experiment

There are three parts to this experiment:

1. To generate the sample signal to an ADC using a bistable multivibrator circuit
2. To check the linearity of an ADC
3. To map the transducer curve on the ADC output.

The full circuit diagram is shown in Figure 9.

The main features of this circuit are :

- A 12 bit A-D converter is employed but only the most significant 8 bits are used - labeled O/P0 to O/P7 where O/P0 is the least significant bit.
- The 8-bit output has a range 0 to 255 in decimal.
- The input range of 0 volts (output = 0) to 4.3 volts (output = 255) is set by Vref- and Vref+. The 4.3 V for Vref+ is derived from a special voltage reference IC, type LM10CN.
- The diodes on the input are used purely for protection in case an accidental over voltage occurs.
- The input can be connected to one of two sources: (1) linking C to B on the PCB connects the input to a potentiometer that provides a fixed input in the range 0 to 4.5 volts, (2) linking C to A on the PCB connects the input to the output of the op-amp circuit developed in E5-2 through a 1 kΩ resistor.
- The sample signal is derived from a bistable formed by two 74121 monostables using the design shown in Figure 8.
- A Restart push button switch is used for initial start-up of the bistable circuit.
- For simplicity, the power supply connections to the ICs, along with a number of control signals, are not shown.
- The pin numbers on the ICs are those with the "***14***" typeface.

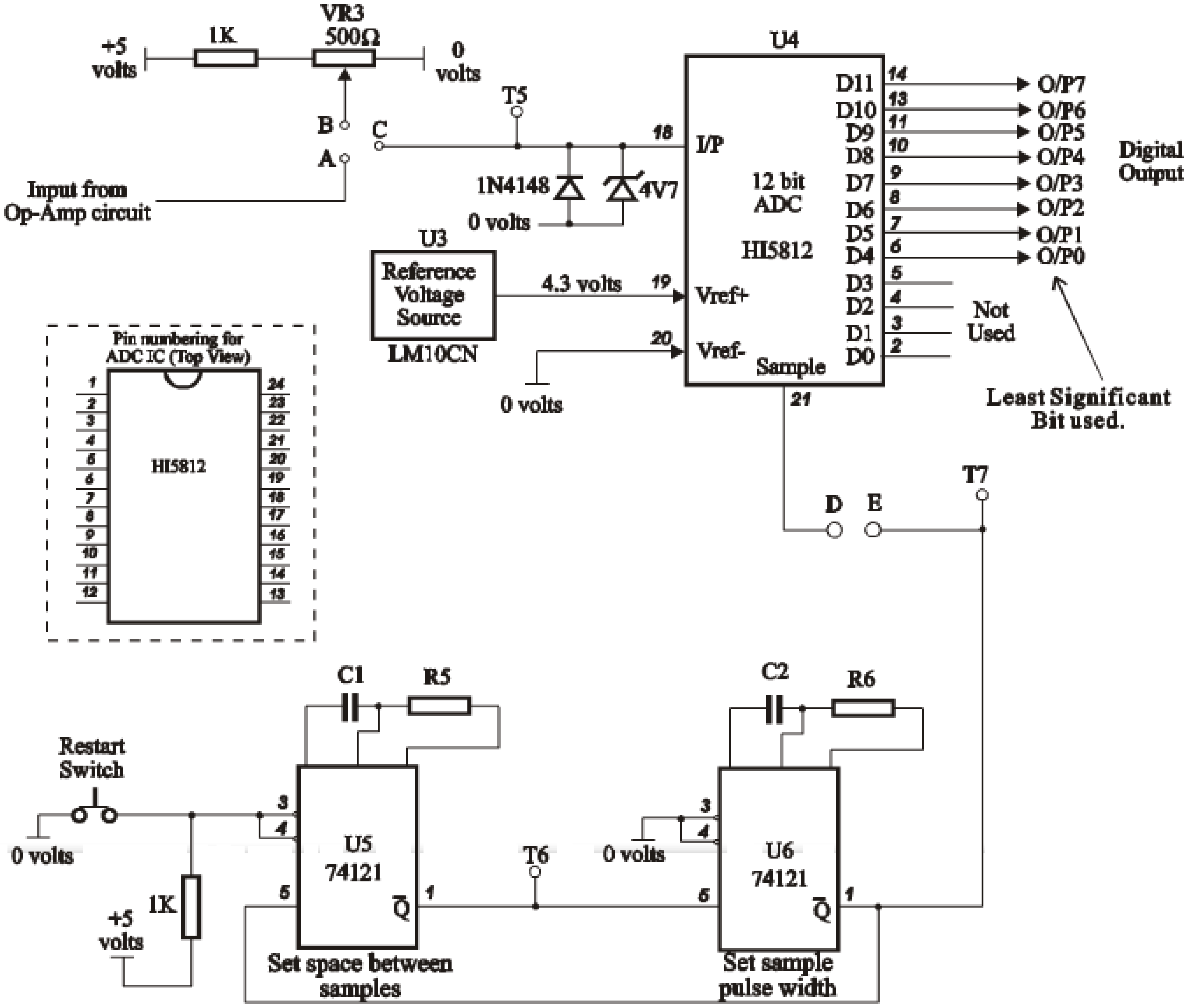


Figure 9. Circuit Diagram of the A-D Converter circuit. Note that we have an external connection to Digital Output, which can be used as input to a PC via "LabJack".

3.3 Experimental technique to be employed.

1 From Equation 4 derive suitable values for R5 and C1 to provide a sample interval of approximately 1 ms. R5 should be in the range 10 kΩ to 39 kΩ.
2 From Equation 4 derive suitable values for R6 and C2 to provide a sample pulse width of 100 μs. R6 should be in the range 10 kΩ to 39 kΩ
3 **Make sure all the power supplies are switched off.**
4 Insert the LM10CN voltage regulator, the H15812 A-D converter and two 74121 ICs into the PCB in positions U3, U4, U5 and U6 respectively. NOTE CAREFULLY THE ORIENTATION OF THE NOTCH ALIGNMENT IN EACH CASE. Plug in selected values of R5, R6, C1 and C2.
5 Switch on all the power supplies, and with an oscilloscope, earth connection on probe connected to 0 V, check sample pulse width ('0' level signal on T6) and spacing ('0' signal on T7). Draw the waveforms that are shown. If no waveform is present, try momentarily depressing the Restart switch.
6 Connect Link D to E on the PCB. This now applies the sample signal to the A-D converter. Connect Link C to B. This connects the A-D input to the output of the potentiometer.
7 For 10 positions of the potentiometer (VR3) setting between minimum and maximum (1) note the A-D input voltage with a DVM on T5 and (2) use an oscilloscope, earth connection on probe connect to 0 V, to measure the A-D binary output by placing the probe on the A-D pins for O/P0 to O/P7. Convert the binary readings to decimal and draw a graph of input voltage against output. The graph should be a straight line.
8 Connect Link C to A on the PCB. The output of the op-amp circuit is now connected to the A-D. For 4 different temperatures at the thermistor measure the output from the A-D. Are these values as are expected?

- *What features of the A-D converter circuit could account for errors in your values.*

E5-4 Digital Display

4.1 Introduction

All digital circuits are built from four primary circuit elements, the AND gate, OR gate, INVERTER and EXCLUSIVE OR gate. The circuit symbols for these are shown in Figure 10 along with their associated Truth Tables.

AND

Inputs A	Inputs B	Output Q
0	0	0
0	1	0
1	0	0
1	1	1

OR

Inputs A	Inputs B	Output Q
0	0	0
0	1	1
1	0	1
1	1	1

INVERT

Input A	Output Q
0	1
1	0

EXCLUSIVE OR

Inputs A	Inputs B	Output Q
0	0	0
0	1	1
1	0	1
1	1	0

Figure 10: The basic digital circuit elements and their associated truth tables

AND gate with an INVERTER, which provides the NAND function, where the output is the inverse of the AND output. A slightly more complicated example is a 2 bit ADDER where the outputs for the two inputs are :

Inputs A	Inputs B	Outputs Q2	Outputs Q1	Decimal equivalent of output
0	0	0	0	0
0	1	0	1	1
1	0	0	1	1
1	1	1	0	2

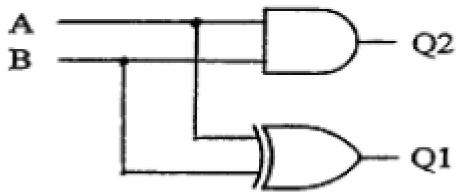


Figure 11: the circuit and output for an ADDER

Fortunately semiconductor manufacturers have saved, to a very large extent, the digital circuit design engineer the trouble of having to design circuits at this very basic level by producing integrated circuits (ICs) that carry out many commonly required functions. An example of this is the monostable employed in experiment E5-3. This monostable could be constructed from AND gates and INVERTERS but an IC is available to perform the function. The level of complexity inside an IC is dependent upon the function. One IC available is a 4 BIT ADDER which adds two 4 bit numbers together. This IC incorporates the equivalent of 36 basic elements (AND, OR etc..) and is relatively simple in design. Much more complex are the microprocessor ICs such as the Intel 80386, 486 series employed in PCs which incorporate many thousands of basic elements.

It is with these building-block ICs that the digital circuit designer works and the basic elements are only used if required for 'gluing' building blocks together.

4.2 Object of the experiment

To display the temperature being measured with an accuracy of one degree over the temperature range 0 to 80 C. There are three problems associated:

1. For a rise in temperature the output voltage from E5-2 decreases
2. The output voltage is non-linear with temperature
3. The output of the A-D converter is binary, the display requires a binary coded decimal (BCD) input. In BCD each 4 bits of the binary information are restricted to the range 0000 (decimal 0) to 1001 (decimal 9). For example the decimal number 75 in BCD is 0111 0101 whereas in binary it is 01001011.

There are a number of ways of overcoming these problems. For example, an inverting amplifier can be used to provide increasing voltage with increasing temperature, a different transducer can be used for linearizing the output voltage curve, and a binary to BCD converter IC used for code conversion. However, a simple 'trick' can be played here and all three problems overcome with one simple circuit.

Memory ICs, as are used in all computers, come in two basic types: Read Only Memory (ROM) and Random Access Memory (RAM). Data stored in ROM cannot, under normal circuit operation, be overwritten whereas data in RAM can be changed at will. A schematic of a memory IC is shown in Figure 12.

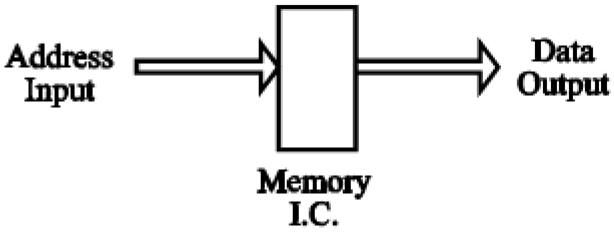


Figure 12. Schematic of a Memory I.C.

An Address, in binary form, is applied to the memory and the data stored in that location is then output. To overcome the problems listed above, a pre-programmed ROM can be used. Input as the Address is the output of the ADC, output as the data is the required value for display. For example, the design implement under E5-2, E5-3 should give an output of 0 (decimal), 00000000 (binary), for a temperature of 80 C. The data required for the display is 1000 0000 (80 in BCD). The ROM can be pre-programmed to provide such an output with an Address of 0.

A block diagram of the Display circuit is shown in Figure 13.

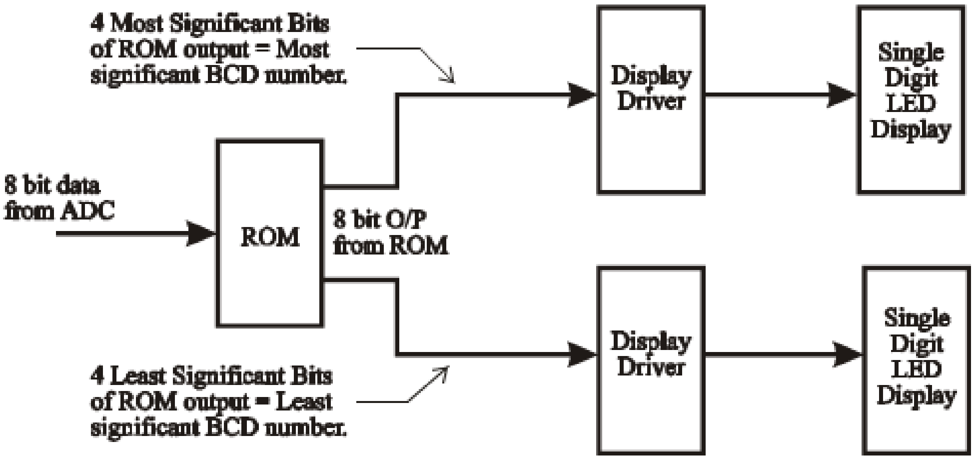


Figure 13. Block Diagram of the Display Circuit

Here the data from the ADC is initially converted to the code required for display by the ROM. The output of the ROM then feeds into two Display Driver ICs, these being in the family of integrated circuits described in the Introduction and provide the required outputs for driving LED displays. The circuit diagram associated is shown in Figure 14.

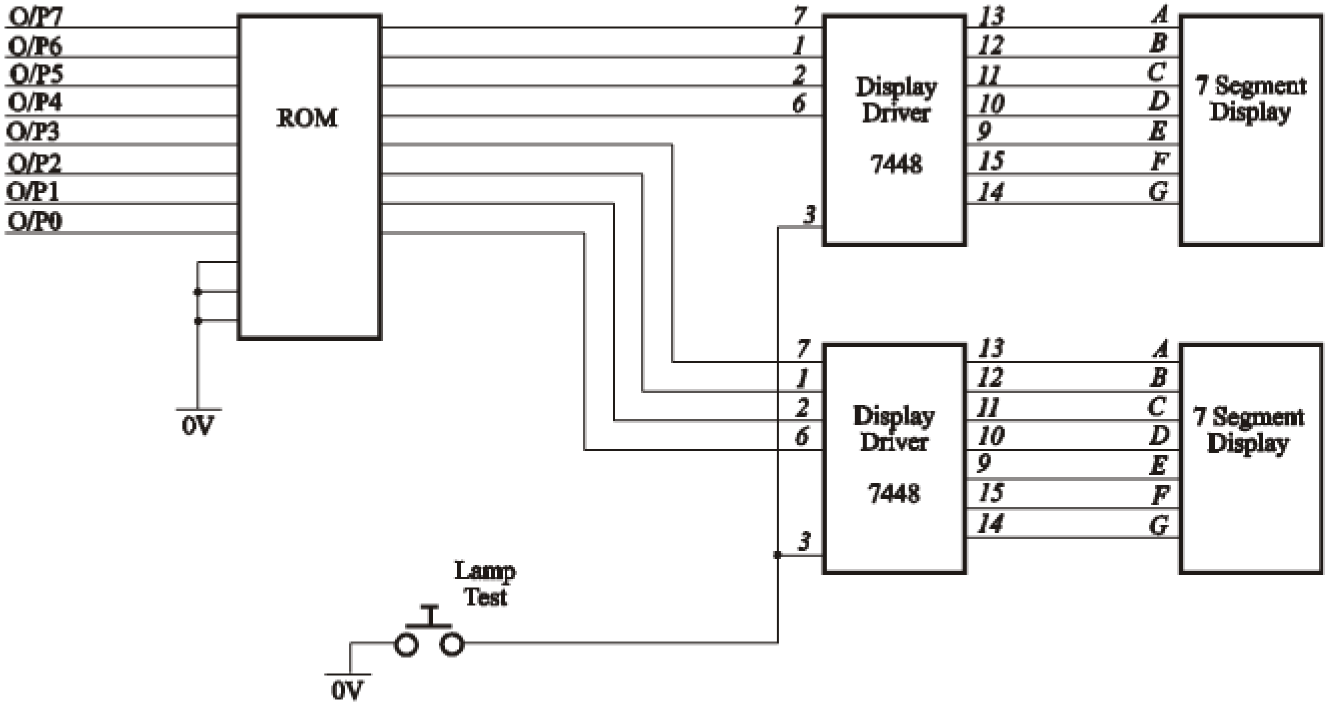


Figure 14. Circuit diagram for Code Converter and Digital Display

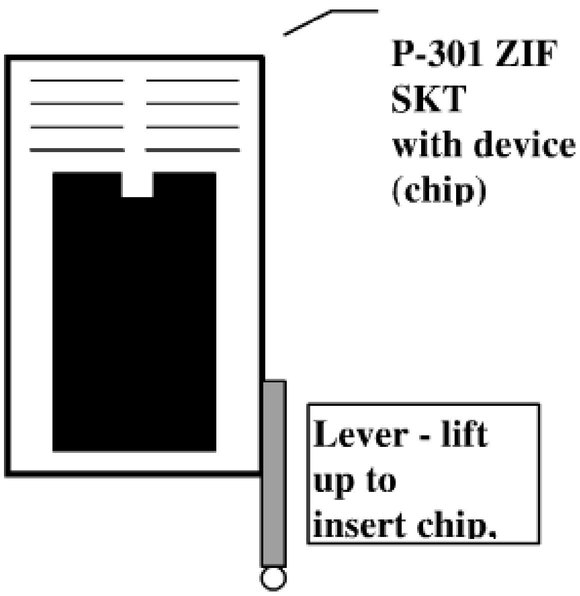
4.3 Experimental technique to be employed

1) The data obtained in 1.3(1) have to be fed into the digital thermometer program (icon labeled E5 on most of the laboratory computers). The program will first ask you if you want to run with test data. Reply "n" to this. You will then be prompted for the maximum temperature, the coefficients of the fitted graph you have produced (a, b, c, d......) and the gain and bias you have determined in section 2.3. Next, double-click on the 'Write Floppy' icon; this will display a message asking you to insert a floppy disk. (we can lend you one, you only need it for this phase of the experiment) When this program has run, you will be asked to take this floppy disk to the dedicated PC connected to the EPROM programmer.

2) The PC, which is dedicated to the Eprom programmer, has some extra icons in the Digital Thermometer group. Insert the floppy disk in the drive, then double-click on the 'Convert' icon; this runs a program which converts the data output from the

E5 program into INTEL-HEX, a format for the EPROM programmer. (Technical details are available for anyone who is interested!)

Next, double-click on the 'Blow Eprom' icon. This will run the software to actually blow the data into the EPROM - you will be prompted to insert the 'chip' into the programmer. The chip should be inserted with the notch at the top, and should be located at the bottom of the socket (see figure 15).



Warning
NEVER power on or off with a device in the socket.

Figure 15. Placement of the chip in the EPROM programmer

Click on 'OK'. This will transfer the converted data into the EPROM programmer, and then blow the data into the chip itself. It also verifies that the data has been transferred correctly. This is a 'sit back and watch' operation, and avoids users needing to get involved in the details of the software which runs the EPROM programmer. After this completes successfully, remove the EPROM from the Programmer.

3) Having blown the PROM place it along with the Display Driver and 7 segment display ICs (decimal point to the right as a reference for insertion) into the PCB - remember to switch the power off before doing this.
4) Check the displayed data against that from a digital thermometer for a number of input temperatures. Plot your results.
5) Comment on the results obtained. Where may errors in the system result from?

E5-5 Further Experiments

If you have time, as an optional exercise you can try to interface your thermometer to one of the PCs, via the data logger "LabJack". This will enable you to measure temperature as a function of time, for example to monitor the temperature of a beaker of hot water as it cools down, and to fit a theoretical cooling curve to your data using Sigmaplot. At the time of going to press we are beta-testing software for this interface.

Appendix 1

Resistance/Temperature characteristics for RS thermistor type 151-215

Temperature C	Resistance Ω
0	9795.0
10	5970.0
20	3747.0
25	3000.0
30	2417.1
40	1598.1
50	1080.9
60	746.4
70	525.6
80	376.5

Appendix 2

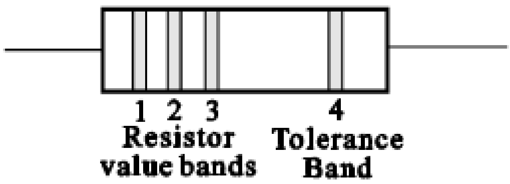
Standard Resistor values

1.0 Ω	10 Ω	100 Ω	1.0 kΩ	10 kΩ	100 kΩ
1.2 Ω	12 Ω	120 Ω	1.2 kΩ	12 kΩ	120 kΩ
1.5 Ω	15 Ω	150 Ω	1.5 kΩ	15 kΩ	150 kΩ
1.8 Ω	18 Ω	180 Ω	1.8 kΩ	18 kΩ	180 kΩ
2.2 Ω	22 Ω	220 Ω	2.2 kΩ	22 kΩ	220 kΩ
2.7 Ω	27 Ω	270 Ω	2.7 kΩ	27 kΩ	270 kΩ
3.3 Ω	33 Ω	330 Ω	3.3 kΩ	33 kΩ	330 kΩ
3.9 Ω	39 Ω	390 Ω	3.9 kΩ	39 kΩ	390 kΩ
4.7 Ω	47 Ω	470 Ω	4.7 kΩ	47 kΩ	470 kΩ
5.6 Ω	56 Ω	560 Ω	5.6 kΩ	56 kΩ	560 kΩ
6.8 Ω	68 Ω	680 Ω	6.8 kΩ	68 kΩ	680 kΩ
8.2 Ω	82 Ω	820 Ω	8.2 kΩ	82 kΩ	820 kΩ

Colour coding of Resistors

Two standard methods are used by resistor manufacturers to define the resistance of a resistor :

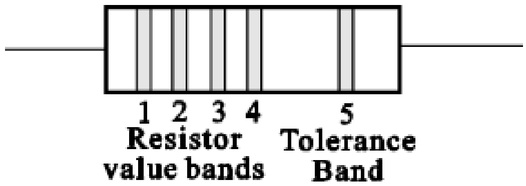
4 band

	Colour coding for Bands 1,2,3		**Band 4**
	Black = 0 Brown = 1 Red = 2 Orange = 3 Yellow = 4	Green = 5 Blue = 6 Violet = 7 Grey = 8 White = 9	Silver =10% Gold = 5% Red = 2% Brown = 1%

Band 1 = Most significant digit of resistance value
Band 2 = Second most significant digit of resistance value
Band 3 = Number of "zeroes" that follow second most significant digit

Examples:
Band 1 = Orange, Band 2 = White, Band 3 = Black is a 39 Ω resistor
Band 1 = Brown, Band 2 = Black, Band 3 = Red is a 1000 Ω, or 1 kΩ, resistor

5 Band



Colour coding as per 4 band definitions

Band 1 = Most significant digit of resistance value
Band 2 = Second most significant digit of resistance value
Band 3 = Third most significant digit of resistance value
Band 4 = Number of "zeroes" that follow third most significant digit

REFERENCES:

Horowitz and Hill, “The Art of Electronics”, 2nd edition, Cambridge