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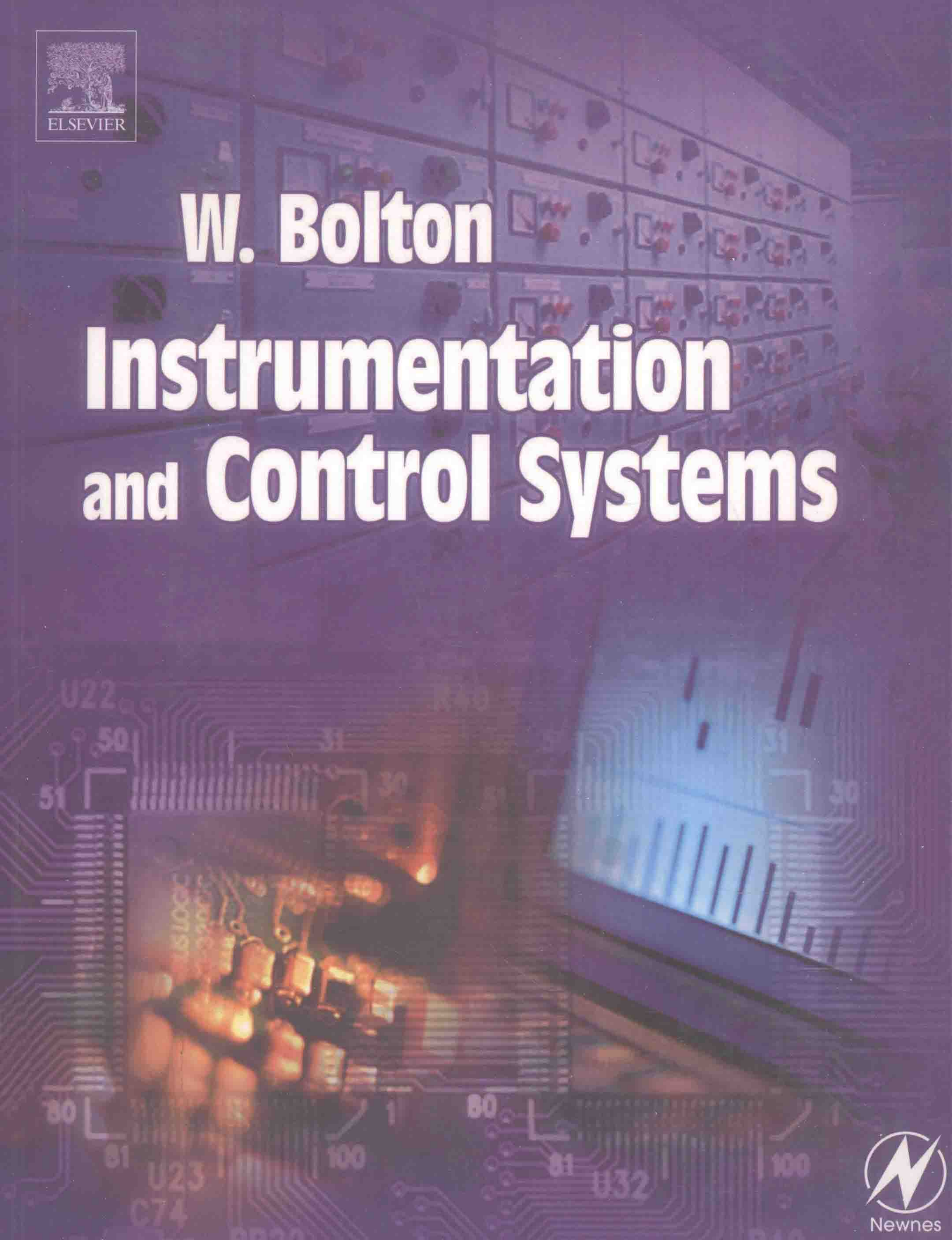
W. Bolton

Instrumentation and Control Systems



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Preface

Aims

This book has the aims of covering the new specification of the Edexcel Level 4 BTEC units of *Instrumentation and Control Principles* and *Control Systems and Automation* for the Higher National Certificates and Diplomas in Engineering and also providing a basic introduction to instrumentation and control systems for undergraduates. The book aims to give an appreciation of the principles of industrial instrumentation and an insight into the principles involved in control engineering.

Structure of the book

The book has been designed to give a clear exposition and guide readers through the principles involved in the design and use of instrumentation and control systems, reviewing background principles where necessary. Each chapter includes worked examples, multiple-choice questions and problems; answers are supplied to all questions and problems. There are numerous case studies in the text and application notes indicating applications of the principles.

Coverage of Edexcel units

Basically, the Edexcel unit *Instrumentation and Control Principles* is covered by chapters 1 to 6 with the unit *Control Systems and Automation* being covered by chapters 8 to 13 with chapter 5 including the overlap between the two units. Chapter 7 on PLCs is included to broaden the coverage of the book from these units.

Performance outcomes

The following indicate the outcomes for which each chapter has been planned. At the end of the chapters the reader should be able to:

Chapter 1: Measurement systems

Read and interpret performance terminology used in the specifications of instrumentation.

Chapter 2: Instrumentation system elements

Describe and evaluate sensors, signal processing and display elements commonly used with instrumentation used in the measurement of position, rotational speed, pressure, flow, liquid level and temperature.

Chapter 3: Instrumentation case studies
Explain how system elements are combined in instrumentation for some commonly encountered measurements.

Chapter 4: Control systems
Explain what is meant by open and closed-loop control systems, the differences in performance between such systems and explain the principles involved in some simple examples of such systems.

Chapter 5: Process controllers
Describe the function and terminology of a process controller and the use of proportional, derivative and integral control laws.
Explain PID control and how such a controller can be tuned.

Chapter 6: Correction elements
Describe common forms of correction/regulating elements used in control systems.
Describe the forms of commonly used pneumatic/hydraulic and electric correction elements.

Chapter 7: PLC systems
Describe the functions of logic gates and the use of truth tables.
Describe the basic elements involved with PLC systems and devise programs for them to carry out simple control tasks.

Chapter 8: System models
Explain how models for physical systems can be constructed in terms of simple building blocks.

Chapter 9: Transfer function
Define the term transfer function and explain how it used to relate outputs to inputs for systems.
Use block diagram simplification techniques to aid in the evaluation of the overall transfer function of a number of system elements.

Chapter 10: System response
Use Laplace transforms to determine the response of systems to common forms of inputs.
Use system parameters to describe the performance of systems when subject to a step input.
Analyse systems and obtain values for system parameters.
Explain the properties determining the stability of systems.

Chapter 11: Frequency response
Explain how the frequency response function can be obtained for a system from its transfer function.
Construct Bode plots from a knowledge of the transfer function.
Use Bode plots for first and second-order systems to describe their frequency response.
Use practically obtained Bode plots to deduce the form of the transfer function of a system.

Compare compensation techniques.

Chapter 12: Nyquist diagrams
Draw and interpret Nyquist diagrams.

Chapter 13: Controllers
Explain the reasons for the choices of P, PI or PID controllers.
Explain the effect of dead time on the behaviour of a control system.
Explain the uses of cascade control and feedforward control.

W. Bolton

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1 Measurement systems

1.1 Introduction

This chapter is an introduction to the instrumentation systems used for making measurements and deals with the basic elements of such systems and the terminology used to describe their performance in use.

1.1.1 Systems

The term *system* will be freely used throughout this book and so here is a brief explanation of what is meant by a system and how we can represent systems.

If you want to use an amplifier then you might not be interested in the internal working of the amplifier but what output you can obtain for a particular input. In such a situation we can talk of the amplifier being a system and describe it by means of specifying how the output is related to the input. With an engineering system an engineer is more interested in the inputs and outputs of a system than the internal workings of the component elements of that system.

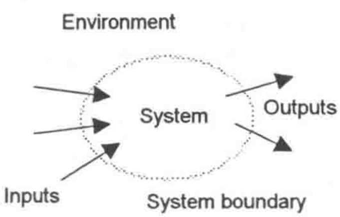

Figure 1.1 *A system*

A *system* can be defined as an arrangement of parts within some boundary which work together to provide some form of output from a specified input or inputs. The boundary divides the system from the environment and the system interacts with the environment by means of signals crossing the boundary from the environment to the system, i.e. inputs, and signals crossing the boundary from the system to the environment, i.e. outputs (Figure 1.1).

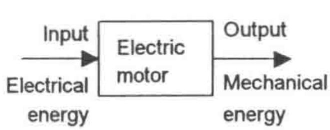

Figure 1.2 *Electric motor system*

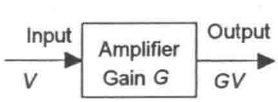

Figure 1.3 *Amplifier system*

A useful way of representing a system is as a *block diagram*. Within the boundary described by the box outline is the system and inputs to the system are shown by arrows entering the box and outputs by arrows leaving the box. Figure 1.2 illustrates this for an electric motor system; there is an input of electrical energy and an output of mechanical energy, though you might consider there is also an output of waste heat. The interest is in the relationship between the output and the input rather than the internal science of the motor and how it operates. It is convenient to think of the system in the box operating on the input to produce the output. Thus, in the case of an amplifier system (Figure 1.3) we can think of the system multiplying the input V by some factor G, i.e. the amplifier gain, to give the output GV.

Often we are concerned with a number of linked systems. For example we might have a CD player system linked to an amplifier system which, in turn, is linked to a loudspeaker system. We can then draw this as three interconnected boxes (Figure 1.4) with the output from one system becoming the input to the next system. In drawing a system as a series of interconnected blocks, it is necessary to recognise that the lines drawn to connect boxes indicate a flow of information in the direction indicated by the arrow and not necessarily physical connections.

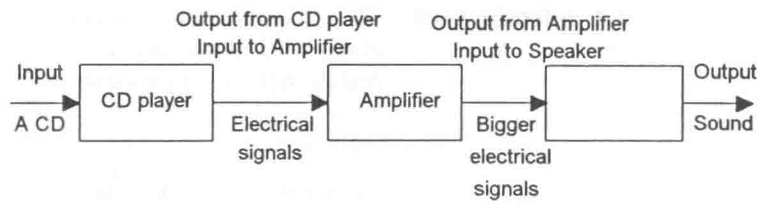

Figure 1.4 *Interconnected systems*

1.2 Instrumentation systems

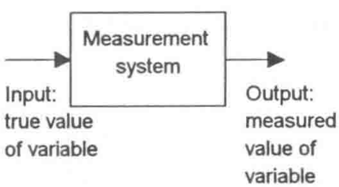

Figure 1.5 *An instrumentation/ measurement system*

The purpose of an *instrumentation system* used for making measurements is to give the user a numerical value corresponding to the variable being measured. Thus a thermometer may be used to give a numerical value for the temperature of a liquid. We must, however, recognise that, for a variety of reasons, this numerical value may not actually be the true value of the variable. Thus, in the case of the thermometer, there may be errors due to the limited accuracy in the scale calibration, or reading errors due to the reading falling between two scale markings, or perhaps errors due to the insertion of a cold thermometer into a hot liquid, lowering the temperature of the liquid and so altering the temperature being measured. We thus consider a measurement system to have an input of the true value of the variable being measured and an output of the measured value of that variable (Figure 1.5). Figure 1.6 shows some examples of such instrumentation systems.

> An *instrumentation system* for making measurements has an input of the true value of the variable being measured and an output of the measured value.

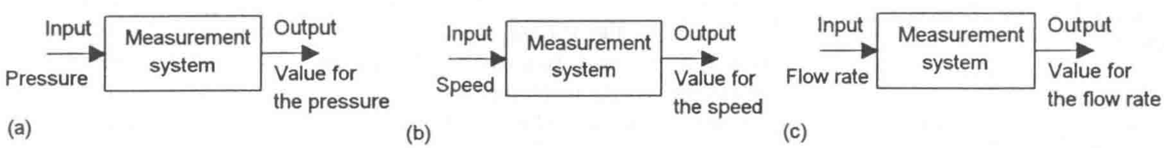

Figure 1.6 *Example of instrumentation systems: (a) pressure measurement, (c) speedometer, (c) flow rate measurement*

1.2.1 The constituent elements of an instrumentation system

An instrumentation system for making measurements consists of several elements which are used to carry out particular functions. These functional elements are:

1 *Sensor*
This is the element of the system which is effectively in contact with the process for which a variable is being measured and gives an output which depends in some way on the value of the variable and which can be used by the rest of the measurement system to give a value to it. For example, a thermocouple is a sensor which has an input of temperature and an output of a small e.m.f. (Figure 1.7(a)) which in the rest of the measurement system might be amplified to give a reading on a meter. Another example of a sensor is a resistance thermometer element which has an input of temperature and an output of a resistance change (Figure 1.7(b)).

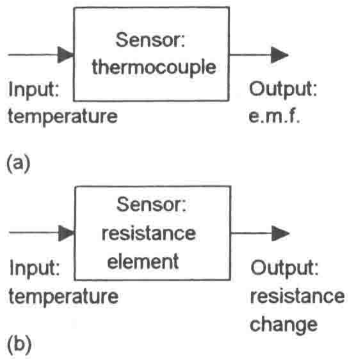

Figure 1.7 *Sensors: (a) thermocouple, (b) resistance thermometer element*

2 *Signal processor*
This element takes the output from the sensor and converts it into a form which is suitable for display or onward transmission in some control system. In the case of the thermocouple this may be an amplifier to make the e.m.f. big enough to register on a meter (Figure 1.8(a)). There often may be more than item, perhaps an element which puts the output from the sensor into a suitable condition for further processing and then an element which processes the signal so that it can be displayed. The term *signal conditioner* is used for an element which converts the output of a sensor into a suitable form for further processing. Thus in the case of the resistance thermometer there might be a signal conditioner, a Wheatstone bridge, which transforms the resistance change into a voltage change, then an amplifier to make the voltage big enough for display (Figure 1.8(b)).

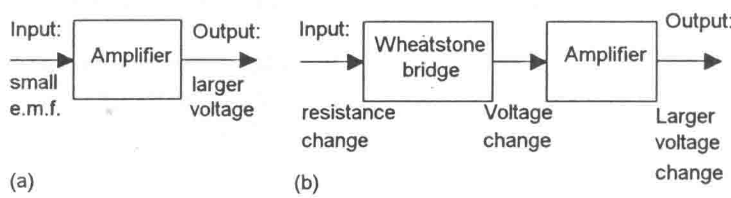

Figure 1.8 *Examples of signal processing*

3 *Data presentation*
This presents the measured value in a form which enables an observer to recognise it (Figure 1.9). This may be via a display, e.g. a pointer moving across the scale of a meter or perhaps information on a visual display unit (VDU). Alternatively, or additionally, the signal may be recorded, e.g. on the paper of a chart recorder or perhaps on magnetic disc, or transmitted to some other system such as a control system.

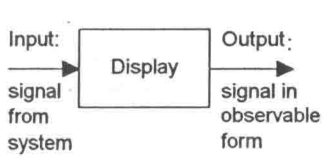

Figure 1.9 *A data presentation element*

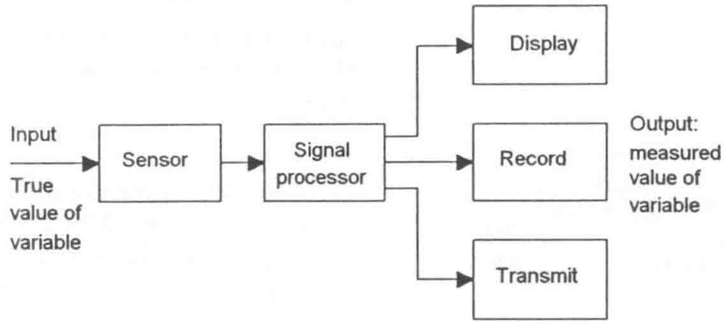

Figure 1.10 *Measurement system elements*

Figure 1.10 shows how these basic functional elements form a measurement system.

The term *transducer* is often used in relation to measurement systems. Transducers are defined as an element that converts a change in some physical variable into a related change in some other physical variable. It is generally used for an element that converts a change in some physical variable into an electrical signal change. Thus sensors can be transducers. However, a measurement system may use transducers, in addition to the sensor, in other parts of the system to convert signals in one form to another form.

Example

With a resistance thermometer, element A takes the temperature signal and transforms it into resistance signal, element B transforms the resistance signal into a current signal, element C transforms the current signal into a display of a movement of a pointer across a scale. Which of these elements is (a) the sensor, (b) the signal processor, (c) the data presentation?

The sensor is element A, the signal processor element B and the data presentation element is C. The system can be represented by Figure 1.11.

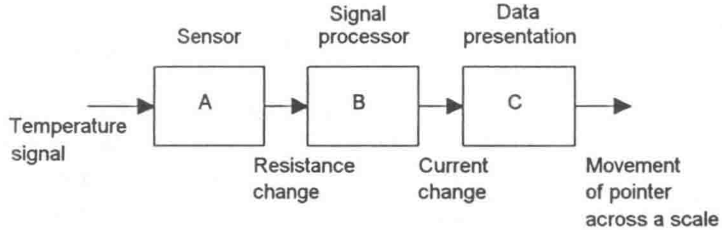

Figure 1.11 *Example*

1.3 Performance terms

The following are some of the more common terms used to define the performance of measurement systems and functional elements.

1.3.1 Accuracy and error

Application
The accuracy of a digital thermometer is quoted in its specification as:

Full scale accuracy - better than 2%

Accuracy is the extent to which the value indicated by a measurement system or element might be wrong. For example, a thermometer may have an accuracy of ±0.1°C. Accuracy is often expressed as a percentage of the full range output or full-scale deflection (f.s.d). For example, a system might have an accuracy of ±1% of f.s.d. If the full-scale deflection is, say, 10 A, then the accuracy is ±0.1 A. The accuracy is a summation of all the possible errors that are likely to occur, as well as the accuracy to which the system or element has been calibrated.

The term *error* is used for the difference between the result of the measurement and the true value of the quantity being measured, i.e.

error = measured value – true value

Thus if the measured value is 10.1 when the true value is 10.0, the error is +0.1. If the measured value is 9.9 when the true value is 10.0, the error is –0.1.

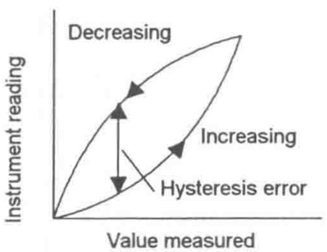

Figure 1.12 *Hysteresis error*

> *Accuracy* is the indicator of how close the value given by a measurement system can be expected to be to the true value. The *error* of a measurement is the difference between the result of the measurement and the true value of the quantity being measured.

Errors can arise in a number of ways and the following describes some of the errors that are encountered in specifications of instrumentation systems.

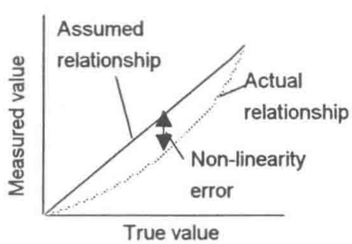

Figure 1.13 *Non-linearity error*

1. *Hysteresis error*
   The term *hysteresis error* (Figure 1.12) is used for the difference in outputs given from the same value of quantity being measured according to whether that value has been reached by a continuously increasing change or a continuously decreasing change. Thus, you might obtain a different value from a thermometer used to measure the same temperature of a liquid if it is reached by the liquid warming up to the measured temperature or it is reached by the liquid cooling down to the measured temperature.

2. *Non-linearity error*
   The term *non-linearity error* (Figure 1.13) is used for the error that occurs as a result of assuming a linear relationship between the input and output over the working range, i.e. a graph of output plotted against input is assumed to give a straight line. Few systems or elements, however, have a truly linear relationship and thus errors occur as a result of the assumption of linearity. Linearity error

Application
A load cell is quoted in its specification as having:

Non-linearity error ±0.03% of full range
Hysteresis error ±0.02% of full range

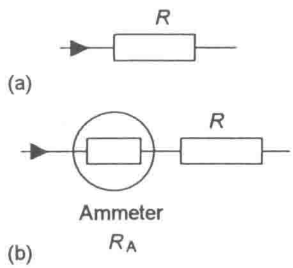

Figure 1.14 *Loading with an ammeter: (a) circuit before meter introduced, (b) extra resistance introduced by meter*

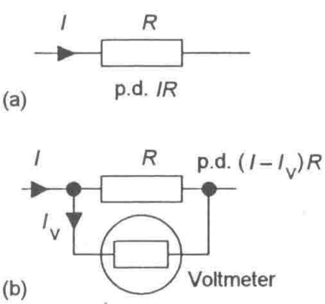

Figure 1.15 *Loading with a voltmeter: (a) before meter, (b) with meter present*

Application
See Appendix A for a discussion of how the accuracy of a value determined for some quantity can be computed from values obtained from a number of measurements, e.g. the accuracy of the value of the density of some material when computed from measurements of its mass and volume, both the mass and volume measurements having errors.

is usually expressed as a percentage error of full range or full scale output.

3 *Insertion error*
When a cold thermometer is put in to a hot liquid to measure its temperature, the presence of the cold thermometer in the hot liquid changes the temperature of the liquid. The liquid cools and so the thermometer ends up measuring a lower temperature than that which existed before the thermometer was introduced. The act of attempting to make the measurement has modified the temperature being measured. This effect is called *loading* and the consequence as an *insertion error*. If we want this modification to be small, then the thermometer should have a small heat capacity compared with that of the liquid. A small heat capacity means that very little heat is needed to change its temperature. Thus the heat taken from the liquid is minimised and so its temperature little affected.

Loading is a problem that is often encountered when measurements are being made. For example, when an ammeter is inserted into a circuit to make a measurement of the circuit current, it changes the resistance of the circuit and so changes the current being measured (Figure 1.14). The act of attempting to make such a measurement has modified the current that was being measured. If the effect of inserting the ammeter is to be as small as possible and for the ammeter to indicate the original current, the resistance of the ammeter must be very small when compared with that of the circuit.

When a voltmeter is connected across a resistor to measure the voltage across it, then what we have done is connected a resistance, that of the voltmeter, in parallel with the resistance across which the voltage is to be measured. If the resistance of the voltmeter is not considerably higher than that of the resistor, the current through the resistor is markedly changed by the current passing through the meter resistance and so the voltage being measured is changed (Figure 1.15). The act of attempting to make the measurement has modified the voltage that was being measured. If the effect of inserting the voltmeter in the circuit is to be as small as possible, the resistance of the voltmeter must be much larger than that of the resistance across which it is connected. Only then will the current bypassing the resistor and passing through the voltmeter be very small and so the voltage not significantly changed.

Example

Two voltmeters are available, one with a resistance of 1 kΩ and the other 1 MΩ. Which instrument should be selected if the indicated value is to be closest to the voltage value that existed across a 2 kΩ resistor before the voltmeter was connected across it?

The 1 MΩ voltmeter should be chosen. This is because when it is in parallel with 2 kΩ, less current will flow through it than if the 1 kΩ voltmeter had been used and so the current through the resistor will

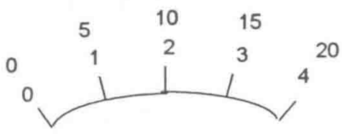

Figure 1.16 *Multi-range meter*

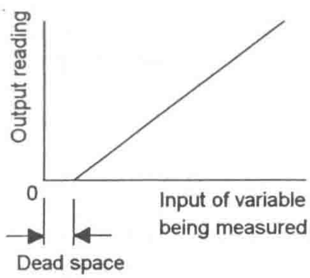

Figure 1.17 *Dead space*

be closer to its original value. Hence the indicated voltage will be closer to the value that existed before the voltmeter was connected into the circuit.

1.3.2 Range

The *range* of variable of system is the limits between which the input can vary. For example, a resistance thermometer sensor might be quoted as having a range of −200 to +800°C. The meter shown in Figure 1.16 has the dual ranges 0 to 4 and 0 to 20. The range of variable of an instrument is also sometimes called its *span*.

The term *dead band* or *dead space* is used if there is a range of input values for which there is no output. Figure 1.17 illustrates this. For example, bearing friction in a flow meter using a rotor might mean that there is no output until the input has reached a particular flow rate threshold.

1.3.3 Precision, repeatability and reproducibility

The term *precision* is used to describe the degree of freedom of a measurement system from random errors. Thus, a high precision measurement instrument will give only a small spread of readings if repeated readings are taken of the same quantity. A low precision measurement system will give a large spread of readings. For example, consider the following two sets of readings obtained for repeated measurements of the same quantity by two different instruments:

20.1 mm, 20.2 mm, 20.1 mm, 20.0 mm, 20.1 mm, 20.1 mm, 20.0 mm

19.9 mm, 20.3 mm, 20.0 mm, 20.5 mm, 20.2 mm, 19.8 mm, 20.3 mm

The results of the measurement give values scattered about some value. The first set of results shows a smaller spread of readings than the second and indicates a higher degree of precision for the instrument used for the first set.

The terms repeatability and reproducibility are ways of talking about precision in specific contexts. The term *repeatability* is used for the ability of a measurement system to give the same value for repeated measurements of the same value of a variable. Common cause of lack of repeatability are random fluctuations in the environment, e.g. changes in temperature and humidity. The error arising from repeatability is usually expressed as a percentage of the full range output. For example, a pressure sensor might be quoted as having a repeatability of ±0.1% of full range. Thus with a range of 20 kPa this would be an error of ±20 Pa.

The term *reproducibility* is used to describe the ability of a system to give the same output when used with a constant input with the system or elements of the system being disconnected from its input and then reinstalled. The resulting error is usually expressed as a percentage of the full range output.

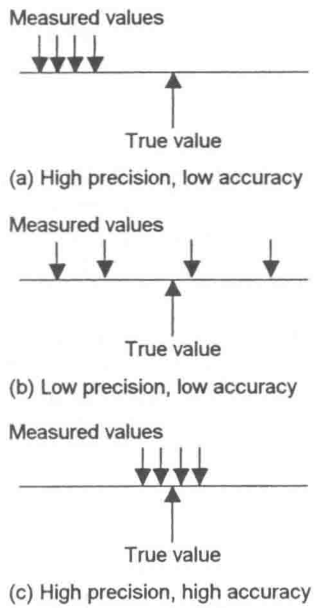

Figure 1.18 *Precision and accuracy*

Figure 1.19 *Sensitivity as slope of input–output graph*

Application
An iron–constantan thermocouple is quoted as having a sensitivity at 0°C of 0.05 mV/°C.

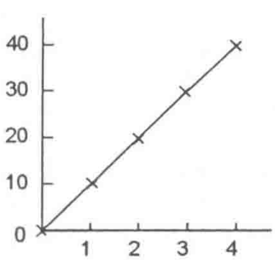

Figure 1.20 *Example*

Note that precision should not be confused with accuracy. High precision does not mean high accuracy. A high precision instrument could have low accuracy. Figure 1.18 illustrates this:

> The term *precision* is used to describe the degree of freedom of a measurement system from random errors. The *repeatability* of a system is its ability to give the same output for repeated applications of the same input value, without the system or element being disconnected from its input or any change in the environment in which the test is carried out. The *reproducibility* of a system is its ability to give the same output when it and/or elements of the system are disconnected from the input and then reinstalled.

1.3.4 Sensitivity

The *sensitivity* indicates how much the output of an instrument system or system element changes when the quantity being measured changes by a given amount, i.e. the ratio ouput/input. For example, a thermocouple might have a sensitivity of 20 μV/°C and so give an output of 20 μV for each 1°C change in temperature. Thus, if we take a series of readings of the output of an instrument for a number of different inputs and plot a graph of output against input (Figure 1.19), the sensitivity is the slope of the graph.

The term is also frequently used to indicate the sensitivity to inputs other than that being measured, i.e. environmental changes. For example, the sensitivity of a system or element might be quoted to changes in temperature or perhaps fluctuations in the mains voltage supply. Thus a pressure measurement sensor might be quoted as having a temperature sensitivity of ±0.1% of the reading per °C change in temperature.

Example

A spring balance has its deflection measured for a number of loads and gave the following results. Determine its sensitivity.

Load in kg	0	1	2	3	4
Deflection in mm	0	10	20	30	40

Figure 1.20 shows the graph of output against input. The graph has a slope of 10 mm/kg and so this is the sensitivity.

Example

A pressure measurement system (a diaphragm sensor giving a capacitance change with output processed by a bridge circuit and displayed on a digital display) is stated as having the following characteristics. Explain the significance of the terms: