Chapter 1

Introduction

Learning Objectives

- To define different types of sensors.
- To list recognition elements.
- To list the transducers used in sensors.
- To learn the methods of attaching recognition elements to transducers.
- To understand the most important performance factors.
- To know three main areas of application.

1.1 Introduction to Sensors

1.1.1 What are Sensors?

DQ 1.1

What is a sensor?

Answer

We have at least five of these, i.e. our noses, our tongues, our ears, our eyes and our fingers. They represent the main types of sensor. In the laboratory, one of the best known types of sensor is the litmus paper test for acids and alkalis, which gives a qualitative indication, by means of a colour reaction, of the presence or absence of an acid. A more precise method of indicating the degree of acidity is the measurement of pH, either by the more extended use of colour reactions in special indicator solutions, or even by simple pH papers. However, the best method *of measuring acidity is the use of the pH meter, which is an electrochemical device giving an electrical response which can be read by a needle moving on a scale or on a digital read-out device or input to a microprocessor.*

In such methods, the *sensor* that responds to the degree of acidity is either a chemical – the dye litmus, or a more complex mixture of chemical dyes in pH indicator solutions – or the glass membrane electrode in the pH meter.

The chemical or electrical response then has to be converted into a signal that we can observe, usually with our eyes. With litmus, this is easy. A colour change is observed, because of the change in the absorbance of visible light by the chemical itself, which is immediately detected by our eyes in a lightened room. In the case of the pH meter, the electrical response (a voltage change) has to be converted, i.e. *transduced* (= led through), into an observable response – movement of a meter needle or a digital display. The part of the device which carries out this conversion is called a *transducer*.

We can divide sensors into three types, namely (a) physical sensors for measuring distance, mass, temperature, pressure, etc. (which will not concern us here), (b) chemical sensors which measure chemical substances by chemical or physical responses, and (c) biosensors which measure chemical substances by using a biological sensing element. All of these devices have to be connected to a transducer of some sort, so that a visibly observable response occurs. Chemical sensors and biosensors are generally concerned with sensing and measuring particular chemicals which may or may not be biological themselves. We shall usually refer to such a material as the *substrate*, although the more general term *analyte* is sometimes used. Figure 1.1 shows schematically the general arrangement of a sensor.

SAQ 1.1

Draw a labelled diagram of a chemical sensor.

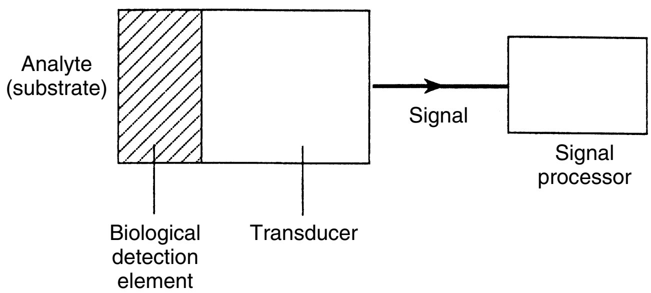

Figure 1.1 Schematic layout of a (bio)sensor. From Eggins, B. R., *Biosensors: An Introduction*, Copyright 1996. © John Wiley & Sons Limited. Reproduced with permission.

1.1.2 The Nose as a Sensor

One might consider the ears, eyes and fingers to be physical sensors as they detect physical sensations of sound, light and heat, etc., respectively. What we detect with the nose – smells – are in fact small quantities of chemicals. The nose is an extremely sensitive and selective instrument which is very difficult to emulate artificially. It can distinguish between many different chemical substances qualitatively and can give a general idea of 'quantity' down to very low detection limits. The chemicals to be detected pass through the olfactory membrane to the olfactory bulbs, which contain biological receptors that sense the substrate. The response is an electrical signal which is transmitted to the brain via the olfactory nerves. The brain then transduces this response into the sensation we know as smell. The tongue operates in a similar way.

Figure 1.2 shows a schematic diagram of the nasal olfactory system, illustrating the comparison with our generalized sensor. The nostrils collect the 'smell sample', which is then sensed by the olfactory membrane, i.e. the sensing element. The responses of the olfactory receptors are then converted by the olfactory nerve cell, which is the equivalent of the transducer, into electrical

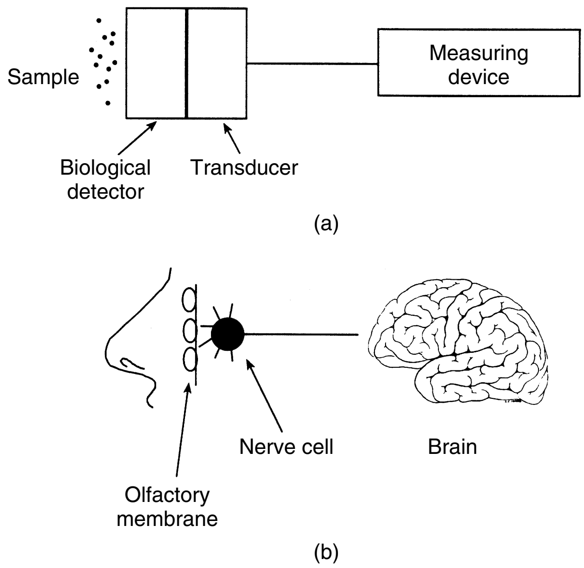

Figure 1.2 (a) Schematic of a sensor, showing the component parts, i.e. analyte, recognition element, transducer, actuator and measuring device. (b) Analogy with the nose as a sensor (actually a biosensor), in which the olfactory membrane is the biological recognition element, the nerve cell is the transducer, the nerve fibre is the actuator and the brain is the measuring element. From Eggins, B. R., *Biosensors: An Introduction*, Copyright 1996. © John Wiley & Sons Limited. Reproduced with permission.

signals which pass along the nerve fibre to the brain for interpretation. Thus, the brain acts as a microprocessor, turning the signal into a sensation which we call smell.

1.2 Sensors and Biosensors – Definitions

There are sometimes differences of usage for the terms *sensors, transducers, biosensors and actuators*, so it is necessary for us to define how they will be used in this book:

- We will use the term *sensor* to describe the whole device, following the Oxford English Dictionary definition, i.e. *a sensor is a device that detects or measures a physical property and records, indicates or otherwise responds to it*. (This is in contrast to the definition in Chambers Dictionary, quoted by Usher and Keating in their book 'Sensors and Transducers'.)
- We will define a *transducer* as *a device that converts an observed change (physical or chemical) into a measurable signal*. In chemical sensors, the latter is usually an electronic signal whose magnitude is proportional to the concentration of a specific chemical or set of chemicals.
- The term *actuator* i.e. *put into action*, is sometimes encountered. This is the part of the device which produces the display.

We can think of three types of sensor, i.e. physical, chemical and biosensors.

DQ 1.2

Distinguish between chemical sensors, physical sensors and biosensors.

Answer

Physical sensors are concerned with measuring physical quantities such as length, weight, temperature, pressure, and electricity – for their own sakes. This present book is not concerned with these as such except that the response of a sensor is usually in the form of a physical response. The book by Usher and Keating (see the Bibliography) is actually entirely concerned with physical sensors.

A chemical sensor is defined in R. W. Catterall's book (see the Bibliography) as **a device which responds to a particular analyte in a selective way through a chemical reaction and can be used for the qualitative or quantitative determination of the analyte.** *Such a sensor is concerned with detecting and measuring a specific chemical substance or set of chemicals.*

Biosensors are really a sub-set of chemical sensors, but are often treated as a topic in their own right. A biosensor can be defined as **a**

device incorporating a biological sensing element connected to a transducer. *The analyte that this sensor detects and measures may be purely chemical (even inorganic), although biological components may be the target analyte. The key difference is that the recognition element is biological in nature.*

> **SAQ 1.2**
>
> Distinguish between physical sensors, chemical sensors and biosensors.

1.3 Aspects of Sensors

1.3.1 Recognition Elements

Recognition elements are the key component of any sensor device. They impart the selectivity that enables the sensor to respond selectively to a particular analyte or group of analytes, thus avoiding interferences from other substances. Methods of analysis for specific ions have been available for a long time using ion-selective electrodes, which usually contain a membrane selective for the analyte of choice. In biosensors, the most common recognition element is an enzyme. Others include antibodies, nucleic acids and receptors.

1.3.2 Transducers – the Detector Device

Analytical methods in chemistry have mainly been based on photometric transducers, as in spectroscopic and colorimetric methods. However, most sensors have been developed around electrochemical transducers, because of simplicity of construction and cost. While electrons drive microprocessors, the directness of an electrical device will tend to have maximum appeal. However, with the rapid development of photon-driven devices through the use of optical fibres, it could well be that electrical appliances will soon become obsolete – starting with the telephone. In addition, the use of micro-mass-controlled devices, based mainly on piezo-electric crystals, may become competitive in the near future.

Transducers can be subdivided into the following four main types.

1.3.2.1 Electrochemical Transducers

(i) *Potentiometric*. These involve the measurement of the emf (potential) of a cell at zero current. The emf is proportional to the logarithm of the concentration of the substance being determined.

(ii) *Voltammetric*. An increasing (decreasing) potential is applied to the cell until oxidation (reduction) of the substance to be analysed occurs and there is a sharp rise (fall) in the current to give a peak current. The height of the peak current is directly proportional to the concentration of the electroactive material. If the appropriate oxidation (reduction) potential is known, one may step the potential directly to that value and observe the current. This mode is known as *amperometric*.

(iii) *Conductometric*. Most reactions involve a change in the composition of the solution. This will normally result in a change in the electrical conductivity of the solution, which can be measured electrically.

(iv) *FET-based sensors*. Miniaturization can sometimes be achieved by constructing one of the above types of electrochemical transducers on a silicon-chip-based field-effect transistor. This method has mainly been used with potentiometric sensors, but could also be used with voltammetric or conductometric sensors.

1.3.2.2 Optical Transducers

These have taken a new lease of life with the development of fibre optics, thus allowing greater flexibility and miniaturization. The techniques used include absorption spectroscopy, fluorescence spectroscopy, luminescence spectroscopy, internal reflection spectroscopy, surface plasmon spectroscopy and light scattering.

1.3.2.3 Piezo-electric Devices

These devices involve the generation of electric currents from a vibrating crystal. The frequency of vibration is affected by the mass of material adsorbed on its surface, which could be related to changes in a reaction. *Surface acoustic wave* devices are a related system.

1.3.2.4 Thermal Sensors

All chemical and biochemical processes involve the production or absorption of heat. This heat can be measured by sensitive thermistors and hence be related to the amount of substance to be analysed.

Further details of all of these types of transducers are given below in Chapters 2 and 7.

SAQ 1.3

Summarize the main features of sensors.

1.3.3 Methods of Immobilization

The selective element must be connected to the transducer. This presents particular problems if the former is biological in nature. Several classes of methods of connection have evolved, as follows:

- The simplest method is *adsorption* on to a surface.
- *Microencapsulation* is the term used for trapping between membranes – one of the earliest methods to be employed.
- *Entrapment*, where the selective element is trapped in a matrix of a gel, paste or polymer – this is a very popular method.
- *Covalent attachment*, where covalent chemical bonds are formed between the selective component and the transducer.
- *Cross-linking*, where a bifunctional agent is used to bond chemically the transducer to the selective component – this is often used in conjunction with other methods, such as adsorption or microencapsulation.

Further details about these various procedures are presented below in Section 3.6.

1.3.4 Performance Factors

(i) *Selectivity*. This is the most important characteristic of sensors – the ability to discriminate between different substances. Such behaviour is principally a function of the selective component, although sometimes the operation of the transducer contributes to the selectivity.

(ii) *Sensitivity range*. This usually needs to be sub-millimolar, but in special cases can go down to the femtomolar (10^{-15} M) range.

(iii) *Accuracy*. This needs to be better than ±5%.

(iv) *Nature of solution*. Conditions such as pH, temperature and ionic strength must be considered.

(v) *Response time*. This is usually much longer (30 s or more) with biosensors than with chemical sensors.

(vi) *Recovery time*. This is the time that elapses before the sensor is ready to analyse the next sample – it must not be more than a few minutes.

(vii) The *working lifetime* is usually determined by the stability of the selective material. For biological materials this can be a short as a few days, although it is often several months or more.

Further details of the above are given later in Chapter 4.

1.3.5 Areas of Application

1.3.5.1 Health Care

Health care is the main area of application of biosensors and chemical sensors (*chemisensors*). Measurements of blood, gases, ions and metabolites are regularly needed to show a patient's metabolic state – especially for those in hospital, and

Table 1.1 Common assays that are required in diagnostic medicine

Analyte	Method of assay
Glucose	Amperometric biosensor
Urea	Potentiometric biosensor
Lactate	Amperometric biosensor
Hepatitis B	Chemiluminescent immunoassay
Candida albicans	Piezo-electric immunoassay
Cholesterol	Amperometric biosensor
Penicillins	Potentiometric biosensor
Sodium	Glass ion-selective electrode
Potassium	Ion-exchange-selective electrode
Calcium	Ionophore ion-selective electrode
Oxygen	Fluorescent quenching sensor
pH	Glass ion-selective electrode

even more so if they are in intensive care. Many of these substrates have been determined by samples of urine and blood being taken away to a medical analytical laboratory for classical analysis, which may not be complete for hours or even days. The use of on-the-spot sensors and biosensors enable results to be obtained in minutes at most. The latest ExacTech® glucose sensor gives a reading in 12 s.

This would obviate the need for *en suite* analytical units with specialist medical laboratory scientists. A trained nurse would be competent to carry out sensor tests at the bedside. Modern 'smart' sensors, based on field-effect transistors (FETs), may combine several measurements in one sensor unit. This particularly applies in the case of ion sensors for sodium, potassium, calcium and pH. Attempts are also being made to make combination biosensors, e.g. for glucose, lactate and urea. Table 1.1 shows a list of common assays that are routinely needed for diagnostic work with patients.

A potential 'dream application' is to have an implanted sensor for continuous monitoring of a metabolite. This might then be linked via a microprocessor to a controlled drug-delivery system (e.g. an iontophoretic system) through the skin. Such a device would be particularly attractive for chronic conditions such as diabetes. The blood glucose sensor would be monitored continuously and, as the glucose level reached a certain value, insulin would be released into the patient's blood stream automatically. This type of system is sometimes referred to as an *artificial pancreas*. The latter would be far more beneficial for the patient than the present system of discrete blood glucose analyses which involve pricking a thumb every time, followed by injection of large doses of insulin every few hours.

1.3.5.2 Control of Industrial Processes

Sensors are used in various aspects of fermentation processes in three different ways, i.e. (i) off-line in a laboratory, (ii) off-line, but close to the operation site, and (iii) on-line in real time. At present, the main real-time monitoring is confined to such measurements as temperature and pH, plus carbon dioxide and oxygen measurements. However, biosensors which monitor a range of direct reactants and products are available, such as those for sugars, yeasts, malts, alcohols, phenolic compounds, and perhaps, undesirable by-products. Such monitoring could result in improved product quality, increased product yields, checks on tolerance of variations in quality of raw material, optimized energy efficiency, i.e. improved plant automation, and less reliance on human judgement. In general, there is a wide range of applications in the food and beverage industry.

1.3.5.3 Environmental Monitoring

There is an enormous range of potential analytes in air, water, soils, and other environmental situations. Such measurements in water include biochemical oxygen demand (BOD), acidity, salinity, nitrate, phosphate, calcium and fluoride, while pesticides, fertilizers and both industrial and domestic wastes require extensive analyses. A current concern is for endocrine disruptors that can be active at very low levels of concentration (ng l^{-1}), due to a wide range of oestrogens and oestrogenic mimics. Continuous real-time monitoring is required for some substances, and occasional random monitoring for others. In addition to the obvious pollution applications, farming, gardening, veterinary science and mining are all areas where sensors are needed for environmental monitoring.

SAQ 1.4

Write down an example of a sensor used in (a) health care, (b) industrial control, and (c) environmental monitoring.

Summary

This chapter discusses what sensors are, defining physical, chemical and biosensors. The various parts of a sensor are described, including (the analyte), recognition element, transducer, actuator, and measuring device. The biosensor is compared to the human nose. An introduction is given to various aspects of sensors, including types of recognition elements, transducers, connection methods, and performance factors. Three main areas of application are described.