Introduction to Sensors
Primary Knowledge
Participant Guide

Description and Estimated Time to Complete

This learning module is one of three SCME modules that discuss the types of components found in microelectromechanical systems (MEMS). This module covers "sensors" – what they are, how they work and how they are used in both macro and micro-sized systems. An activity provides further exploration into specific sensors and how they are used in everyday devices. Two related learning modules cover MEMS transducers and actuators.

This lesson familiarizes you with sensors in both the macro and micro-scales. The following topics are discussed:

- What are sensors and how do they differ from transducers?
- Type of sensors in both the macros and micro-scales

The understanding of this information is important to microelectromechanical (MEMS) or microsystems technology.

<u>Estimated Time to Complete</u>
Allow approximately 45 minutes to complete this lesson and presentation.

Introduction

A sensor is a device that receives and responds to a signal. This signal must be some type of energy, such as heat, light, motion, electrical, or chemical reaction. Once a sensor detects one or more of these signals (an input), it converts it into an analog or digital representation of the input signal. Based on this explanation of a sensor, you should see that sensors are used in all aspects of life to detect and/or measure many different conditions. What are some sensors that you are familiar with or use daily?

Human beings are equipped with 5 different types of sensors.

Eyes detect light energy, ears detect acoustic energy, a tongue and a nose detect certain chemicals, and skin detects pressures and temperatures. The eyes, ears, tongue, nose, and skin receive these signals then send messages to the brain that outputs a response. For example, when you touch a hot plate, it is your brain that tells you it is hot, not your skin.

This unit describes the basic concepts of sensors and introduces the different types in both the macro and micro scales.

Objectives

- Define sensor.
- Describe three types of sensors. Include at least one microsensor.

Key Terms (These terms are defined in the glossary at the end of this unit.)

actuator
energy
mechanical
optical
photoelectric
sensors
transducer

Basic Concepts of Sensors

Transducers convert one form of energy into another form of energy. Sensors detect the presence of energies as well as changes in or the transfer of energies. Sensors detect by receiving a signal from a device such as a transducer, then responding to that signal by converting it into an output that can easily be read and understood. Typically sensors convert a recognized signal into an electrical – analog or digital – output that is readable. In other words, the sensor takes the output of the transducer and converts it to a readable format. In many sensors, the sensor compares the input and output signals to the transducer or sensor, quantifies the change, and responds with an appropriate output.

Consider the definition of a transducer. A transducer converts one form of energy to another, but does not quantify the conversion. For example, a light bulb converts electrical energy into light and heat; however, it does not quantify how much light or heat. A battery converts chemical energy into electrical energy but it does not quantify exactly how much electrical energy is converted. If the purpose of a device is to quantify an energy level, it is a sensor.

So let's take a look at a sensor that should be familiar to everyone – a temperature sensor.

Digital Readout and Mercury Thermometers

An environmental energy condition that is commonly sensed is temperature. A thermometer senses and converts temperature into a readable output, thus it is a sensor. This output can be direct or indirect. A mercury thermometer that uses a level of mercury against a fixed scale is a direct output. A digital readout thermometer is an indirect output. *(see images above)* For a digital readout thermometer, a converter is used to convert the output of the temperature transducer to an input for the digital display. The measured temperature is displayed on a monitor. The thermometer is both a transducer (usually a thermocouple that converts heat energy to voltage) and a sensor (quantifies the transducer output with a readable format).

The mercury thermometer utilizes mercury's property of expanding or contracting when heated or cooled, respectively. In mercury thermometers, a temperature increase is sensed by the mercury contained in a small glass tube. The thermal energy from the temperature increase is transferred into the mercury (the transducer) causing the mercury to expand. The expansion of mercury is scaled to numbers on the tube indicating the temperature.

Following are different types of sensors that are classified by the type of energy they detect.

Thermal Sensors

Thermal sensors use transducers that convert temperature or heat to another form of energy and provide an output reading of the temperature.

- Thermometer – Measures absolute temperature or temperatures relative to absolute zero. There are many different types of thermometers. Two common thermometers are the mercury thermometer discussed previously and the infrared thermometer.
- Thermocouple gauge– Measures temperature and temperature changes using a thermocouple transducer.
- Sensors using Resistance Temperature Detectors (RTDs) – Measures temperature and temperature changes by measuring the output of a RTD. A RTD is a coiled wire that exhibits a change in resistance when the temperature of the wire changes.

For each of these sensors, an output is provided indicating the value of the parameter being detected and measured.

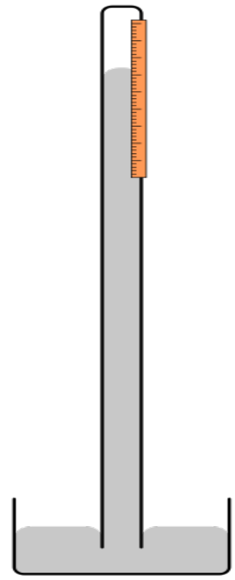
Mechanical Sensors

Mechanical sensors use movement of some type to sense a specific parameter such as pressure, the flow rate of a fluid, or acceleration. Once sensed, the mechanical sensor provides a readout of some type indicate a representative value of the parameter.

- Pressure sensor – measures pressure
- Barometer – measures atmospheric pressure
- Altimeter – measures the altitude of an object above a fixed level
- Liquid flow sensor – measures liquid flow rate
- Gas flow sensor – measures velocity, direction, and/or flow rate of a gas
- Accelerometer – measures acceleration, deceleration

Let's take a look at a barometer. Barometers measure atmospheric pressure. The figure to the right illustrates a simple mercury barometer. A tube is initially filled with mercury and then inverted into a dish. Some of the mercury from the tube flows into the dish (reservoir) creating a vacuum in the upper portion of the tube. The flow stops when equilibrium is reached between the pressures on the surfaces of the mercury inside the tube and in the reservoir. When the atmospheric pressure increases, the level of the mercury in the tube rises. This is due to an increase in pressure on the mercury's surface in the reservoir. When the atmospheric pressure drops, a decrease in the level of mercury is seen in the tube.

Markings on the tube *(in orange)* indicate the barometric pressure by measuring the level of mercury. Therefore, a barometer converts the energy from the pressurized gases of the atmosphere into a change in the mercury's height (potential energy) in the column, as read by the markings. Question for thought: How does a mercury barometer differ from a mercury thermometer?



Schematic of a mercury barometer

Another type of barometer is the aneroid barometer that senses changes in atmospheric pressure by the expansion or compression of an aneroid capsule (a thin, disk-shaped capsule, usually metallic, and partially evacuated of gas). An external spring is connected to the capsule and a needle is mechanically linked to the spring. As the pressure on the outside of the capsule increases, the capsule compresses causing the spring to move the needle indicating an increase in barometric pressure. As the pressure drops, the capsule expands, and the spring moves in the opposite direction, moving the needle to show a decrease in barometric pressure.

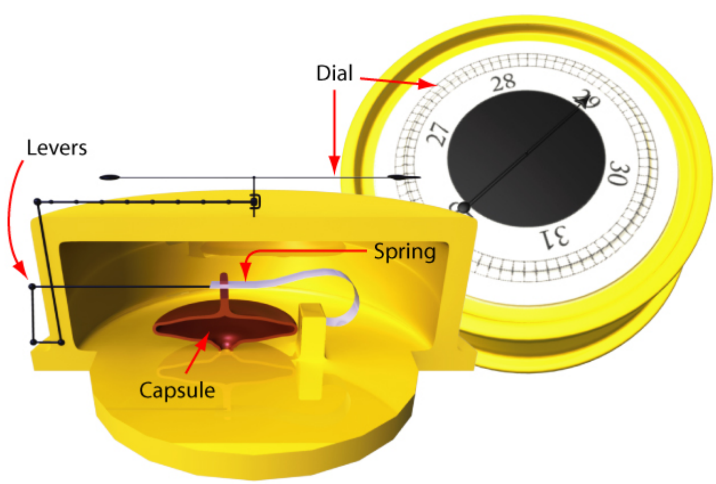
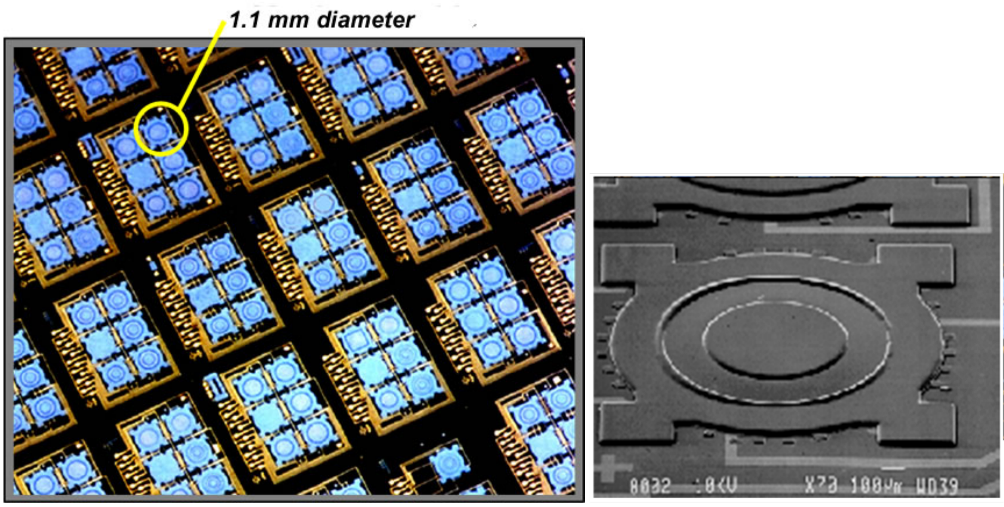


Diagram of Aneroid Barometer

The images below are of a MEMS barometric pressure sensor that uses a diaphram over a reference vacuum (similar to the aneroid barometer) to measure small changes in barometric pressure. The left image shows several electromechanical sensor chips each with an array of 6 pressure transducers. The right image shows the pressure transducer, a micro-sized unit that converts motion from changes in pressure to an electrical signal. The electrical signal is converted by the electronics of the sensor to an appropriate format for the system. These MEMS sensors are currently being used in wind tunnels and for various weather monitoring applications.

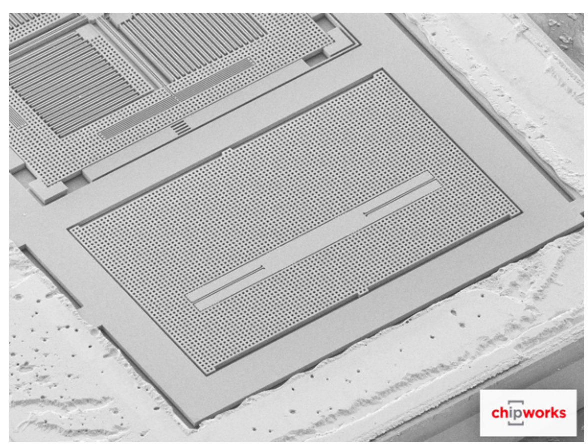


Barometric Pressure Sensors (Photos courtesy of Khalil Najafi, University of Michigan)

MEMS Accelerometer Sensor

In *Introduction to Transducers* we talked about the microaccelerometer transducer. A MEMS accelerometer sensor contains the transducer and the circuitry required to interpret the output of the transducer. One type of sensor in which accelerometers are used is the MEMS airbag deployment sensor. This sensor contains three microaccelerometer transducers and the electronic circuitry for each transducer. Each transducer senses acceleration on one axis – x, y, or z. As a MEMS sensor, this device simultaneously senses and quantifies movement in all three directions and triggers the airbag(s) when needed. The scanning electron microscope (SEM) image below shows the mechanical components of a 3-axis accelerometer.

Three-axis accelerometer sensor
Three microaccelerometer transducers connected internally to sensor electronics. Sensor and packaging about the size of a sugar cube.[Image courtesy of Chipworks]



Electrical Sensors

Electrical sensors are sensors that measure resistance, current voltage, or electrical energy and provide an output that the value of the electrical component.

- Ohmmeter – measures resistance
- Voltmeter – measures voltage
- Galvanometer and ammeters – measure current
- Watt-hour meter – measures the amount of electrical energy supplied to and used by a residence or business

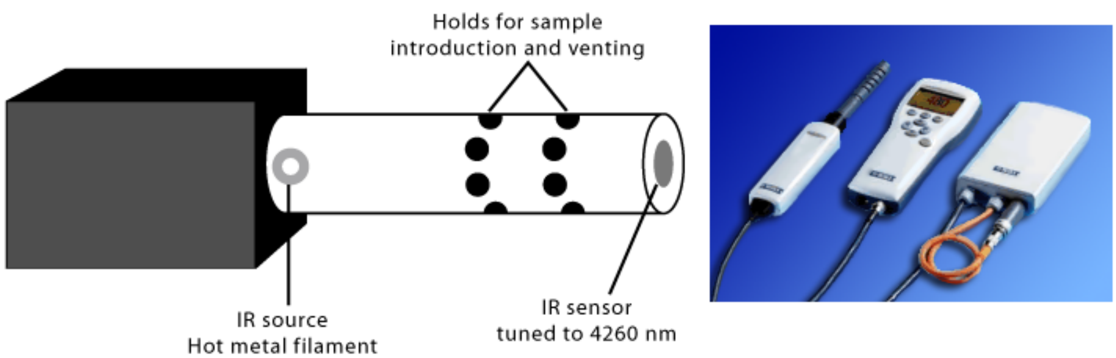
Schematic and photograph of a Galvanometer used for sensing electrical currents

A Galvanometer is a specific type of ammeter used for sensing an electrical current (see figures above). Current flows through a coil (the red wire wound around a metal cylinder) creating a magnetic field. Permanent magnets surround the coil. The interaction of these two magnetic fields causes the coil/cylinder combination to pivot around its central axis. The amount and direction of the pivot move the needle at the readout *(right image)* left or right, indicating the level of current and its polarity (negative or positive, respectively). This device uses two energy conversions to sense and quantify an electric current: electrical to magnetic and magnetic to mechanical rotation.

Chemical Sensors

Chemical sensors detect the presence of certain chemicals or classes of chemicals and quantify the amount and/or type of chemical detected.

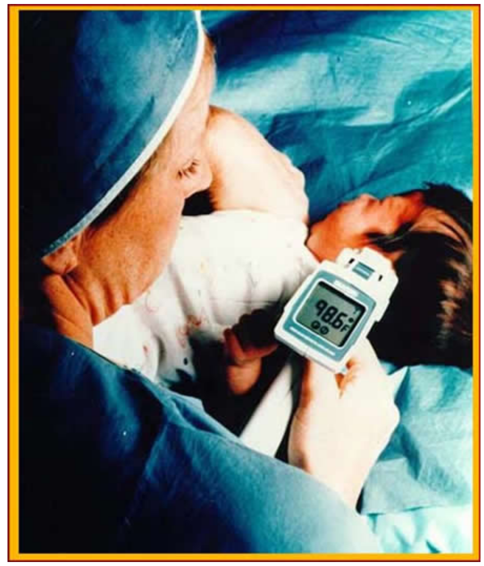
- Oxygen sensor – measures the percentage of oxygen in a gas or liquid being analyzed
- Carbon dioxide sensor – detects the presence of CO_2 *(see diagram below)*



Schematic and Photo of a Carbon Dioxide Sensor
(IR – infrared)

Chemical sensing is an application that really taken off with microtechnology. Just like the macro-sized components, MEMS chemical sensors can detect a wide variety of different gases but because of their size, they can go places that macro-sized sensors can't really go. MEMS sensors can also be incorporated into objects for continuous sensing of a gas or selection of gases. These devices have numerous medical, industrial, and commercial applications such as biohazard detection, quality control in food processing, and medical diagnosis. Such devices are sometimes referred to an ENose or electronic nose.[1]

Other Types of Sensors



Optical sensors detect light and electromagnetic energy

- Photodetectors – light sensitive materials that range from simple resistive photocells to photodiodes and transistors.
- Proximity detectors – use light to detect nearby objects
- Infrared sensor – detects infra-red radiation (heat or black body radiation (https://en.wikipedia.org/wiki/Black-body_radiation)). The picture to the right shows an infrared ear thermometer used to measure body temperature.

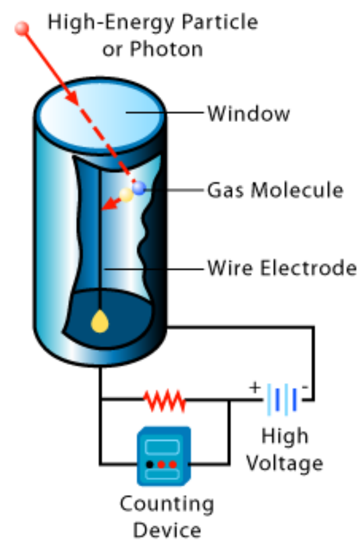
Infrared ear thermometer
[Image courtesy of NASA Jet Propulsion Laboratory

Acoustic

- Seismometers – measures seismic waves
- Acoustic wave sensors – measures the wave velocity in the air or an environment to detect the chemical species present

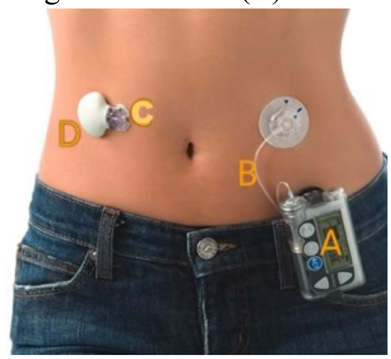
Other

- Motion – detects motion
- Speedometer – measures speed
- Geiger counter – detects atomic radiation *(see graphic)*
- Biological – monitors human cells



Geiger Counter: Detects Atomic Radiation

The biological sensor is another field that has expanded due to advances with microtechnology. Already on the commercial market are biological sensors that detect and measure the amount of glucose in one's blood *(diagram below)*. The glucometer shown in the picture monitors glucose (C) in vivo (internal) using a chemical transducer and delivers insulin on an as-needed basis (A/B) using a micropump. D is the transmitter that relays the information from the glucose sensor (C) to the computer (A). The computer calculate the amount of insulin needed, if any, and signals the insulin pump to supply a precise amount of insulin to the cannula (B) that directs the insulin to a microneedle under the skin and into the body.[2]



MiniMed Paradigm[R] REAL-Time System from Medtronic Diabetes [Printed with permission from Medtronic Diabetes].

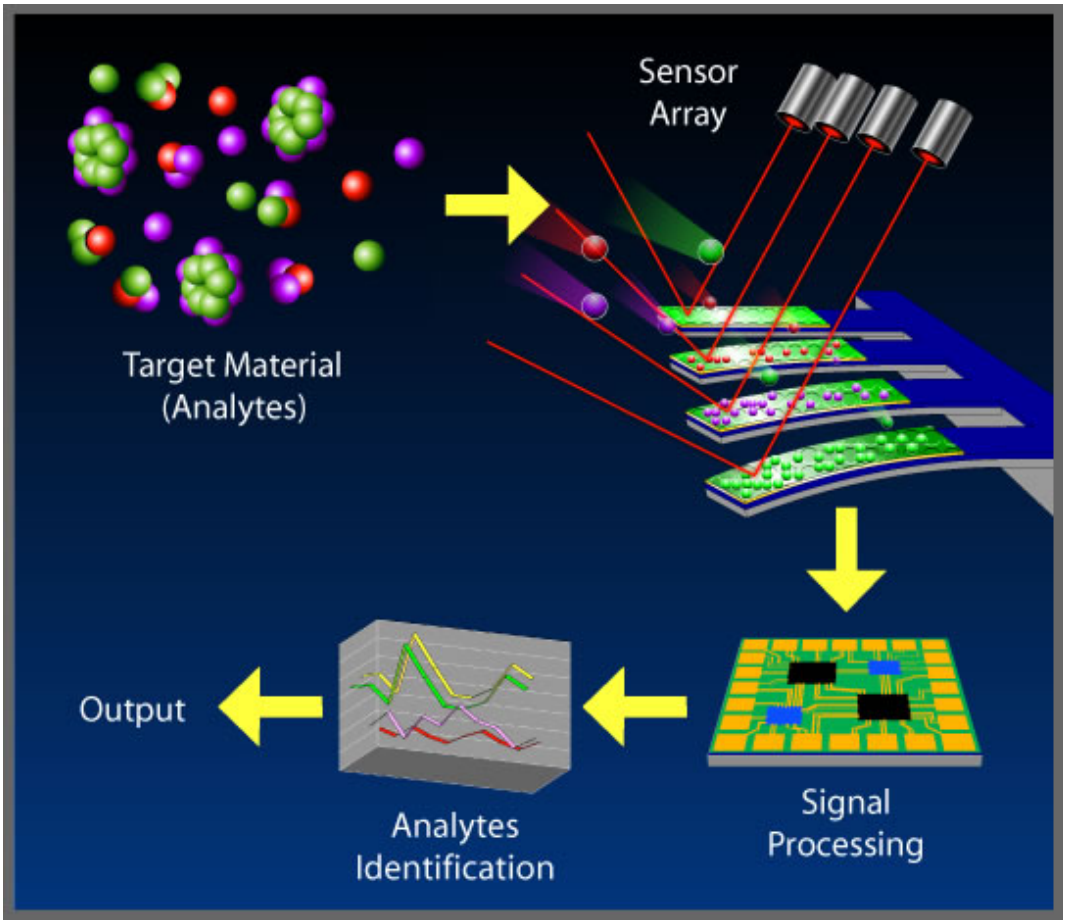
Macro vs. Micro Sensors

Transducers, sensors and actuators can all be found in the macroscale (those visible to the naked eye) and the microscale (microscopic). Micro and nanotechnology are enabling such devices in the micro and nanoscales. Microsystems use microtransducers, (e.g., temperature sensitive resistors and strain gauges), as elements in microsensing devices, such as flowmeters and chemical sensors. Types of microsensors consist of chemical sensor arrays, optical sensors, inertial sensors and thermal sensors.

Micro-sized sensors, in most cases, are more efficient, more durable and more reliable than their macro-sized equivalents. Micro-devices, when mass produced, are also cheaper to manufacturer and can therefore, be sold for lower prices. An example of this is the MEMS accelerometer sensor used to trigger airbag deployment in automobiles (the sensor we discussed previously). The cost of the earlier macro-sized sensors was over $50.[3] Today's microaccelerometer sensors cost between $5 to $10, and provide quicker response to rapid deceleration, and more reliable functionality.[5]

Another characteristic of MEMS sensors is the ability to transmit the collected data and receive data wirelessly via today's wireless communication systems. This connectivity and transfer of information is referred to as the Internet of Things or IoT. For example, the data from a glucose monitoring sensor can be sent to the patient's smart phone and directly to the patient's physicians. Today's pacemakers send just-in-time data directly to the physician indicating potential problems that need to be addressed. These medical devices also supply a history of data collected concerning the health of the patient.

Another sensor that can be found in both the macro and micro-scales is the chemical sensor array or CSA. The diagram below illustrates a MEMS chemical sensor array. This device is designed and fabricated to detect specific analytes (target materials) such as a specific virus and/or bacterium. The analytes are detected and captured on the cantilevers of the sensor array. The presence of the analytes and sometimes the amount captured is sensed, processed and interpreted by the signal processor. The output provides the results. To give you an idea of the scale, the cantilevers illustrated in the diagram are usually around 100 micrometers (µm) long, 20 µm wide and 5 µm thick. The analytes can be anywhere from 10 µm to 1 nanometer (nm) in diameter.



Coaching Question

Is it possible for a device to be defined as both a sensor and a transducer? Give an example.

Key Terms

Actuator – a specific type of transducer that coverts energy into motion

Energy: The sources of energy encompass electrical, mechanical, hydraulic, pneumatic, chemical, thermal, gravity, and radiation energy. There are two types of energy---kinetic and potential. Kinetic energy is the force caused by the motion of an object for example a spinning flywheel. Potential energy is the force stored in an object when it isn't moving.

Mechanical: Pertaining to or concerned with machinery or tools.

Optical: Referring to the behavior and properties of light and the interaction of light with matter.

Photoelectric: Relates to the electrical effects caused by light.

Sensors: A device that responds to a stimulus, such as heat, light, or pressure, and generates a signal that can be measured or interpreted.

Transducer: A substance or device that converts input energy of one form into output energy of another.

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