Processing storage and display of physiological measurements

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Learning objectives

After reading this article, you should be able to
- describe basic measurement principles (such as noise, drift, accuracy, precision)
- explain basic electrical measurement techniques, particularly for measuring temperature using a thermistor

Abstract
Core issues in physiological measurement are explained using temperature and thermistors as running examples. Modern issues in display, such as adequate resolution and patient identification, are also covered for correct interpretation of physiological data.

Keywords Digital signal processing; Ohm's Law; principles of measurement; temperature measurement; thermistor; Wheatstone Bridge

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Temperature provides a clear example of physiological measurement. Scientists in the 18th Century, including the great Fahrenheit and Celsius, developed mercury thermometers to measure temperature.

Mercury thermometers use the expansion of mercury in a narrow glass tube to convert temperature into the visible length of the mercury column. Once the thermometer has been calibrated by the manufacturer, a clinician reads off the temperature from the scales marked on the tube. Mercury thermometers for clinical use often had a maximum reading feature: the mercury expands with increasing temperature, but when the temperature drops (e.g. when the thermometer is removed from the patient's body), the mercury column breaks but retains the maximum value until the thermometer is vigorously shaken.

Unfortunately, shaking a mercury-in-glass thermometer is a bad idea, and they have been phased out, but they illustrate key principles of physiological measurement.

The clinician is interested in a physiologically relevant **physical variable**, such as temperature. Temperature has to be converted to something the clinician can see and preferably record. The expanding column of mercury does this transformation. However, as Celsius himself noticed, mercury is not the only thing expanding: for accurate measurements, the expansion of the glass tube matters and has to be **compensated** for. Then there is **noise**, unwanted or irrelevant changes in temperature; for example, the patient may have just had a hot drink, and while the temperature being measured may be "correct" it will not be a clinically relevant temperature.

Temperature is one of many physical values that **drift**; the thermometer may take a few minutes to **stabilize** as it warms up to the patient temperature. At what point should a 'final' reading be taken? And which temperature do you want: mouth, underarm (axilliary), rectal, in-ear, … ? What time of day? They all give different measurements, and there is no 'standard' value of normal body temperature.

Thermometers need to be **calibrated**, so the markings on them correspond to real temperatures (not millimeters!). Calibration highlights the difference between precision and accuracy: **precision** refers to how many numbers can be read off the markings, whereas **accuracy** refers to how well the numbers correspond to the actual temperature being measured.

For example, 37.01 °C, is a precise temperature (we say 'to four figures'), but if the patient is at 36 °C, it is not very accurate. Confusion between precision and accuracy bedevils digital equipment, since it is easy for a digital thermometer (or computer screen) to display something that looks precise like 37.45 °C as if it was accurate, *which it may not be* — only an expensive laboratory thermometer can achieve this sort of accuracy. Unfortunately, adding a digit to a display is much cheaper than making a thermometer more accurate, so high precision displays are rarely more than misleading marketing.

We probably want to measure temperature to within 0.1 °C around 37 °C. Thermistors, which we discuss below, can easily achieve this, though cheap ones are only accurate to around 5%. However, even these can be **calibrated** to measure more accurately — the main reason they are cheap is the manufacturer has not measured their parameters accurately, not that they are intrinsically inaccurate.

It is important to make sure clinical digital thermometers are regularly checked and recalibrated in case they **drift**, for instance caused by batteries ageing. Of course, cheaper thermometers drift more, so they need frequent recalibration. Sensors may also suffer from **contamination**; that is, if they get wet or dirty, the electronics may not be able to measure accurately.

Thermistors

Many thermometers use a **thermistor** to convert temperature to an electrical value that can be measured and displayed for easy reading. Thermistors are robust and reliable, and they come in many varieties. They have many uses, from handheld thermometers to thermometers on pulmonary artery catheters.

A resistor is a simple electrical device that satisfies **Ohm's Law** over its operating range. If a current flows through a resistor, the voltage measured across the resistor is proportional to the resistance. Hence, $V = IR$, for voltage in volts, current in amps (usually denoted I, not A), and resistance in ohms. Current in a resistor creates heat, which will change the resistance — in particular, too much current will burn a resistor out (which is the principle behind fuses, which are *intended* to burn out when current reaches a preset limit). Usually, one would choose resistors that have stable resistance over the range of intended

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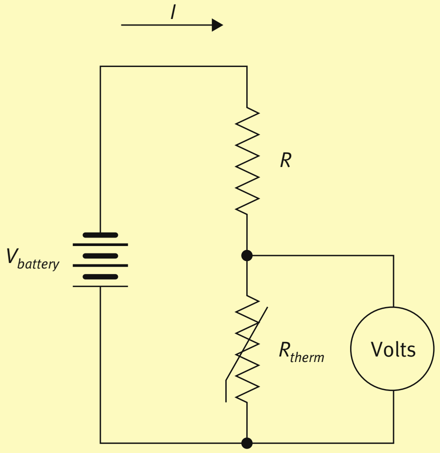
Potential divider used to measure thermistor resistance



Ohm's Law relates voltage V, resistance R and current I. Ohm's Law can be expressed equivalently as $V = IR$, $I = V/R$ or $R = V/I$, when they are measured in units of volts, ohms, and amps. Referring to the circuit (left), the battery voltage is $V_{battery}$ so the current flowing, I, through the two resistors, is given by using $I = V/R$ thus:

$$I = \frac{V_{battery}}{R + R_{therm}}$$

Using Ohm's Law again, the voltage V measured by meter is given by using $V = IR$ thus:

$$I \times R_{therm} = \frac{V_{battery}}{R + R_{therm}} \times R_{therm}$$

Rearranging:

$$R_{therm} = \frac{VR}{V_{battery} - V}$$

Figure 1 The thermistor resistance can be worked out by measuring the voltage in this simple circuit, which is called a potential divider because it divides the battery voltage depending on the two resistors.

temperatures, but a thermistor is *intended* to change resistance with temperature. A thermistor therefore converts temperature to a measurable electrical value.

With a mercury thermometer you just convert distance (say, mm) to temperature (say, degrees C). With a thermistor you convert resistance (ohms) to temperature, but thermistors are more complicated because their resistance does not vary linearly with temperature. The Steinhart—Hart equation is used to do the conversion, but it is complex and relies on manufacturer's data to use. Despite the complexity of the equation, it is still only an **approximation**.

Because the equation is complex, thermometers use a computer chip to do the calculation. Useful features like displaying the average or maximum value are then easy to provide by programming the computer appropriately.

Resistance measurement

Resistance itself is measured indirectly, usually by measuring voltage. The circuit shown in Figure 1 uses a **potential divider** to provide a voltage that depends on a thermistor's resistance. The meter measures the voltage drop across the thermistor, and

Wheatstone Bridge to measure resistance — two ways to draw the same circuit

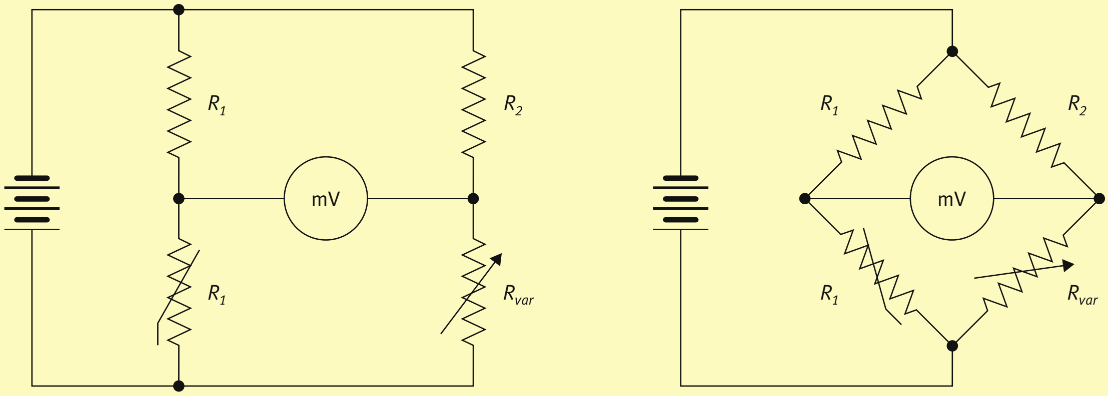


Figure 2 R_1 and the thermistor make one potential divider; R_2 and the reference resistor, R_{var}, make the other potential divider. If $R_1 = R_2$, the meter measures zero when R_{var} equals the thermistor resistance. The problem has changed from measuring *absolute* voltage (which needs calibrating) to measuring voltage *differences* (which is easier), and the voltage of the battery no longer matters — as long as it's not zero! Note R_{var} can be controlled by a computer so this circuit can measure resistance digitally.