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# The Sensor Cube Revisited

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Today, not only information processing but also information acquisition plays a crucial role in the modern information society. Acquisition of information is based on transducers and, therefore, a systematic search for suitable transducers and transducer principles was initiated several decades ago. The result is a wealth of new knowledge, making it rather difficult for scientists and engineers to acquire the needed overview. To bring some order in the field, a general science of transducers has evolved with its main objectives to compile, systemize and unify knowledge of transducers and transducing principles. One of the first endeavours yielded the so-called "sensor cube," an updated version of which is the subject of this paper.

## 1. Introduction

To understand the principles that led to the sensor cube, let us first consider the concept of information and information transfer.

Mankind's needs can be divided into three groups. The first group (Fig. 1) is related to its need for matter (rice, cement, silicon, etc.), the second group is related to its need for energy (mechanical, thermal or electrical energy), and the third group is related to its need for information (knowledge about sensors, the political situation or stockmarket prices, for example). Although at first sight the three groups seem equivalent, in practice this is not the case. When information is transmitted from a source to a receiver, the information at the receiver's side increases without a corresponding decrease in information at the source's side. Unfortunately this does not apply to matter and energy. Consequently,

| Needs of Mankind | |
|---|---|
| **Needs** | **Units** |
| Matter | kilogram |
| Energy | joule |
| Information | bit |

Fig. 1. The needs of mankind

mankind is much more generous in giving away information than in giving away matter or energy.[1] Another interesting feature of information is the hypothesis, already implicitly stated by Wiener[2] and Brillouin,[3] that information transport must be accompanied by the transport of matter or energy. This hypothesis, which is certainly not supported by fortune-tellers or people with supernatural gifts, states that when a wall impenetrable to matter or energy is positioned between a source and a receiver no information exchange is possible. Furthermore, it is wise to call to mind the definition of information as given in the *IEEE Standard Dictionary of Electrical and Electronics Terms.*[4] According to this dictionary, information is:

"the meaning assigned to data by known conventions."

Without conventions data cannot have a meaning; and the hand gestures in Fig. 2 do not mean anything without conventions. It is also possible that the gestures do not mean the same thing in different countries, as conventions can differ from country to country.

Finally the systems used for information processing merit some attention. Such a system is like a triptych, which consists of three sections (Fig. 3). The first section is labelled "input transducer" by scientists and is labelled "sensor" by people who earn their living selling these devices. In the input transducer the form of the input signal is changed from, for instance, a thermal to an electrical signal. In the second section, called a processor, the signal is processed without changing the form of the signal. The signal again changes its form in the "output transducer." Such an output transducer could be a display in which an electrical signal is changed into an optical signal.

To design efficient input and output transducers, good knowledge of the immense number of physical and chemical effects in the solid-state is required.[5] It was therefore logical that a general science of transducers evolved, culminating in the construction of a so-called "sensor cube" containing all transducers or effects.[6]

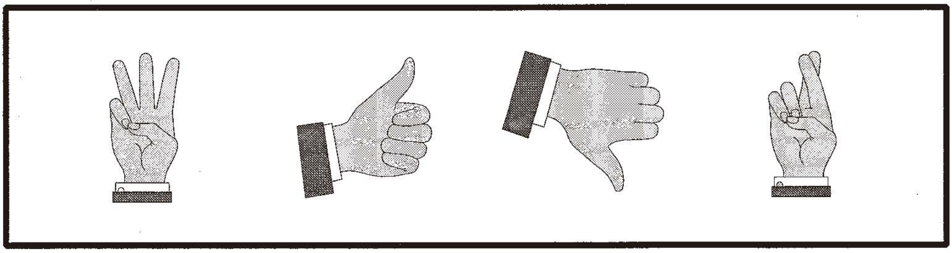

Fig. 2. Hand gestures only represent information if conventions exist and are known to the source and the receiver.

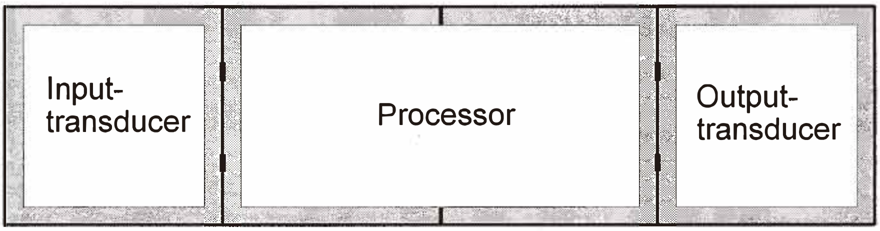


Fig. 3. Triptych representing an information processing system.

## 2. Information Transduction in Transducers

From a theoretical point of view, the process of information transduction in a transducer can be seen as a coupling between the states of two systems.(7,8) If the states of both systems are described by a set of variables, then these variables are said to represent their information content. When a change in state of one system affects the state of the other system (i.e., there is no impenetrable wall), then we say that both systems are coupled and that this coupling enables information exchange between the two systems. The coupling causes a functional relationship between the variables, allowing the information, modulated on the variables according to certain conventions, to be transduced into different physical domains. To achieve an efficient classification of all the coupling effects, it is useful to examine with which variables a system can be described. We distinguish two types of variables:

1. Extensive variables such as: mass, charge, strain and polarization.
2. Intensive variables such as: potential, stress, temperature and field.

Each extensive variable has its corresponding intensive variable, and their product represents the energy stored in the material. Furthermore, we can distinguish generalized forces which are defined as the gradients of the intensive variables, and we can define generalized currents which are related to the time derivatives of the extensive variables.

The products of the two represent the energy irreversibly dissipated in the material.

Considering the products of matching intensive and extensive variables, six energy domains can be defined.[9]

1. Radiant energy domain: electrical and magnetic field times polarization in vacuum
2. Mechanical energy domain: stress times strain
3. Thermal energy domain: temperature times entropy
4. Electrical energy domain: electrical field times polarization in matter
5. Magnetic energy domain: magnetic field times polarization in matter
6. Chemical energy domain: chemical potential times mass.

These six energy domains do not fully represent all possibilities. For instance, nuclear binding energy is not mentioned, since it seems rather improbable that this energy can lead to widely used transducers.

Using the six energy or signal domains, an information processing system can generally be represented by Fig. 4. As an example, an electronic thermometer with an LCD display is depicted. In the input transducer the analog thermal signal is transduced into an analog electrical signal. In the processor the electrical signal is amplified and converted into a digital electrical signal. In the output transducer the digital electrical signal is converted into a radiant signal, which can be perceived by the human eye.

The introduction of planar silicon technology several decades ago made it possible to manufacture electronic components with a very high performance/price ratio. Therefore, to take advantage of these new components today, the electrical domain is preferred for the central processor. Consequently, this means that in the input transducer, a nonelectrical signal must be transduced into an electrical signal and in the output transducer, an electrical

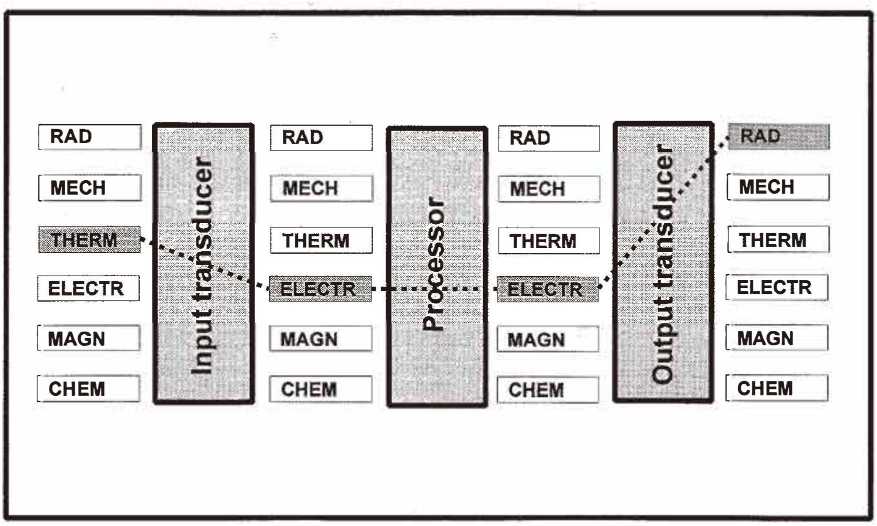


Fig. 4. An information system based on the six signal domains. The dashed lines indicate an electronic thermometer with optical display.

signal into a nonelectrical one.[10]

Reviewing the various effects employed in transducers, it appears that some effects can be used to make transducers that do not require auxiliary energy sources for signal conversion, while others only yield useful transducers when energy is supplied in some form. The first group of transducers is referred to as "self-generating transducers," examples of which are the solar cell based on the photovoltaic effect and the thermocouple based on the Seebeck effect.

The second group of transducers is called "modulating transducers." In such transducers, an energy flow supplied by an energy source is modulated by the variable to be measured. Examples are a pressure sensor based on the piezoresistive effect and a photo detector based on the photoconductive effect. Transducers can be depicted as small boxes as in Fig. 5. The input energy is represented by the arrow at the left and the output by the arrow at the right. In the case of a self-generating transducer, the signal is modulated on the incoming energy flow (Fig. 5a), whereas in the case of a modulating transducer, the input signal is represented by the vertical arrow (Fig. 5b).

## 3. The Transducer Cube

Using the boxes as defined above, a large cube can be constructed containing all physical and chemical transducers or effects. The cube is presented in Fig. 6. The cube

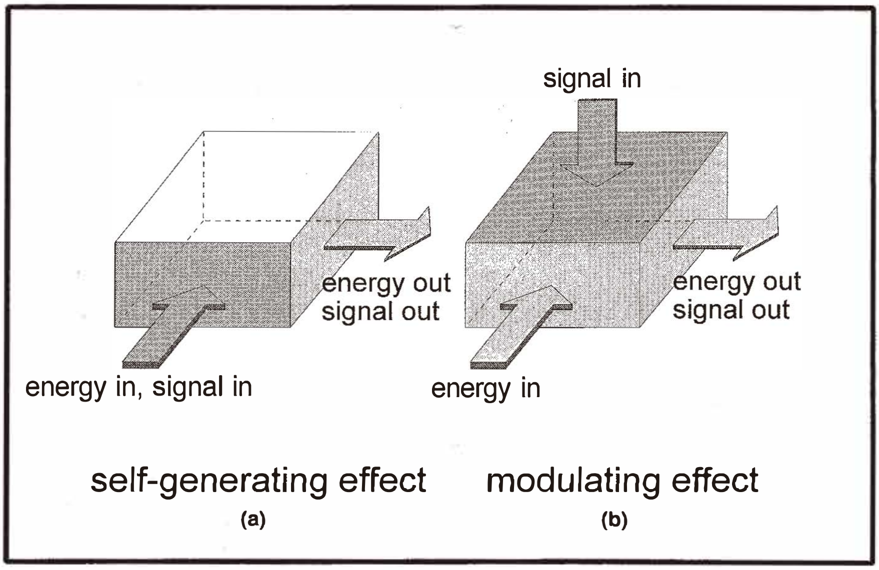


Fig. 5. (a) Self-generating and (b) modulating transducer.

consists of layers of transducers. The bottom layer contains all self-generating transducers. The six signal domains are indicated by six arbitrarily chosen colors, which are indicated in the figure. The bottom layer contains all transducers in which the signal to be transduced is modulated on the input energy flow. The upper side is white as no modulating input signals are present. The bottom layer also contains six processors (radiant to radiant, mechanical to mechanical, thermal to thermal, electrical to electrical, magnetic to magnetic and chemical to chemical). The electrical to electrical processor may, for instance, consist of an electrical resistor or a diode.

All other planes contain the modulating transducers. The color of the upper side of the boxes represents the modulating input signal. The topmost layer, for example, contains all

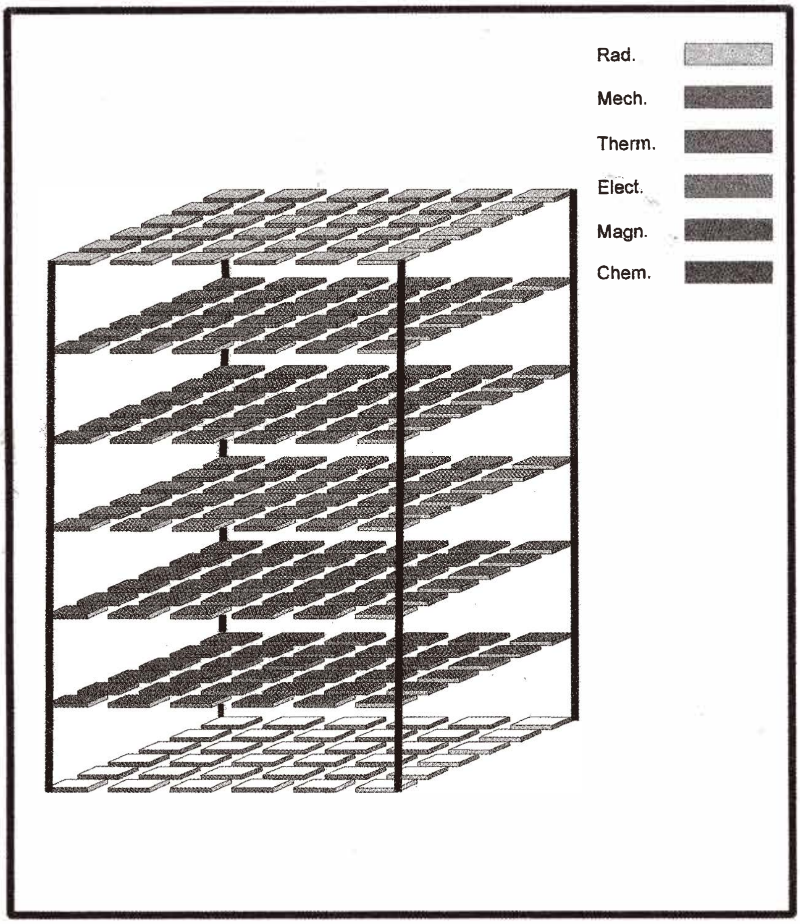


Fig. 6. The Transducer Cube.

boxes that represent modulating transducers with a radiant input signal. The layer also contains a processor, namely, the box in which a radiant flow is modulated by another radiant input signal. All layers contain 36 – 1 modulating transducers and one processor. The layer with an electrical input signal contains an electrical processor which can also act as a transistor. In such a device, a flow of electrical energy is modulated by another electrical signal. In summary, we find that we have a cube that consists of $7 \times 36 = 252$ boxes of which $36 - 6 = 30$ represent self-generating transducers and $216 - 6 = 210$ represent modulating transducers. Of the 252 boxes, only 2 represent the burgeoning field of electrical processors. As we observe, this does not reflect the economic activity in the transducer and processor field. In earlier publications, the cube was referred to as "the sensor cube."[6] At that time, input transducers received practically all attention. At present, output transducers, like actuators and displays, also stand in the limelight, as many novel devices can be fabricated of silicon. Therefore, it is better to henceforth call the cube "the transducer cube." The cube contains many boxes that do not represent a transducer in which an electrical input or output signal occurs. Yet it is very useful also to consider these boxes, as many transducers, in practice, consist of two transducers in tandem. In a colorimeter, for example, the color of a fluid is a measure from the concentration of metal ions in solution. To measure this concentration, the chemical input signal (metal ion concentration) is first transduced into a nonelectrical signal, namely a radiant signal (color). This color is subsequently measured using a light beam incident on a photo detector, in which the light intensity is transduced into an electrical signal. Many examples of tandem transducers exist, as tandem transducers are often much easier to realize than single-effect transducers.

The transducer cube contains all known transducers or physical and chemical effects. It is not too difficult to find the boxes that match a certain effect or transducer. For instance, the piezoresistive effect is represented by a box in which a flow of electrical energy is modulated by a mechanical signal. The PEM (photo-electromagnetic) effect is represented by a box in which the conversion of a radiant energy into an electrical energy flow is modulated by a magnetic field.[11]

Things become more difficult when an arbitrary box is chosen and one tries to find the matching effect or transducer. Many boxes do not represent well-known transducers. To understand the transducer field, it might be revealing to find as many boxes as possible that match an effect. We expect that this activity may even yield a few interesting transducers which, until now, have not been very well known.

## 4. Conclusions

All transducers and all physical and chemical effects can be represented by boxes that together form the so-called transducer cube. This cube provides an overview of the interesting field of transducers for information processing systems. A careful study may even lead to the invention of new transducers.

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