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Information and its carriers

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Information plays an important role in our natural and technological environment. In this article the authors show how the concept of information can play a major role in the structure of a middle or high school physics course. With the help of the concept of 'information carrier', this course represents an extension of an analogously-structured course for beginners based upon the concepts 'energy and energy carrier' introduced in a previous article, 'Energy and its carriers' (1982, *Physics Education* **17** 212).

The quantity 'information' as introduced by C Shannon (1949) is:

$$H = -f \sum_{i=1}^{N} p_i \cdot \ln p_i. \qquad (1)$$

where H is a measure of the amount of information which an information source emits with each symbol. The sum extends over the total number N of distinguishable symbols available from the source. p_i is the probability that symbol i will be generated and f is a constant of proportionality. H is usually measured in bits where the term 'bit' is shorthand for 'binary digit' in data processing. In this case the value of f is bit/ln 2.

Just as the energy course mentioned above permits the treatment of various branches of physics (mechanics, electricity, thermodynamics) and even chemistry according to the same rules governing the flow of energy and its carriers (Falk *et al* 1983, Schmid 1984), the information course introduced here permits the treatment of various other branches of physics (acoustics, optics) as well as hi-fi, video and computer technology according to the same rules governing the flow of information and its carriers. These subjects are presented as lecture units in the latter part of this course. Because the importance of the three technologies mentioned continues to increase in our everyday life, we feel it is necessary that they become part of a modern physics course.

On the basis of the concept introduced here, the subject of information can be taught at several different levels. However, to be specific, we discuss the application of the course to 13- or 14-year-old pupils.

Before we introduce the course itself, we would like to point out an important didactic aspect: we choose to call Shannon's measure of information H 'amount of data'. We do this because Shannon's quantity H is independent of the contents of a message, and, in particular, independent of whether or not a message is important to the receiver. However, experience of the everyday use of the word 'information' shows that the meaning of this word includes the following connotation: the more important a message is to the receiver, the more 'information' this message contains. On the other hand, we believe the word 'data', as opposed to the word 'information', is less susceptible to this connotation. Furthermore, the word 'data' has also become part of our everyday vocabulary, as is shown by the familiar words 'data line', 'data carrier', 'data flow' etc. (For the same reason, incidentally, the word 'data' has already been used by Schopenhauer to express the data flow from our sensory organs to our brains.)

We will now describe first the simplest structure of a data transmission—source, carrier and

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receiver—which can be understood without recourse to a strict definition of the quantity transported and without a detailed description of how to measure it. We will then introduce a quantitative measure for the amount of data, followed by some quantitative examples of data transmission processes and the introduction of the concept of data current. Finally we discuss data containers.

The structure of data transmission

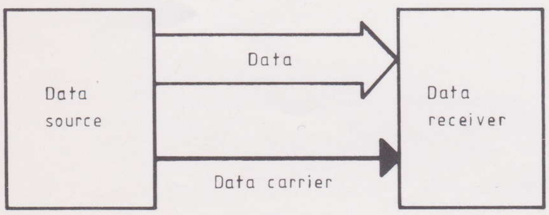
Let us take as an example a typical house. Several different cables, pipes and openings connect the inside of a house with the outer environment: some of these channels transmit *energy* (*via* a definite energy carrier) into the house—for example electric cables, gas pipes and hot water pipes. On the other hand, telephone lines and cables from the radio or TV antenna on the roof serve another purpose: thanks to these channels, one has access to sounds and pictures. These channels transmit *data* into the house from the external world.

What is true of energy transmission is also true of data transmission: data transmission is always accompanied by a *data carrier*. In the examples just considered the data carrier is electricity. Other examples of data carriers are sound, light and other electromagnetic radiation.

Just as for descriptions of energy transmission, the concepts of source and receiver are useful when describing data transmission. With every data transmission, a *data source*, a data carrier and a *data receiver* are involved. The carrier brings data from the source to the receiver. It is reasonable to represent data transmission graphically in terms of *data-flow diagrams* (see figure 1) (analogous to energy-flow diagrams for energy transmission). Figure 2 gives three examples.

Another useful concept for the description of energy transport is that of *energy transceiver*, wherein energy is changed from being transported by one carrier to another. During its transport, data also commonly changes carrier. For example, in a microphone, data are changed from being transported by the carrier, sound, to the carrier, electricity (figure 3a). The reverse of this exchange of data carriers takes place in a loudspeaker (figure

Figure 1 General data-flow diagram



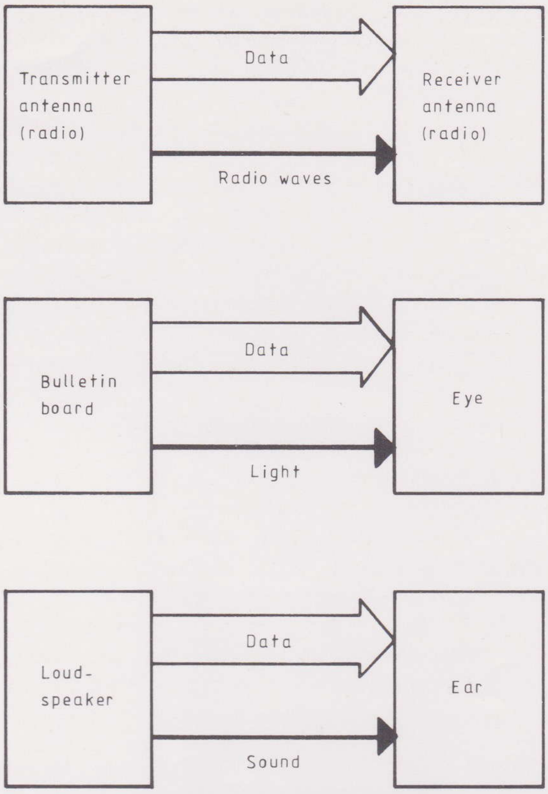


Figure 2 Data-flow diagrams for several examples

3b). Accordingly, we call a device where data are exchanged from one carrier to another a *data transceiver* (figure 3c).

Just as for energy transceivers, data transceivers can be connected up in series according to the 'domino' rules. In this way, data transmission involving complicated chains of data transceivers can be easily represented. Figure 4 shows the chain of data transceivers involved in the transmission of data *via* television. The concepts of energy and data transceivers are quite useful, because many technical devices found in a pupil's everyday world fall into one or other of these categories. Table 1 gives examples of several common energy and data transceivers.

Shannon's measure of information

The next item to be introduced in the course is a quantitative measure of the amount of data, in a beginner's version. Instead of the general relation given in equation (1), only the special case of equally probable symbols is treated. Furthermore, the introduction proceeds in such a way that the concept of logarithm does not explicitly appear.

First, examples of data transmission are investigated in which the source emits one of only two

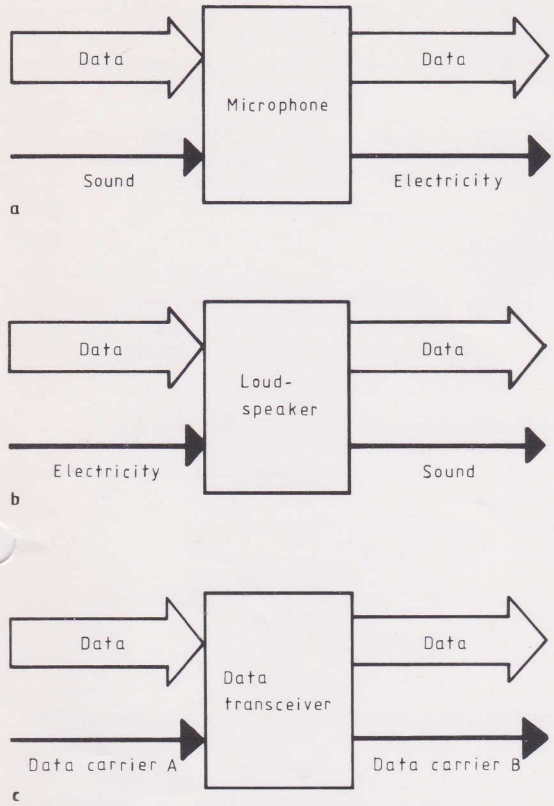


Figure 3 **a** The microphone as a data transceiver; **b** the loudspeaker as a data transceiver; and **c** general data transceiver diagram

different symbols. In such cases, the data source can send the receiver exactly one yes–no decision. In other words, a previously agreed-upon question which allows only one of two possible replies can be answered by the transmission of one symbol.

In the classroom we illustrate this kind of data transmission by the example of two children who send messages back and forth between their houses at night with the help of red and green flashlights which they can shine from one bedroom window to the other. Several different situations are described to the pupils in which a previously agreed-upon question can be answered with either a 'yes' (green light) or a 'no' (red light). [It is important to this demonstration that the actual content of the question plays *no* role in the transmission of the answer.] The data transmission always takes place in the same way: either a green or a red light is sent from one of the windows. Because the process of data transmission is the same in each case, independent of the content of the question understood, the amount of data in each transmitted answer is always the same.

On the basis of these special examples of data transmission, the *bit*—the unit of measure for the quantity 'amount of data'— is defined as follows: *the amount of data per symbol transmitted by a source with only two different symbols at its disposal is 1 bit.*

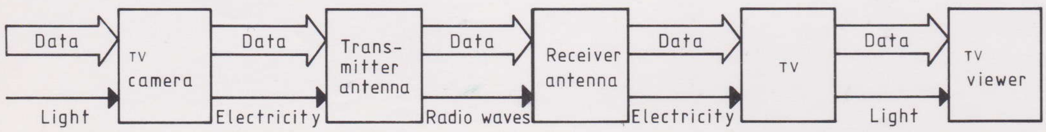
Accordingly, in the above example with the two children, the receiver of each 'yes–no' reply gets one bit. Obviously, a source which has only one symbol at its disposal and which, accordingly, can send only one kind of symbol (say a single continuous tone or light) is useless for data transmission. (Note: Including the possibility of turning such a source off and on again would, of course, be useful for data transmission. However, this would then introduce two symbols—'source on' and 'source off'.)

The way in which more than one bit can be transmitted with a single 'yes–no' source is obvious: several yes–no replies are sent, one after another, to several different previously agreed-upon questions: with two successive replies, the receiver has been given two bits, with three successive replies, three bits etc. This illustrates the additive nature of the amount of data.

The next point of discussion is that questions having more than two answers can be answered with a series of yes–no (or green–red) responses. The introduction of a 'decision tree' (figure 5) is helpful to close this discussion. It can be recognised from the decision tree that a question with four possible replies can be answered with a series of two one-bit decisions: in answering such a question, the receiver is given two bits with each reply.

Instead of a data source which has only two different symbols, e.g. green and red light, at its disposal, we may have a data source employing four different symbols—say, red, green, blue and yellow light. In this case, a question with four possible replies can be answered with a single

Figure 4 Chain of data transceivers



symbol. Thus a data source with four different symbols at its disposal sends a receiver two bits per symbol.

The step-wise expansion of the decision tree of figure 5 finally leads to table 2. This table discloses how the amount of data per symbol depends upon the number of different symbols at the disposal of the data source: *the amount of data per symbol emitted by a data source with* $N = 2^n$ *different symbols at its disposals is* n *bits*.

In order to specify the exact amount of data per symbol of a data source with M different symbols at its disposal where M cannot be expressed in the form $M = 2^n$, n = integer, one needs the concept of logarithm. But the pupils we taught in this course had not yet learned about logarithms. Therefore, we approximated the amount of data per symbol for such a source as mentioned above. For example, for a source with $M = 26$ symbols at its disposal (this corresponds to the number of letters in the English alphabet), we find

$$2^4 = 16 < 26 < 32 = 2^5.$$

Accordingly, the amount of data per letter sent or received lies between 4 and 5 bits, assuming that the appearance of each letter in the English alphabet is equally probable in a message. A similar approximation for the amount of data per symbol (dot, dash and blank) in a morse code message lies between 1 and 2 bits whereas the amount of data per character of the Chinese 'alphabet' (with about 2000 different characters) is just about 11 bits.

If the pupils have learned about logarithms they can calculate the exact amount of data: *the amount of data per symbol emitted by a data source with* N *symbols at its disposal is* $\log_2 N$ *bit*.

Data flow

In order that different means of data transmission can be compared quantitatively with one another, it is useful to introduce the concept of *data current* in addition to the concept of amount of data. The pupils already know from their everyday experience and the previous course on energy that a current is a measure of how much of a substance, say, water, electricity or energy flows across a specified boundary in a certain period of time. The same is true for the concept of data current:

$$\textit{data current} = (\textit{amount of data})/(\textit{time interval}).$$

Accordingly, the quantity *data current* can be measured in bit s^{-1}. For short, we introduce the symbols H and I_H for the quantities amount of data and data current, respectively. Then the above equation becomes

$$I_H = \Delta H/\Delta t.$$

Table 3 lists the data currents of several different data transmission processes. Several of the given examples can be calculated in class by the pupils themselves, others are simply mentioned. It is interesting to note that a very much smaller data current is necessary for the transmission of sound than for the transmission of pictures. This is illustrated by a comparison of radio and television transmissions as well as by a comparison between the channels for data transmission between ear and brain and between eye and brain: the data current

Figure 5 Decision tree

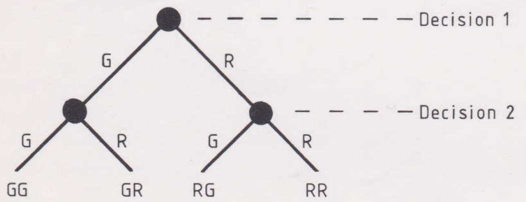


Table 1 Energy and data transceivers

Type	*Example*
Energy transceiver	Generator, light bulb, electric motor, compressor, solar cell, water turbine, radiator, ventilator, gasoline motor, light wheel, solar collector, steam engine, electric oven
Data transceiver	Microphone, transmitter antenna, receiver antenna, eye, ear, loud speaker, television, light emitting diode, photo diode, radio, magnetic pick-up, bulletin board, siren

Table 2 Amount of data per symbol associated with the number of different symbols at the disposal of the data source

Number of different symbols	*Amount of data per symbol (bit)*
$2 = 2^1$	1
$4 = 2^2$	2
$8 = 2^3$	3
$16 = 2^4$	4

Table 3 Comparison of different data currents

Type of data transfer	*Data current (kbit s^{-1})*
Morse code	~ 0.003
Teletype	~ 0.04
Telephone	~ 64
Radio	~ 10^2
Television	~ 10^5
Nerves:	
ear–brain	~100
eye–brain	~ 10^5

Table 4 Common data container

Data container	*Write device*	*Read device*
Video tape	Video recorder	Video recorder
Magnetic tape	Tape recorder	Tape recorder
Film	Movie camera	Movie projector
Book	Printing press	Person
Slide	Camera	Slide projector
Record	Record press	Record player
Floppy disc	Floppy disc I/O device	Floppy disc I/O device

strengths in the optical cases are roughly a factor of 10^3 larger than in the auditory cases.

Data containers

There is a large number of devices which obviously have something to do with data but which are not simply data sources, data receivers or data transceivers. Such devices are used to store sounds, pictures etc. We call that part of such a device where the data is stored a *data container*.

We distinguish between the actual data container and the peripheral equipment which is necessary to store data in the container or to retrieve data from it. With some data containers, the same device can be used to 'read' and 'write' data; with others the latter functions are carried out with other equipment. Several common data containers are listed in table 4, together with the corresponding read- or write-equipment.

Our classroom experience has shown that pupils are already familiar with numerous other examples of data containers: books; the human brain; the memory of a computer; punched cards and punched tapes; and the spiked drum inside a music box or player piano. We also discuss in class the difference between pure read containers and read–write containers. It is pointed out that this difference is not one of principle, because the user himself often decides whether or not a given data container is to be operated as a pure read or read–write container. Records, slides, books, the drum in a music box and computer read-only memories are examples of pure read containers. Magnetic tapes, video tapes, floppy disks and random-access memories are examples of read–write containers. For several common data containers, the maximum data content (in bits) is given, estimated or calculated in class.

Summary

The way in which the concept of information can be used to structure a physics course has been shown. The structure of this course is similar to that of an earlier physics course based upon the concept of energy. The physical basis for the similarity between these courses has been discussed. It has been pointed out that, just as the energy course permits the treatment of different branches of physics according to the same rules which govern the flow of energy and its carriers, the information course permits the treatment of various other branches of physics according to the same rules which govern the flow of information and its carriers. For example, as mentioned in the introduction, later units in this course include *optics* (information carrier = 'light'), *acoustics* (information carrier = 'sound'), *computers* or *data reduction* (under the heading of 'data reducing machines') and data technology (dealing with everyday devices like hi-fis or videosets, where the close relationship between data transport and energy transport is especially obvious).

The simplest kind of information flow has been described with the help of the concepts data, data carrier, data source, data receiver, data transceiver and data container. In particular, the method of measuring the bit has been demonstrated—the amount of data has been introduced in the classroom and quantitative examples of data transmission processes have been investigated with the help of the concept of data current.

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Physics teaching symposium

An international symposium on physics teaching will be held in Brussels on 11–13 November 1985. The emphasis will be on the transition from school to university level, teacher education and physics for non-physicists, and there will be keynote addresses by I Prigogine, G Marx and M Hulin.

Further details can be obtained from Professor A Art, Chairman of the Organising Committee, Faculté des Sciences CP 234, Université Libre de Bruxelles, B-1050 Bruxelles, Belgium.