Physical Relationships among Matter, Energy and Information

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"Information is the difference that makes a difference."
Gregory Bateson

Abstract

General systems theorists often refer to matter, energy and information as fundamental categories. The three concepts – matter, energy and information – are related through scientific laws. Matter and energy relations are more thoroughly understood than relations involving information. At the level of data or signal "difference" is suggested as a more elementary term than "information."

1 Basic Entities and the Relationships among Them

At least two previous civilizations ventured to define the basic building blocks of the universe. The ancient Greeks believed that the constituents of the universe were earth, air, fire, and water. [Aristotle, 1952] The Chinese believed that the basic elements were metal, wood, water, fire, and earth. [Gao, 1985] Currently physicists emphasize space and time. General systems theorists often speak of matter, energy, and information as fundamental categories. For example James G. Miller's [1978] living systems theory is based on the idea that cells, organs, organisms, groups, corporations, nations, and supranational organizations all process matter, energy, and information. In biological systems (e.g., cells, organs, and organisms) matter and energy are so closely related that they are often treated as one entity – matter/energy. A social organization such as a corporation processes matter (e.g., by transforming raw materials into finished products), energy (including the fuel and electricity needed to operate machines and heat buildings), and information (e.g., customer orders, advertising messages, and accounting records).

Although matter and energy have been the subject of scientific investigation for several hundred years, a scientific conception of information is relatively new. A variety of definitions of information have been proposed. Shannon [1949] defined information as a reduction of uncertainty. Bateson [1972] defined information as "that which changes us" or "the difference that makes a difference." A crucial point is that information, unlike matter and energy, is a function of the observer. [von Foerster, 1974] For example, the same message may have different meanings for different people. Although information requires the perception of a difference, the difference will require a matter or energy carrier (e.g., a page in a book or sound waves in air). In addition, cognition requires a nervous system.

In 1967 at a panel discussion at the University of Illinois I heard Ross Ashby mention Bremermann's limit. Bremermann's limit states a relationship between matter and information. A relationship between matter and energy had been proposed by Einstein [1905]. A connection between energy and information had been described by Szilard [1929]. With a connection established between matter and information, it appeared that the contributions of Einstein, Szilard, and Bremermann imply that matter, energy, and information, on the level of atoms, are related. See Figure 1.

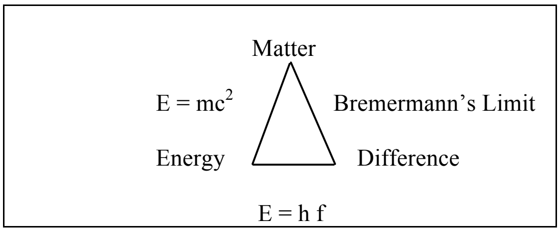

Figure 1. A triangle of relationships

How are these basic categories -- matter, energy, and information -- related? Einstein [1905] presented a relationship between matter and energy: $E = mc^2$. Indeed, physicists now regard matter as another form of energy.

Around 1900 Planck [1949] observed that electromagnetic energy is not emitted over a continuous range but rather in bundles or quanta, the energies of which are proportional to the frequency of the radiation. The expression $E = h f$ means that the energy of a photon is proportional to its frequency. The constant h is called Planck's constant. Planck's constant also appears in the equation that defines the uncertainty in observing subatomic particles. The uncertainty principle formulated by Heisenberg [1930] states that an experiment cannot be devised which simultaneously fixes the momentum and the position of a particle with unlimited precision, but only within a momentum-position range where Planck's constant defines the limit of how precise an experiment can be. Hence, $h \leq Dm\ Dp$.

Szilard [1929] showed that there is a relationship between information and energy. Szilard recognized that Maxwell's demon would require information in order to sort high and low energy particles. He demonstrated that the act of measuring the velocity of gas molecules would produce more entropy than the sorting process would remove.

Bremermann [1962, 1965] suggested that there is an upper bound on the rate at which symbols can be processed by matter. They can be processed at speeds not exceeding Bremermann's limit of 10^{47} bits/gram/sec. Bremermann's limit is derived from the equations $E = mc^2$ and $E = hf$, when one photon is considered equivalent to one bit. [Ashby, 1968] That is, combining the relationship between matter and energy with a relationship between energy and information yields a new relationship between matter and information, at least at the atomic level. Ashby used Bremermann's limit in pointing out the dramatic physical impossibility of some pattern recognition strategies used in the early days of artificial intelligence. He urged more attention to how the human brain functions.

If we consider all the possible carriers of information, it is clear that the relationship between matter and signal is not continuous. The relationship depends on the material in which a pattern appears. That is, a pattern or set of differences can be observed at the atomic level (where Bremermann's limit applies), in molecules (DNA), cells (neurons), organs (the brain), groups (norms), and society (culture).

2 From "Information" to "Difference"

An early formulation of the ideas in this paper used the term "information." [Umpleby, 1975] Indeed the works of Szilard and Bremermann also use the term "information." But because of the complexities introduced by having to specify one or more observers, the term "information" is not an elementary concept. "Difference" denotes the elementary building block of data or signal or information. Hence, when dealing with physical foundations, I believe it is preferable to speak in terms of matter, energy and difference. To define terms, a "difference" is a physical entity that can be noted by an observer. Drawing a "distinction" is a purposeful act that creates two categories.

Scientists today understand phenomena related to matter and energy more thoroughly than phenomena related to information. Perhaps reflecting on the physical relationships among matter, energy and information can help natural scientists and social scientists understand better the nature of their disciplines. Efforts to apply the methods of the natural sciences to social systems have led some people to conclude that matter and energy relationships are the appropriate subjects of attention for social scientists. However, in social systems, distinctions are essential. Bateson [1972] made this point as follows:

> (my colleagues in the behavioral sciences) have tried to build the bridge to the wrong half of the ancient dichotomy between form and substance. The conservative laws for energy and matter concern substance rather than form. But mental process, ideas, communication, organization, differentiation, pattern, and so on, are matters of form rather than substance. Within the body of fundamentals, that half which deals with form has been dramatically enriched in the last thirty years by the discoveries of cybernetics and systems theory.

3 Conclusion

As civilization has progressed from agricultural societies to industrial societies to post-industrial societies, there has been a shift of attention from matter to energy to information. No doubt our scientific knowledge of information will improve as information societies continue to develop. This article points out that signals, distinctions, data, information, and communication depend upon matter and energy and that a physical difference is a more elementary phenomenon than information. Moreover, the triangle in Figure 1 is consistent with the idea that observers and the distinctions they make are the means whereby the substance of the universe becomes aware of itself.

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References

[Aristotle, 1952] Aristotle. Physics, Book II, Chapter l, *The Great Books.* Chicago: Encyclopedia Britannica, 1952.

[Ashby, 1968] W. Ross Ashby. Some Consequences of Bremermann's Limit for Information-processing Systems, in Hans Oestreicher and Darrell Moore (eds.), *Cybernetic Problems in Bionics*. New York: Gordon and Breach, 1968, pp. 69-79. Reprinted in R.C. Conant (ed.). *Mechanisms of Intelligence: Ross Ashby's Writings on Cybernetics.* Intersystems Publishers, 1981.

[Bateson, 1972] Gregory Bateson. *Steps to an Ecology of Mind.* New York: Ballantine, 1972, pp. xxv-xxvi.

[Bremermann, 1962] Hans J. Bremermann. Optimization through Evolution and Re-combination, in M.C. Yovits, G.T. Jacobi and G.D. Goldstein (eds.). *Self-organizing Systems.* Washington, DC: Spartan Books, 1962, pp. 93-106.

[Bremermann, 1965] Hans J. Bremermann. Quantum Noise and Information. *Fifth Berkeley Symposium on Mathematical Statistics and Probability.* Berkeley, CA: University of California Press, 1965.

[Einstein, 1905] Albert Einstein. Ist die Tragheit eines Korpers von seinem Energieinhalt abhangig? *Annalen der Physik*. See also Lincoln Barnett, *The Universe and Dr. Einstein*, 2nd revised edition. New York: W. Sloane Associates, 1950.

[Gao, 1985] M. Gao. *Monkey's Conversion*. Beijing: Foreign Languages Press, 1985.

[Heisenberg, 1930] Werner Heisenberg. *The Physical Principles of Quantum Theory*. New York: Dover Publications, 1930.

[Miller, 1978] James G. Miller. *Living Systems.* New York: McGraw-Hill, 1978.

[Planck, 1949] Max Planck. *Scientific Autobiography and Other Papers* (English translation). New York: Greenwood Press, 1949.

[Shannon and Weaver, 1949] Claude Shannon and Warren Weaver. *The Mathematical Theory of Communication*. Urbana, IL: University of Illinois Press, 1949.

[Szilard, 1929] Leo Szilard. Uber die Entropieverminderung in einem thermodynamischen System bei Eingriffen intelligenter Wesen. *Zeits. Physik*, 53: 840-856. English translation: On the Decrease of Entropy in a Thermodynamic System by the Intervention of Intelligent Beings. *Behavioral Science*, 9:301-310 (1964). Both versions are reprinted in *The Collected Works of Leo Szilard: Scientific Papers*, Bernard T. Feld and Gertrud Weiss Szilard (eds.). Cambridge, MA: MIT Press, 1972.

[Umpleby, 1975] Stuart Umpleby. *Some Applications of Cybernetics to Social Systems.* PhD Dissertation, University of Illinois at Urbana-Champaign, 1975, pp. 6-10.

[Von Foerster, 1984] Heinz von Foerster. On Constructing a Reality. Originally published in 1974. Reprinted in *Understanding Understanding*. Springer, 2003.