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Information, evolution and "error-friendliness"*

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Shannon's information

Bernhard Hassenstein (eg. 1966) has been puzzled by the concept of information in living systems throughout his scientific life. What is it that leaves from an observed object, (be it a prey or a darling's face or a sequence of black-and-white stripes on a rotting cylinder), arrives at the retina , travels to the brain and elicits motoric or emotional reactions? Is it still the same thing when it arrives at the retina? Can Claude Shannon's (1948) formula of information being the negative logarithm of an event's probability help solve the puzzle? Or does it rather confuse and blur the philosophical question about the nature of the "thing"?

Shannon's co-worker Warren Weaver (1948) seems to have supported the confusion assumption when stating that: "Two messages, one heavily loaded with meaning, and the other pure nonsense, can be equivalent as regards information." Of course, if information is defined the way Shannon and Weaver (and, almost simultaneously, Norbert Wiener) defined it, Weaver's astounding statement is plainly correct. This, however, means that the logarithmic definition of information is completely separated from meaning and will not help answer any semantic puzzle.

The confusion was not exactly removed (we think rather intensified) when Léon Brillouin (1962) tried to solve some of the puzzles left by Shannon and Weaver. He observed, rightly, that information was normally used to *remove* uncertainty and "entropy" while Shannon was using information and entropy essentially interchangeably. Shannon's choice of the letter H (after the Greek capital letter Eta) was an explicit quotation of Ludwig Boltzmann's thermo-dynamic entropy, although he considered it a mere *analogy*. Brillouin went further and said that informational entropy and thermodynamic entropy were identical. He therefore felt that Shannon had taken the wrong sign for information and introduced on his part the new term "negentropy" for information, in line with its function of removing entropy. Everybody (or nearly) was now pleased, and Brillouin's verbal creation made its way into the everyday language of intellectuals.

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But the ”negentropy” concept was erroneous too, as Francis J. Zucker (1974) has demonstrated. The removal of entropy for the creation of information presupposes the existence of a larger amount of entropy in the first place. If there is no entropy, negentropy can't exist either. Shannon was quite right (in a sense) in using the *same* sign for both information and entropy. Zucker's observation is correct but it leads us back to square one ragarding Weaver's ”nonsense-puzzle”.

Novelty and confirmation

Mathematically, this whole debate didn't create any problems because everybody was able to quantify pieces of information using Shannon's formula, regardless of the sign. But philosophically, it's a rather unsatisfactory state of affairs. We suspected (Weizsäcker and Weizsäcker, 1972) that behind the arguments about the sign there might be a basic conceptual deficiency regarding the meaning of information. Essentially, what we finally suggested was that meaningful information, i.e. information as biologists would naturally use and understand the term, cannot be quantified by one single formula, be it entropy or negentropy. Both signs make sense.

We believe that meaningful information will always consist of *two* mutually complementary components, *novelty* and *confirmation*. Novelty relates to entropy, confirmation relates to negentropy. However, while entropy and negentropy by definition are mutually commensurate while novelty and confirmation are not. They cannot be plotted on the same axis. Their mutual relation has a certain resemblance with what in theoretical physics is calles complementarity.

Any novelty has to be embedded in a large envelope of confirmation, otherwise it cannot meet with understanding. The very process of understanding involves the creation of information. But if understanding means any degree of learning on the part of the receiver, it is not confirmation alone: it means adding novelty to the receiver.

”Confirmation” is a more complex, and abstract, concept. It comprises a variety of stabilising factors such as the *canal* through which messages are being transmitted, the *code* or *alphabet*, and, of course, the body of knowledge the receiver possesses and may use to recognise and interpret the incoming message. Without a canal, the receiver is not able to identify a message as a message. And without a code, the receiver cannot decipher the incoming characters or signals.

Shannon, of course, was tacitly assuming the existence both of a canal, of a reliable code and of a large body of receiver knowledge. In the presence of a canal structure, of code reliability, and of pre-existing knowledge, novelty will appear as useful information, — at least if it comes packed in a meaningful message. This is the agreeable situation where common-sense tells us that novelty is information and where mathematically such novelty, or information, can be measured by the logarithmic entropy formula.

Biological systems, however, tend to be of a different nature. Novelty comes in mostly unplanned, scantily coded, full of noise, and through a multitude of imperfect canals. Biologists are not surprised to learn that where novelty grows too large, it is far from being useful and understandable throughout. Some of the novelty may even serve to blur the code (e.g. by the appearance of unknown signs or words) or to endanger the functions of the canal. Such novelty will not be valued as information and may be considered as nonsense or as destructive.

Novelty is closely related to what Shannon called entropy. But now we realise that Shannon was legitimated to call this information entropy (and vice versa) as long as the highly restrictive (”agreeable”) conditions were fulfilled. Using our terminology the agreeable Shannonian conditions can be said to consist of a large and comfortable excess of ”confirmation”. The amount of novelty is zero when everything is known and certain (probability 1) and it grows as matters become uncertain (probabilities below 1). That is the mathematical behaviour also of the negative logarithm of the probability. At probability 0, the negative logarithm is °.

Total novelty, therefore, is mathematically not permitted which is plausible from the ontological point of view.

Confirmation and novelty both may be quite different for different *receivers*, - which is not surprising from the point of view of a common sense understanding of information. It’s ”information as if the receiver mattered”, - to allude to a famous saying by E. F. Schumacher who was after ”economics as if people mattered”. A message can be novel and incomprehensible to a receiver but after twenty repetitions (confirmations) in a similar context may be perfectly understood by the same receiver. This is also what learning experiments with humans and animals consistently show.

Shannon’s formula requires a high degree of confirmation. In fact his formula can only be defined in a rather small range of low values of novelty, near the probability-value 1. This is the situation where *probabilities* can be established for signals or alphabet letters. Probabilities, in turn, are the mathematical basis for entropy measurements. If probabilities for each letter remain constant, the entropy attributed to any particular letter will also remain constant. This is a reasonable assumption for letters of the English alphabet.

On higher semantic levels such as syllables, words, and combinations of words, constant probabilities are no longer be expected. Statistics are impossible at even higher semantic levels: Nobody can establish probabilities of meaningful sentences. There, the degree of novelty is simply too high.

The high degree of ”confirmation” at the low level of letters (or phonems) is very useful also for the deciphering of noise-affected messages. Should the sender have the very unusual intention of introducing a new letter to the alphabet, the receiver will do everything to interpret the new entity as noise that has to be cleared away. The sender has to repeat and emphasise his unusual (novel) intention to make himself understood. He has to wrap his novelty into a lot of confirmation.

The high redundance of the alphabet and, less so, of the word dictionary, is not only useful for correcting noise-caused errors. It serves also as the precondition (the necessary excess confirmation) for communicating novelty at the higher levels of sentences and entire messages, articles, books.

Genetic information

There are striking similarities with this reasoning in the informational properties of the genetic code. You don’t find letters other than A, C, G and T on normal DNA, and you have U for T at the RNA. Rarely, some other letters occur, such as HX. But in the replication process they will be treated as if they were one of the four standard letters. However, at the higher semantic levels of *combinations* of letters, we find all kinds of novelties.

Three letters each are packed together to signify and to lead in the transcription process to the adding of one particular amino acid. That's the famous genetic code. Any alteration at the DNA level can led to a change in the sequence of amino acids. Some redundance (confirmation) is provided against changes: 64 combinations of four DNA letters are available for the coding of essenially 20 amino acids, so that some DNA changes will not lead to changes of the amino acid.

Beyond this rather primitive semantics there are trickier mechanisms, not all well understood. First comes, of course, the composition of proteins with their three-dimensional structures, which depends on the ”manufacturing order”. Different procedures may lead to different structures even if the sequence of amino acids remaines identical. What is more, the *time* pattern of making use of the existing DNA information leads to specific space and time patterns of the manufactured proteins. All this contains a lot of unpredictability, flexibility etc., i.e. novelty.

One mechanism may play a prominent role in the development and use of confirmation and novelty. It is the sheer replication of strands of DNA. The doubling (confirmation) of one strand later allows one of the two to ”experiment” with unusual (novel) sequences on one strand while the other remains unaffected and can be relied upon if the experiment fails.

Information as if the receiver mattered, is also the typical situation for biological information. DNA not encountering the biochemical environment in which messenger RNA can be synthesised, is of little value for ”life”. Messenger RNA, in turn, has to encounter the ribosome structure and the availability of transfer RNA including their attached amino acids to become ”meaningful”. Whereever information occurs in biological systems, be it antibodies, travelling excitations of neurons or complex cerebral ”messages”, it's the immediate receiver that makes the information live up to its meaning. It is an uninterrupted chain of events, excitations or messages that ”keeps the ball rolling”.

As C.F. von Weizsäcker (1971) has put it: *Information is what creates new information*. In the same paper, he also says: *Information is only what is understood* (by the receiver). A nonsense message does not create new information and it will not be understood. Biological communications are always meant to be understood and to create new information. But there is always an element of novelty involved, be it the novelty of the situation or of errors in the transmission or or new comprehension on the part of the receiver. Determinism has no place in the context of biological information. As matter of fact, if information invariably contains some novelty, one should rather say *information is only what is* almost *understood.*

Evolution

The phenomena of biological evolution seem to follow the same pattern of living and creative information. Novelty is represented by mutations. Without mutations, evolution would stagnate. Confirmation, on the other hand, is related to *fitness* in the Darwinian sense.

Fitness signifies the fitting of a key with a lock. If the lock changes, the same key is no longer fitting. Thus, fitness must not stagnate either. Nor is fitness something narrowly defined like the scores of a soccer game or the speed of sprinter at the Olympic Games. Many more than three ”champions” are receiving a medal of victory. The puzzle about Darwininan evolution is not the survival of the fittest but the exuberance of survival of the *less* fit. This is also the origin of the miraculous diversity of life forms.

When Charles Darwin, back in London from the Galápagos Islands, had a closer look at the bird’s bodies he brought from the islands, he discovered a surorising number of new species of finches, with very unusual adaptations. His explanation, quite correctly, was that in the absence of rivals from other taxa they were able to develop adaptations

One phenomenon of diversity in particular deserves our attention. It is the diversity rich gene pool which conceptually was establishes in the early 1930s by Ronald Fisher, C.B.S. Haldane and Sewall Wright. The remarkable thing about it in terms of diversity is that it allows ”weak” genes to accumulate if they are ”recessive” i.e. usually invisible in the phenotype. The mechanism of recessivity appears almost as being *designed* to protect lots of ”weak” genes from being eradicated. This plainly contradicts the vulgar perception of the Darwinian selection mechanism.

However, looking at recessivity from a long term evolutionary perspective, it appears rather ingenious. Recessivity combined with the steady occurrence of new mutations leads to the accumulation in large populations of a huge diversity of genes and their combinations. If the population is decimated by environmental stress, parasites or predators, small pockets of mutually isolated populations are likely to survive. In these very small populations inbreeding drastically increases which statistically enhances the probability for homoallel occurrence of recessive genes. This in turn means that now the once hidden genes have a high likelihood of becoming visible. There will be a certain distinct probability for some of those genes of being useful for overcoming the new stress factors.

Sometimes recessivity is being depicted as a lamentable mechanism preventing the eradication of unwanted, even lethal genetic factors. But such complaints don’t do justice to the mechanism. Quite often, the recessive gene carries a feature that is useful for survival. Perhaps best known is the malaria and betathalassemia resistances enjoyed by heteroallel carriers of the sickle cell anemia gene. Heteroallel carriers of the muscoviscidose gene seem to have a higher robustness against infant diarrhea. And the heteroallel disposition for diabetes appears to be adavantageous in times of hunger.

Vulgar Darwinism now appears as biologigically *bad* Darwinism not accounting for the occurrence from time to time of novel stress situations for which the existing wild type may just not be well prepared while some sleeping variants prove to be robust.

Moreover, certain evolutionary achievements such as the size of the dinosaurs or the huge teeth of pre-neolithic sabre tooth tiger don’t seem to be successful under all circumstances. Evolution must not be ”streamlined” too much. It ought to be kept open to be successful in the long range. Also, mutations should not be avoided even in a very successful species. As Ronald Fisher (1930, p35) put it, ”the rate of increase in fitnessof any organism at any time is equal to its genetic variance in fitness at that time.”

”Weak” variants are protected against premature selection, and a sufficient supply of new ”weak”variants is constantly provided by the mechanism of mutation. This must be n extremely old and fundamental mechanism of evolution. Eigen and Schuster (1979) in their famous paper on the evolution of the pre-biotic ”hypercycle” play a ”game” with the symbolic sentence of letters TAKE ADVANTAGE OF MISTAKE.

Error-friendliness

The protection and creation of weak variants seems to be a rather universal phenomenon, not restricted to the biological evolution. It can be observed in *all* learning processes. To conceptualise and popularise the underlying common phenomenon, one of us (C.v.W.) has proposed in the late seventies a new term, *Fehlerfreundlichkeit* (”error-friendliness”). Error-friendliness evidently does not just mean the robustness against internal or external attacks or errors. Rather it means inviting variance, experimentation, novelty and even errors. However, such experimental ”errors” should not as a rule be allowed to rock the boat. Novelty should be embedded in or matched by a sufficient amount of confirmation. The two of us have later summarised the discussion in a learned paper (Weizsäcker and Weizsäcker, 1984).

Pedagogy always emphasises the essential role of errors in human learning. A magnificient way of gaining experience with errors is *playing*. In the animal kingdom, playing is widespread, chiefly with young animals. But the adults also assume a crucial role in playing: they reduce the risks involved in the play and games of their offspring. They are part of the error-friendliness of the learning environment. The young produce the novelty and the errors, while the adults secure the ”confirmation” and come to the rescue when needed. Error-friendliness means both in in pedagogical and real-world situations thats novelty and confirmation are in balance and that risks are being kept at a manageable level. Letting children climb onto a sofa in the living room is tolerable. Letting them climb onto the window sill of an open window is not.

What is plausible for parenthood and pedagogy has its correspondence in technology. Construction errors are tolerable for a hut, but not for a skyscraper or a highway bridge. Skyscrapers are not very error-friendly from an architect’s point of view. Of course, there are many elements of error-friendliness also in skyscraper construction and maintenance. The architect can ”play” with his design on a computer before the first stone has been moved. And he or she will always plan for a certain extra robustness of the construction to absorb unexpected challenges.

The situation is a lot trickier in complex systems such as the nuclear energy cycle. Nuclear energy can hardly be regarded as error-friendly; this can be deducted from the fact that no country going nuclear dares to demand full insurance coverage from its nuclear power installations, although that is routine for ”normal” industrial installations. The concept of error-friendliness may give a clue to the mathematical puzzle why 10^{-6} ”mega-deaths” is not equivalent in our common-sense assessment with one death. Anything involving an appreciable probability of mega-deaths is not error-friendly.

The situation is comparable with genetic engineering, notably with the deliberate release into the environment of genetically modified organisms (GMO’s). The risks could be very high but at the same time difficult to predict.

How will ecosystems react to the abundance of ”ferries” for genes or viruses crossing the borders of species? Particular worries can be associated with the release of plants or microorganisms carrying all kinds of resistance factors eg against herbicides. Also, the introduction into plants of the bacillus thuringiensis (BT) toxin is disturbing. It creates the evolutionary conditions for BT-resistant pests, which could mean the end to certain types of organic farming which were dependent on BT as a last resort. What is perhaps more worrying in newly designed plants is the slowness at which the effects can be observed. Neophytes of earlier centuries typically needed a couple of generations as a lag phase to develop the vitality for spreading like in a log-phase in their new environments. Why should GMO’s behave differently?

Also genetic engineering in drugs and in environmental clean-up jobs is not that harmless as the business community seems to think. A recent report by the NIH in the USA assessing benefits and risks concluded that the effects are not yet well understood and recommended a ”back to the lab” strategy as a general attitude. Waste sludges from manufacturing may theoretically turn into sources of novel and potentially hazardous germs.

Small wonder that the biotech industry fights all efforts to introduce obligatory insurance coverage.

Generally it can be said that the willingness of the insurance industry (including reinsurers) to cover technological risks and the willingness of the respective manufacturers to seek insurance contracts are fair indicators for the error-friendliness of the respective technology.

Once the abstract concept of error-friendliness was born, is was easy to associate with it a large number of well-known concrete mechanisms.

One ubiquitous mechanism of securing error-friendliness is compartmentalisation. In evolution theory we have already looked at isolation as a geographical fact and as a ”means” to keep diversity high, and to prevent parasites and other infectious nuisances from affecting the entire world. In the body, the cellular structure provides

- redundance: if one cell fails, there is another one available to do the job;
- a basis for cell differentiation: if one cell mutates to do a new job, there are others left to do the old one.

Taken together, these features make the cellular organisation eminently error-friendly.

Other concrete biological mechanisms of error-friendliness include:

- the immune system, - allowing the body to cope with novel chemicals;
- mutations;
- recessivity (see above); and
- curiosity, - inducing individuals to explore their environment, to run risks and to learn;
- ageing and death, - enabling a species to throw plenty of new individuals into a very limited living space.

Also, mature societies have developed a large number of mechanisms which can be understood as securing the system’s error-friendliness. They include:

- democracy, - allowing people to change government as long as the errors ar small enough not to warrant the troubles of a revolution;
- division of power;
- freedom of press, - allowing a free flow of information - also about embarrassing errors - to those who can initiate the necessary remedies;
- accident insurance, - see above;
- patents, - allowing engineers to protect their inventions thus motivating them and their firms and encouraging banks to lend money for innovation.

All in all, error-friendliness can be seen as a new concept, as a new magnifying glass to perceive and describe the cybernetic functions of living and social systems, notably of those undergoing evolutionary change.

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