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Self-organisation of symbolic information

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Abstract. Information is encountered in two different appearances, in native form by arbitrary physical structures, or in symbolic form by coded sequences of letters or the like. The self-organised emergence of *symbolic information* from *structural information* is referred to as a *ritualisation* transition. Occurring at some stage in evolutionary history, ritualisation transitions have in common that after the crossover, arbitrary *symbols* are issued and recognised by information-processing devices, by transmitters and receivers in the sense of Shannon's communication theory. Symbolic information-processing systems exhibit the fundamental *code symmetry* whose key features, such as largely lossless copying or persistence under hostile conditions, may elucidate the reasons for the repeated successful occurrence of ritualisation phenomena in evolution history. Ritualisation examples are briefly reviewed such as the origin of life, the appearance of human languages, the establishment of emergent social categories such as money, or the development of digital computers. In addition to their role as carriers of symbolic information, symbols are physical structures which also represent structural information. For a thermodynamic description of symbols and their arrangements, it appears reasonable to distinguish between *Boltzmann entropy*, *Clausius entropy* and *Pauling entropy*. Thermodynamic properties of symbols imply that their lifetimes are limited by the 2nd law.

La parole distingue l'homme entre les animaux[1]

Jean-Jacques Rousseau, 1781

1 Structural and symbolic information

From the perspective of this article, the cheeps of Sputnik orbiting our planet in October 1957 heralded an unparalleled scientific achievement of human cognition that still outshines any later space exploration, be that as spectacular as human footsteps on the Moon or close-up inspections of outer planets. What makes the flying little metal bowl so special?

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[1] Speech distinguishes man among the animals. English translation by John H. Mohan [2]

When the Danish astronomer Tycho Brahe meticulously observed the motion of wandering stars across the nightly sky, he took down in tables their positions changing with time. The light of the stars can be understood as carrying *structural information* about the world far above the human's living place, sent down to the terrestrial astronomers without any intention or purpose. Starting about 1580 at Uraniborg with instruments such as his "mural quadrant", Brahe measured the altitudes of stars crossing the meridian and registered the numerical values, as eventually published by Johannes Kepler in the *Tabulæ Rudolphinæ* (Rudolphine Tables[2]) in 1627. Those lists of numbers represent *symbolic information*; the immediate purpose of the tables is to be readable and usable by humans in the future, such as later done for successful predictions of the solar transits of Mercury in 1631 and of Venus in 1639. The meaning of those written symbols is subject to various conventions; to take advantage, the potential reader must know the number system used, the measuring units of time and angle, the reference frames of time and space against which the numbers are counted, and the meaning of associated words such as "Mercury" or "Venus". By scientific measurements, Brahe converted instantaneous, volatile, irrecoverable structural information into relatively durable symbolic information about past structures and processes. It "is measurement in which a rate-dependent dynamical state is coded into quiescent symbols" [1].

Brahe died in 1601. Painstakingly analysing the measured data, his assistant Johannes Kepler extracted novel laws of planetary motion and published them in the books *Astronomia nova* of 1609 and *Harmonices mundi* of 1619. In 1687, Isaac Newton demonstrated his fundamental physical laws of motion and of universal gravitation to be consistent with Kepler's findings. Ultimately, in turn, Newton's laws were used by Soviet scientists and engineers for theoretical predictions of Sputnik's orbit after its release at the intended position and speed, under conditions that had never before been explored or visited by humans or technical devices. From the viewpoint of this paper, the structural information extracted and converted to symbolic information by Brahe, subsequently processed by Kepler and Newton, was later exploited for successfully predicting the results of intended future human activities, such as the construction and launch of a satellite. Until 1957, all that humans ever knew about celestial bodies was their light shining down on us (except perhaps some meteorite impacts). Creating an artificial celestial body and predicting its motion in the sky was an outstanding success of human information processing by generations of scientists, mutually communicating via symbolic information.

As the narrative historical example may plausibly suggest also for the general case, symbolic information is originally obtained from ambient structural information. Symbolic information has a purpose, namely the prediction of effects of future activities, derived from experience gathered in the past and safely stored away. Biological species carry symbolic information in their genes, collected over billions of years during the evidently successful struggle for existence of all ancestor generations back to the very origin of life, in order to equip recent offspring with inherited symbolic information as a recipe for their survival in the future. This method of transmitting information from the past to the future, using symbols as a "time capsule", was overly successful in the biological, social, scientific and technological evolution. The method relies on certain environmental continuity which ensures that experience gathered in the past may still be useful in the future; it fails in cases of abrupt changes such as large-scale catastrophes.

The monument of Ludwig Boltzmann at the Central Cemetery in Vienna, Figure 1, may demonstrate the distinct natures of *structural* and *symbolic*

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[2] Rudolphine Tables: `https://en.wikipedia.org/wiki/Rudolphine_Tables`, page accessed 01 Apr 2016

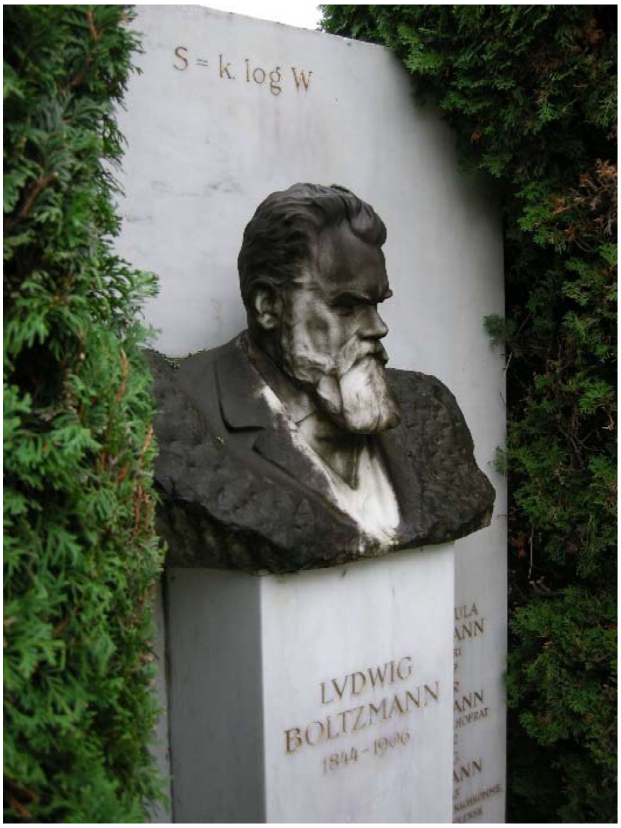

Fig. 1. Monument of Ludwig Boltzmann at the Wiener Zentralfriedhof. While the shape and the composition of the marble represent structural information, the symbolic information carried by the engraved letters and numbers relies on conventions between writer and reader. Photo taken in October 2010.

information [3–5]. Symbolic information relies on a convention between the transmitter, in this example the creator of the monument, and the receiver, namely the visitor at the grave. Symbolic information is carried by the letters, numerals and special signs engraved; the meaning of the equation at the top is symbolic information as well as the names and numbers displayed. Structural information, on the contrary, is not based on conventions for the meaning of symbols used. Colour, shape, isotopic or chemical composition of the marble is structural information that can be investigated or measured, irrespective of whether the object was artificially formed by humans or by natural processes.

Symbolic information is exclusively associated with the existence of life [5], while structural information may be attributed to any physical processes or structures, and may often be quantified in terms of physical entropy [6–9], see also Section 3. Structural information defined by thermodynamic entropy or residual entropy is conserved in reversible processes.

The self-organised emergence of symbolic information from structural information exhibits typical features of kinetic phase transitions of the 2^{nd} kind, see Section 2, and is referred to as a *ritualisation* transition [10], a term originally coined by Huxley [11,12] in behavioural biology. In this article, *ritualisation* is understood quite generally as a universal qualitative transition from basic structural to the emergent symbolic information properties of signals or coded sequences of letters, in the

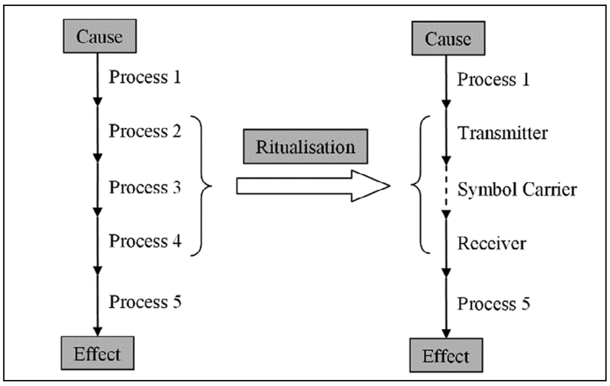

Fig. 2. By ritualisation, in the course of evolution, a certain part of an original causal chain becomes substituted by symbolic information-processing steps.

course of evolution processes. Ritualisation had been defined previously in several ways [13], such as the development of signal-activity from use-activity of animals [14], or as the self-organised emergence of systems capable of processing symbolic information [5].

From the general perspective of physics of self-organisation and evolution, the origin of life, the appearance of human language or the establishment of emergent social categories such as private property or money can also be understood as ritualisation transitions [4,5,10]. All these transitions have in common that as their results, arbitrary conventional symbols are issued and recognised by information-processing devices. These "transmitters" and "receivers" in the sense of Shannon's communication theory [15] had developed during an evolutionary process along with the actual sets of symbols, such as an alphabet and a dictionary, and coding rules such as syntax [16,17]. The combination of sender, transmitted symbols and receiver ultimately replaces a related original non-symbolic causal chain, see Figure 2.

Typically, three evolution stages of a ritualisation transition are observed [5,10]. In an initial phase, the original structure may vary only slowly in order to keep the system's essential functionality intact. Successively, affected structures reduce to some rudimentary "caricatures" of themselves, or "icons" or "pictograms", which represent the minimum complexity indispensable for maintaining the actual function [18]. Irrelevant modes or redundant partial structures are no longer subject to restrictions or restoring forces, and related fluctuations may increase substantially. At the transition point, the caricatures turn into mere symbols that may be modified arbitrarily, thus expressing the emerging *code symmetry*, and permit divergent, macroscopic fluctuations. As a result, the kind and pool of symbols may quickly expand and adjust to new requirements or functions. Somewhat later, in a final phase, the code becomes standardized to maintain intrinsic consistency and compatibility of the newly established information-processing system. Fluctuations are increasingly suppressed, the code becomes frozen-in and preserves in its arbitrary structural details a record of its own evolution history. In the examples presented in Section 4, these stages will be discernible in more or less pronounced form.

A written text like this article is typically a physical structure consisting of dark and light dots. The information carried by the text is in no way reducible to the physical properties of the given spatial distribution of dye or brightness; in this sense, symbolic information is an *emergent property*. Rigorous definitions of what *emergence* [19,20] means may be expressed in simpler words by the proverbial fact that "the whole is more than the sum of its parts" [5,21]. Despite its emergent character, written text, for example, appeared historically as a result of the evolution of human language from more primitive signal systems used by animals, and those in turn from elementary physical and chemical processes. “Higher levels of the hierarchy must have emerged from lower levels. Life must have emerged from the physical world” [1]. Any given DNA chain may represent a sequence of symbols or just a meaningless organic macromolecule; what makes the difference is not the physics or chemistry of the DNA itself, it is the presence or absence of a separate conjugate system, namely of a receiver and its symbolic information-processing capability [13, 22].

2 Code symmetry of symbols

A so-called *Hopf bifurcation*[3] is a typical example for a kinetic phase transition of the 2nd kind during which a stationary regime of a dynamical system changes to an oscillating one. Characterising such a transition, the two regimes possess different symmetries but are indistinguishable from one another at the transition point [23]. The continuous time symmetry of the first state is broken in favour of a periodic time symmetry of the second. At the threshold, the stationary and the periodic regimes coincide, i.e., oscillations appear with zero amplitude. This phase transition is accompanied by strongly enhanced, “critical” fluctuations [5, 24, 25].

A similar scenario is observed when a *ritualisation transition* [3–5, 9, 10, 13, 26] takes place in the course of an evolutionary process. The initial physical state possesses structural information and may or may not show certain symmetries. Beyond the threshold, symbols have appeared which carry symbolic information in addition to their structural information. Symbolic information is emergent and cannot be reduced to the structural information of the symbols, consequently, it is a mere convention which particular symbol is in use to represent a certain meaning. If everybody understood under the word “green” the colour of the sky and under “blue” the colour of leaves, all communication would work quite the same as the other way around [27]. This invariance is the new fundamental *code symmetry* of symbolic information; symbols may be substituted by physically different symbols without affecting the meaning of the message. This invariance is in striking contrast to structural information, where a different physical structure always implies different information, inseparable from one another. Immediately at the threshold, the nascent symbolic information is still identical with the structural information, but large fluctuations may occur which increasingly liberate the first from the latter. Ritualisation has the features of a kinetic phase transition of the 2nd kind. Elsewhere [5], various properties are discussed in more detail which distinguish structural from symbolic information.

The code symmetry has several important and general implications which elucidate the reasons for and the related selective advantage brought along by the self-organised emergence of symbolic information, repeatedly and in various forms, in natural evolution history, see Figure 3. Symbols may alternatively appear as sequences, such as in languages, or as communication signals, such as neuronal transmitter substances, pheromenes or human gestures. Some key features of the code symmetry are [13]:

(i) Discrete symbols are robust against small perturbations, i.e., symbols may be replaced by similar imitations. As an example, written letters are recognised as being equal even if their symbols are displayed in different fonts, sizes or colours; they may be irregularly hand-written, distorted, damaged or partially obscured. Mathematically, the set of different versions of a symbol forms an

[3] Hopf bifurcation: `https://en.wikipedia.org/wiki/Hopf_bifurcation`, page accessed 10 April 2016

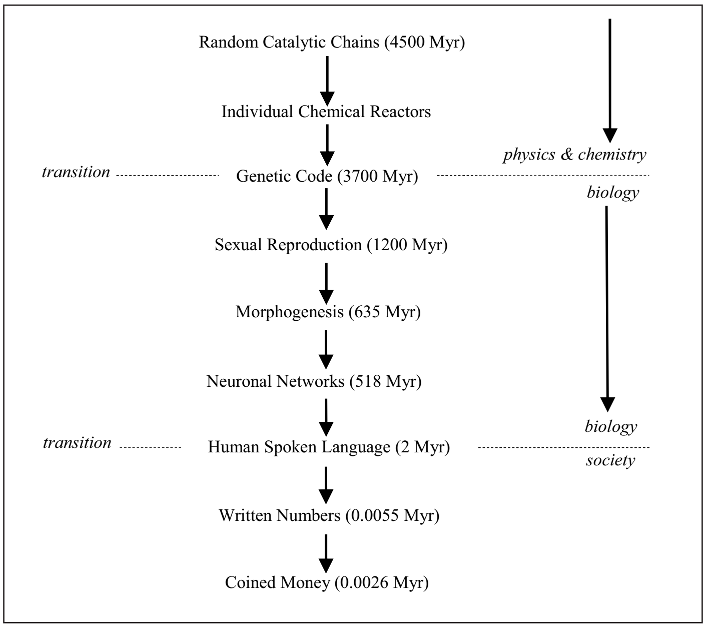

Fig. 3. Schematic hierarchy of ritualisation transitions during the evolution from prebiological chemistry to the human society. Estimated times when those events happened in history are given in million years (Myr) before present (modified from [5,26]).

equivalence class[4]. Reading a symbol can refresh it this way, permitting largely *lossless copies* to be produced if the refreshment happens within the physical lifetime of the symbol(s).

(ii) Robustness against small symbol perturbations permits *dialects* to evolve which increasingly use modified symbols that are similar in the sense that upon reading, they produce the same results as their originals. Dialect formation permits gradual modification of the equivalence class, or even spawning of a new class, that is, *drift and diversification* of symbols.

(iii) Symbolic information is *conventional*. A system of symbols may be replaced by a completely different set of symbols if this transformation is simultaneously applied to the message, the transmitter and the receiver. Symbolic information is invariant against symbol transformations to, e.g., others signs, words, languages, or symbol carrier media.

(iv) The replacement of a symbol by a physically different structure, either with the same or with a different meaning, is energetically practically neutral, i.e., symbols are "energy-degenerate" [1,10]. Any potential forces driving a structurally modified message back to some fictitious distinguished "equilibrium message" are virtually absent. Physically formulated, so-called *Goldstone modes* [28,29] with vanishing Lyapunov exponents appear at the ritualisation threshold and permit exceptionally large fluctuations. Thermodynamically, particular messages appear as alternative groups of microstates that populate a Boltzmann shell of an information processing system, see the next section.

(v) As a result of the coincidence of structural and symbolic information immediately at the ritualisation threshold, in the Goldstone modes the structural

[4] Equivalence class: `https://en.wikipedia.org/wiki/Equivalence_class`, page accessed 10 April 2016

information of the symbols keep a *trace of the evolution history* of the symbolic information system. The physical form of symbols expresses and reveals their *historicity*. As time proceeds, this trace may gradually be eroded by fluctuations and neutral drift.

(vi) Looking at symbols from the symbolic side, the code symmetry *impedes conclusions* to be drawn from the meaning of the information on the physical properties of symbols.

(vii) Looking at symbols from the structural side, the code symmetry *impedes conclusions* to be drawn from the structure of the symbols on the meaning of the symbolic message. This means, *symbolic information is an emergent property*. The same message may be expressed by different symbols, tokens or languages; a sequence of symbols may be reversibly compressed or redundantly inflated without affecting the meaning of the message.

(viii) Added redundancy, such as partial repetition or embedded grammatical rules combined with orthographic vocabularies, leaves the meaning of symbolic information immediately unaffected but allows additional information-protection tools to evolve for *error-detection* and-*correction* of random perturbations. During later stages after the ritualisation, such tools partially counteract the neutral drift of symbols and constrict the set of available Goldstone modes.

Code symmetry, or coding invariance, is a key property of symbolic information that is established along with every complete ritualisation transition.

3 Symbols and entropy

What is a *symbol*? The original Greek word "σύμβολον" (sýmbolon)[5] means something like an identifier for a certain *item* which represents the *meaning* associated with the given symbol. "Symbols are related to a referent by an arbitrary code" [1], a relation that will be termed a *convention* here, which is implemented in the symbol's context. More rigorously analysed, the word "symbol" may stand for several different but related meanings [30]. Here, the symbols considered in the following are structures that are used by organisms, humans or machines to transfer or store information. Modern technology may even use single quantum objects for this purpose, but here we focus on traditional macroscopic symbols which permit a thermodynamic description of their physical states.

The very first self-organised symbols appeared at the molecular level, namely as RNA and DNA chain molecules in protocells during the origin of life [5]. Later, when the original single-cell organisms began to assemble in the form of multi-cellular clusters, new symbolic substances known as *morphogenes* emerged which controlled the intercellular intra-organismic communication required for growth, reproduction, active motion and cell differentiation. In turn, specialised communication cells evolved which successively formed sensors, wires for signal transfer, and clusters for more complex signal processing. The active response of an organism to external chemical, optical, thermal or mechanical conditions could also be recognised by receptor cells of ambient organisms, and permitted the development of symbolic communication between individuals in the form of smells, colours, body shapes or movements in the context of mating or predator-prey interaction. Latest at this point, the signals exchanged became macroscopic objects that allow their description in terms of thermodynamics. The evolution hierarchy, Figure 3, went on to human languages and

[5] Symbolon: `https://en.wikipedia.org/wiki/Symbol`, page accessed 12 May 2016

technical, mostly mechanical devices such as clay tablets or printed books. Nowadays, advanced information systems of computers return to the molecular and even the sub-molecular quantum level where the laws of thermodynamics may no longer be appropriate description tools.

Symbols, we may conclude, may take almost any physical form from, say, a single photon to a giant Peruvian Nazca geoglyph. Assumingly, information may well be processed also by non-thermodynamic systems such as large molecules or entangled quantum states, a fact which would imply that information entropy and thermodynamic entropy cannot be identical [5]. In this section, we shall consider macroscopic symbols and discuss their thermodynamic properties in relation to entropy. However, even this cautious, conservative approach will touch the borderline to some unsettled physical grounds, and a few more general remarks in advance appear in order here.

It is somewhat confusing that in the literature various different quantities [31] may be encountered under the same name of just "entropy". Here, it is suggested to explicitly distinguish between three closely related entropy measures, namely Boltzmann entropy, S_{B}, Clausius entropy, S_{C}, and Pauling entropy, S_{P}, which obey the identity

$$S_{\mathrm{B}} = S_{\mathrm{C}} + S_{\mathrm{P}}. \tag{1}$$

Boltzmann entropy, or *Boltzmann-Planck entropy*, or *statistical entropy*, or *microcanonical entropy*, is defined here by the phase-space volume, or the number of physical microstates, $W(E,V)$, associated with the total volume, V, and energy, E, of the given system (with fixed particle numbers), in the form as introduced by Planck [32] and written on Boltzmann's monument, see Figure 1:

$$S_{\mathrm{B}} = k_{\mathrm{B}} \ln W. \tag{2}$$

This definition in terms of E and V implies that S_{B} does not change during irreversible processes that may take place at constant E and V. As E and V are physical quantities reducible to microscopic and geometric properties, Boltzmann entropy is not an emergent property, in contrast to other entropy measures [9], and cannot change irreversibly. Boltzmann entropy is conserved for closed non-equilibriums systems:

$$\frac{\mathrm{d}}{\mathrm{d}t} S_{\mathrm{B}} = 0. \tag{3}$$

Boltzmann entropy is convex,

$$S_{\mathrm{B}}(1+2) \geq S_{\mathrm{B}}(1) + S_{\mathrm{B}}(2), \tag{4}$$

with respect to dividing a system in two parts such that $E(1+2) = E(1) + E(2)$ and $V(1+2) = V(1) + V(2)$.

Shannon entropy, or *information entropy,* is a part of the Boltzmann entropy of an information carrier whose microstates are grouped in equivalence classes, see item (i) of Section 2; each class is representing a different message. Rather than counting all microstates, Shannon entropy counts only the number of equivalence classes.

Clausius entropy, or *thermodynamic entropy*, or *thermal entropy*, or *empirical entropy*, is defined here in terms of measurable isochoric heat capacity, C_V, and temperature, T, of a body,

$$S_{\mathrm{C}}(T,V) = S_{\mathrm{C}}(T_0,V) + \int_{T_0}^{T} \frac{C_V(T',V)}{T'} dT'. \tag{5}$$

For the existence of a well-defined temperature, the system must be at local equilibrium [33,34]. "Only. . . the chaotic flying around of very many atoms establishes the preconditions ... for the existence of a finite entropy and a finite temperature" [35, p. 116, English translation from 9]. In the variables (T, V) of the canonical ensemble used in equation (5), there appears no mixing entropy of ideal gases [23]. For this reason, the formulation (5) is preferred here over the equivalent entropy definition of Planck [36] in terms of (T, p). Clausius entropy is defined only up to an arbitrary reference value, $S_C(T_0, V)$, which is conventionally specified by Nernst's theorem, the so-called 3$^{\text{rd}}$ law [36,37]:

$$\lim_{T_0 \to 0\ K} S_C(T_0, V) = 0. \tag{6}$$

According to the 2$^{\text{nd}}$ law, Clausius entropy is non-decreasing for closed non-equilibriums systems:

$$\frac{\mathrm{d}}{\mathrm{d}t} S_C \geq 0. \tag{7}$$

Clausius entropy is additive,

$$S_C(1+2) = S_C(1) + S_C(2), \tag{8}$$

with respect to dividing a system in two parts such that $E(1+2) = E(1) + E(2)$ and $V(1+2) = V(1) + V(2)$.

Clausius entropy can formally be associated with a number of microstates, $\Omega(t)$,

$$\Omega(t) \equiv \exp\left\{\frac{S_C(t)}{k_B}\right\}. \tag{9}$$

Clausius entropy, along with temperature, is an emergent physical property [9]. In the sense of Planck's statement that "the macroscopic state…is the state of the observer. A macroscopic state always comprises a large number of microscopic states that he combines to an average value" [35, §121], the quantity $\Omega(t)$, equation (9), may be understood as an effective number of microstates that the system had visited within a reasonable observation period Δt at the time t, or as a currently occupied part of the Boltzmann energy shell [5,9,26,38]. Note that, according to Liouville's theorem [33], the instantaneous phase volume, Ω_{inst}, occupied by each successively taken single microstate is time-invariant during irreversible processes. Therefore, the growing value of $\Omega(t)$, equation (7), cannot be associated with either of those two quantities Wor Ω_{inst}, rather, it is likely related to an average microstate number visited during the observation period, controlled by the magnitude of fast thermal and quantum fluctuations. However, physical arguments may be raised against a simple mechanical interpretation of $\Omega(t)$ being a number of visited microstates, or being a time average over visiting frequencies [39,40]. In fact, microscopically, thermodynamic systems are quantum systems, and the question of whether or not a system is "really" in a certain microstate at some sharp instance of time may not make definite physical sense unless that state has actually been measured and its wave function has collapsed, similar to the paradoxical case of Schrödinger's cat. While the existence and definition of $\Omega(t)$ is not in question here, obstreperous problems arise with the attempt of painting a plain common-sense picture of it. Anyway, bearing this precaution in mind, in the following one may think of $\Omega(t)$ for simplicity as some average number of occupied microstates [41].

Pauling entropy, or *residual entropy*, or *frozen entropy*, or *entropy lowering*, or *negentropy*, is defined here by the identity (1). Pauling entropy describes the fraction of "frozen" microstates which are inaccessible by thermal fluctuations and do not contribute to the body's heat capacity,

$$S_P(t) = k_B \ln \frac{W}{\Omega(t)}, \tag{10}$$

Pauling entropy is convex,

$$S_{\mathrm{P}}\left(1+2\right)\geq S_{\mathrm{P}}\left(1\right)+S_{\mathrm{P}}\left(2\right), \tag{11}$$

with respect to dividing a system in two parts such that $E\left(1+2\right)=E\left(1\right)+E\left(2\right)$ and $V\left(1+2\right)=V\left(1\right)+V\left(2\right)$.
Converted from thermal units to bits, the quantity

$$M\left(t\right)=\frac{S_{\mathrm{P}}\left(t\right)}{k_{\mathrm{B}}\ln 2} \tag{12}$$

may be regarded as a structural information storage capacity, or the amount of memory that until the time t preserves a trace of the system's initial state. From the perspective of thermodynamics, one may say that Pauling entropy "represents the perhaps closest link between theoretical physics and information" [5]. In general, Pauling entropy is an emergent physical property [9] because Clausius entropy is emergent in equation (1), and Boltzmann entropy is not. Exceptions are the zero point, where Pauling entropy equals Boltzmann entropy, or equilibrium states where Clausius entropy equals Boltzmann entropy.

According to the 2nd law, Pauling entropy, and also information capacity, is non-increasing for closed non-equilibriums systems:

$$\frac{\mathrm{d}}{\mathrm{d}t}S_{\mathrm{P}}\leq 0. \tag{13}$$

At zero temperature, the residual entropy of ice Ih is a well-known example for equation (1) [5,42,43]. At finite temperatures, glassy structures are described by residual entropies [40,44]. A tutorial textbook example for the difference between Boltzmann and Clausius entropy is the case when two systems, such as fluid samples of the same substance, are both individually at thermodynamic equilibrium, but not mutually. Let their Boltzmann entropies be $S\left(1\right)=k_{\mathrm{B}}\ln W\left(1\right)$ and $S\left(2\right)=k_{\mathrm{B}}\ln W\left(2\right)$, respectively, where $W(1)$ and $W(2)$ are the numbers of microstates available in each system at given energies $E(1)$, $E(2)$ and volumes $V(1)$, $V(2)$. As soon as the two systems come in mutual contact, isolated from the rest of the world, Clausius entropy will start growing until the value of equation (2) is approached, where W is the number of microstates available in the combined system with the total energy $E=E(1)+E(2)$ and volume $V=V(1)+V(2)$.

In equation (1), in analogy to mechanical energy, Pauling entropy may be understood as a "potential entropy" and Clausius entropy as a "kinetic entropy". Natural processes tend to approach states of minimum potential energy and similarly of minimum "potential entropy".

A fictitious tutorial example may illustrate the different physical roles of Boltzmann, Clausius and Pauling entropies of a transmitted sequence of symbols, see Figure 4. Let the transmitter be some printer that periodically produces identical copper coins from supplied raw material in the form of copper spheres with maximum Clausius entropy. The final coins are assumed to be anisotropic and are placed on the conveyor either transversally or longitudinally oriented, depending on the voltage detected on an input wire.

(i) *Entropy of a symbol*: By deforming the surface, the minting process reduces the Clausius entropy of the original sphere by a certain amount of Pauling entropy. We may imagine this entropy lowering to be recovered if the coin consisted of a viscous fluid that irreversibly and spontaneously returned to its original spherical equilibrium shape. The printer's squeezing work also converts to heat

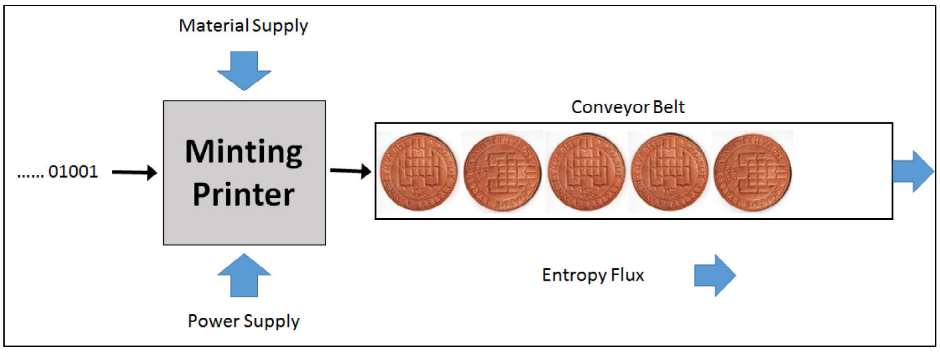

Fig. 4. A fictitious printer that is minting coins acts as an information transmitter. Each bit of the message is encoded along the conveyor belt by either longitudinal or transversal orientation of an anisotropic symbol, a copper medal. The entropies of the medals form the thermodynamic entropy flux of the transmission, while their mutual arrangements form the information entropy flux.

of the coin due to friction/viscosity of the metal. Thermodynamically, all coins are identical and possess the same entropies regardless of their orientations. The Pauling entropy of the coin seems to play a role in order to permit distinguishing the transversally placed symbols from the longitudinal ones, but in fact non-zero Pauling entropy of the symbols does not constitute a necessary condition here. If the symbol is an anisotropic crystal at equilibrium, and there is no Pauling entropy associated with it, different orientations of symbols are nevertheless detectable. So, *both the particular Clausius and Pauling entropies of the symbols in use are not relevant for the message transmitted and for any information entropy possibly associated with it.* This conclusion is consistent with the fact that symbols may also be physical systems which do not necessarily possess any associated entropy, such as an electron spin or an isomeric molecule.

(ii) *Entropy of a sequence of symbols*: Because of the additivity, equation (8), the Clausius entropy of the sequence of symbols is the sum of the entropies related to each symbol, and the related flux of Clausius entropy caused by the conveyor is just (entropy per symbol) × (symbols per time), independent of the encoded binary message. In contrast, Boltzmann entropy is convex, equation (4), and mutually different orientations of the symbols within the sequence represent alternative groups of possible microstates of the set of coins. The same holds for the Pauling entropy when the Clausius entropy is subtracted from the Boltzmann entropy, equation (1). If the conveyor is noisy, the medals may randomly change their orientations over time. If we consider a Gibbs ensemble of conveyors, the Pauling entropy of this ensemble will decay in favour of its Clausius entropy, indicating a loss of information. In the form of probabilities, such an ensemble permits predictions of expected error frequencies in transmitted messages in the future [15]. *Shannon entropy, we may conclude, is related to only a certain part of the Boltzmann entropy of the sequence which is essential for decoding the message* (such as distinguishing only two equivalence classes of angles by the receiver rather than their continuum, see item (i) in Section 2). The flux of information entropy is related to the Pauling entropy of configurations of coins rather than to the entropy of individual coins.

Due to equation (13), the production of entropy dictated by the 2nd law implies the destruction of information capacity. More precisely, the entropy production rate of irreversible processes affecting certain frozen groups of microstates, limits the lifetime of symbols formed by those states. Evidently, for proper symbolic information transfer, the time elapsed between transmission and reception of a symbol must not exceed its lifetime. Particularly long lifetimes are characteristic for frozen or frustrated structures such as glasses [44,45], rocks, burned clay tablets, or books. Also, the light received from remote galaxies may preserve structural information from a very distant past. In contrast, laser pulses in optical cables or charged capacitors in computer memories typically hold their structural or symbolic information only for tiny fractions of a second.

4 Ritualisation: Examples for emerging symbols

Ritualisation was first described for animal populations and later generalised to certain forms of social behaviour of humans, but in fact this transition process is also highly relevant already at the molecular level for the understanding of how life emerged. Here some representative cases are briefly reviewed, from the genetic code to programming languages, along the schematic hierarchy of Figure 3. More details of the examples presented below are described in [5,10,13].

4.1 Origin of life

Symbolic information permits fast and (almost) loss-free multiple copying, and is superior to random mechanical division of growing protocells containing complex catalytic networks that represent structural information. It is plausible to associate with the origin of life the ritualisation transition by which the molecular symbolic information carriers such as RNA and DNA emerged which characterise each living being to the present day in the form of the genetic apparatus. Starting from under-occupied random catalytic networks in an energy-rich "primordial soup" and the spontaneous formation of spatial compartments in pores or droplets, a hypothetical model may include ten successive qualitative steps to logically provide the basis for the actual ritualisation process [16]. At an initial stage of the crossover, self-reproducing protocells are assumed to consist of a few catalysts supporting key reaction steps (similar to recent proteins), and related chain molecules whose folded RNA copies [46] formed the building blocks which assembled the catalysts in the specific order. This first phase of the ritualisation transition likely ended with codons that had lost their direct chemical relation to the building blocks they represent, that is, their symbolic information had separated from the structural one. Their mutual link turned into an arbitrary convention embodied by the t-RNA molecule, the codon became an arbitrary symbol [47], and the m-RNA molecules became symbolic information carriers for the instructions on how to mount a catalyst (i.e., a protein) step by step from a standardized set of building blocks (i.e., amino acids), similar to forming words and sentences from a standardized alphabet.

As a result of the separation of the physical form of a symbol from its meaning, that is, as a result of the fundamental coding symmetry of symbolic information, in the second phase of the ritualisation process the symbols in use may randomly drift and diversify. To some extent, this process can be reconstructed from the symmetries of the modern genetic code [5,16,47–50]. Crick's "wobble hypothesis" [51] suggests that initially there was a large number of different codons representing the same building block (the recent amino acid), and that this redundancy, or "degeneracy", was successively reduced by differentiation of t-RNA types and more accurate distinction of the related codons. Because physically the arbitrary symbols possess structural information themselves, symbolic information systems always keep a trace of their own evolution history. The recent genetic code and the physico-chemical structures of the t-RNA molecules provide such traces [52,53]. The existence of a genome and the genetic code distinguishes living organisms from unenlivened matter [54,55]. The origin of symbolic information processes is fundamentally associated with the evolution of life [56–59]. Rigorously formulated, *there is no life without symbolic information processing, and there is no symbolic information without life* [5]. Here, technology is understood as an "honorary living thing" [60], as a part of the human culture that belongs to the realm of life [61].

4.2 Morphogenesis and neuronal networks

With increasing multiplication speed of protozoons, their metabolism caused local depletion of available nutrients and accumulation of possibly toxic waste chemicals. Detecting the "taste" of surrounding water, i.e., its structural information, and actively responding to it was certainly of selective advantage already at the early stages of life. Substances released by one organism, such as metabolic by-products, and recognized by another, may develop into signals for active communication. The substances that control the differentiation of genetically identical cells into different tissues [62,63], commonly termed *morphogenes*, ultimately become conventional signals that act internally within a body, isolated from the external chemistry.

The emergence of morphogenes and of neuronal transmitters can be understood as ritualisation transitions [5,10]; they are derived from use-activities of the cell metabolism and developed to signals specified by conventions between the cells of an organism. The evolution of neurons from ordinary tissue cells is a subsequent ritualisation [5,10] that permits neurons to diversify and modify for information processing in the central nervous system by signals and network structures that exist completely separate from the external physical and chemical conditions and from the vital tasks the original tissues had to serve before.

4.3 Insect communication

Vibrational communication is widespread in insect social and ecological interactions [64]. Several insect taxa respond to tactile stress by internally releasing stress hormones. If the hormone level exceeds a critical threshold, the individual may change certain properties, such as its behaviour or its colour. If the behavioural change includes intensified active motion, the stress becomes amplified by a positive feedback loop. Such phenomena have been investigated in great detail for swarming locusts [65–69]. The crossover from solitary to swarming behaviour is caused by critical population densities as a result of rapid multiplication (due to, e.g., abundant feeding grounds) or shrinking territories (due to, e.g., seasonal or climatic changes) such as desiccating grass lands.

Swarming in honey bees is also triggered by excessive tactile stress. It developed into a symbolic communication activity, the so-called waggle dance [70,71], by which bees returning from excursions inform other bees symbolically about the distance and direction to food sources. The transition from swarming to communication by means of body contacts may be understood as a ritualisation transition; the existence of subspecies dialects [72–74] supports the assumption that the bee-dance elements are arbitrary symbols that are subject to coding invariance of the message conveyed.

4.4 Sexual selection

Many birds present flamboyant plumage colours [75] that are assumed to result from sexual selection. Darwin [76] wrote that he could "see no good reason to doubt that female birds, by selecting during thousands of generations the most melodious or beautiful males, according to their standard of beauty, might produce a marked effect". Typically, bird colours resulted from the use-activity of depositing metabolic waste such as melanin in feathers [77,78]. Selective pressure with respect to the capricious taste of potential mating partners is subject to arbitrary convention in the form of "their standards of beauty" and will likely result in traits such as coloration that may strongly differ from place to place and from species to species. Such traits act as signals for sexual attractiveness that promise successful multiplication. Numerous examples for the ritualisation of acoustical, optical or olfactory sex signals in plants, animals or humans are described in the ethological literature [79–81].

4.5 Human kisses

According to the most likely hypothesis, *kissing* between humans derived from oral feeding, both in the sexual context as well as in mother-infant relations [80–84]. Modern humans feed each other orally only in exceptional situations such as amorous plays. The original use-activity of presenting food, often performed by animals, has turned into a human signal-activity where the original feeding has changed to various social forms such as symbolic kisses between politicians which originate from Easter kisses in the Orthodox Catholic Church and the Roman *osculum*, the kiss of peace. In the course of evolution, kissing activities have diversified from mouth-to-mouth to symbolically kissing hands, cheeks or feet [82], most of those incompatible with the original aim of feeding, which indicates a complete ritualisation crossover.

4.6 Spoken language

Already long before Darwin, von Herder [2] had argued that humans evolved from animals, and that it is language that distinguishes the one from the other. In the course of this process, "the voice of nature turns into an arbitrarily penciled symbol" [2]. The *infant hypothesis* of the origin of spoken language [5,85,86] is consistent with the way we learn to speak during our infancy [87]. About 1.8 Myr ago, in contrast to chimpanzees and other mammals, humans developed the ability of willfully controlling their airflow of breathing, a physiological prerequisite for fluent speech, singing and laughter [86,88,89]. On the receptor side, the spectral analysis of complex sound patterns by mammals had evolved already during the Jurassic [90,91]. From the first days on after birth, babies can suckle and drink. For these use-activities, the neuronal and mechanical control of lips, tongue, jaw and throat is well advanced. By those tools, babies are able to modulate the airflow of crying and to start babbling. The first oral communication happens between babies and their mothers, amplified by a feedback loop [92,93]. It is plausible that the phylogenetic origin of spoken language was similar; crying babies could also babble and developed a symbolic acoustic information exchange with their mothers with respect to the baby's needs. The hypothesis that human speech as a signal-activity is phylogenetically derived from feeding as a use-activity, is well supported by physiological evidence [86,94]. The existence of various modern languages and dialects [95] and their observed ongoing evolution and modification are typical indicators for a completed ritualisation transition.

As a consequence of the coding symmetry, it is a characteristic feature of symbolic information that some structural information "fossils" of the ritualisation transition

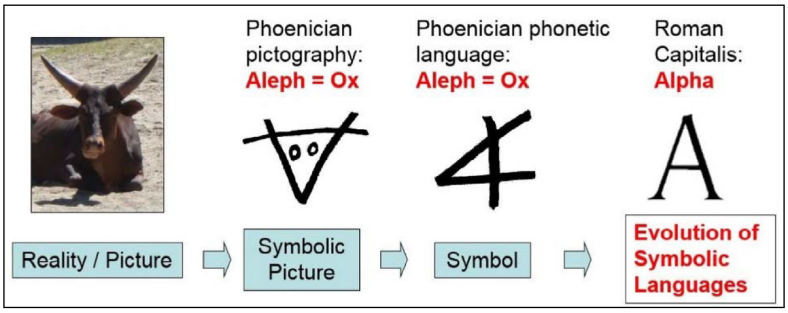

Fig. 5. Ritualisation transition of a real-world picture, such as an ox, to an abstract phonetic letter, such as an A, in the course of social evolution [16,18,103].

are preserved in the physical structure of symbols over a characteristic relaxation time, that is, symbols keep a trace of their own evolution history. The virtual paradox whether our spoken words are conventionally defined or of onomatopoetic origin [16, 86,96] represents such a trace.

4.7 Written language

In contrast to spoken language that may have developed 1–2 million years ago, the earliest evidence of written language is the Sumerian's cuneiform writing which dates about 6000 years back [87]. The most convincing argument for writing is the existence of private property in a developed state [97], for registering cattle and other commodities, fixing the tax to be paid to the sovereign, taking notes of oral contracts and agreements, safely carrying such information over large distances and storing it away from one year to the next [18,87,98]. Likely, objects such as cows or huts had to be specified and counted. Similar to the onomatopoetic origin of many spoken words, many first "written words" were just pictograms of the objects they represented. Those pictograms were already simplified caricatures, symbols of real objects, but they were not completely arbitrary.

An instructive example for the ritualisation process of written language is that of the Phoenician ox, Figure 5. It shows how through the use in history the visual representation of an object gradually transformed into an abstract symbol which is now arbitrarily associated with an acoustic pattern. In the text of this article, the original relation between the letter A and an ox has completely disappeared. The arbitrariness of written symbols came with the ritualisation transition caused by social evolution, the need for new and more abstract words, the flexibility of written language required to document, say, the personal and family history of an emperor, his glorious victories in wars, or the many titles and crowns carried by him.

Starting already before 3000 BCE, cuneiform symbols had evolved from pictograms in a very similar way, such as the Assyrian cuneiform sign SAG[6] that arose from a schematic drawing of a human head [99]. Implied by the code symmetry of symbolic information, the structural information of natural languages offers detailed preserved records on the evolution of human societies [10,16,26]. Comparative language analyses provide insight in the progress of natural sciences, historical events and ethnographic relations [87,100–102].

[6] Cuneiform sign SAG: `https://en.wiktionary.org/wiki/File:Cuneiform_sign_SAG.svg`, page accessed 11 April 2016

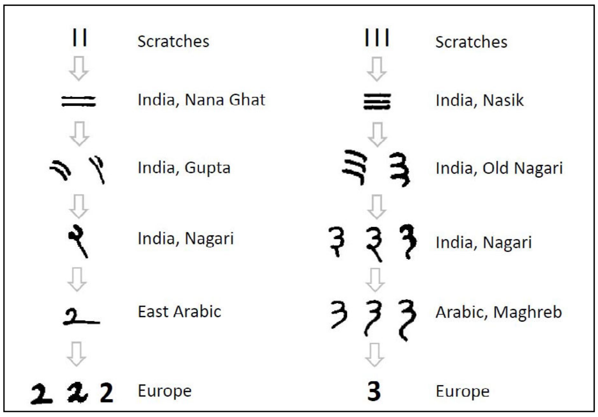

Fig. 6. Ritualisation and neutral drift of the "Arabic" numeral symbols 2 and 3, starting from the original physical structures. Schematic modified from Ifrah [104]; branches leading to other descendant Asian numerals omitted.

4.8 Numerals

Ifrah [104, p. 40] describes the evolution of numerals in terms of the typical three phases of the ritualisation transition. In a precursory phase, numbers are confined in the human's mind to multiple objects that can be recognised at a single glimpse. The imagination of numbers is bound to the observed reality and is not separable from the nature of the object immediately present [105]. At this stage, numbers still represent structural information. In the second phase the actual ritualisation occurs. Spoken numerals are basically names for body parts used for counting, they increasingly lose their original meaning when representing amounts of certain items, this way turning into half-concrete and half-abstract constructions. Numerals show the tendency to gradually separate from their original meaning to be applicable to arbitrary objects [105], i.e., as symbolic information. In a final phase, the words used for counting developed to abstract numerals, to true symbols that may be freely modified and are then well distinguished from their original concrete objects [106].

The written symbols for numerals underwent a ritualisation process similar to that of letters of the alphabet shown in Figure 5. Adapted from Ifrah [104, p. 541, p. 542], two examples are displayed in Figure 6 for the transition from physical structures to simplified pictograms and then to abstract numerals, finally losing their links to the original scratches (or fingers).

4.9 Money

Likely, along with the human evolution of personal property as a social category, the wish for documenting ownership was a significant driving force for the emergence of written language and numerals. A special kind of property is money, and its transformation to a symbol of property can also be understood as a ritualisation process [5,10].

Exchange of property between two owners is primarily a mental process of the participants rather than a physical process affecting the items of the deal; if appropriate, the objects are physically handed over from the one to the other. Direct binary exchange of useful things may be difficult when the two have very different values to their owners, or are available at different times or locations [107,108]. In such cases, a widely accepted, durable and preferably countable intermediate exchange good is temporarily used to confirm the barter, commonly known as money. The market price appears as a measurement result for the exchange value, obtained by comparison and expressed as a multiple of the currency as the measurement unit. However, as a mental rather than a physical process in this context, comparison is affected by emergent social influences such as fashion or vanity, and can be reduced to physical comparison only if the exchanged commodities are of the same kind, such as two loafs of bread compared to one. As an emergent property, the unit of money cannot be reduced to the physical units of the international system of units (SI). "Exchange values of commodities . . . cannot be either a geometrical, a physical, a chemical, or any other natural property of commodities" [109].

Early coins represented their values in the form of precious metals they consisted of. If there is an authority which grants the equivalence between symbolic money and a certain amount of gold or a similar valuable commodity, fiat money as a legal tender has a number of advantages over commodity money [110]. Already Plato[7] had suggested that money should be an arbitrary symbol rather than a metallic coin as proposed by Aristotle. The possibility of lossless copies is a fundamental feature of symbolic information associated with its code symmetry. The latter permits modifications of the structural information of the symbols without affecting the symbolic information they convey. A new banknote and various of its physically deteriorated instances belong to the same equivalence class and represent, by definition, exactly the same symbol and in turn the same value. The disestablished use-value of the money units during evolution indicates a ritualisation transition; the original exchange of values is replaced by an exchange of symbols for those values. Those symbols are arbitrary, they can be diversified, they are subject to coding invariance (improved paper notes may replace obsolete versions; damaged or dirty notes can be exchanged for fresh ones). The shape and structure of symbolic money preserves information on its evolution history.

Marx and Schumpeter described typical features of the ritualisation transition of money. "By their metallic weights, gold, silver, copper had already . . . scales before their becoming money, such that, e.g., a pound serves as a measurement unit. . . . Thus in each metallic circulation, the names of the related weight scale constitute the original names of the money scale or the scale of prices. . . . For several reasons, the money names of the metal weights gradually separate from their original weight names. . . . When the turn-over of money divides the real content from the nominal content of a coin, its metal existence from its functional existence, the latent possibility is implied that the metal money of the coin function may be substituted by tags of a different material or by symbols. . . . The coin existence of gold [eventually] separates completely from its value substance. Relatively worthless things, chits of paper, can function as a coin in its place. In the metallic money tags the purely symbolic character is somewhat hidden. In paper money that character is obvious [109, English translation from 13]. "Not only that names and appearances of coins often indicate a meaning of a commodity, . . . not only that often the coin verifiably replaced commodity money used at the same place at earlier times; even the transition of commodity money to the coin is detectable step by step" [107, English translation from 13].

4.10 Digital computers

Computers are machines capable of automatically performing extended and complicated manipulation tasks in a fast and reliable manner. Mechanical cash registers

[7] Joan Bardina Studies Center. Chapter 5: Aristotle against Plato. `http://chalaux.org/epdduk05.htm`, page accessed 11 April 2016

(tills) and cipher machines such as the German ENIGMA were in regular use in the 20^{th} century. With the increasing availability of electricity and electrical devices, mechanical switches in such computers became replaced by electrical gates such as relays, vacuum tubes or transistors. Analog computers are dynamical systems whose initial and boundary conditions were often imposed in the form of mechanical levers or wheels, or electrical switches or plugs, powered by wound-up springs, lifted weights or electricity. The resulting phase trajectory of the system, such as the changing positions of the clock's hands, or its final attractor state in particular, such as a calculation result, represent the purpose of the machine for humans.

Punched cards like those introduced by Hollerith in 1890 for the US census are a paradigm for the ritualisation transition from analog to digital computers. Upon reading the card, the holes at various positions in the stiff paper can be detected by mechanical feelers or electric contacts, so that the card represents an array of mechanical or electrical switches whose actual settings specify the intended transition step from the current computer state to the next. From this perspective, the punched card provides structural information that is fed into a physical dynamical system, and the holes appear as reduced and extremely simplified "caricatures" of the original switches mounted at previous machine generations.

On the other hand, the holes in each column of the card represent a symbol for a numeral, a letter or a special sign, such as defined by the EBCDIC[8] specification, a former quasi-standard for mainframe computers. This way, each card encodes a written line of 80 characters, for example of the ALGOL or FORTRAN programming languages, or of numerical values in certain formats. These languages represent symbolic information, such as mathematical algorithms, in the form of software, which - along with the further technical evolution – gradually separated from the hardware representation given by the punched card. Modern computers may internally use ASCII[9] or ANSI[10] code tables that still resemble EBCDIC but are not fully mutually consistent. Algorithms can be written and executed in certain languages almost regardless of hardware details of the enormous variety of computers in worldwide use today. From the viewpoint of ritualisation, the relation between hardware and software, respectively, is similar to the relation between structural and symbolic information.

Punched cards may mark the point of the ritualisation transition of computers in the course of technological evolution, from mere structural information of electrical circuits before the crossover to symbolic information processing after it. Modern code specifications still keep a historical trace of the arrangements of switches used before the transition. Programming languages convey the symbolic information and possess the code symmetry of being implemented and executed on platforms with largely arbitrary structural information of their hardware. Various new programming languages developed, and still develop, as a result of the freedom of coding.

5 Conclusion

Despite their complexity and vulnerability, symbolic information systems proved superior to their structural precursors at various stages in the natural history from

[8] EBCDIC: Extended Binary Coded Decimal Interchange Code, `https://en.wikipedia.org/wiki/EBCDIC`

[9] ASCII: American Standard Code for Information Interchange, `https://en.wikipedia.org/wiki/ASCII`

[10] ANSI: American National Standards Institute, `https://en.wikipedia.org/wiki/Windows_code_page`

molecular evolution to modern economy. The ultimate purpose of symbolic information is predicting successful recipes for competition and future survival. The selective advantages of symbolic information arise from the code symmetry and certain related properties, such as fast and largely loss-free copying. Ritualisation, as a kinetic phase transition of the 2^{nd} kind, is a self-organised phenomenon that resulted in the emergence of conventional symbols and their code symmetry in numerous incarnations of widely varying nature, maturity and significance. Genetic, neuronal and numerical information processing are particularly dramatic examples with far-reaching evolutionary consequences. Spoken words, written letters and numbers are fundamental elements that characterize the human society.

Almost any physical system or process may act as a symbol. For macroscopic symbols, a thermodynamic description of an information carrier is usually possible. In this context, a distinction is made between Boltzmann, Clausius and Pauling entropies, which possess different relations to microscopic dynamics and consequently, different time evolution symmetries. The information flow is independent of the flux of Clausius entropy, but the lifetime of symbols or messages is limited by the increase of Clausius entropy, as imposed by the 2^{nd} law. Information entropy is related to Boltzmann and Pauling entropies.

Symbolic information systems appeared exclusively during the evolution of life, provided that technical devices are understood as "honorary living things". Similarly exclusively, ritualisation may be the universal transition process by which symbolic information emerged from structural information. Accordingly, very different symbolic information system have universal properties in common which find their roots in the properties of the ritualisation transition, in particular, in the code symmetry which fundamentally distinguishes symbolic from native information. In turn, the physical carriers of symbols possess structural information apart from their symbolic meaning; these physical structures are percussions of the symbols' evolution history. The way emergent symbolic information, the "soul", became liberated from its original physical nature, the "body", may offer an evolutionary approach to a future unified theory of information [31,111].

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