Self-Accumulation of Information in the Nature

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To understand why information accumulates despite the global entropy increase, we argue that existing composite entities, from atoms to galaxies, including lives, are information condensates, which accumulate information in a self-explanatory manner. In order to confirm and to illustrate this idea, we investigate the role of information in survival of a hydrogen atom.

1. Introduction

Animals store large amounts of information in their brains, bodies and environments to live and to overcome varieties of hardships. Biological species accumulate their survival information in individuals' genes, behaviors, distributions etc. Similarly, mountains keep their existence by internal balances of forces and matters. Rivers keep their identities with interplays of the water and the riverbeds etc. Many entities seem to have their own information to keep their existence. Why does the information accumulate in the nature despite the second law of thermodynamics? Proactive explanations are desired beyond mere consistency. As for lives, the modern evolutionary theory seems to answer convincingly. But, why only for lives? As for ordered entities associated with lives, humans, societies, and complex systems, enlightening theories were extensively studied, such as self-organizations, dissipative structures, systems theories, and so forth. They are, however, still specific to relevant classes of systems. We need a universal principle to explain why information accumulates locally, and to complement the second law of thermodynamics to found the theories on them. For a small step toward it, here we advocate the notion of information condensates, which, we argue, accumulate information in a self-explanatory manner.

Faced with diversities of definitions in the literature, we specify meanings, properties and usages of the various concepts as follows. Information is kept in internal states and environmental statuses of the system, and yields effects through logical and causal networks of its pieces and natural laws. Information implicates its "agent" who manages it and needs its effects. We are interested in the information of which the agent is an entity and the effect is its existence. Information accumulation is gathering of many pieces of information managed by some agent. Information condensation is the drastic change in quality where its pieces get organized with natural laws to yield distinct status. The ultimate is that between existence and nonexistence of an entity. An entity is a system which maintains its unity and identity due to physical and informational connections. Systems treated in physics are not necessarily entities, since its scope is indifferent to unities and identities. For example, an atom in a bound state is an entity, but the system of the constituents in an unbound state is not. The nature selects existing entities as consequences of real processes, and selects the associated information, on average. Hence, probabilistic treatments are useful. To discuss amounts of information, we use the Shannon entropy \( H = -\sum_i p_i \log p_i \), where \( p_i \) is the probability of the state \( i \). We should be careful because a quantitative measure exhibits only specific aspects of the information. It resembles the body weight which exhibits only specific aspects of health. It would be desirable to consult multiple measures.

An elementary particle has only information on its properties and the environmental status, while a composite entity may have many internal states to keep information. In some cases, the information is organized and used so as to keep it existing, whereas that without such information cannot exist. Therefore, the existing composite entity inevitably has information to keep it existing, and hence it is an information condensate. The entities may provide environments or disturbances for other entities. They are often cooperative or competitive for their existence. The more information contributes the more to their existence. The more refined information helps their survival the better. Consequently, information is accumulated by the surviving entities. Thus, any existing composite entities, from atoms to galaxies, including lives, are information condensates surviving competitions and selections by virtue of the information itself. They accumulate information, though it may incidentally decay by disturbances, and entropy increases as a whole.

This accumulation mechanism is self-explanatory, i.e. its logical explanations are innately implied by itself without any postulate other than natural laws. In order to confirm it, we need to explicate the information to keep the entities existing, and to compare it with the observations. For complex entities like lives, the mechanism would be well understood along with the evolutionary theory. We claim that it is universal and fundamental in the nature. Then, it is urgent to examine if the mechanism works even in simple entities. For this purpose, we will investigate the role of information in survival of primitive entities.

2. Information kept by primitive entities

The hydrogen atom has the information that it is a system of an electron and a proton bound by electric force, with that on their precise properties and status. According to the quantum law, it obeys the Schrödinger equation. They are organized as to yield the bound-state solutions with energies \( E_n = -E*/n^2 \), where \( E* = \)
where $\langle E \rangle$ is the average energy. Then, $S = k H(T)$ ln 2 is the same in form as the thermodynamic entropy, although the single atom has no temperature, and $T$ is that of the environment. From (1) and (2), we have

$$\langle E \rangle \approx -E^*$$ in I,  
$$\langle E \rangle \approx 3kT/2$$ in III,  

and in II, $\langle E \rangle$ rapidly increases across 0 to transfer from I to III. According to (1)–(4), we plot $H(T)$ with the solid curves in FIG. 2. It vanishes exponentially as

$$H(T) \approx \frac{3E^* + 4kT}{kT \ln 2} e^{-\frac{4E^*}{3kT}}$$ in I,  

it rapidly increases in II, and slowly increases as

$$H(T) \approx \log_2(\pi^{1/2}h^{-3} R_s^{3}(8emkT)^{3/2})$$ in III.  

When the atom is formed in cooling of the environment across II, the information of the amount $I = H(T^*_c)$ is accumulated by the atom, meanwhile the energy $E^*$ is transferred to the environment, and the entropy of the environment increases by $S_{env} \geq kI \ln 2$. On the other hand, when the atom is dissolved due to the thermal disturbance with $T' > T^*_c$, it loses the information $I$, while the entropy of the environment decreases by $S'_{env} \leq kI \ln 2$. They are in accordance with the second law of thermodynamics, if we define the thermodynamic entropy of the single atom by $S = k H(T) \ln 2$.

The atom accumulates additional information and acquires further security measures by forming a molecule with a set of atoms $13$. The molecules adopt their electronic state for the binding and get into the secure states. The atoms cooperate for their existence. The molecule itself is an entity and cooperative with the atoms. Let us roughly estimate the amount of information accumulated by binding. We assume that the partner set of atoms is so big that its translation and rotation degrees of freedom are mostly similar as those of the molecule. So we omit these degrees of freedom because we are interested in...
the drastic differences brought by binding. Then, we approximate the bound states by those of a truncated linear harmonic oscillator with the energy $\tilde{E}_n = -\tilde{E}^* + n\varepsilon < 0$, where $\tilde{E}^*$ and $\varepsilon$ are constants and $n = 0, 1, 2, \cdots, \tilde{n}_{\text{max}}$. We approximate the unbound states by the ideal gas of the atom. Then, the bound and the unbound state sums are given by, respectively,

$$Z_B = \sum_{n=0}^{\tilde{n}_{\text{max}}} e^{-\tilde{E}_n/kT} = \sqrt{\frac{R}{h^3} T^{3/2}} (8\tilde{m}kT)^{3/2}$$

(7)

with the mass $\tilde{m}$ of the atom. The total state sum is $Z = Z_B + Z_U$. The existence probability $\tilde{P} = Z_B/Z$ of the molecule rapidly decreases from 1 to 0 in the narrow range $(\tilde{T}_c^-, \tilde{T}_c^+) \equiv (T|\tilde{P}=1-\delta, T|\tilde{P}=\delta)$(FIG.1 dashed curves). We call the ranges of temperature $T < \tilde{T}_c^-$, $(\tilde{T}_c^-, \tilde{T}_c^+)$, and $(\tilde{T}_c^+, \infty)$ as I, II, and III, respectively. Comparing with the atom, we can see that $\tilde{T}_c^\pm < T_c^\pm$ because of $\tilde{m} > m$ and $E^* < E^*$. In I, the low lying multiple (not a single) states dominate over the higher, so that we can approximate it as

$$\tilde{Z}_B \approx e^{\tilde{E}^*/kT}/(1-e^{-\varepsilon/kT}).$$

(8)

The Shannon entropy $\tilde{H}(T)$ with (7) obeys

$$\tilde{H}(T) = \langle \tilde{E} \rangle/kT \ln 2 + \log_2 Z,$$

(9)

where $\langle \tilde{E} \rangle$ is the average energy of the molecule. It is calculated with (7) and (8) to be

$$\langle \tilde{E} \rangle \approx \begin{cases} \frac{-\tilde{E}^* + (\tilde{E}^* + \varepsilon)e^{-\varepsilon/kT}}{1 - e^{-\varepsilon/kT}} & \text{in } \tilde{I} \\ 3kT/2 & \text{in } \tilde{III} \end{cases}$$

(10)

and in II, $\langle \tilde{E} \rangle$ rapidly increases across 0 to transfer from I to III. We plot the values of $\tilde{H}(T)$ with (7) and (9) with dashed curves in FIG. 2 for typical values $\tilde{E}^* = 7.18 \times 10^{-19}$J and $\varepsilon = 5.75 \times 10^{-20}$J [14]. We have

$$\tilde{H}(T) \approx \frac{\varepsilon \log_2 e}{(e^{\varepsilon/kT} - 1)kT} - \log_2(1 - e^{-\varepsilon/kT})$$

in $\tilde{I}$, (11)

it rapidly increases in $\tilde{II}$, and slowly increases as

$$\tilde{H}(T) \approx \log_2[\pi^{1/2}\hbar^{-3}R^3(8\tilde{m}mkT)^{3/2}]$$

in $\tilde{III}$. (12)

When a molecule is formed in cooling of the environment to the temperature $T < \tilde{T}_c^-$, the energy $\langle \tilde{E} \rangle|T$ is transferred to the environment on average, and the information of the amount $\tilde{I} = \tilde{H}(\tilde{T}_c^+) - \tilde{H}(T)$ is accumulated by the molecule on average. Meanwhile the entropy of the environment increases by $\tilde{S}_\text{env} \geq k\tilde{I}\ln 2$. Conversely, when the molecule is dissolved by the thermal disturbance with $T' > \tilde{T}_c^+$, it loses the information $\tilde{I}$ while the entropy of the environment decreases by $\tilde{S}_\text{env}' \leq k\tilde{I}\ln 2$. They are consistent with the second law of thermodynamics, as far as we identify $S = 2k\ln \tilde{H}(T)$ with the thermodynamic entropy of the single molecule $\tilde{H}$.

The atoms and molecules further accumulate information by forming gas, liquid, solid, crystal, and various structures. The structures are assemblies of molecules which maintain unity by intermolecular forces, gravitational forces, or confining effects of holders. The atoms and molecules adapt to the structures and get securities against various disturbances [13]. The atoms, the molecules and the structures are, on average, cooperative for their existence. Such structures have another security strategy, proliferation, where the repetition size benefits its survival. The basic information amount is roughly proportional to the repetition size. For example, if the structure is gas of the molecules in some container in equilibrium with environments of a high temperature, the Shannon entropy is given by the thermodynamic entropy of the ideal gas. Then, the information amount (defined as the decrease of the entropy) is proportional to the number of molecules, the repetition size of the system.

3. Conclusion

We have seen how information is stored, organized and used for survival of the hydrogen atom. It takes a bound state, recovers from damages, competes or cooperates with others, adapts to the circumstances, proliferates, assembles, and tends to securer states, as consequences of natural selections [6]. Only those with properly organized information can survive. Thus, the information is condensed and accumulated. We have precisely shown that this mechanism is working even in atoms. It is much refined and reinforced through repeated accumulations to yield intensive condensates like lives. The superlative strategies such as self-organization, self-replication, heredity, cognition, communication, civilization, etc. are selected and developed during the long course of the information accumulation in the entities.
The information condensates include, e.g. lives, societies, machines, softwares, languages, sciences, typhoons, stars, and so many things. The accumulated information, and hence their behaviors and interplays should be directly or indirectly rooted in existence-keeping of some entities. It is important to investigate the informational structures based on qualitative and quantitative analyses. Our numerical results for the atom are almost accurate, while those for the molecule are not, and require refinements. A quantitative measure exhibits only specific aspects, and it would be desirable to consider further multiple measures. Other interesting problems left untouched are those of the quantum effects, including quantum complexity, von Neumann entropy, quantum entanglements etc. We wish that this self-accumulation mechanism of information would shed a little light over the trail to the fundamental principle of information accumulation, which is desired to complement the second law of thermodynamics.

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