SHORT VIEW

Entropy and Maxwell's Demon: The Degree of Disorderliness in Concept

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The present article is motivated toward delving into the concept of entropy, a fundamental consequence of the second law of thermodynamics with particular emphasis on the thought experiment by James C. Maxwell, famously known as the "Maxwell's demon", which in turn enables our visualization of the connection of entropy with information.

Keywords: Entropy, Maxwell's Demon, Degree of disorderness

In thermodynamics, the Entropy is conventionally defined by the equation $dS=(dq_{rev})/T$ where, dS denotes the change of entropy (S) and dq_{rev} is the heat change in a reversible process. However, the concept of entropy attracts all the more interest and significance when it comes to practical application and utility of the same beyond the notion of just a mathematical equality describing the quantity. It is here that we readily realize that the physical significance attached to the concept of entropy applies almost always beyond the terrains of a reversible process, in practice. Entropy is a fundamental consequence of the second law of thermodynamics, and in itself a unique yet enigmatic concept. Commonly the physical visualization of entropy is often connected to disorder or randomness, and entropy has come to have been popularly described as a measure of disorderliness or randomness. To this end, few points need attention.

(1) Firstly, we must realize what it means to be a fundamental consequence of a law of thermodynamics, the branch of science largely derived from and directly related to practical applications almost never turning a hair to the otherwise common (and sometimes comfortable!) seat called 'an exception'.

(2) Entropy must be understood in the spirit that it is experimentally determinable (unit of entropy is $J\ K^{-1}$ in SI). If so, we must question our understanding and capability of being able to measure something called 'disorder or randomness'.

(3) The above point intrinsically fetches the query (worry!) of assigning an apt unit to randomness on the basis of a scientifically sound notion.

(4) Regarding entropy we must also ask ourselves the very fundamental questions: 'Do we really understand properly what randomness is all about? How and how far is randomness connected to entropy?' A comparatively better approach toward the conceptualization of entropy (at least initially) should be to underscore its relation to unavailable work and its subsequent physical interpretation.

So to state in very simple terms, one consequence of the second law of thermodynamics is that the entropy of the universe can never decrease. In other words, the universe is on an inevitable route toward increasing disorder. Primarily, it is largely due to this unidirectional (one-way traffic!) property of entropy that is invoked to lay the grounds for realizing that time only flows one way, the forward direction (always into the future!). Such connection of entropy to time ignites one's natural inquisition if it is a fundamental property of nature, or even something deeper having the potential of explaining the core reality?!

Scottish Physicist James Clerk Maxwell (1831–1879) came up with a thought experiment in which the entropy of the closed could be reversed eventually violating the second law of thermodynamics. This paradox remained unresolved for a period of more than a century when finally researchers in computer science from IBM, Rolf Landauer (1927–1999) and Charles Benneth (1943–) resolved the paradox showing that entropy is related to something even more fundamental, the information.

Before getting into the scenario let's consider the motion of a planet orbiting around the sun. If we, for a moment, think of the motion of

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the planet in the reverse direction, we would arrive at nothing impermissible by the laws of Physics. Similarly, if we consider the motion of flow of a river in a direction opposite to what we observe in nature, no objection from the laws of Physics would be in our way, except that our practical experience would oppose these views as they are seemingly impossible (not observed!). As far as we know, the fundamental laws of Physics, or to say the Physical laws, are time-reversible. The only fundamental law that appears to be irreversible in time is the law of increasing entropy, the second law of thermodynamics. Our practical experience would never allow room for an observation in the likes of spontaneous flow of river in opposite direction or a cup of cold coffee receiving heat from the surroundings and getting hot on its own.

According to the second law of thermodynamics, the entropy is not allowed to decrease for a process in an isolated system. However, this statement hardly leads us to an intuitive and/or visual interpretation of what entropy is. As an example, let us consider that only half of a container is filled with gas and the rest of half is empty because of the presence of an impermeable partition (situation a in the diagram below). Now, the partition is removed and the gas is allowed to occupy the entire volume of the container (say at fixed temperature).

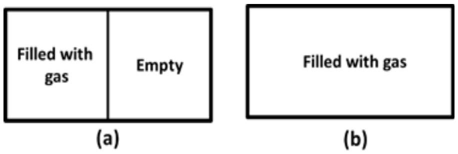

Figure 1: Expansion of gas into vacuum (schematic diagram).

Naturally, one would view this process as to accompany an increase of entropy because in a larger volume the randomness of the gas molecules is supposed to be higher: increase of volume makes room for greater number of ways of arrangement of the gas molecules, and it is in connection with this increase of number of ways of arrangement that the increase of entropy in the process can be better accounted for. This extraordinary visualization of the concept of entropy was introduced by the Austrian Physicist Ludwig Boltzmann (1844–1906).

Now, let us think of the process described in the diagram given below in which the filled chamber is pushed from one side by a piston to reduce the volume of the gas to half.

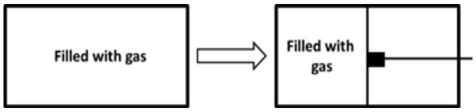

Figure 2: Compression of gas with the aid of external agency (schematic diagram).

The question here is whether the reduction of volume of the gas to half in this process would accompany lowering of entropy. The answer to this question is to cover both the following points: (i) Decrease of entropy due to compression (lowering of volume) (ii) Increase of entropy due to increase of temperature because the process described above would require investment of work into the system (whereby raising the temperature of the gas in the smaller volume in its final state). The fundamentally more important point in this context is to realize that the rationale for increase of entropy with increasing temperature is connected with the increase in number of ways the motions of the gas molecules can be described (the gas molecules acquire higher kinetic energy at an elevated temperature). At this stage we feel prone to ask whether it is possible that the gas molecules in the filled container would spontaneously move in a way as to arrange themselves in only one half of the container (with the aid of no extrinsic agency). Apparently, we may feel like being driven to think of this scenario as an impossibility on the basis of violation of the second law of thermodynamics, but the truth is that there is no law of Physics that would apparently prevent this phenomenon except that the probability of its occurrence is exceedingly tiny. This argument establishes us on the ground of realization that the second law of thermodynamics is not an absolute law in itself, but a statistical law. In simpler terms, we may feel inclined to say that it is not absolutely impossible to violate the second law of thermodynamics, but it is overwhelmingly unlikely to occur, and it is imperative to note that this is all that thermodynamics requires. In 1867, a thought experiment was devised by J. C. Maxwell that provoked the risk of violation of the second law of thermodynamics, and continued to remain so for more than a century. Rightfully, this was termed as 'Maxwell's Demon' by the British Physicist Lord Kelvin (1824 – 1907). Let us imagine a chamber with a divider in the middle. The question here is whether the reduction of volume of the gas to half in this process would accompany lowering of entropy. The answer to this question is to cover both the following points: (i) Decrease of entropy due to compression (lowering of volume) (ii) Increase of entropy due to increase of temperature because the process described above would require investment of work into the system (whereby raising the temperature of the gas in the smaller volume in its final state). The fundamentally more important point in this context is to realize that the rationale for increase of entropy with increasing temperature is connected with the increase in number of ways the motions of the gas molecules can be described (the gas molecules acquire higher kinetic energy at an elevated temperature).

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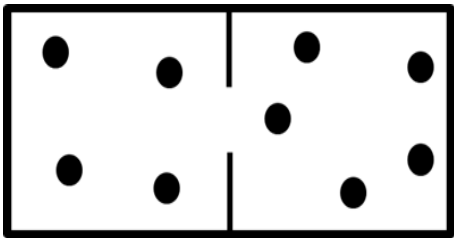

Figure 3: A gas chamber with a divider (schematic diagram).

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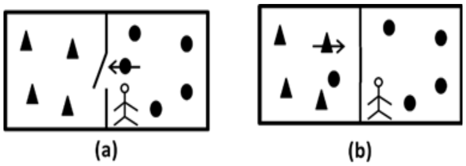

Figure 4: A gas chamber with a divider controlled by a demon (schematic diagram).

Here, the demon is intelligent enough to control the movement of the molecules in one direction only. The demon lets the window open for molecules traveling from the right (solid circles) to the left chamber (solid triangles) only, and thus the gas molecules are granted passage for travel from right to left only (situation a in the above diagram), no molecules traveling from the left chamber to the right can acquire the required passage from the demon (situation b in the above diagram). (So to say, visa is granted for travel from right to left only, and visa is denied for travel in the reverse direction under all circumstances, Figure 4). Different symbols, namely, solid triangle and circle are used only to distinguish between the gas mole-

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The number of symbols representing the gas molecules are only very few, the number is to be taken only for an illustrative purpose]. Let this scenario continue over time and one would certainly observe that all the gas molecules, at some point in time, are collected in the left chamber. However, no work was added to the system and the temperature remained the same throughout the process. Consequently, the decrease of volume of the gas to only one half (the left chamber, Figure 4) appears to conform to decrease of entropy of the system with no aid from extrinsic agency whereby violating the second law of thermodynamics (apparently). Well, an obvious reply to this paradox could be based upon its very nature of being imaginary. Nevertheless, the problem does not cease to bother an inquisitive mind especially in today's time when we are living in an era of astonishing technological advancement. With the concepts of nano-robotics, cules microprocessors pushing the frontiers of modern science, it is not exaggerative to conceive that in the near future we might be presented with a computer-controlled device imitating the little demon in J. C. Maxwell's thought. Consequently, the paradox offered by the thought experiment could not be disproved. In 1982, Rolf Landauer and Charles Benneth finally came up with a solution to this paradox in which entropy was linked to a fundamental idea, that is, information. Landauer and Benneth argued that in order for the above process to take place the demon has to be smart enough to gather information to be accurate as to when to open the window and when to close it. In the process, a memory record is being built up in the demon's brain (!) and gathering information leads to an increase of entropy of the system because the demon itself is part of the system. They indeed showed that the decrease of entropy of the system due to decrease of volume is exactly compensated by increase of entropy due to increase of information in the demon's brain. Well, at this stage one may argue that the memory in the demon's brain could, in all possibilities, be erased off (decrease of information and hence entropy) if it is a computer-controlled device. The point to remember at this argument is that even erasing a memory (if the demon's brain is a device equivalent to a computer hard disk) is not achieved free of cost, rather is associated with generation of heat energy and hence increase of entropy. The amount of heat generated might well be too small to be measurable with our available instruments/ equipment, but what is more fundamental to realize is that the entire process is in keeping with the second law of thermodynamics (decrease of entropy due to loss of information when the hard disk memory is formatted or erased is exactly counter-balanced by the increase of entropy resulting from generation of heat). The above argument aiding to the resolution of the more than a century-old paradox also reveals a clue to a more fundamental understanding of entropy, which describes entropy in terms of the measure of information required to describe a system/ the state of a system. The higher entropy state of a system conforms to a state when an appropriate description of the microstates of the system would require greater amount of information. Note that this description of entropy in terms of information required to express the state of a system is aptly commensurate with our understanding of increase of entropy with rise of temperature or increase of volume. Overall, it is perhaps not about the degree of disorderliness in entropy rather the disorderliness in our concept about entropy. At this stage, we are confronted with the obvious question of how time does make its entry into the picture. How is time connected to entropy and information? Considering all the laws of Physics, we get to realize that they are symmetrical (reversible) with respect to time; as a result, there does not appear to have a reason to justify that time would be asymmetrical (irreversible) except, of course, through the concept of entropy the flow of which is unidirectional – toward the higher value. Also imperative to note is that the property of the universe that changes with time is its entropy. Motivated by this connection, British astrophysicist Sir Arthur Edington (1882 – 1944) postulated entropy as the 'arrow of time'. So to say, this statement might well invite the inquest if it is because of increase of entropy that time always marches forward. This is indeed not very well understood. In its capacity of being developed into a theoretical idea too, it is not very well received within the scientific community. The underlying reasons are pretty simple because it is not difficult to observe premises within our surroundings in which decrease of entropy is common. For example, the entropy inside a refrigerator undergoes a decrease (no violation of the second law of thermodynamics considering the system in entirety), the entropy of the Earth at night is lower; nevertheless, no one has ever observed time to flow backward in such premises. Consequently, the fundamental question of unidirectional flow of time always into the future remains unresolved.

At this point, it is necessary to keep in mind that the fact of increase of entropy is conveyed by one fundamental law of Physics but the fact is not governed by the law. In simpler terms, we cannot look into the scenario with a preoccupied mindset that the increase of entropy is simply due to some fundamental law; rather the number of ways of arrangements of the microstates in the future is greater than those are in the past. So to say, our universe is more likely to be in a state of higher entropy in the future than in the past, that is, the amount of information required to describe the system in the future is greater. Now, with a view to the fact that entropy is fundamentally a statistical law, the natural inquisition we feel is whether time can also be described in statistical terms, that is, the probability of flow of time in the forward direction (into the future) is significantly higher. This view, interestingly, does not negate the possibility of a backward flow of time, of course along with the constraint that the probability of flow of time in the backward direction (into the past) is statistically exceedingly thin. If entropy increases with the passage of time, this should imply that entropy must have been at its lowest possible state at the time of inception of the universe (the Big Bang!). This idea, popularly known as the 'Past Hypothesis', appears to offer a clue to the understanding of unidirectional forward march of time in terms of this low entropy start. A low entropy state of the universe at the start would obviously imply a very ordered state for the universe at the beginning. Now the question is why it had to be so, given all the energy and matter accessible to the universe why at all it had to choose a state of low entropy (high order) out of the enormous number of possible states it could have been in. An unequivocal answer to this question is unknown, yet a number of leading ideas attempt to address the matter. Maybe it has something to do with a fundamental property of the universe (like the fundamental constants), something that we have not yet been able to discover, or maybe there is something deeper which we have till date been oblivion to. American Theoretical Physicists Alan Guth at MIT (1947-) and Sean Carroll at CalTech (1966-) came up with the proposition that if there is upper limit to entropy (if it is infinite) then irrespective of the question of where the universe came into being, it is not impossible to fathom that at the beginning it would have been in a low entropy state following which it has no other option but to go into a state of higher entropy with the passage of time. If it is such that time passes only into the future (forward march) and entropy increases (forward march), it must be understood that our existence is in turn is a consequence of the second law of thermodynamics, a state of thermal equilibrium for the universe would then have denied our existence, denied our causality and hence the evolution of the race of every living organism we know of. As a matter of fact, in the absence of our causality, we could have never our consciousness: according to Alan Guth the very existence of our memory and consciousness is to be attributed to the increase of information (and hence entropy) in our brain. Consequently, entropy will continue to increase for forthcoming billions and billions of years until all the galaxies have expanded apart, all the stars have been exhausted of their fuel, dark energy has engulfed in all matters and even sub-atomic particles leading to the attainment of thermal equilibrium at some point in time (at least locally in our coordinate space within the universe). At this point, the inevitable increase of entropy may cease, but there will still remain the existence of space in the universe. According to the fundamental laws of Physics at that point, there will remain quantum fluctuations in the 'fabric of spacetime' (the uncertainty!!), and with the passage (or lapse!) of sufficient length of time (direction?) the random energy fluctuations within the vast empty space would lead to spontaneous formation atom(s), even molecule(s), even interstellar objects according to the laws of statistics in a time period of around 10^(10^(10^(10^120))) years even a whole universe could be formed, if we could wait for an eternity, we would, without a grain of doubt, be the luckiest people in existence to include this inevitable into our observation and experience!!

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Author's brief biography

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