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On the Occasion of International Light Year

Light and Information

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Light is not just the major source of energy that supports life and it is also a very viable information carrier. In this article, we showed that there is an intimate relationship between information and light as a carrier. We discussed the Uncertainty Principle of Heisenberg as related to information, in which we showed that every bit of information (or quanta of light) is limited by an unit cell of information and it is associated with a cost of entropy. Examples are given within the limit and beyond the Uncertainty Principle. We have shown that time and frequency resolutions cannot be observed simultaneously and yet the imaging can also be obtained within the limit of Certainty!

1 Light as An Information Carrier

In physical world, light is not only part of the mainstream energy that supports life; it also provides us with an important information carrier. One can imagine that without light, the human civilization would never take place! Furthermore, humans are equipped with a pair of exceptionally good, although not perfect, eyes. With the combination of our intelligent brains and remarkable eyes, humans were able to advance themselves above the rest of the animals in this planet earth. In the presence of light, humans are able to search for the food they need and the art they enjoy, and to explore the unknown. Thus light has provided us with a very useful information carrier. The purpose of this article is to show a few key relationships between light and information.

Let us now define information measure from a probabilistic stand point, as formally accepted: For example, the more uncertain a message that we anticipate to occur, the higher the amount of information the message contained. In short, an optical communication system can be represented by a block diagram shown in Fig 1.

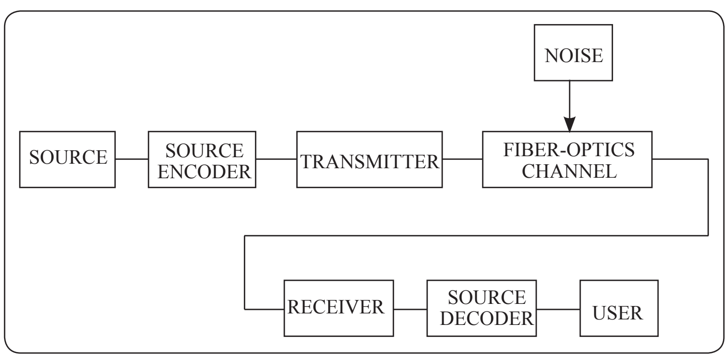

Fig 1. Block diagram of a digital light communication system.

We assume a message (either temporal, spatial, or both) to be sent via the fiber-optics channel, first we need to convert the message into digital-light form before the transmission. And after the signal is received, it has to be properly decoded for the user; otherwise the user may not understand the message!

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Strictly speaking there are two types of information transmission strategies; one was developed by Wiener [1], and the other by Shannon [2]. Although both Wiener and Shannon share a common though of extracting signal from noise, but there is a basic distinction between them. The significance of Wiener's communication is that, if a transmitted signal is corrupted by some physical means (e.g., noise, nonlinear distortion), it may be possible to recover after the effect of corruption. It was for this purpose Wiener developed the correlation detection, optimum prediction, matched filters and others. On the other hand, Shannon's signal transmission carried a step further. He advocated that signal can be optimally transmitted provided it was properly encoded. In other words, the signal can be processed before and after the transmission. It was precisely what Shannon developed the theory of information. One of the major aims in Shannon's theory is; the efficient utilization of the communication channel. Nonetheless both Wiener and Shannon shared the same objective; namely faithfully reproduction of the signal! Yet, it was Shannon's binary coding idea enabling us of developing the modern digital computer and communication! Let us now start with an input-output information channel as shown in Fig 2,

Fig 2. An input-output communication channel.

In which we denote the input and the output ensembles respectively; $A = \{a_i\}$ and $B = \{b_j\}$, where $i = 1, 2..., M$ and $j = 1, 2, ..., N$. Then the amount of information (or information measure) provided at the input and the output ends can be written as

$$I(a_i) \triangleq -\log_2 P(a_i) \text{ bits}$$

$$I(b_j) \triangleq -\log_2 P(a_j) \text{ bits}$$

where $P(a_i)$ and $P(a_j)$ are the probability measure of input and output events a_i and a_j, respectively.

Then the information provided at the output event b_j with respect to the input event a_i can be written as

$$I(a_i; b_j) \triangleq -\log_2 \frac{p(a_i, b_j)}{p(a_i)} \text{ bits}$$

Where $p(a_i, b_j)$ is the conditional probability of depending upon a_i. And this is precisely the information measure defined by Shannon [2] as the mutual information (or the amount of information) transferred between event b_j and a_i.

2 Finite Bandwidth and Uncertainty Principle

Strictly speaking, all physical systems are finite bandwidth systems. A low-pass system is defined as a system that possesses a nonzero transfer characteristic from zero frequency to a definite frequency. Since the analysis of a band-pass system can be easily reduced to the case of an equivalent low-pass system, we restrict our discussion to only the low-pass analysis. Let us now provide a low pass system shown in Fig 3.

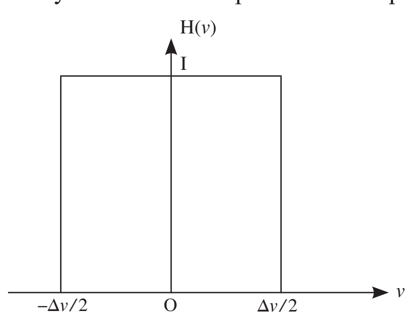

Fig 3. An idea low-pass filter.

And it's transfer function is written as

$$H(\nu) = \begin{cases} 1 & |\nu| \le \Delta\nu / 2 \\ 0 & |\nu| > \Delta\nu / 2 \end{cases}$$

If the input signal to this low-pass system has a finite time-duration of Δt then to have a good output reproduction of the input signal, it is required the system bandwidth Δv be greater than or at least equal to $1/\Delta t$ that is

$$\Delta v \ge 1/\Delta t$$

where $1/\Delta t$ is known as the input signal bandwidth. Alternatively we can write the following relationship:

$$\Delta v \,.\, \Delta t \ge 1$$

This is known as the Uncertainty Principle as related to the Heisenberg's Uncertainty Principle in Quantum Mechanics as given by

$$\Delta x \,.\, \Delta p \ge h$$

where Δx and Δp are the position and momentum errors, respectively, and h is the Planck's constant. The Heisenberg Uncertainty Relation can also be written in the form of energy and time variables;

$$\Delta E \,.\, \Delta t \ge h$$

where ΔE and Δt are the corresponding energy and time deviations. Thus one may see that every bit of information takes time and energy to transmit, to process, to record, to retrieve, to learn and to assemble!

3 Gabor's Information Cell

In 1946, Gabor [3] published a paper entitled "Theory of Communication" in the Journal of the Institute of Electrical Engineers", about 2 years before Shannon's [2] classical article, "A Mathematical Theory of Communication," appeared in the Bell System Technical Journal" [4]. Several of Gabor's concepts on information aspects were quite consistent with Shannon's theory of information. Here we briefly illustrate one of his concepts in information as related to the Heisenberg's Uncertainty Principle. Let us look at a frequency and time plot shown in Fig 4.

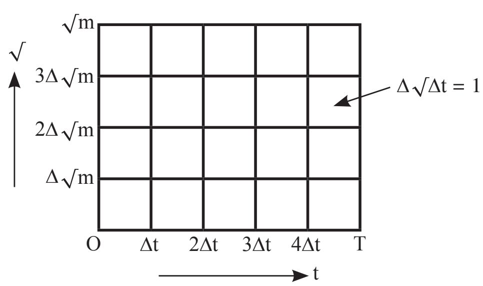

Fig 4. Gabor's information cell.

with v_m and T are the frequency and time limits of a time-signal. Notice that this frequency-time plot can be subdivided into elementary information elements or cells, as Gabor called them Logons, as given by

$$\Delta v \,.\, \Delta T = 1$$

In which we see that it is essentially the lower bound of the uncertainty relation. By referring to Fig 4, the plot can contains

$$N' \,.\, v_m T$$

numbers of information cells. Nonetheless that signal within each of the cell can accommodate two possible elementary signals, symmetric and anti-symmetric signals (i.e., orthogonal signals). Thus we see that the total number of information cells would be twice the numbers, as given by

$N = 2N' = 2v_m T$

Notice that the shapes of the information cells are not particularly critical, it is however the unit area $\Delta v \,.\, \Delta t = 1$. As for the elementary signals, Gabor has proposed of using use of Gaussian cosine and sine wavelets shown Fig 5,

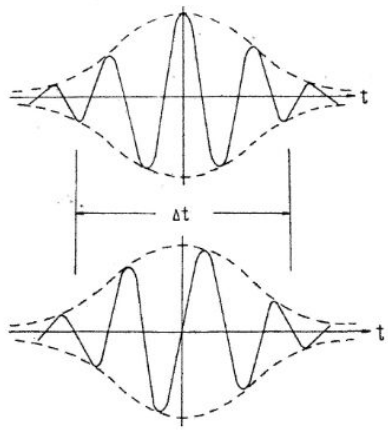

Fig 5. Gaussian envelop; cosine and sine elementary signals.

We further note that each information cell is in fact the lower bound of the Heisenberg Uncertainty Principle in Quantum Mechanics:

$\Delta E \,.\, \Delta t \geq h$

We emphasize that the band-limited signal must be a very special type. For which the function has to be well behaved; it contains no discontinuity, no sharp angles and has only rounded-off features. This type of signals must be analytic functions!

Let me now provide a pair of practical examples to show that the Uncertainty Principle indeed holds as depicted in Fig 6,

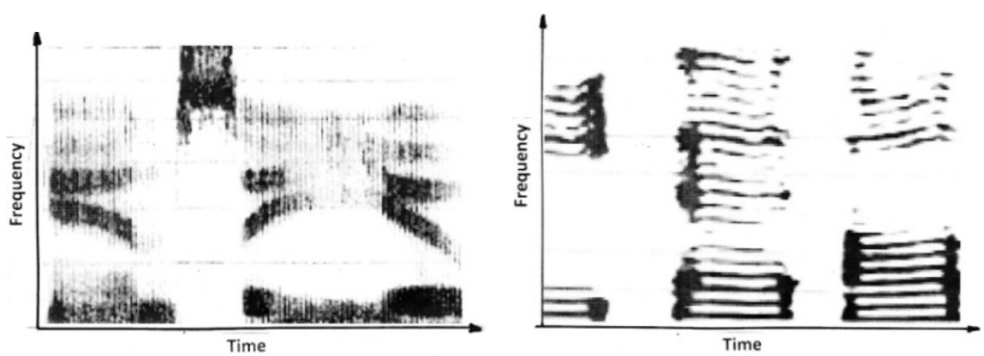

Fig 6. Wide-band and Narrow-band Sound Spectrograms

On the left hand side we show a wide-band sound spectrogram in which the time resolution Δt (i.e., time striation) can be easily seen with the expense of finer frequency resolution Δv. On the other hand as we view the narrow-band analysis on the right-hand side, we see finer spectral resolution Δv can be achieved at the expense of the time striation Δt! In view of these results, we notice that the observations are quite consistent with Uncertainty Principle's prediction; one cannot resolve (or observe) the frequency resolution Δv and the time resolution Δt simultaneously [5] !

4 Certainty Principle and Coherence Theory

Notice that if one reverses the inequality of the Uncertainty Principle as written by

$$\Delta t \, \Delta v < 1$$

it is reasonable to name the preceding inequality "Certainty Principle", as in contrast with the Uncertainty Principle. This means that when the light beam (e.g., the signal) propagates within the time resolution Δt, the complex light field preserves a high degree of certainty! Thus, as the bandwidth Δv of the light beam becomes narrower, the signal property is self preserving (i.e., unchanged) within a longer time window Δt, or vise versa! This is in fact precisely the temporal Coherence limit of the light beam (or signal). If one multiplies the preceding certainty inequality with the velocity of light c, we have

$$c \, \Delta t < c/\Delta v$$

which is essentially the **Coherence length** (or **certainty distance**) of a signal beam (or light source), as written by

$$\Delta d \leq c/\Delta v$$

This means that within the coherence length Δd**,** the transmitted signal is highly correlated with the original signal within a time window as can be expressed by the Mutual Coherence Function [6] as given by

$$\Gamma_{12}(\tau) = \lim_{\tau \to \infty} \frac{1}{T} \int_0^T u_1(t + \tau) u_2^*(t) dt$$

where $\tau < \Delta t$,* denotes the complex conjugate, u_1 is the original signal before u_2*. And the degree of certainty (i.e., mutual coherence) can be determined by the following equation:

$$\gamma_{12}(\Delta t) = \frac{\Gamma_{12}(\Delta t)}{[\Gamma_{11}(0)\Gamma_{22}(0)]^{1/2}}$$

As regarded earlier, the shape of information cell (i.e., $\Delta t \, \Delta v$) is not a critical issue, as long it is within a unit-cell. Notice that, it is this unit region that has not been fully exploited as applied to signal transmission, information processing, measurement and imaging. Nevertheless I will show a couple of examples to illustrate that within the Certainty Region, $\Delta t \, \Delta v < 1$, imaging can be actually exploited!

One of the successful applications within the Certainty Regime (i.e., Certainty Principle) must be due to the Wave Front Reconstruction (i.e., Holography) of Gabor [7]. We may know that a successful holographic construction is much depending on the coherence length (i.e., Temporal Coherence) of the light source. This light source provides the constraint that the object beam and the reference beam are mutual coherent. Otherwise the complex wave front would not able to be properly recorded on a photographic film. Another example is applying to synthetic aperture radar (SAR) imaging. The returned radar signal is required to be combining with a highly coherence local signal, so that the complex distribution of the returned radar wave front can be synthesized on a square-law medium.

Now let me provide two wave front recording examples, shown in Fig 7.

Hologram image

SAR image

Fig 7.

Notice that these results were obtained owning to the operation within the Certainty Regime (i.e., coherence length limit Δd). On the left we show a holographic image that was reconstructed from a hologram, which was recoded within the coherent length (Δd) of a laser (i.e., light source). This guaranty that the object and reference beams were coherently encoded on a photographic film. On the right hang side we posted a radar imagery that was obtained from a synthetic aperture format [8], which was synthesized by a series of reflected radar signals with a mutually coherent local signal. We further note that, some micro wave radar has a very narrower bandwidth, and its coherence length Δd could be over hundreds of thousands of feet!

5 Uncertainty Principle and Relativity

Since every bit of information is limited by the Uncertainty Principle;

$$\Delta v \cdot \Delta t \geq 1$$

in which we see that the spectral resolution and time resolution can be traded. In other words it is the unit cell, but not the shape of the cell, sets the limit. Now let us take the Relativity Theory's Time Dilation equation [9] as written by,

$$\Delta t' = \frac{\Delta t}{\sqrt{1 - v^2/c^2}}$$

where $\Delta t'$ is the dilated time window, Δt is time window, v is the velocity and c is the speed of light. Now if we assume the observer is travel at a velocity v and the observer is aiming at an experiment with zero velocity i.e., v = 0. Then we would use $\Delta t'$ instead of Δt as applied to the Uncertainty Principle as given by,

$$\Delta v \cdot \Delta t' \geq 1$$

Since the dilated time window $\Delta t'$ is larger than Δt, that is

$$\Delta t' \geq \Delta t$$

We see that a finer spectral resolution limit Δv, in principle, can be obtained. In other words when the observer travels at a velocity of v and he is aiming at the changes of an experiment with a velocity $v = 0$, then he would have a larger time window limit $\Delta t'$, instead of Δt , for observing the experiment.

It is interesting to note that, as the velocity of the observer v approaches to the speed of light (i.e., $v \to c$), then $\Delta t' \to \infty$ the time window $\Delta t'$ would become very large (i.e., $\Delta t' \to \infty$)! This means that the observer, in principle, can observe the experiment as long as he wishes, while he is travelling at the speed of light! In this case the observer would have, in principle, infinitesimal spectral resolution (i.e., $\Delta v \to 0$).

On the other hand, if the observer is standing still at v=0 and observing an experiment which is traveling at velocity v, then the time window would be,

$$\Delta t = \Delta t' \sqrt{1 - v^2/c^2}$$

By substituting Δt in the Uncertainty relation $\Delta v \cdot \Delta t \geq 1$, we see that a broader spectral resolution limit Δv is expected, since $\Delta t \geq \Delta t'$ in this case.

Again, If the velocity of the experiment is approaching the speed of light (i.e., $v \to c$), then the observer would have no time to observe since $\Delta t \to 0$. And the spectral resolution limit would be infinitely large (i.e., $\Delta v \to \infty$) !

Let us now look at the Heisenberg principle, which can be written in several forms, as follows;

$$\Delta E \cdot \Delta t \geq h$$

$$\Delta p \cdot \Delta x \geq h$$

We notice again that, the limitations are not by the shape but the constraint of the Plank's Constant h. Similarly one can show that the energy resolution ΔE and the time resolution Δt can be traded; as well the momentum resolution Δp and the position resolution Δx are interchangeable. This depends upon where the travelling-observer and the experiment are located.

One final though is that, by reversing the Heisenberg Uncertainty Principle as we have shown earlier named it as Certainty Principle (i.e., $\Delta v \cdot \Delta t \le 1$) . This means that within the unit information cell, the observation is at high degree of certainty.

We have provided two preceding illustrations shown that exploiting the certainty principle (i.e., within the unit information cell) were possible, namely the complex wave front construction for holography and synthetic aperture radar format. For these reasons it is rather encouraging to see, in the future, more applications within the Certainty Principle for signal processing, detection, imaging, measurement and others will emerge! It is not just only limited to the certainty relation of $\Delta v \cdot \Delta t \le 1$, it can also be applied in the following certainty relationships;

$$\Delta E \cdot \Delta t \le h$$

$$\Delta p \cdot \Delta x \le h$$

We further note that, the application of certainty relation is not just limited to low velocity condition; it can also be applied in very high speed relativistic regime!

6 Information and Entropy

We note again, the information measure is strictly defined from a statistical stand point. Let us now consider an information source has N possible outcomes. If these possible outcomes are assumed to be equal in probability (or equiprobable), then the average amount of information provided by the information source is

$$I_0 = -\sum_{j=1}^{n} P_j \log_2 P_j = \log_2 N \text{ bit/outcome}$$

where $P_j = l/N$. Now let us assume an amount of information I is acquired by some means and it is possible to reduce to a smaller set of outcomes M. If we again assume that the M outcomes are equiprobable, then the average amount of information provided by the M outcomes is

$$I_0 = -\sum_{j=1}^{M} P_j \log_2 P_j = \log_2 M \text{ bit/outcome}$$

where $P_j = l/M$, and $N > M$. Thus we see that the amount of information required for this information reduction is

$$I = I_0 - I_1 = \log_2 \frac{N}{M} \text{ bits/outcome}$$

Let us now seek a relationship between information and entropy [10] of which we consider mainly only information provided by some physical means so that entropy theory can be easily treated. In order to derive the relationship between information and entropy we turn to a physical system in which equal probability in complexity of the structures has been established, a priori. Now let us get back to the previous example (where the N possible outcomes have been reduced to M) and assume the system cannot be isolated, since the second law of thermodynamics prevails. The corresponding entropies for the N and M equiprobable outcomes or states are given respectively by

$$S_0 = k \text{ In } N$$

And

$$S_1 = k \text{ In } M$$

where $N > M$, and k is the Boltzmann's constant. Thus we have

$$S_0 > S_1$$

It can be seen that the system entropy can be reduced, if and only if an amount of information I is acquired at the expense of some external source. Thus we have,

$\Delta S = S_1 - S_0 = -kI \text{ In } 2$

Or equivalently,

$S_1 = S_0 - kI \text{ In } 2$

However, the information I is required to be proportional to the decrease in entropy ΔS. This is the basic connection between entropy and information. Thus we see that the information and entropy in principle can be simply traded!

By the second law of thermodynamics, if we isolate the entire system, which includes sources of I, then for any further evolution within the whole system the entropy will increase or remain constant:

$\Delta S_1 = \Delta(S_0 - kI \text{ In } 2) \geq 0$

Thus we see that any further increase in entropy ΔS_1 is due to ΔS_0 or ΔI or both. Although in principle it is possible to distinguish the changes in ΔS_0 and ΔI, but in some cases the separation of the changes may be difficult to discern.

It is interesting to note that, if the initial entropy S_0 of the system, without the influence of external sources, we have

$\Delta I \leq 0$

since $\Delta S_0 = 0$, thus we see that the changes in information ΔI were negative, or decreasing. The interpretation is that, when we do not have a prior knowledge of the system complexity, the entropy S_0 is assumed maximum (i.e., the equiprobable case). Hence the information provided by the system structure is maximum. Therefore $\Delta I \leq 0$ is due to the fact that, in order to increase the entropy of the system, $\Delta S\ S_1 > 0$, a certain decrease in amount of information is needed. In other words, information can be provided or transmitted (a source of negentropy) only by increasing the entropy of the system. However, if the initial entropy S_0 is at a maximum state, then $\Delta I = 0$ and the system cannot be used as a source of negentropy. This illustrates that entropy and information can be interchanged, at the expense of some external source of entropy, as given by;

$\Delta I \leftrightharpoons \Delta S$

7 Digital transmission at Light Speed

In this information age, most of the people including some engineers and scientists, know how the digital (e.g., 0 and 1) system operate, yet some of them may not know why we developed it? Let me start with the major differences between the digital and analog system as follows:

Digital system operates in binary form (i.e., 0, 1) while analog system operates in analog form (i.e., multi-level), digital system provides lower information content (e.g., one bit per level) while analog system provides higher information content (e.g., more bits per level), and others. Since the information content of a digital system is lower than an analog system, why does one go through all the troubles to transform the analog to digital and then to transform back to analog for the receiver? The answer is that by exploiting the transmission at velocity of light**,** which can carry a lot of information at that speed. And it is precisely the price paid for the transmission.

Remember that although the major purpose of using digital transmission firstly was for noise immunity in binary-signal transmission, otherwise, we won't pay for a longer data rate transmission in digital form. The reason is that, in digital transmission, the signal can be easily repeated, as in contrast with analog-signal transmission, it cannot. One may see that, after a few cycles of amplifications, an analog-signal will be completely swallowed up by the noise. While in digital-signal transmission, the transmitted signal can be easily refreshed by means of repeaters. Thus, a digital-signal can be transmitted over thousands and thousands miles, and the received signal is just as good as the original! As an example, if one consecutively copying a compact disc or a DVD for many times, one would discover that the latest copy is just as good as the original one! Although the digital-transmitted signals strictly speaking are not real time, but it appears to be very close to real-time because of the light speed transmission! And this is precisely the price we paid for the transmission at the speed of light!

8 Diffraction-Limited Demon Exorcist

The sorting demon of Maxwell has intrigued scientists and engineers for some time. Maxwell's demon is an excellent example for the application of entropy theory of information. Since we are in the computer age, we will extend Maxwell's demon to a diffraction-limited regime in which we assume that the demon has a diffraction-limited eye and he is operating within a thermally insulated chamber [11], as shown in Fig 8.

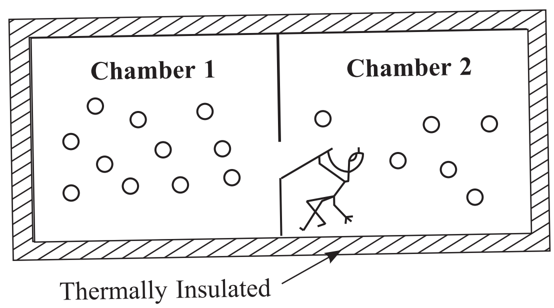

Fig 8. Diffraction limited demon exorcist.

Since the demon is within the thermally insulated chamber, in order for him to see the molecules we equipped the demon with a Light Emitting Diode (LED) for the illumination. Thus by using the negentropy provided by the LED, the demon can see the molecules for which the demon is able to let the molecules go through the trapdoor. In this manner, he is able to decrease the entropy of the chamber from a higher entropy state to a lower one. However, a question may be asked: How can the demon actually see individual molecule since he is diffraction limited and added he is located within a thermally insulated environment? To alleviate these limitations, we added the demon with a computer to assist him for the processing. To see the arriving molecules, the demon first turns on the LED, which is required to emit at least a quanta of light for the observation, that is,

$$h\nu = kT$$

We assume that the quanta of light reflected by the approaching molecules is totally absorbed by the diffraction limited eye of the demon, this corresponds to an increase of entropy that is

$$\Delta S_d = \frac{h\nu}{T}$$

This is equivalently to the amount of information provided to the demon, that is,

$$I_d = \frac{\Delta S_d}{k \ln 2}$$

Because of the diffraction-limited nature of the demon's eye, he needs to process the absorbed quanta to a higher resolution, so that he is able to resolve the molecules to allow the passages of the high- and low-energy molecules through the trapdoor. However the amount of information gain, through the processing by the equipped computer, constitutes an equivalent amount of entropy increased as given by

$\Delta S_d = k\, \Delta I_d \ln 2$

And this is the incremental amount of information gain from the computer so that the demon is able to reduce the entropy of the isolated chamber to a lower state. To compute the amount of entropy reduction by the demon's intervention, we let the initial entropy of the chamber be

$S_0 = k \ln N_0$

where N_0 is the initial microscopic complexity of the chamber. After receiving I_d from the LED illuminator and ΔI_d from the computer processing, the demon is able to reduce the initial complexity from N_0 to N_1,

$N_1 = N_0 - \Delta N$

where ΔN is the net changed in complexity. Thus the final entropy of the chamber is given by

$S_1 = k \ln N_1$

For which the net entropy reduction of the chamber is

$$\Delta S_1 = S_1 - N_0 = k \ln \left(1 - \frac{\Delta N}{N_0}\right) \approx -k\, \frac{\Delta N}{N_0}$$

where $\Delta N < N_0$. And the overall net entropy changed in the chamber per trapdoor operation by the demon can be shown as

$$\Delta S = \Delta S_d + \Delta S_p + \Delta S_1 = k \left(\frac{hv}{kT} + \Delta I_d \ln 2 - \frac{\Delta N}{N_0}\right) > 0$$

where we see that the diffraction limit demon's exorcist is still within the limit of the second law of thermodynamics!

There is however a question remains unanswered: What would be the minimum cost of entropy required for the demon to operate the trapdoor? Let the arrival molecules at the trapdoor at an instant be one or more molecules, then the computer is required to provide the demon with a "yes" or a "no" answer to open the trapdoor. If we assume a 50 percent chance of one molecule is arriving at the trapdoor, the demon needs one bit of information from the computer, to open the trapdoor. This additional bit of information represents an entropy increase provided by the computer, i.e.,

$\Delta S_p = k \text{ In } 2 \approx 0.7k$

And this is the minimum cost of entropy required for the demon to operate the trapdoor. Thus we see that the overall net entropy increased in the chamber is

$$\Delta S = k \left(\frac{hv}{kT} + 0.7 - \frac{\Delta N}{N_0}\right) > 0$$

However if we take into account the other bit of "no" information, provided by the computer, then the average net entropy increased in the chamber per operation would be

$$\Delta S_{ave} = k \left(\frac{2hv}{kT} + 1.4 - \frac{\Delta N}{N_0}\right) >> 0$$

where two quantas of light from the illuminator were paid for. It is trivial, if one includes the slower molecule approaching the trapdoor, the average cost of entropy per operation is even higher. Even though we omitted the two quantas of light absorption in the calculation, the overall net entropy changed in the chamber is still increasing by

$$\Delta S_{ave} = k \left(1.4 - \frac{\Delta N}{N_0}\right) >> 0$$

where $\Delta N < N_0$. In other words, just for the entropy compensated by the computer is still higher than the entropy reduced by the demon. Thus we see that even just taking only the account of the computer compensation, the demon's exorcist is still within the second law of thermodynamics!

8 Conclusion

I would like to iterate again that light is not just the main stream of energy that support life; it is an important carrier of information. In principle every bit of information is limited by the Heisenberg Uncertainty Principle. Yet, we have shown that observation can also be obtained within the Certainty Limit, by means of coherent combination of signals. Since the information measure is related to entropy theory, information and entropy can be traded! In this context, we see that every bit of information is associated with a cost of entropy. And every bit takes time and energy to transmit, to process, to store, to retrieve, to learn and to assemble. And it is not free! In other words; one cannot get something from nothing there is always a price to pay, even by a simple observation. We have also shown one of the most significant aspects of light and information must be the exploitation of light velocity, in which a hugh amount of information can be transmitted at light speed! Finally we have shown a diffraction limited demon exorcist. Even equipped the demon with a powerful computer, the demon still cannot operate the trapdoor beyond the second law of thermodynamics!

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