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Margolus-Levitin Theorem Applied To Electromagnetic Waves

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ABSTRACT
According to Margolus and Levitin's Theorem (MLT) the highest speed with which a physical system can move to a state to another is directly proportional to its energy. It does not depend on the nature of the system but only the quantity of energy available for the computation.
If we apply MLT to physical systems as electromagnetic waves, we have that the higher their energy the higher their speed, and vice versa.
These results are confirmed by Heisenberg's Uncertainty Principle.
Keywords: *Margolus-Levitin Theorem(MLT); Photons(P_s); Electromagnetic Waves(EMW_s);momentum(**p**); Heisenberg Uncertainty Principle(HUP).*

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I. INTRODUCTION

Margolus and Levitin analysed*the maximum speed of dynamicalevolution* that a computer can reach counting the maximum number of distinct states that an isolated physical system can pass thorough in a given period of time. For a classical computer, this would correspond to the maximum number of operations per second. On the contrary "the minimum time needed for a quantum system to pass from one orthogonal state to another has also previously been characterized in terms of the standard deviation of the energy.Given a maximum energy eigenvalue(E_{max}), the frequency(ν) with which states can change should be bounded by Eq.(1)"(Margolus):

$\nu \leq \frac{E_{max}}{h}$(1),

where h is the Planck's constant. Given a fixed average energy(E), rather thana fixed maximum energy eigenvalue, there is a similar bound:

$$\nu \leq \frac{2E}{h} \quad (2).$$

This equation has the following interpretation: "In appropriate units, the average energy(E) of a macroscopic system is equal to the maximum number of orthogonal states that the system can pass through per unit of time. This is the maximum rate that can be sustained for a long evolution. The rate at which a system can oscillate between two states is twice as great. Let time(T) be the time it takes for an arbitrary quantum state to evolve into an orthogonal state"(Margolus). We will now show that, with a fixed average energy (E), it is always true that:

$$T \succ \frac{h}{4E} \quad (3).$$

As Margolus and Levitin wrote "this result is somewhat surprising, since earlier results gave a bound only in terms of the standard deviation of the energy(Δ_E):

$$T \geq \frac{h}{4\Delta_E} \quad (4).$$

This earlier bound would suggest that, given a fixed average energy(E), one could construct a state with a very large $\Delta_E$in order to achieve an arbitrarily short time(T)" (Margolus).

II. DISCUSSION

To this purpose we learn from Lloyd that "the Margolus-Levitin Theorem(MLT) states that the maximum speed with which a physical system (i.e.an electron) can move from a state to another is directly proportional to the energy of the system itself: it is a general result. The nature of the system is not important, nor the way it records or processes information: what really counts is the energy available for the computation.A medium computer contains electrons and atoms moving continuously as an effect of the thermic agitation. The thermic energy of an atom or an electron is more or less the same, it is proportional to the temperature, independently from the kind of particle in agitation. Thus, the maximum speed an atom or an electron can change its state (from 0 to 1, from here to there) is the same. MLT is not just qualitative, it also provides a specific formula to calculate the maximum commutation speed reachable in a physical system and the maximum number of commutation per second in a bit. If we apply the *MLT formula* to a medium particle we have that it can commutate a maximum of 30.000 billiards times per second. It is a speed much higher than the normal computer's, the latter, in order to commutate bits, load and unload condensers of electrons, continuously, taking a billiard as much the energy necessary to make a particle change its state. Though the energy is much higher, a classical computer is 10.000 times less fast than an atom. A quantum computer(QC), instead, always works at the maximum speed possible. MLT is always valid independently from the size of the system and the way the energy is used. We get from the MLT the maximum limit of the number of elemental operations which can be carried out every second, it does not depend on the way the energy is distributed in the system. Thus, if we use a certain quantity of energy to commutate 2 bits (rather than 1), the two operations will take place with half speed, since the energy available has halved. However, the two bits work in parallel, so the overall number of commutations, per second, is unchanged. If we divide the energy available in 10, 100, 1000 packages, distributing it to as many bits, the single operations will be slackened proportionally, though the total number of operations per second does not change" (Lloyd).All this agrees perfectly with MLT since, in a computer, just as in any physical system, *energy* and *velocity* are strictly correlated, with a directly proportional relation(Puccini 2011,c).

2.1 PHYSICAL CORRELATION between ENERGY and VELOCITY

We have considered physical systems represented by atoms or electrons. Let's try now to analyse, in similar circumstances, the behaviour of electromagnetic waves (EMW_s) and photons (P_s), since they are used in QC. P_s are real particles and have a their own energy and *momentum*, so they are considered proper physical systems.

As shown by the Newtonian *momentum*(***p***)formula(Newton), the *velocity*(v) is directly proportional to ***p***:

$\boldsymbol{p} = m\,\mathrm{v}$ (5),

where *m* represents the mass of any *quantum object.* At this regard, in fact, Feynman writes: "velocity and *momentum* are proportional"(Feynman 1965a).Fermi adds:"To the quantum of light is attributed an *energy* (*E*) proportional to their *frequency* (*ω*), and expressed precisely by:

$E = h\,\omega$ (6),

where *h* is the Planck's constant. As for the light quantum it is necessary to give it a quantity of motion, or *momentum* (*p*) too. So, the *electromagnetic momentum*(*E/c*) is linked to the propagation of light energy(*E*). We must therefore also give the momentum (***p***) to a *quantum of energy* (*h ω*):

$\boldsymbol{p} = \frac{h\omega}{c}$ (7),

where *c* is the speed of light in vacuum"(Fermi 1926),(Fermi 2009).

The Eq.(7) can also be written as follows:

$\boldsymbol{p} = \frac{E}{c}$ (8),

Besides we have the famous equation related to the*Mass Energy Equivalence Principle* of Einstein (1905):

$E = mc^2$(9),

thus Eq. (8) can be represented as follows:

$\boldsymbol{p} = \frac{mc^2}{c} = m\,c$ (10).

The Eq.(10) is completely superimposable to Eq.(5), ***p*** =*m*v, indeed it is exactly identical in the case of the photon.

We can conclude that velocity (*v* or *c*) and *momentum* (***p***) are closely linked, in a directly proportional relationship, so that in our opinion it can be affirmed, without any doubt, that a particle with a higher ***p*** value also implies a higher speed, compared to an analogous particle, i.e. two photons of different wavelength (λ). To this purpose, in effect,in Quantum Mechanics any particle may be also considered as a wave. As we know, in fact, without experimental data, de Broglie(1923) suggested to give each particle an its own wave length (λ) depending only on the *momentum* (***p***) ofthe particle itself:

$\boldsymbol{p}=\frac{h}{\lambda}$(11),

where h is thePlanck's constant(de Broglie). Therefore, according to the *de Broglie formula*, any particle seems to be something periodic, oscillating as a wave, with a universal relation between the λof the particle and modulus ***p*** (Puccini 2011,a),(Puccini 2017).

Let's to analyse de Broglie's formula. As known, thePlanck's constant (h) is equal to 6.626 $\cdot 10^{-27}$ [erg·s] and λ is the wave length of the considered photon (or other particles). The mean wave length of a photon in the optical band corresponds to $\approx 5\cdot 10^{-5}$ [cm](Weinberg 1977) and its ***p*** is:

$$\boldsymbol{p} = \frac{6.626\cdot 10^{-27}[erg\cdot s]}{5\cdot 10^{-5}[cm]} \quad (12).$$

Since 1 *erg*= g·cm^2/s^2, we have:

$$\boldsymbol{p} = \frac{6.626\cdot 10^{-27}[g\cdot \frac{cm^2}{s}]}{5\cdot 10^{-5}[cm]} \quad (13),$$

$$\boldsymbol{p} = 1.3252\cdot 10^{-22}\,[\frac{g\cdot cm}{s}] \quad (14).$$

As Eq.(14) shows, the momentum (***p***) of a visible photon carries out a *dynamic-mass*(Puccini 2005 b),(Camejo), a *pushingmomentum* bigger than the *rest mass* of 100 protons(Puccini2019d). No surprise! At this regard, Feynman(1965,b) states: "The *momentum*, as a mechanical quantity, is difficult to hide.Nevertheless, momentum *can* be hidden –in the electro-magnetic (EM) field, for example. This case is another effect of relativity".It's like saying that *momentum* carries, albeit *hidden*, a dynamic-mass(Puccini,2019,a). In this connection Feynman warns: "It is very important to know that light behaves like particles: light is made of particles"(Feynman1985).

Let's now to consider a gamma photon (γP) with a wavelength(λ) $\approx 10^{-12}$[cm].In this case we have:

$$\boldsymbol{p} = \frac{6.626\cdot 10^{-27}[g\cdot \frac{cm^2}{s}]}{10^{-12}[cm]} \quad (15),$$

$$\boldsymbol{p} = 6.626\cdot 10^{-15}\,[g\cdot \frac{cm}{s}] \quad (16).$$

We have, in other words, that the p value of a γ photon is of 7 orders of magnitude bigger than that of an optic photon.

Moreover, they are precisely these p value differences, in relation to the different considered wavelengths, that represent the only valid explanation, in our opinion, to explain a characteristic physical phenomenon, that occurs continuously in reality, above our heads: the so-called *Çerenkov phenomenon.*

2.2 ÇERENKOV PHENOMENON

In 1934 the Russian physicist PavelAlekseyvicÇerenkov(Nobel Prize for Physics, 1958) was the first to highlight the effect generated by the impact of γ radiation and the layers of high terrestrial atmosphere(Çerenkov). As is well-known, the most energetic γ radiations hitting the Earth are emitted by intense electromagnetic(EM) sources. Çerenkov pointed out that γradiations, hitting the molecules of the high atmosphere, can make them free electrons.

As Feynman remind us "any object moving through a medium faster than the speed at which the medium carries waves will generate waves on each side. This is simple in the case of sound, but it is also occurs in the case of light. It is possible to shoot a charged particle of very high energy through a block of glass such that the particle velocity is close to the speed of light in vacuum, while the speed of light in the glass may be only 2/3 the speed of light in vacuum. A particle moving faster than the speed of light in the medium will produce a conical wave of light with its apex at the source, like the wave wake from a beat. By measuring the cone angle, we can determine the speed of particle. This light is called *Çerenkov Radiation*"(Feynman,1965,a).

Namely, what surprised Çerenkov was that electrons hit by γ radiations travelled with a speed higher than the visible light in the air, and that at this speed they could emit EMR$_s$ which wavelength(λ) moved from brilliant blue, to violet, and in bigger quantity to ultraviolet(UV): theseEM frequencies represent the so-called *Çerenkov Light* (*ÇL*). This can be explained easily considering that the atmospheric *refraction index*(n) is bigger than the vacuum refraction index: n_{υ}. If we consider n_{υ} =1, we have that the atmospheric refraction index is: 1.000293, carbon dioxide's is 1.00045, water's is 1.333. Thus, common visible light going through the atmosphere travels with a speed lower than in vacuum (c). In fact, as known when thelight goes through a mean different from vacuum its speed is given by the ratio c/n. Hence, as the light goes through the water its speed is 299792.458/1.333= 224000 m/sec, that is it travel ≈1/3 slower than in vacuum.

That is why a small particle as an electron can travel in the atmosphere (n>1) with a speed bigger than common visible light. Besides, the particles we are considering are the lightest elementary particles, thus the impulse they receive by γ photons(P$_s$) can make them accelerate till a relativistic speed. And 'interesting to note that*ÇL*is emitted only if the hit particle is also accelerated sufficiently. *Conditio sine qua non*: within EM spectrum only γ photons manage to give electrons such a speed to be able to emit the *ÇL.*

Why doesn't it happen with EMR_s with lower frequency(ω)? It is useful to underline that *ÇL*, or*Çerenkov Effect*, seems to us very similar to the photoelectric effect or to the Compton effect. In these cases too the electrons are thrown out from the struck atom by a sufficient energetic EMR.

The only difference is that for the photoelectric effect it is necessary just the visible light, in thecase of Compton effect it is necessary the force, the *radiation pressure* given by X P_s to throw out electrons from graphite,whereas in order to have the *Çerenkov Effect* it is necessaryexclusively the γP(Puccini2012). Why? An explanation can be found in the different EM frequencies used.

As is well-known, our atmosphere is constantly bombed by EMR_s of several types. Just as γ rays, Xradiation too, or the UV radiation hit the atoms of the atmospheric molecules, throwing awayelectrons from them, however in these cases the electron will not be able to emit the *ÇL*.

Why? The X photon does not manage to give the hit electron a sufficient *kinetic energy* (K_E), that is a speed similar to the one given by a γP(Puccini 2011,b).

This may be the difference and the explanation. But this explanation seems to us not sufficient.

What is the intimate physical mechanism so that, in the atmosphere, an electron hit by a X photon does not emit *ÇL*? We can say because it has not been sufficiently accelerated, as a γP is able to do instead. We wonder then: why a γP manages to accelerate the electron with a speed bigger than a X photon is able to do, or a less energetic photon(P)? It hasn't been explained properly, however it is what happens with photoelectric effect. As Lenard first pointed out, when some metals are struck by EMR_s with different wavelength(λ), electrons are pushed out with different velocities, in a rate inversely proportional to the value of λ and directly proportional to the frequency(ω) of the EM wave (EMW)(Lenard). Therefore, what we learn from the Lenard's experiment?

We learn that the EMR_s having a greater frequency of oscillation(ω), that is the more energetic, transmit a greater speed to the hit particles, compared to what the less energetic EMR_s can do.

It is unmistakable.In this respect, Fermi points out: "The photon too, as other particles, is a corpuscle, a *light'squantum* and has a its own *momentum* (***p***), through which transfers allits energy to the hit particle"(Fermi 1926).

These are the facts. That is, the more energetic photons give a greater and faster thrust to the particles they hit. Therefore, it is easy to infer that the EMW_s with greater frequency transmit a greater K_E to the struck particles, compared to the less energetic EMW_s (it is possible to indirectly infer that the more energetic photons travel faster than the less energetic ones)(Puccini 2018).

It is precisely this different K_E transmitted that can make us understand why only the electrons affected by γ rays can generate the *ÇL*. And yet, just the *ÇL*, and its induction mechanism, provide us with another very important piece of information: the particles capable of striking the electrons so violently (so as to generate the *ÇL*), i.e. γ photons(γP_s), receive at their origin, from their own EM source, a very high energy and thrust (proportionally greater than the P_s belonging to the other less energetic bands) which likewise they transmit to the affected particles.In fact, "these collisions are *elastic* collisions and, therefore, the K_E is conserved"(Feynman 1965,a).

Let us suppose we can use a next Quantum Computer, that is computers not working with electrons but with EMW_s of different frequencies, that is with P_s of different energy. Since we know, also from MLT, that in every physical system the speed the system operates is directly proportional to the energy available, it comes that a future computer, operating with P_s more energetic, should work with a higher speed than an identical computer operating with P_s less energetic.

But we know that the speed of light is the same for all the EMW_s of the electromagneticspectrum: it is 299792.458(±0,4) Km/sec(Achenbach).

Moreover, we think it is very important to consider a fundamental principle of Quantum Mechanics: theHeisenberg's Uncertainty Principle(HUP)(Heisemberg1927). As we know HUP considers two*complementary parameters*: energy and time, which are indicated with Δ_E and Δ_T(Heisemberg1930). They are related in the following formula:

$$\Delta_E \cdot \Delta_T \geq \frac{h}{2\pi} \qquad (17).$$

We infer that the second member of the Eq.(17) is a constant. Hence, the variations of the first factor(Δ_E) will have to be appropriately compensated by the variations of the second factor (Δ_T). That is, when the energy changes, Δ_T will inversely have to change too(Puccini, 2005a).

It comes out that the greater the energy of the involved P_s (that is the greaterthe frequency of the EMW_s), the lessits time of transit, so that the second member of Eq.(17). Thus, if we apply HUP to P_s,we have that the more energetic a P is, the faster it will travel, and *viceversa*.

III. CONCLUSIONS

Of course we are talking about infinitesimal differences, a difference which cannot be perceived in our macroscopic world, however they should have a their own scientific significance. Of course we have on our side the extremely valid mathematical formalism expressed by HUP and MLT.

The veracity of the HUP has been constantly confirmedin a multitude of physical experiments concerning the subatomic world.

On this regard, Hawking warns:"The HUP is a fundamental, inescapable property of the world"(Hawking). In his turn, Feynman adds: "No one has ever found (or even thought of) a way around the *uncertainty principle.* So we must assume that it describes a basic characteristic of nature" (Feynman1965,b).

Anyway, we can't exclude that considering that the EMW_s travel all to the same speed, it is in contradiction with the HUP, since in this case they should all carry the same energy: but they don't! (Puccini 2005,a). Indeed, it can't disagree with the HUP.

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