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Física emergente: breve exploración de nuevas tendencias en física teórica

Emergent physics: brief exploration of new trends in theoretical physics

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Abstract

In this essay we present a brief critical scrutiny of some popular theoretical models developed by the scientific community within the framework of Fundamental Physics. These models develop the hypothesis that it is possible that current physical laws can be derived or emerge from much more fundamental physical entities than those studied to date, which constitutes another way to achieve the Unification of said laws within a single common conceptual structure. We expose String-nets of Condensed Matter Physics, Loop Quantum Gravity, Superstrings and Branes, Entropic Gravity, the BCJ model, Stochastic Quantum Mechanics, Matrix Statistical Quantum Mechanics, and AdS/CFT Duality. These models are a small sample of an important trend that is gaining strong momentum within the scientific community.

***Keywords**:* Fundamental, laws, models, quantum, unification

Resumen

En este ensayo presentamos un breve examen crítico de algunos modelos teóricos populares desarrollados por la comunidad científica dentro del marco de la Física fundamental. Estos modelos desarrollan la hipótesis de que es posible que las leyes físicas actuales pueden derivarse o emerger de entidades físicas mucho más fundamentales que las estudiadas hasta la fecha, lo cual constituye otra forma para alcanzar la Unificación de dichas leyes dentro de una sola estructura conceptual común. Exponemos las String-nets de la Física de Materia Condensada, la Gravedad Cuántica de Lazos, las SuperCuerdas y Branas, la Gravedad Entrópica, el modelo BCJ, la Mecánica Cuántica Estocástica, la Mecánica Cuántica Estadística Matricial, y la Dualidad AdS/CFT. Estos modelos son una pequeña muestra de una tendencia importante que está ganando un fuerte ímpetu dentro de la comunidad científica.

Palabras clave: Cuántica, fundamental, leyes, modelos, unificación.

Introduction

The main objective of this essay is to present a brief qualitative analysis of an extremely important aspect of current Physics: the study of emerging phenomena. Thanks to recent theoretical and technological advances, a much more detailed study of this type of phenomena has been possible. Several very intriguing aspects and/or trends have thus arisen that opened doors for conducting research that has gone beyond the conventional: there is theoretical evidence that suggests that all known basic Physical laws, currently considered as "*fundamental*", are nothing more than an emerging product of a "*deeper reality*" than what has been thought until now.

Due to the difficulty of providing an exhaustive analysis of the topic within the limited space of a few pages, we will only discuss some particular cases that we consider extremely intriguing: *String-nets* of *Condensed Matter Physics* [CMP] and their impressive similarity to theories such as *Quantum Loop Gravity* [QLG] and *Superstring/Branes Theories* [SSBT], both dealing with *Quantum Gravity* and/or Unification of Fundamental Forces; the possibility that the gravitational interaction can be described as emergent – *Entropic Gravity* model, *BCJ* model *[Gravity as a 2-gluon propagator]*; the possibility that Quantum Physics can also be described as emerging – *Stochastic Quantum Mechanics model*, *Statistical Mechanics of Matrix Model*; the possibility that the entire Universe can be described as an emerging "*holographic*" physical system – the *AdS/CFT duality*. It is strongly emphasized that there are many other models/hypotheses on the subject, and those discussed in this work are only a very small sample of the immense literature that exists. The Unification of physical laws based on emergence hypotheses is the main purpose of these theoretical attempts, which we conclude is justified enough.

We will not present any introduction to the topic of emerging phenomena in general, so the interested reader should consult the extensive literature on the topic and the respective references therein (Holland, 2014; McKenzie, 2023; Laughlin, 2005).

Preliminary context

The *Standard Model of Particle Physics* [SMPP], although still imperfect, is the best available model [confirmed by physical experiments] to date, to describe the 4 Fundamental Interactions and matter entities of the known Universe. It's based on the so-called *non-Abelian Gauge Theories* [nAGT], which in turn are *Quantum Field*

Theories [QFT], which physically & mathematically describe each particle of matter and each interaction, as *quantum fields*, totally independent of each other, heavily using mathematical symmetries called *gauge symmetry groups*, $G_{gauge} = SU(3)_{strong} \times SU(2)_{weak} \times U(1)_{electromag}$. From SMPP, the *ElectroWeak theory* [with symmetry group $G_{gauge} = SU(2)_{weak} \times U(1)_{electromag}$] is the only one, to date, that achieves a kind of already experimentally proven unification between the Weak interaction and Electromagnetism (Baty, 2024). Other models are, for now, purely theoretical constructions under intense study, with no experimental confirmation so far. For a formal review on these theories, the reader can access Cottingham & Greenwood (2007) and references therein.

Nor will we review the problem of the complete and coherent quantum formulation of Gravity and the different strategies to try to quantize it. The reader interested in the topic, can consult Keifer (2007) and the references therein.

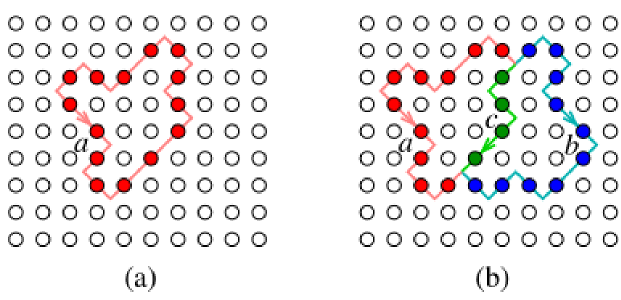
First, we will use the following notation: $M^{D+1} \approx M^D \times R$ ≡ classical physical space-time in (D+1)-dimensions; M^D ≡ classical physical space in D-dimensions; H^D ≡ quantum Hilbert space in D-dimensions.

String-nets

In *Quantum Condensed Matter Physics* [QCMP], there are bosonic lattice quantum models analogous to the Ising Model [based on spin and very few other degrees of freedom], but somewhat more complex, which have already been studied and applied experimentally for the advanced study of certain aspects of Condensed phenomena. Among these, the purely theoretical model of *String-nets* (Levin & Wen, 2005) is of particular interest because, under certain conditions, these can describe some bosons and fermions, considered "*fundamental*" and "*independent*" by the SMPP, as if they were excitations of a much more fundamental physical system: they are perturbations that emerge, somehow in an analogous way to how phonons and other quasiparticles of Condensed Matter do. For example, phonons [bosons] are quasi-localized waves resulting from excitations or vibrations of a lattice of atoms. In the String-nets model, the ontology of the physical lattice system that is proposed is not relevant and can be ignored [as a first approximation, just to simplify the calculations]; what matters are the “*waves*” that propagate in such a system, which take the form of small extended *strings* [with bosonic degrees of freedom], which can be closed [without free ends] or open. Such perturbations originate due to a new type of phase, called *Topological Order,* which emerges as a long-range quantum entanglement between various parts of the physical system [for example, the nodes of the lattice; see Figure 1]: a “*string/wave*”, in this model, is nothing more than the “*coupling*”, via quantum entanglement, between several nodes that are in the same quantum state, in a quasi-similar way as occurs in a “*pair of Cooper*” description of Superconductivity [the electron-phonon interaction, within an atomic lattice, attracts another electron towards the positive deformation of the lattice], in which the individual electron spins are “*coupled*”, via quantum entanglement, within the atomic lattice (Tinkham, 1996; Bordoloi, 2022). Within the String-nets lattice system, several types of strings can exist, depending on the quantum state of various nodes in it. These *strings* can form a complex interconnected network whose dynamic structure is very rich, ergo, the name “string-nets”.

Figure 1

String-nets: circles denote the vertex of the lattice, aka, the states of the system; colored circles are in the same state. Links are “strings” that denote entangled states (Levin et.al., 2005)



Within this model, several gauge symmetry groups, G_{gauge}, can be mathematically assigned to each type of string, so these can describe the SU(3)-gluon and U(1)-photon bosons of the SMPP as emergent excitations: not as fundamental physical entities independent of each other, but as the emergent product of the collective dynamics of a single, much more basic [yet unknown] physical entity.

Massive Dirac fermions can be described as localized disturbances at the extremes or endings of open strings, and it is possible to assign several of quantum numbers to characterize such fermions. An electron, for example, can be represented as one ending of a string with symmetry G_{gauge} = U(1), and with electric charge "-e" and spin ½. In a similar way, it is possible to describe all the quarks of the SMPP, together with their G_{gauge} symmetry. Where this model fails is in the description of individual massless chiral fermions [those that are described by the Weyl irreps of the Lorentz group], of W-bosons of the Weak interaction, and of the "*graviton*" of the gravitational interaction. But such problems are still being investigated.

This hypothesis of a type of unification of Fundamental Forces and matter fields, coming from QCMP, is too attractive to be ignored: *the same physical system can give rise to particles and forces, considered fundamental by the current accepted models, in terms of emergent excitations of the collective dynamics of the system*. Even though the model *per se* is not perfect, the hypothesis behind it is worth pursuing, and more research can be done to look for the right corrections or modifications. An impressive feature of this model is that it curiously resembles the hypotheses proposed by advanced theories of unification of fundamental forces [including gravitation] found in other areas of Theoretical Physics: the LQG and the SSBT.

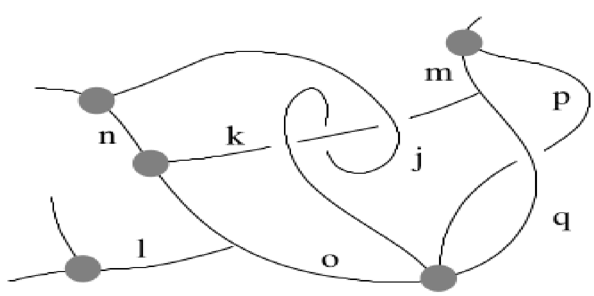
Loop Quantum Gravity

In LQG, classical M^{3+1} space-time is also modeled by an abstract mathematical state-space, which can be seen as a bosonic lattice-like structure [i.e., with bosonic spin-like, and few other, degrees of freedom; see Figure 2] at extremely high energies; including time as an evolutionary parameter, this state space is called

Spin-foam, which in turn is constructed from the time-evolution of simpler bosonic lattice-like structures, called *Spin-networks* [which do not include time, ergo, only serve to describe the static state of the M^3] (Gambini & Pullin, 2020). The Spin-foam then represents a mathematical dynamical abstract model of *the states* of the M^{3+1} and possibly its non-linear interactions, that is almost free of many problems that rise in other models that use the conventional variables of *General Relativity* [i.e., the canonical pseudo-Riemannian *metrics, curvature tensors, etc.* that appear in the geometric-differential formulation of this theory]. Each Spin-network represents a possible static state in which M^{3+1} could be found, and after quantization these states are taken as a basis vectors, $|SN\rangle_j$, of a very constrained H^D space. The Spin-foam is then the Feynman path-integral sum-over-histories over all these base vectors. In this way, LQG manages to quantize the gravitational interaction, which has been one of the most important problems in Theoretical Physics of the 20th century. However, the price to pay is very high, for such a degree of abstraction has make it very difficult its application to explain the current observed Universe. What catches our attention about this theory is the intensive use of bosonic lattice-like mathematical structures, in a strikingly similar way to what is done in the QCMP string-nets.

Figure 2

Spin-network: Atemporal lattice-like graphs with assigned quantum d.o.f.s that represent a possible state of space-time (Gambini & Pullin, 2020).



Fermions are not described by LQG, for it's a model of quantized geometry only. These and the other physical bosons are introduced by hand, in a separated interaction Hamiltonian. In other words, the rest of the SMPP particles do not *emerge* from LQG. However, it's supposed that the use of lattice-like structures [the graphs] can, at the low-energies limit, describe classical M^{3+1} as "*emerging*" from a more fundamental physical entity. This idea has a very curious resemblance to the string-nets hypothesis, although I have to remark that LQG is not a unification framework.

Superstrings/Branes Theories

In SSBT, on the other hand, [and ignoring for the moment the branes] physical entities are ontologically postulated in the form of *strings*, open and closed, propagating in a flat [zero curvature, no gravity] M^{9+1} (Polchinski, 1998), also at extremely high energies, with a rich variety of symmetry groups [Diffs, Conformal, SUSY, etc.]. And all the bosons and fermions are simply different modes of vibration of these strings: the bosons are closed strings and depending on the state of vibration, these can describe [within certain restrictions on the energy scale] all the SMPP bosons, including various other additional particles; all SMPP fermions are described as states of the extremes/endings of open strings, similar to the String-nets model. The gravitational interaction is described [in terms of the hypothetical *graviton*] as spin-2 closed strings, propagating in a completely flat M^{9+1} [i.e., without any curvature], but GR equations are recovered in the classical low-energy limit. In addition to the whole zoo of particles that SSBT predicts, there are other physical entities that are multidimensional generalizations of strings, called "*branes*". Both strings and branes are, in turn, supposed to be described as perturbations/excitations of a universal String/Brane field, within the context of *String Field Theory* [SFT] (Siegel, 1989), but this theory is still under very intensive scrutiny. These theories do pretend to be a unification framework. ▪

It can be seen then it is truly remarkable that a String-net model [or similar models], based on [very low energy] Condensed Matter Physics, could have such similarities to other models created in areas as disparate and different as High Energy Physics. String-nets, open-closed loops, open-closed strings, could suggest that exist some kind of connection? History of Physics taught us that important discoveries could result if one takes these types of hints or coincidences seriously. But how can these be interpreted? At face value, this situation seems to suggest that there is an unknown physical entity (at least one) much more fundamental than the ones that have been studied to date, and that its dynamic behavior could be almost universal at all energies scales. It is possible then to speculate that from this "*unifying*" physical entity, everything emerges as excitements of the quantum vacuum that is proper to said entity. It could be hypothesized that SSBT strings could be seen as the analogues of the String-nets strings, where the former theory is just ignoring the existence of the String-nets_like fundamental physical entity simply by postulating the strings as the basic building blocks; and, on the other hand, the underlying lattice structure proposed by String-nets models could have characteristics similar to those described by the quantum lattices used in LQG. Perhaps it is possible that deeper insights within SFT will clarify more about the nature of such structure and its possible relationship with the famous 11-dimensional *M-Theory* [i.e., the still unknown hypothetical unifying structure that encompasses all SSBT as special cases that emerge when certain types of constraints are taken, with still undefined degrees of freedom, i.e., no ontology so far].

These types of theoretical relationships are so intriguing and disconcerting that many other authors have started to question their possible meanings (Nastase 2017), and there are many studies that try to find possible stronger links between these ideas (Gambini & Pullin, 2014; Verlinde 2015).

Too many possible alternative explanations exist, and it's not obvious which is the right path to follow: is it possible that researchers are writing or finding the same laws but "*just in another mathematical language*", ergo, those coincidences arise due to hidden relationships in the used language? For example, it could be possible that for there are a lot of connections in Algebraic Topology that link algebraic structures with topological ones, it is natural then the emergence of similar interconnections in Physics just because it uses this type of language, and those similarities does not really mean anything important. Just like the case of the classical Maxwell-Faraday equations of Electromagnetism that can be written as partial differential equations, or as integral ones, or in tensor form in Minkowski flat M^{3+1}, or by using differential 1-forms and 2-forms, or in quaternionic or Clifford notation. This argument sounds very tempting, however, it does not seem to be the case, since we're not dealing with pure mathematical quirks, but with the *physical behavior* of supposedly physical [although still hypothetical ones] entities.

On the other hand, if these *patterns* must be taken seriously, it's obvious that the approximation of using point-like physical entities has already reached its limit of serving as an explanatory image of our Universe, and all these *coincidences* are the way the Universe uses to guide researchers toward better approaches based on the idea that using extended physical entities, such as strings/loops, etc., are the correct way to go. And/or perhaps, there is really a much deeper fundamental physical entity [or many?] from which all basic physical laws emerge. If this is so, could it have something to do with the still unknown fundamental structure of *M-Theory*? It seems reasonable to speculate that it's perfectly possible that everything in the Universe is, in some way, interconnected and that the many apparently different mathematical structures, used to describe a wide variety of [from our very limited perspective] *dissimilar* physical systems, are an *obligatory consequence* that depends in some way [directly or indirectly] on other physical-mathematical structures that in principle describe some kind of deeper physical system, but due to our constant use oversimplified approaches, it has eluded any type of detection so far. After all, in Theoretical Physics, it is very common the practice to describe or approximate physical systems as "*isolated*" from the rest of the Universe [thus ignoring non-linearities and other complexities that arise when interactions with the environment are considered], just because this approach help us to make predictions easier. Does this practice throws away important clues about something deeper? Are there any other clues that could guide us? It's obvious that we need to strongly focus on the development of non-perturbative, non-linear methods, to attack these issues, but, it is also painfully clear that our current understanding and technologies constitute very serious limitations.

Besides, not all researchers embrace the highly speculative LQG or the SSBT as possible unifying theories, and prefer to attack, for example, the problem of the quantization of the gravitational interaction using other working hypotheses. If gravitational interaction is a manifestation of the curvature of space-time, as described by General Relativity, then it is possible that space-time itself is a physical structure that emerges from a much more basic [yet unknown] structure.

Emergent Gravity and Relativity: Entropic Gravity

One strategy that has been considered serious is to simply define gravity as a non-fundamental force, that may or may not need to be quantized. Under this context, the *Entropic Gravity* [EG] model is postulated.

This is based on another important postulate, which has been part of preliminary results of Quantum Gravitation studies for many decades, the so-called *Holographic Principle* [HP] (Bousso, 2002). Before describing it, lets introduce a some context: in Quantum Information Theory, "*qbits*" are commonly postulated as fundamental units of "*information*", which in turn are nothing more than the possible observable quantum states that a physical system can have. If we accept the working hypothesis that space-time is a physical system that has states, then it is possible to assign the abstract mathematical descriptions of "*qbits*" to these states.

The HP basically establishes an extremely intriguing property of physical space-time: *it is possible to represent or describe the states [in terms of qbits of information] of a 3-dimensional [3D] volume of some region of space-time, in terms of the states [qbits of information] of the 2-dimensional [2D] surface that enclose the volume.* In other words, all the information contained within the 3D-volume can be described by the information contained in its enclosing 2D-surface, and viceversa, in analogy [not *"equal to"*] to a real physical hologram. Although it is a conjecture originated by countless studies and attempts to quantize gravity, it is a fairly robust result that seems to arise naturally in all the strategies studied so far. In this sense, the number of qbits of the volume, N = constant × A, where A ≡ area of the surface that encloses said volume; written in differential form, we have dN = constant × dA. Amazingly, the HP, in turn, is in some way related to the area-law of *entanglement entropy* [EE] in many-body systems, typically studied in QCMP: the EE of certain states of a sub-region of such a system is directly proportional to the area of said sub-region, despite the fact that, in Classical Physics, the entropy is an extensive property [i.e., it depends on the volume of the system, not on the surface].

Then, EG establishes that if the Energy Equipartition theorem is valid, the mass of a physical system that occupies a volume in M^{3+1} is proportional to dN and the temperature of the system, also expressed in terms of N (Verlinde 2011). This relation, rewritten in geometric terms using the Killing vectors [which represent the isometries] of M^{3+1} can be worked out [using certain geometric identities] in such a way that the field equations of the *General Relativity* [GR] emerge naturally.

We have to remark the following: it's obvious that the fact of deriving theoretically GR equations as an emergent behavior of a physical system does not mean that such a hypothesis is correct. Despite this, the almost direct relationship that this model has with the QCMP, through the HP postulate, is intriguing: it seems that physical relations that have to do with the *quantum* entanglement of many-body systems [more concretely, the EE], is somehow linked to *classical* [non-quantum] systems, but, how exactly? Expressed in other words, why when certain aspects of the physics of quantum systems with entanglement are considered, it is possible to derive certain classical [i.e., non-quantum] relations? It's well known [the *Correspondence Principle* - CP] that classical physics is a subset of quantum physics, and the former *must* emerge from the latter, but in practice this has been achieved by oversimplifications and/or by taking certain limits that kill the quantum aspects of the phenomena under study. The CP tell us what is obvious, but it's too vague and it does not tell us exactly how. And EG is about gravity, which has not been very quantum friendly. So, the relation or link is not clear or explicitly obvious, but it seems that some kind of renormalization procedures are in play, in a very subtle way. These types of scenarios seem to suggest that there is a deep connection in the behavior of many apparently different physical systems, which has not yet been well understood.

Emergent Gravity: BCJ model or Double-copy Duality

Another intriguing theoretical hypothesis is the *BCJ* model *or Double-copy Duality*, (Bern et.al., 2010) which suggest that the gravitational interaction [described at the quantum level as hypothetical self-interacting, massless, spin = 2 bosons, famously called "*gravitons*"] could not be fundamental since it is possible to express it as two copies of *gluons* [the strong interaction carriers described by the SMPP *perturbative Quantum Chromodynamics theory* - QCD]: in nAGT, the formula for the total "probability amplitude", A, of interaction/scattering between gluons, is

A_{QCD} = constant × Σ_i ($\int \Pi$ Dm C_i K_i / D_i)

[presented here in an extremely oversimplified form, where the sum is over all the Feynman amplitude diagrams, each represented by its Feynman graph '*i*']. Each *partial amplitude* [i.e., the expression between curved parenthesis] in this sum can be factored into two terms, C_i ≡ related to the QCD-color degrees of freedom, and K_i ≡ related to the kinematics of the interacting gluons. The Di term is related with the Feynman propagator of each graph. Amazingly, in a perturbative canonical Quantum Gravity model [pQG], interacting gravitons have a very similar formula for the total scattering amplitude, A_{pQG} . It turns out that if the C_i factor, is replaced by another K_i factor, the total amplitude is similar to the A_{pQG} that characterize scattering gravitons. The substitution is done by hand, it does not arise naturally; but the fact that [at this level of deep complexity] such a substitution is theoretically possible is not something that can be taken lightly. Is it possible that by some unknown renormalizable physical law, C_i could evolve towards K_i , so gravitons are really gluons in disguise? It appears as if the similarity between Newtonian electric and gravitational forces $F_e = Kq_1q_2/r^2$ and $F_g = Gm_1m_2/r^2$ could not just be a mathematical curiosity, after all. These types of mathematical "*dualities*" are very common in theories like SSBT.

Emergent Quantum Physics: Stochastic Theories of Quantum Mechanics [STQM] & **Statistical Mechanics of Matrix Models [SMMM]**

One of the peculiarities of Theoretical Physics is that it develops extremely quickly, so much so that Experimental Physics cannot keep up. But, without experimental data to guide us, it is difficult to decide which path to take to solve this or that problem. All that remains is trial and error and trying to attack the problem from all possible angles. Many scientists propose modifying GR, others propose modifying Quantum Physics. Along these lines, there are also many attempts that try to present Quantum Physics as emerging from more fundamental [and possibly classical] physical entities, of hitherto unknown ontology. If true, then quantum is a subset of classical, and scientists have been doing all wrong since the beginning.

An interesting attempt is the **STQM** (De La Peña et.al., 1990). A fluctuating vacuum is proposed as the cause of the impossibility of describing microscopic phenomena using Classical Physics. The ontology of the physical entity that possesses such characteristic is not defined, at least in the models proposed to date, which is a very common situation in these types of models, where the existence of said fundamental physical entity is only proposed, but there's no attempt to explain exactly what it is: after all, there are many theoretical quantum vacuums, not only one. So, QM is not fundamentally probabilistic because "nature behaves that way", but because the quantum vacuum is not a static physical entity, and is perpetually in constant random fluctuations, and since microscopic physical systems are inevitably immersed within such a fluctuating vacuum, interacting with it, this alone transfer the stochastic character [similar to the Brownian motion] to the system. Hence the formalism that describes its behavior is not deterministic, but probabilistic. In this sense, the rules of QM emerge as a product of the interaction between a physical system and the fluctuating quantum entity. In this type of models, the randomness of a QM physical system is transferred to another entity "external" to it, which in turn is inherently chaotic but deterministic.

The Theory of **SMMM** (Adler, S. (2004)), is another attempt to derive the laws not only of Quantum Mechanics, but also of QFT, from purely classical arguments. This starts from the beginning working on an Operator algebra, which act in a general Hilbert space, H^D, without any relation to any quantum system [which differs from conventional canonical quantization]. It is noted that H^D is not an exclusive mathematical tool of Quantum Physics, and it is a fundamental part of conventional Functional Analysis, which can also be used in Statistical Physics and in many other research areas.

The degrees of freedom of a classical physical system are modeled by matrix representations of these operators, where bosons are described by matrices over complex numbers, and fermions, by matrices over a Grassmann algebra, all of which [along with the derivatives with respect to time] form a classical Phase space of Operators. It is then postulated that the dynamics of a classical system is described by a Statistical (Micro)Cannoical Ensemble, which obeys the Ergodic theorem [i.e., under certain conditions, in the state space of a deterministic physical system, the time-average of a physical quantity along a single trajectory on this space, taken during a long-enough period of time, is equal to the spatial-average of it over the entire state space], and under certain restrictions and/or suitable conditions, it is possible to deduce quantum commutation relations and the Heisenberg & Schrodinger pictures, for said classical system. It is even possible to derive many relations relevant to QFT. In this sense, quantum laws emerge as *average effective laws* [that is, with a smaller number of degrees of freedom than those initially assumed] from the statistical thermodynamics of a totally classical system. However, not everything is perfect: Planck's constant is introduced by hand as an invariant of the theory.

One worrisome aspect of these types of models is that they reproduce the predictions of canonical QM, and it seems there's no way [at least, to my current knowledge] to predict different phenomena in order to choose which is the correct ontological model for QM.

AdS/CFT duality in Superstrings and Branes theories

This duality is a mathematical conjecture (Maldacena 1998) that arises in SSBT, which have a mathematical structure very rich in symmetries: among these, the one known as *Supersymmetry* [SUSY], requires that the number of fermions [within the theories] be equal to the number of bosons, and that each fermion has a related boson, and vice versa; Conformal symmetry groups [CFT] are also used, which have to do with scale transformations and mathematical relationships that remain invariant under these transformations. From the collective dynamics of the strings and branes, at low energies, it is possible to obtain theoretical models similar to the SMPP, but with the SUSY and the CFT deeply rooted in them, and the space-time that serves as the background for these models, is flat [i.e., without gravity described by terms of geometrical curvature, etc.] and 4-dimensional [4D]. Since SUSY and CFT do not manifest in the real world, such models are purely theoretical, but they represent powerful mathematical tools that have the potential to serve as a guide to try and find something more realistic. It turns out that the resulting 4D $SMPP_{SUSY\text{-}CFT}$, through certain geometric manipulations [called *Dualities*] of the initial 10-dimensional flat space-time of the theories, seem to be related to the gravitational field of a non-flat space-time, called 5-dimensional Anti-deSitter [AdS^5], but with SUSY symmetry. Unlike pseudo-Riemannian spacetime $M^{1,3}$ used by the RG, the AdS^5 space has non-trivial asymptotic symmetries that form the basis of the conjectured equivalence between gravity and SMPP-like models. The conjecture is called AdS/CFT or Gravity/Yang-Mills Duality.

This mathematical duality then establishes that the 4D "edge or frontier or boundary" of AdS^5 space has a physico-mathematical structure very similar to the one of the 4D $SMPP_{SUSY\text{-}CFT}$, so it is argued that [SUSY]gravity, that is, the curvature of AdS^5, is "*closely related*" to [i.e., "*it is dual to*"] $SMPP_{SUSY\text{-}CFT}$ theories. How? Through a series of mathematical transformations analogous [but no equal] to the one mentioned in the BCJ Duality section. The intensity of the gravitational interaction in AdS^5, is inversely proportional to the intensity of the "coupling constant" [i.e., a parameter that measures the intensity of interaction between the physical entities described by the model] of the $SMPP_{SUSY\text{-}CFT}$, which means that mathematically describing a low intensity, weak, curvature in the volume of AdS^5, is equivalent to describing a non-gravitational phenomenon in boundary of this same space, where the models of $SMPP_{SUSY\text{-}CFT}$ live, but with a very high, strong, coupling constant: it is well known that most calculations carried out in canonical QCD are perturbative, with a very low coupling constant, for performing calculations at very high intensity/coupling introduces non-linear effects that are very difficult to resolve. But, using the AdS/CFT duality, it is possible to perform those strong coupling non-perturvative quasi-similar calculations for SMPP-like phenomena, for the mathematical relations of the duality are used to find the equivalent weak coupling [super-]gravitational equations, which greatly facilitates the computational tasks. Once the calculations are completed with the low-intensity weak gravity equations, the duality relations are used again to map the result back to the high-intensity strong regime of the $SMPP_{SUSY\text{-}CFT}$. For example, this type of computation allowed me to compute the mass of a supersymmetric glueball of a N = 1 SUSY-Yang-Mills model by using the equations of 5D [super-]gravity (Amador 2004).

In some sense, this duality is a kind of Holography: suppose a physical system that occupies a 3D volume in space; under certain conditions, it is possible to store and retrieve some type of information, about such a system, in a 2D surface that surrounds the object. In the case at hand, information is obtained about a physical system that "lives" in a 5D space, from information contained in the 4D-boundary of said space, and vice versa. But the argument of the AdS/CFT duality takes this idea to the extreme: all the physics of 5D space is encoded in the 4D boundary of said space. It must be reminded that this is only a theoretical conjecture. Again, we find the HP mentioned earlier, which seems to be related to certain aspects of the QCMP.

In this sense, it could be said that, if we take as a reference point the 4-

dimensional $SMPP_{SUSY-CFT}$, the gravitational interaction in AdS^5 "*emerges*" as a dual phenomenon to quantum field theories in 4D flat space-time: the gravitational physics of the 5D volume emerges as a kind of hologram from the 4D physics that exists at the boundary of the 5D volume. The inverse of the idea is also a valid statement.

Obviously, such a duality still has the status of a purely theoretical conjecture, and, to date, there is no experiment that can validate it, just like its progenitor, the SSBT. However, the mathematical structures involved in such theories are so similar to the physical structures of certain current real [experimentally tested & confirmed] theories that it's very difficult to ignore such "*coincidences*." Many high-caliber scientists believe that there is a very serious possibility that future research will be able to decipher these mysterious relationships.

Conclusion

Current known Physics Laws, although supported by experimental verification, are not perfect, and do not describe or explain everything. For this reason, to extend & try to perfect our knowledge, there are many new theoretical models that are being investigated from all possible angles, by many groups of scientists around the world. Some of these models have received a lot of good and bad criticism and few of these have had strong financial support based on non-scientific prejudices; despite all that, researchers keep on working.

In our brief analysis of all the cases presented so far, we clearly see that it is strongly suggested that there must be an interrelation of everything with everything, and that we have not yet discovered all the secret links. On the other hand, one of the main current dogmas of Physics [to date] is that there are not "*[local] hidden variables*", or hidden entities, that can explain the observable Universe. So, the possible existence of much more basic, elemental, or fundamental physical entities is intriguing: for years, the scientific community working in these tasks have believed that potential hidden degrees of freedom were ruled out by countless QM experiments. All the ideas exposed before, could invalidate all this dogma, just by supporting that some kind of hidden entities do really exist, and that the Universe is a lot more subtle than previously imagined. If these ideas are to be taken seriously, it'd be a profound change in the current scientific paradigms, so then, there is hope that problems such as the real nature of Dark Matter and/or Dark Energy, the anomalies detected by the James Webb Space Telescope, the many cosmological conundrums, etc., can be solved.

As we mentioned before, one curious and problematic aspect of almost all these approaches to unify all Physics laws, is that the fundamental physical entity [a quantum vacuum or maybe another structure], from which everything emerge, is not ontological defined, but just it's epistemology: it's just postulated to exist, with few convenient properties needed for everything to work as expected. The issue is that [according to the current accepted knowledge] there are many quantum vacuums, one for each particle of the SMPP plus another hypothetical one for the space-time [17+1, in total]. Which one of these is the correct candidate? In addition, there are uncountable numbers of other quantum vacuums of other hypothetical entities postulated by uncountable number of models that pop-out in the framework of Theoretical Physics. Ergo, unless something fantastic occur soon in the next decades, there is a huge amount of research work to be done.

It is true that Physics tries to explain *observable* phenomena, but what happens when these same phenomena seem to point towards a *reality* that goes beyond what is *observable*? It's obvious that this "*observable*" aspect of *reality* is done under our current perspective, guided either by our physiological sensors or by the artificial ones that we created to extend our own. Neuroscientists know this very well: our perspective of "*reality*" could be very deceiving; and in Physics we base our understanding of the Universe precisely on our perceived or observed *reality*, that we nonchalantly call "scientific facts". The trends exposed in this essay clearly suggest that we have been working in a misleading path and we need to change that. That's precisely how Science works: when we do not know which way is the correct one to follow, there's no other alternative than to do research on a trial-and-error basis, by attacking the problems in all the possible angles that we can think of, with the hope to achieve positive results that could guide us further, to reach our scientific goals.

Although these topics are of extreme importance for the current development of Theoretical Physics, we have barely touched the tip of the iceberg. In future works, we will try to analyze other cases.

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