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On the unintelligibility of the vacuum

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1. Intelligibility as depth of understanding

The astonishing fact that the human mind can apprehend the laws of Nature escapes any trivial consideration. We may ask why is it so. We may as well wonder whether the laws of Nature that humans have discovered are unique or just a cultural artifact deeply rooted in the details of our own history. These questions need quite an elaborated analysis and it would be pretentious to claim that a reasonable and satisfactory answer is at hand. This is somehow fortunate, otherwise we would miss the fun of exploring one of the most profound intellectual debates in (and beyond) Science.

It is compulsory to open any discussion on the intelligibility of the universe by presenting the famous quote by Albert Einstein[1]:

> *"Das ewig Unbegreifliche an der Welt ist ihre Begreiflichkeit".*
> *("The eternally incomprehensible about the world is its comprehensibility".)*

Awe and astonishment underlie the subjective observation that humans, as a subpart of the universe, can comprehend it, can understand the workings of Nature and produce mathematical equations that faithfully represent it. Eugene Wigner wrote a famous essay about the unreasonable effectiveness of Mathematics to describe physical phenomena. It is clear that Einstein, Wigner and probably any person confronted with the challenge of spelling the idea of intelligibility in a concise sentence must resort to an expression of human feelings. For the comprehensibility of Nature corresponds to our intelectual relation with the outer world. The human brain, generator and recipient of all emotions, is confronted with the misleadingly objective task of arguing about its own ability to understand. Mystery, awe, astonishement, humbleness, depth, beauty, we can just produce words that are too short an expression to satisfy our intellect when it comes to understand its own skill to apprehend.

A wiser approach to intelligibility might start by defining the elements of our discussion. We may, for instance, take the Merriam-Webster dictionary and verify that it provides two definitions for the adjective intelligible:

1. apprehensible by the intellect only.
2. capable of being understood or comprehended.

Intelligibility is a statement about human intellect. As a consequence, a discussion on intelligibility is bound to depend on culture, gender or local circumstances in space and time. Moreover, Science itself may well be an artifact of a successful culture that might be surpassed by a different kind of understanding in the long term.

This preliminary observation seems to invalidate any objective discussion on intelligibility. This may not be the case if we concentrate on a concrete characterization of intelligibility. This essay is structured in a peculiar way. We shall first discuss briefly a computational approach to intelligibility. This is a passionate debate that we shall simply sketch. We shall then propose our main idea, namely, intelligibility may be experienced as a journey through depth. There is no other way to express this idea but to go through it. We shall illustrate the progression along deeper comprehension of Nature using two examples. First, we shall review our increasing understanding of a basic law of nature, namely Coulomb's law. Second, we shall go at the heart of our lack of intelligibility: the vacuum. What we have learnt about the vacuum is a fuzzy shadow of the inscrutable discussion about Nothingness. It would be wonderful to phrase our discussion on intelligibility as a missing never-written platonic dialogue on the ethernal problem of Nonthingness.

2. A preliminary: Inteligibility and algorithmic complexity

A hard-core scientific line of thought would claim that the understanding of Nature reduces to obtaining a theory that allows for the computation of any observable quantity. Though no global theory of the whole universe is provided by out present Science, we may argue that some specific fields of research do already offer such a powerful machinery. Indeed, it is possible to predict a vast plethora of electromagnetic phenomena from first principles. A set of precise rules can be blindly executed in order to faithfully predict the apparently complicate structure and evolution of electromagnetic systems. Nature can be largely simulated in our computers because we do have a series of laws that reproduce any observed behavior of physical systems with an amazing degree of precision. Century after century, the human made laws of Nature have changed. Imperfect ad hoc explanations have developed into structured theories, where few axioms are assumed as true in order to derive the rest of observations. It is an obvious success of reduccionism the fact that we can build superb skyscrappers and gigantic bridges. Our control on Newton's laws is so detailed that our constructions easily violate our naïve intuitions. Reduccionism has also led to our control on atomic clocks, lasers and MRI, has allowed for understanding the basic blocks in the DNA. The laws of Nature are now better known than ever, as shown by our engineered use of them. This reasoning seems to favour the algorithmic element underlying intelligibility. Understanding is nothing but obtaining a theory. According to this idea, it is of little interest whether a theory has been obtained following an inference (abduction) process or whether it is just an effective theory with no claims of any profound insight. No fundamental understanding is required provided we are endowed with an algorithm that produces clear predictions, free of error or incompleteness. We could argue that Nature is intelligible because there is a known underlying algorithm that describes it.

This strong point of view can be taken one step further (as argued by Chaitin, IBM). Full intelligibility corresponds to finding the shortest possible algorithm that describes Nature. This extreme position encounters several paradoxes. Let us discuss only two of them.

First, let us accept momentarily the fact that intelligibility corresponds to finding the shortest possible algorithm describing physical phenomena. Here, the emphasis is placed on the conciness of the algorithm that explains Nature. Old theories needed a detailed analysis of cases, whereas our present understanding is more general and efficient, it is also shorter. Let us take for instance the Ptolomeic system for the motion of planets as compared to the Copernican one. The old understanding of the cosmos was unsatisfactory, unprecise, short of generality. Instead, Copernico brought symmetry, elegance and an economical description of the motion of celestial bodies. His algorithm was better and succinct. Our intellect will only be satisfy if a theory is proven to be the most possible concise set of rules producing identical predictions. But here comes the paradox for, quite remarkably, this is known to be an unsolvable problem! Intuitively, negating the existence of a better algorithm is an extremely hard problem. For instance, there is no known classical algorithm for efficient (that is, an algorithm using an execution time which grows only polynomially with the size of the input number) factorization of large numbers. Yet, there is no proof that this is impossible. The real and profound surprise is that finding the shortest length of a statement corresponds to the problem of assessing its Kolgomorov complexity, which is known to be not decidable. This problem is an example of Gödel's undecidability theorem which states that any set of axioms contains statements that cannot be proven either true or false and, therefore, can be included as a new axiom of the theory. We may summarize this digression stating that we shall never know whether our most elegant and predictive theory is the most succinct set of rules that describe our universe. This takes us back to a humble position. We are forced to realize our explanatory limitations. It must be conceded that it is a remarkable intellectual achievement to have realized the undecidability of basic statements.

Second and last, it is easy to argue against short descriptions of Nature. Some effective descriptions of local phenomena may be extremely simple and elegant. Yet, such elementary and simple models lack generality. They are of no use away from their domain of applicability. Let us take Newtonian gravity versus Einstein's General Relativity. The former is a perfect theory to describe all gravitational phenomena that surround us. So is the more elaborated and complicate General Relativity. Nevertheless, the theory of General Relativity also explains the subtleties of Mercury's perihelium, the bending of light by massive bodies, the varying ticking of clocks at different orbits. General Relativity relies on deeper symmetry principles, it predicts new observable phenomena, it carries a profound sense of elegance and beauty which entices any human intellect. Given only a few gravitational data that could be described by both Newtonian gravity or General Relativity, our choice to take one or the other cannot be simply based on conciseness but must include other subjective values such as beauty, symmetry and sense of depth.

The algorithmic element of intelligibility remains at the heart of the discussion, though not through conciseness. Algorithmic efficiency is tantamount to the effectiveness of Mathematics. The question moves from short and efficient algorithms to structured Mathematics. Let us come back to this point after our first journey is finished.

3. Intelligibility as depth: a journey through Coulomb's law

Depth of understanding is a recurrent and elusive idea that pervades the discussion on intelligibility. It was claimed above that General Relativity is based on deeper symmetry principles than Newtonian gravity. What do we mean by that? Why a symmetry principle is a deep concept or a deep organizational idea? Is depth related to beauty? Is depth a matter of conciseness?

The increasing sense of depth that accompanies the better understanding of Nature can be illustrated using the example of Coulomb's law for the attraction of two electrostatic charges. It is taught in school that two charges at rest do experience an attraction or repulsion force from each other according to the so-called Coulomb's law. To be precise, charge 1 produces a force on charge 2 which is given by the expression

$$1) \qquad \vec{F}_{1\to 2} = K\frac{q_1 q_2}{r^2}\hat{r}$$

where q1 and q2 correspond to the electric charges of the two particles, K is a universal constant and r is the distance between both charges. The farther apart the two charges are, the weaker the interaction between them. Whether both particles attract of repels each other depends on the sign of their charges.

Our discussion will focus on the dependence of Coulomb's law on the distance r between charges. To be more precise, we will discuss in detail the exponent 2 in the decay law $1/r^2$. Why is it 2? Is it a pure mathematical 2 or, rather, an approximate number close to 2? Why not 3 or π? Is there a deep reason to have an exponent equal to the pure number 2? Let us proceed by stages.

3.1 *Stage 1: experimental precision*

Any scientist would doubt about simple explanations. Nature has a large record of deceiving evidences. It is necessary to assert with exhaustive experimental analysis whether the exponent 2 in Coulomb's law is a consistent observation. This was indeed the path taken by an extensive list of relevant researchers. We summarize part of the experimenters that have analyzed the possibility of an exponent $1/r^{2+\alpha}$ in Coulomb's law in the following table for the exponent α:

1769	Robinson	$\alpha < 6\ 10^{-2}$
1773	Cavendish	$\alpha < 2\ 10^{-2}$
1785	Coulomb	$\alpha < 4\ 10^{-2}$
1873	Maxwell	$\alpha < 4.9\ 10^{-5}$
1936	Plimpton Lawton	$\alpha < 2.0\ 10^{-9}$
1971	Williams et al	$\alpha < 2.7\ 10^{-16}$
1983	Crandall et al	$\alpha < 6\ 10^{-17}$

Note the amazing precision in the current experimental determination of Coulomb's exponent. We can assess that charges interact with a 1/r2 law, where 2 is checked to 1 part in 1017. This is as close as we can get to believe that there must be a deep reason to have the pure number 2 controlling electrostatic interactions!

3.2 *Stage 2: Mystery*

Why a pure 2? Let us think briefly of the consequences of having a pure 2 versus a number that only approximates 2 fantastically well in Coulomb's law. One of the most amazing consequences of the purity of the exponent 2 is the fact that charges create an identical amount of electromagnetic field on any surface shell which is centered at the origin of the charge. This comment needs some mathematical detail. Let us take a single electric charge at the origin and analyzed its effect through a spherical surface surronding it. This corresponds to

2) $$K\int d\Omega \frac{q}{r^2} r^2 = 4\pi K q$$

where we have integrated over the solid angle Ω. Now the miracle is manifest. The factor r^2 that comes from the area of the sphere of radius r exactly cancels the $1/r^2$ factor coming from Coulomb's law! As a consequence any set of charges homogeneously distributed in spherical shells are seen as concentrated in a point at the origin. This is the essential element to simplify the computations in the theory of electromagnetism (a similar phenomenon takes place in gravitation and was essential in the finalization of the Principia by Newton). We have just stated the well-known Gauss' law for electromagnetism.

The relevant and amazing point is that the cancellation of area and Coulomb's exponents would not take place if the latter were not a pure number. Had the interaction between charges decay not exactly but only approximately as $1/r^2$, the cancellation would not take place. Furthermore, a most profound consequence emerges from the above argument. Let us consider a universe full of particles that respect isotropy in space but not homogeneity in the radial direction of an observer. For such a universe, any shell surrounding the point of observation would affect it in an identical way. There would be no way to learn about the radial structure of the universe. This argument goes as is in the case of gravity. The exact cancellation of Coulomb's exponent with the area scaling of shells acts as a censoring mechanism to learn about the universe. All the understanding on the far universe we have achieved comes from actual photons that travel from far away to our eyes.

The exact factor of 2 in Coulomb's law is now a matter of uncanny mystery. It is transcendental in the sense that even our appraisal of the universe would be changed if the law were only approximate.

3.3 Stage 3: quantum

The next level of understanding of Coulomb's law comes by the hand of the most profound revolution in Physics, that is Quantum Mechanics. It is impossible to summarize the fundamental principles of Quantum Mechanics in this essay. Let us just state that Quantum Mechanics provides a description of the information we have about a given physical state. This information is codified in the wave function (ket) and can be retrieved in form of predictions for observables. Quantum Mechanics limits our understanding of a physical system to the accurate description of the available information content.

What is important for our discussion is that Quantum Mechanics in the form of the more elaborated Quantum Field Theory establishes that interactions are mediated by particles. In the case of electromagnetism, those particles are photons, the quantums of light. The interaction between two charges is particularly elegant. They both interchange a photon. This is represented in the following (Feynman) diagram

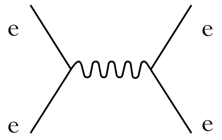

Fig. 1: Feynmann diagram that represents the leading order scattering of an electron and a positron through the exchange of a virtual photon.

Quantum Mechanics also allows for the exact computation of the propagator. In this way we can deduce Coulomb's law from first principles, that is, from more elementary principles! The correct procedure shows that the $1/r_2$ law is related to the propagator of photons, which reads

$$3) \quad \Delta(r) \approx \int d^D q \frac{e^{iqx}}{q^2} \approx \frac{1}{r^{D-2}}$$

Where D is the number of dimensions, including time. In our universe, D=3+1=4. Some more work is necessary to relate this propagator to the exponent in Coulomb's law. The result is that the exponent is, indeed, a mathematical D-2. Our universe displays D=4 dimensions and the exponent for electrostatic interactions is found to be D-2=2, exactly. Our deduction also carries a bonus. The mysterious cancellation of Coulomb's exponent and the area behavior would work identically in any number of dimensions. Gauss' law was a hint that Coulomb's law is deeply related to the dimensions of space-time.

A new sense of depth is now taking over the discussion. Forces in Nature are somehow related to the dimensions of space-time. A seemingly inoquous parameter in the electrostatic Coulomb's law is responsible for the way we perceive distributions of charges. In turn, this parameter is naturally explained as a propagation of photons.

3.4 *Stage 3: gauge symmetry*

Our certainly insufficient presentation of the laws of Quantum Mechanics shows at least that the mathematical equations that control the wave function are, de facto, the way we encode dynamical principles in the theory. In the case of electrostatics, the theory states that interactions are carried by photons and the dynamical principle that controls their propagation is constrained by the so-called gauge symmetry. Actually, it is known that all interactions in Nature follow from a gauge principle, that is, all electromagnetic interactions, weak interactions and strong interactions are structured as gauge theories. While the mathematical construction of gauge principles is known for these three types of interactions, gravity remains elusive and no satisfactory quantum mechanical version of it exists yet.

Let us be more precise about the dynamical principle that controls electromagnetism. The mathematical tool we need is called the Lagrangean, which is made of electromagnetic potential Aμ. It turns out that the correct Lagrangean for electromagnetism is the one that produces Maxwell equations for the propagation of light. In equations, the relation between the Lagrangean and the propagator in momentum space and, then, in coordinate space reads

$$4) \qquad S = \int d^D x \left(\partial_\mu A_\nu - \partial_\nu A_\mu\right)^2 \rightarrow \frac{1}{q^2} \rightarrow \frac{1}{r^{D-2}}$$

It follows that the reason for Coulomb's law that was traced to the propagator behavior of photons can be further understood in terms of the kinetic term in the Lagrangean that describe Quantum Electrodynamics, which carries two derivatives. This is the correct way to represent propagation. A derivative informs us about the change in the field from one space-time point to another. The fact that the propagation term in a Lagrangean always carries two and only two derivatives is dictated by the unitarity of the theory! Lagrangeans with more than two derivatives in the kinetic terms produce theories which violate unitarity, that is, the information content described by Quantum Mechanics would not be properly propagated, loosing probabilities.

This stage in our journey to understand in depth the exponent in Coulomb's law is absolutely superb. A fundamental principle, unitarity, was controlling the way electromagnetic and all interactions behave. We simply did not know about such a subtle mechanism in the early stages of our understanding.

Gauge principles also dictate the shape of interactions. In the case of electromagnetism, we know Coulomb's law may suffer quantum mechanical corrections. The theory provides the searched for set of rules to blindly compute observables. In particular, the interaction between two charges has an infinite number of corrections. The first one can be depicted with a Feynman diagram

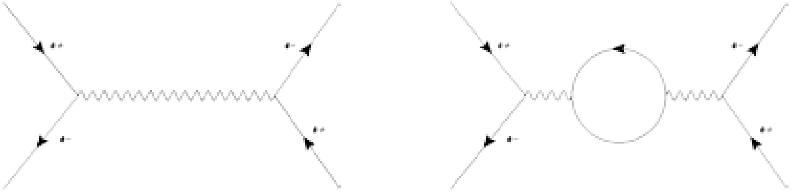

Fig. 2
The classical and first quantum corrections for electron positron scattering.

It is a remarkable fact that the sum of this infinite series does not change the exponent in Coulomb's law. Such a number is protected by gauge symmetry. The complete series of terms can be seen to be reabsorbed into the definition of the electric charge. This is quite a complicate subject (renormalization theory) that takes us to too far away from our goal. We shall not pursue it here.

3.5 Stage 4: geometry

Still, we are missing a final level of understanding. We have argued that propagation of interactions is related to the kinetic term in a Lagrangean, that carries two derivatives. Why is it so? Isn't unitarity a sufficient explanation? We may argue that we still have a deeper layer of mathematical understanding. Quantum Mechanics can be formulated using the path integral formalism. There, the propagation of particles is described by the superposition of classical paths properly weighted with a geometrical invariant. In the case of electromagnetism the propagation of photons weight is controlled by the length of the classical path, that is

$$5) \quad length \approx \sqrt{\dot{x}^2}$$

The dot notation represents a derivative along the line. The exponent is concealing the underlying use of Pitagoras theorem to compute the length of a hypothenusa. Coulomb's exponent or, if preferred, the two derivatives in the kinetic term of a Lagrangean, comes ultimately from the exponent 2 in the computation of lengths. We have found that our best understanding of Coulomb's law reduces to pure geometry!

This last step in the journey towards understanding Coulomb's law may be criticized in different ways. It is certainly true that gauge symmetry remains the organizational principle for the electromagnetic interactions. The fact that the kinetic term for photons is quadratic and that it corresponds to a path integral based on the length of the path cannot provide the understanding of the interaction part. In this sense, gauge symmetry is a far more comprehensive axiom. Nevertheless, though this objection is certainly correct, it may also be argued that the reduction to pure geometry is a correct step in the goal of reducing understanding to basic mathematical facts. To support this idea, we may consider the current candidate for a Theory of Everything, that is, String Theory. Such a theory is based on describing particles as excitations of a fundamental string. The action principle for the theory reduces to the weight given to a propagation of a string based on the area that it sweeps. As a matter of fact, the area (rather than length) weight constrains not only the propagation of particles, but also their interactions. Hence the idea that String Theory may provide a Theory of Everything.

4. Summary of our first journey

We have parcoured quite a non-trivial path from the astonishing precision of the exponent in Coulomb's law to its ultimate geometrical meaning in Quantum Mechanics. Along the way, a sense of depth has built up in our brain. The concepts of fundamental principles like unitarity or symmetries like gauge invariance were used to construct a complete theory of electromagnetism that provides a correct description of all known experimental electromagnetic facts. Moreover, the theory has offered for free new ideas, like the dependence of the electric charge on energies or the protection mechanism impose by Gauss' law to learn the radial structure of an isotropic universe. Some lessons can be learnt from this journey through Coulomb's law. One of them is that intelligibility is progressive. At any stage, our understanding of Coulomb's law has been wildly surpassed by the next layer of comprehension. It is easy to argue that we are living no special time in the history of Science, so future deeper layers of understanding are waiting for us around the corner. We are just witnessing an effective layer of intelligibility, the one available at our time. A second lesson that might be facing us is the ultimate role of Mathematics. It is often claimed that Nature should ultimately rely on Arithmetics. It is wonderful to observe that Coulomb's law is related to the only valid case of Fermat's theorem. On the side of human feelings, depth of understanding came hand in hand with the feelings of awe, astonishment, and mystery. We may also claim that intelligibility irradiates beauty and simplicity. Final apprehension should imply simplicity, uniqueness. Those, though, are human feelings that will depend on the reader.

5. Intelligibility of Nothingness: a journey through the vacuum

Nothingness stands as the most elusive concept for Science. What can be observed or demonstrated for the not being? Nothingness imposes the absence of matter and space, no instruments are available, no mathematical support is applicable. Parmenides argued that the

Being is, Nothing is not. The Rigveda says that before creation there was neither Existence, neither Non-existence. The poetic Tao reads

> *There was someting before sky and earth appeared. Such emptiness!*
> *It is alone, inmutable, it acts everywhere, tireless... I don't know it's name,*
> *I'll name it Tao.*

Science can add very little if not nothing to the discussion on Nothingness. This is the reason why this chapter is devoted to much more humble goal: understanding the vacuum. The vacuum can be analyzed as a limiting case of the absence of matter. Yet, we may argue that any analisis of the vacuum will fail to respect its very definition. Any probe, any sensor fills the space and alters the object of our analysis: we no longer have a vacuum. The study of vacuum is counterfactual by necessity. This said, it is a fact that our present understanding of the vacuum is amazingly sophisticated.

5.1 Stage 1: emptying space

It is not easy to obtain a vacuum. Eliminating all particles from a region of space is a very difficult task. We may quote Blaise Pascal:

> *"Nature would rather suffer its own destruction than allowing for an empty space."*

Pascal explored extensively the vacuum, changing his opinions as he grew older (he even said: "Nature has no fear of vacuum"). Many experiments to understand that our surronding space is full of particles were made in early stages of Science. One particularly famous demonstration of the force that particles in the air can produce was staged by Otto von Guericke in Magdeburg in the XVII century. Two large half-spheres were put together and a partial vacuum was created in the inner volume. Then, sixteen horses were used to separate the two half-spheres, beating the pressure made by particles in the air outside them.

Vacuum can be experienced in our daily life. Let us consider for instance a soft drink served with a sucking straw. The basic idea is to create a small vacuum in our mouth, so that the particles in the surrounding air will push the liquid upwards trough the straw. We may also experience ear pain due to the variations of the density of particles in the air when we flight in an airplane, when we dive under water or when when we climb a high mountain. A potato bag produced and sealed at sea level would appear to be inflated at some skiing resort, as a consequence of the reduced pressure in its outside as compared to its inside. All these phenomena are related to the fact that particles that occupy space move at high speeds and keep colliding with each other and with the walls that contain them. A surface separating a region full of particles from another with fewer particles will receive more collisions on one of its sides. That is, the surface will suffer pressure that may deform it. Temperature relates to the average velocity of particles, so that vacuum effects can be enhanced near the absolute zero.

Emptying space is necessary in quite a number of situations. A remarkable instance is the construction of large particle accelerators. There, particles such as electrons, positrons, protons or antiprotons are accelerated to a speed which is only one part in a billion away from the speed of light and are used as bullets that collide head to head in the core of detectors. The problem of keeping under control such high-energy particles is solved using storage rings. Both the accelerator machine and the detectors must work in the best possible vacuum. Otherwise, unwanted collisions with passing by molecules produce losses, unstabilities and noise in the experiments.

The almost perfect vacuum is not found on earth, but in space. The intergalactic medium, that is, the space standing between galaxies has a density of one atom per cubic meter. The large scale of the universe can be seen as a very dilute gas of galaxies. Matter is the exception, emptyness the rule. Photons can travel freely through space and tell us about the details of the Big Bang. This would be impossible if intergalactic space were dense, since light would scatter with high probability, leaving no traces of its origin.

5.2 Stage 2: flat space-time

Let us imagine that it would be possible to empty of all particles a limited region of space. Would this be the end? Should we be satisfied? Is the realization of an engineered vacuum the ultimate understanding about nothingness? We shall now argue that the absence of particles is far from a final comprehension of the vacuum. The reasoning, though, must now become subtler for, in the absence of all matter, the vacuum retains some property, namely, the structure of space-time.

Space-time is described mathematically as a differentiable manifold. The mathematics of space-time is non-tirivial but some intuition can be developed through simple cases. Let us take the example of two-dimensional spatial manifolds. To make the illustration more colourful, let us think of ants living in a world constrained to two dimensions, with no third vertical dimension. Some ants claim that all evidence shows that space is flat. An adventurous member of the species wants to take a large path claiming that the world is borderless but periodic (a sphere embedded in three dimensions), and the apparent flat shape of space is just a local property of the global manifold. Another ant, soundly trained in mathematics, argues that flatness is compatible with a torus shape, parallel light rays remain so along their propagation. It is necessary for the ants to take long trips in their space to learn about the topological properties of their world. The relevant point for our discussion is that the shape of the world is a property of space-time, underlying the motion of particles. Matter can travel and probe the structure of the universe, but the latter is there regardless of what experiments are conducted. The study of the structure of our space started with the very clever experiment of Carl Friedrich Gauss. He argued that the angles of a triangle add up to 180° in flat space. This sum is larger in elliptic geometries and smaller in hyperbolic ones. The experiment deviced by Gauss consisted in triangulating several cities in Germany using torches to define specific points and the light they emited as signals travelling along straight lines. For the first time, humans had experimental evidence for living in a flat tree dimensional manifold. Later on, the Special Theory of Relativity (1905) created by Albert Einstein established that space and time must be considered together in a four-dimensional manifold endowed with a Minkowskian metric. The fact that the laws of physics remain covariant under the transformations of space-time that respect the differential element of distance is the fundamental concept that guides the construction of any relativistic theory. This is a remarkable achievement. Physical laws must preserve symmetries of space-time. Nothingness in the form of empty space has a symmetric structure to be imposed on any interaction of particles that inhabit it. There is no prefered point in space, no prefered point in time, no preferred direction in space or preferred velocity for an inertial reference frame. So must be when particles interact.

5.3 Stage 3: curved space-time

Let us go back to the idea of an empty space-time which is probed with particles. This apparenty clear experimental setting is not that trivial. We have accepted the idea that a probe does not alter the system which is analyzed. The reason that invalidates this simple approach we have taken so far is that a massive particle, which is prepared in a region of space, does affect the rest of the universe! This is the basic principle of the Theory of General Relativity by Einstein (1915-6). Space-time is a dynamical object characterized by its metric, $g_{\mu\upsilon}$, that obeys a set of differential equations

$$6) \qquad R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G_N T_{\mu\nu}$$

where $R_{\mu\upsilon}$ and R are contractions of the Riemann tensor derived from the metric, G_N is Newton's constant and $T_{\mu\upsilon}$ is the energy-momentum tensor describing the matter content in the universe. Therefore, all matter enters into the energy-momentum tensor which acts as a source of the differential equation, whose solution delivers the point-dependent metric of space-time. In other words, the shape of space-time is self-consistently determined by the distribution of matter and light in the universe. Geodesics, that is, the path followed by light travelling freely through space are dictated by the distributions of all particles in the universe. When we watch the most distant quasar, we are receiving photons that have travelled non-straight lines. Massive galaxies bend the light passing near it. Nothingness becomes a very abstract concept. Space-time is affected by probes. Nothingness is dynamical.

5.4 Stage 4: quantum vacua

Quantum Mechanics brings a new and deeper layer of understanding. Quantum fluctuations alter the vacuum and produce a highly non-trivial structure. The quantum properties of the vacuum have become quite a sophisticated subject. Let us mention briefly how each interaction modifies the concept of nothingness.

Let us first consider the theory of Quantum Electrodynamics (QED). Quantum fluctuations produce the so-called vacuum polarization. Pairs of particle-antiparticles can be created from the vacuum. Let us consider an isolated electric charge. This particle forces the generation of electron-antielectron pairs from the vacuum in order to neutralize its effective charge seen from a distance. Actually, the charge of an electron depends on the distance at which it is analyzed, the nearer we are, the larger the charge we feel. Therefore, the value of the electric charge runs along distance scales. Furthermore, any modification of the external conditions for the QED vacuum results in changes of the properties of the theory. For instance, if space-time becomes curved, a net change of the speed of light may take place (a similar phenomenon takes place when adding temperature, physical plates or external electromagnetic fields). In the case of strong interactions (QCD) the physics of vacuum polarization changes dramatically. In essence, the gluons that can be created through vacuum fluctuations reinforce the color charges. At large distances, color charges become enormous and particles can never get rid of each other. This is the way quarks get confined into protons and neutrons. Vacuum gest populated of condensates of particles. There is no such a thing as a perturbative vacuum. There is no complete understanding of this phenomenon, though extensive work has provided many ways to effectively handle the QCD vacuum. Weak interactions provide, yet, a third realization of vacua. The structure of masses and couplings in the theory needs that the Higgs particle condensates in the vacuum. There is a non-trivial expectation value for this field. Many scientists feel uncomfortable about this fact and consider that this idea is just a first hint that a deeper layer of understanding is waiting for us.

5.5 Stage 5: quantum gravity

What about quantum gravity? Do we understand how gravitational vacuum fluctuations work? The answer to this question is highly speculative. There is no consensus that the present large effort on String Theory is the solution to the quantification of gravity. What is remarkable is that String Theory offers non-trivial solutions to very abstract problems.

Let us first argue that the onset of quantum gravity will, very likely, become the end of our understanding of space-time as a differentiable manifold. The fact that interactions are forced to take integer values of a minimum quantum of action (Planck's constant h) is now affecting the structure of space-time. What is the substitute of differentiable manifolds? This is a very hard question with no experiment to guide us. String theory proposes a change of paradigm in several stages. The first main step is to postulate that particles are excitations of some fundamental string. Different vibration modes describe different properties of the wrongly called elementary particles. The essential point is that strings interact in a unique way, which is by merging and splitting. As a consequence, all interactions of particles should be deduced from a single string interaction. All particle theories are a piece of the larger string theory. The second stage in string theory is to find what is the ultimate symmetry that organizes the creation and destruction of strings. The literature has explored this possibility and offers the so-called M-theory. Whatever a final framework to have a fully consistent string theory, it is a reasonable possibility that its solutions may or may not lead to an underlying space-time structure. Space-time could emerge as a possible but non-necessary solution to the theory. Nothingness is contingent.

6. Final comments

We have proposed two different journeys through the understanding of physical phenomena, one devoted to the precise form for the interaction between electrically charged particles and another one on the structure of the vacuum. In both cases, depth of understanding grows stage by stage in a quite surprising manner. It seems natural to accept that our present Science will be vastly overtaken by future discoveries, so that our understanding can only be considered as effective or circumstantial. The role of Mathematics is unquestionable. Each layer of understanding requires more sophisticated mathematical instruments. It is nevertheless Physics what drives the boat through the journey. It is certainly true that Quantum Mechanics needs Hilbert spaces, but the reason is that such mathematics are the correct way to encode quantum information. So Mathematics cannot be the guiding principle, they are just the right and natural companion for Physics. A final and very personal comment relates intelligibility to beauty. Practitionners of Science will unavoidably speak of the aesthetics of their work. Dirac equation is a beautiful creation. Dirac, himself, said that it is more important to have a beautiful equation than a right one. This sense of beauty is often related to order, necessity, simplicity and symmetry. Search for beauty is also a driving force for individual researchers. A scientist, isolated in his laboratory or at work at his desk, experiences a set of complex emotions that gives meaning to his effort. Researchers assume the intelligibility of Nature, work through it and, when a piece of the big puzzle is solved, enter a state of elation which is difficult to put into plain words. I feel confortable to confess that the search for beauty remains my own motivation for working in Physics.

References

1. Albert Einstein, *Physics and Reality*, 1936