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The Standard Model: The Ultimate (Reductionist) Framework

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It is a tribute to the essential objectivity of modern astrophysics that this consensus has been brought about, not by shifts in philosophical preference or by the influence of astrophysical mandarins, but by the pressure of empirical data.

– Steven Weinberg

The Mainstream Paradigm: *In any given period physics has an all-encompassing worldview.*

The all-encompassing worldview of physics changes periodically. In ancient times the universe was regarded as the creation of God. That was the Theory of Everything. It still is, for many. As long as one is not concerned with the details and mathematical aspects of the laws of nature, this is as good a theory as any other. Then, with the rise of modern science in the seventeenth century, the world came to be regarded as *matter in motion*. In the eighteenth century, the core idea was *force*. Every natural phenomenon was accounted for in terms of forces acting on bodies. In the nineteenth century, the overarching view was that everything may be described in terms of *energy transformations*. Then the perspective was that ultimately there are only atoms and molecules which undergo incessant changes in affiliations. The experimental, conceptual, and mathematical details of these modern scientific paradigms are not based on speculations, nor are they scriptures-related. They rest on findings by countless investigators from different nations and with different cultural backgrounds. They are the fruits of the labors of physicists over many generations.

The current paradigm is that *every aspect of the physical world can be understood in terms of certain ultimate point-like particles in incessant interactions via a small number of fundamental forces which also have particle aspects.* This is the core idea in what is known as the *Standard Model* (SM). Some day, it too may be replaced by a more satisfactory model. No one can foretell how science will evolve.

But as of now, a great many physicists who work in the field of fundamental physics explore and expand the SM in many research centers all over the world. Like quantum mechanics, it has proved to be eminently successful. As in all science, this is its primary appeal. It must be emphasized that the SM arose from sophisticated concepts and mathematics and has been corroborated by a considerable range of experiments.

The Background: ***A wide range of facts, theories, and precise experiments gave rise to the SM.***

For almost two-thirds of the twentieth century, researchers working on fundamental physics were involved in elaborating the theory of special relativity, in formulating a consistent and coherent framework for quantum mechanics, and in the discovery of a growing number of elementary particles. Then it was time to put them all together in a coherent scheme. The SM is such a scheme.

Maxwell's theory of electromagnetism systematized the electromagnetic field. Einstein's special theory of relativity arose from a search to make Maxwell's equations retain their forms from one reference system to another. The theoretical quest to understand radiation (electromagnetic waves) from very hot sources led to some intriguing puzzles in correlating data and theory. These were resolved from Planck's insight to the effect that radiation is emitted and absorbed by matter in discrete amounts. Later in 1905 Einstein suggested that radiation itself exists in discrete quanta subsequently named photons. This notion of light quanta and De Broglie's idea of wave–particle duality merged to generate quantum theory. When the electromagnetic field merged with quantum theory, quantum electrodynamics emerged[1].

The Fundamental Fields: ***Every (currently) known physical phenomenon can be ultimately traced to one or more of four fundamental interactions.***

As noted earlier, the plethora of natural phenomena result ultimately from four basic interactions. We recall that on our scale only two of these are patently observed and directly experienced. The first of these is *gravitation* which pulls us to the ground every time we try to jump. A grand discovery of science (by Isaac Newton) was that this is the same force that keeps planets in orbit. Its quantitative aspects explain why those orbits are elliptical. A variety of other observed physical phenomena, such as currents from batteries and the effects of electric currents on magnetic needles can be understood in terms of a second fundamental interaction, known as *electromagnetic*. It was found that this interaction plays a fundamental role in the stability of atoms and in the play of molecules which are ultimately responsible for the variety of substances in the world. Furthermore, as a result of probing into the nature of the atomic nucleus, two more fundamental interactions were uncovered: the *strong* interaction which accounts for the stability of nuclei, and the *weak* interaction which accounts for their instability and decay.

[1] This was the most important contribution of P. A. M. Dirac to modern physics. See in this context, Graham Farmelo's, *The Strangest Man: The Hidden Life of Paul Dirac, Quantum Genius*, Basic Books, 2009.

The notion of force elaborated in the eighteenth century was replaced by the more powerful notion of field in the nineteenth century[2]. By field, one means that every source of force alters the surrounding space in subtle ways. Thus every mass, which is the source of the force of gravitation, creates a gravitational field around itself. Every other mass which comes into the field will experience a force of attraction towards the source-mass. Likewise, every electric charge creates around itself an electric field, and if the charge is moving, it creates an electromagnetic field.

Quantum Field Theory: ***With every fundamental field is associated a field particle.***

In the classical world molecules appear and disappear in chemical reactions. In the microcosm too particles appear and disappear. Photons are emitted or absorbed by atoms when electrons jump from orbit to orbit. Electrons are emitted from atomic nuclei in radioactivity. Pions are produced when energetic protons collide with nuclei. Pions are annihilated and muons are created. In all these and similar instances there are mathematical techniques for calculating the probabilities of such events. Sometimes the *creation* and *annihilation* of certain fundamental particles become physically possible in violation of conservation laws of matter and energy because they are carried out in extremely short time intervals within which they can occur, thanks to Heisenberg's principle. All this and more are described, analyzed, and accounted for in an elegant theoretical framework known as *quantum field theory* (QFT). This theory had its origins in the 1920s and was developed in the 1930s and later. It has now evolved into a very successful though as yet incomplete theory[3].

QFT has been the most fruitful synthesis of special relativity and quantum theory. It serves as a framework for the SM. Though the qualitative features of quantum field theory can be simply described, its quantitative aspects are technically quite complex.

Conceptually, in QFT one considers, not elementary particles, but fields of which the particles are essentially excited states. These excitations are of two kinds: Those that are entities that we refer to as elementary particles, and those that are intermediaries for forces (interactions). The former are all *fermions* (i.e., they carry half-integral spins), while the latter are *bosons* (spin zero or one). One exception to this is the graviton of supergravity theory. In this theory, the graviton has a spin of 3/2, and hence is a fermion.

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[2] See in this context, Mary B Hesse, *Forces and Fields: A Study of Action at a Distance in the History of Physics*, Littlefield Adams, and Co., 1965.

[3] QFT has a broader scope than in the Standard Model. It is applied, for example, in quantum phase transition, in critical phenomena, in the theory of superconductivity, etc.

All fermions carry mass, and many bosons, such as the *W* and *Z* bosons are very massive also. The photon is the only boson which is massless. Neutrinos are fermions with extremely small mass.

The Role of Symmetry: ***Symmetry is at the root of fundamental laws and particles as well.***

The symmetries we see in leaves and flowers, in art and architecture, in geometrical figures like the isosceles and equilateral triangles are all aesthetically pleasing. These are all visual. But there are also symmetries in the world of sound as in songs and sonnets, as well as in the world of ideas and ideals. There is symmetry in the yin–yang principle, in the dharma–adharma dichotomy, in peace–war relationships, in virtue and vice, and the like. In mathematics we find symmetries in the roots of quadratic equations, in positive and negative numbers, and in reciprocals.

What is not so apparent at the superficial level is that there are symmetries undergirding the laws and structure of the universe. For example, the laws of physics remain the same with respect to all inertial systems. More exactly, the laws of physics are invariant under Lorentz transformations. Similarly, one speaks of invariance under rotation, invariance in time, etc. These symmetries are reflected in the laws of conservation of linear momentum, angular momentum, and energy respectively. Thus one may regard momentum as a quantum number resulting from spatial symmetry, energy as a quantum number related to time symmetry, and so on[4].

It turns out that there are other symmetries called internal symmetries. They do not imply any conserved quantities. They involve constraints that lead to some features of the physical world such as the existence of the kinds of forces and elementary particles we observe.

In the mathematical theory of waves, there arises a parameter called its *phase*. The intrinsic properties of a wave are unaffected by changes in phase. This invariance is associated with a (field) particle. In quantum electrodynamics, the phase of the de Broglie wave of an electron can change without affecting the charge on the electron. This is accomplished by the photon. That is to say, the photon is the particle associated with the electromagnetic field, ensuring its phase invariance. This connection between a type of invariance and the electromagnetic field suggests that other types of invariance may be at the root of other fundamental fields.

Thus, strong interaction is related to another symmetry – that of the *isotopic spin* which regards the proton and the neutron as different charge states of the nucleon. The mathematical analysis

[4] This extremely important insight was first articulated by Amalie Emmy Noether, one of the greatest women-mathematicians in history. See, in this context, Auguste Dick's biography, (English translation, H I Blocher) *Emmy Noether: 1882–1935*, Birkhäuser, Boston, 1981.

of this leads to the existence of three vector (i.e., spin 1) bosons as the field particles for the strong interaction. A vector boson refers to a field particle whose spin can take on values –1, 0, +1 in units of $h/(2\pi)$. The photon is a massless vector boson associated with the electromagnetic field. Likewise, field particles are also associated with the weak interaction.

Quarks: ***Among the ultimate bricks of the material world are quarks of various types*****.**

In the first decade of the twentieth century, a series of spectral lines were discovered, and their wavelengths were carefully measured[5]. The challenge then was to find some order in the apparently random wavelengths in these series, and also to find an explanation as to why they were so. The atomic model of Bohr, presented almost a century ago (1913), was the starting point of our deeper and systematic understanding of the structure of atoms.

Likewise, when a plethora of new (fundamental) particles were discovered in the 1940s and 50s, and their many properties carefully observed and measured, the challenge was to find some order in the plethora of data, and to account for why these were so. It was in this context that the *eightfold way*, referred to in the previous article, was first formulated. This led one to posit hypothetical particles called quarks which are the ultimate constituents of many elementary particles[6].

The quark hypothesis introduced three revolutionary ideas. The first was that the root of the strong interaction is in quarks. In other words, just as mass is responsible for gravitational interaction and electric charge is the origin of the electromagnetic interaction, the source of the strong interaction is the quark. Nucleons (protons and neutrons) are involved in the strong interaction because they are themselves made up of quarks.

Secondly, quarks carry fractional electric charges. This is contrary to the long held view that fundamental particles can have only –1, 0, or +1 units of the charge carried by an electron. Quarks are specified to have +2/3 or –1/3 electronic units. The positively charged quark is called the *u* (*up*) quark, and the negatively charged one is the *d* (*down*) quark. Every quark has its antiquark which carries –2/3 (anti *u*-quark) and +1/3 (anti *d*-quark) charge. All quarks are fermions (spin ½).

In the quark model the proton is pictured as being made up of three quarks (two *u* and one *d*). But given that quarks are fermions, it would be impossible to accommodate three of them in a

[5] These are known as the Lyman, Balmer, Paschen, Brackett, and Pfund series.

[6] The term quark was coined by Murray Gell-Mann. See in this context his book *The Quark and the Jaguar: Adventures in the Simple and the Complex*, W H Freeman & Co., 1994.

system as that would violate the Pauli principle. To overcome this constraint, a new quantum number is attributed to quarks. This quantum number is called the *color charge* or simply *color*. This color charge can take on one of three possible parameters. This is not unlike the charge on an elementary particle having one of three values: –1, 0, +1. The three possible values of the color charge were called *red*, *blue*, and *green*[7]. In other words, every quark has one of three colors: red, green, or blue. The color charge plays the same role in strong interactions as electric charge does in the electromagnetic interactions.

Further developments, both theoretical and experimental, established that there are two more sets of quark pairs like the *u* and the *d*. These have been named *strange* (*s*) and *charm* (*c*) quarks: *s* carries a charge of –1/3, while *c* carries +2/3); *top* (*t*) and *bottom* (*b*) quarks form the third pair. Each variety of *top* is said to have a different *flavor*. Thus we say quarks come in six different flavors: *up, down, strange, charm, top, and bottom*[8].

Quarks can decay through weak interactions. When a quark decays it changes its flavor. Thus, for example, in radioactive beta decay, a neutron becomes a proton and a negative electron (and a neutrino). This happens when a *d* quark in the neutron becomes a *u* quark with the emission of an electron and a neutrino:

n (*udd*) decays into a *p* (*uud*), an electron (e^-) and an antineutrino (ν*).

Quark Composition of baryons: All baryons consist of three quarks of different colors.

Recall that baryons are the heavier fermions in the EP zoo. They include nucleons and hyperons. These are all composite particles, each made up of three quarks of three different colors. Thus, for example, as noted above, the proton consists of two *u*'s and one *d;* their total charge is 2/3 + 2/3 – 1/3 = +1. The neutron is made up of one *u* and two *d*'s; the net charge adds up to + 2/3 – 1/3 – 1/3 = 0.

Quarks of other flavors give rise to the other known baryons as shown in *Table* 1.

In each case, the three component quarks are of the three different colors: red, blue, and green. So we say that the color of any baryon is white. It must be emphasized that this is purely metaphorical language.

[7] The epithet *color* and its various kinds have nothing to do with the visual colors of everyday language and experience. The name was given in jest, but has acquired a technical stature nevertheless.

[8] The quark names top and bottom are also sometimes known as truth and beauty. Their existence was predicted from theoretical considerations in 1973 by Makoto Kobayashi and Toshihide Maskawa. The names top and bottom are due to Haim Harari.

Table 1.

Particle	**Symbol Content**	**Quark**	**MassMeV/*c*²**
Proton	P	uud	938.3
Neutron	N	ddu	939.6
Lambda	Λ^0	uds	1115.7
Sigma	Σ^+	uus	1189.4
Sigma	Σ^0	uds	1192.5
Sigma	Σ^-	dds	1197.4
Xi	Ξ^0	uss	1315
Xi	Ξ^-	dss	1321
Omega	Ω^-	sss	1672

Mesons: *Quarks and antiquarks combine to form unstable mesons.*

Mesons were first proposed as intermediary particles responsible for the strong force between nucleons. The pi mesons were the first ones suspected. Today we know of the existence (actual or created) of a great many mesons. In the standard model, every meson is a quark–antiquark pair. Mesons can be quite heavy. Thus, for example, the D meson consists of a charm quark and an anti-down quark. The Upsilon meson is made up of a bottom quark and its anti-particle. It has the stupendous mass of 9460.4 MeV/c^2. This is more than ten times the proton mass.

Every meson has its anti-particle also. The anti-particle of the π^+ (ud^*) meson is the π^- (u^*d), where * refers to an antiquark. Similarly, as examples of other mesons, we have: K^0 (ds^*), K^+ (us^*), π^- (du^*), π^+(ud^*), ρ^- (du^*), ϕ^0(ss^*).

If the quark and the antiquark in a meson have the same flavor, the meson is said to be flavorless. Thus, for example, the π mesons (–, 0, +) are not flavorless mesons. Likewise, the K^+ meson consisting of an up quark and a strange antiquark, and the D^- meson made up of a down quark and an anticharm quark, are examples of flavorful mesons. The ϕ^0(ss^*) meson and the charmonium (J/ψ) consisting of only a charm quark and its antiparticle, are said to be flavorless quarks.

The first excited state of the charm–anticharm meson (*charmonium*) is known as the (J/ψ) particle. It's almost simultaneous discovery at the Stanford Linear Accelerator and at the

Brookhaven National Laboratory in 1974 created a sensation in the world of particle physics, and was referred to as the November Revolution[9].

Quark Confinement: ***Quarks are permanently sealed in hadrons.***

What is interesting in the quark model is that it posits a particle which, in principle, can never be detected in isolation. Quarks are tremendously valuable in the mathematical theory of hadrons, but it would be wrong to imagine them to be purely conceptual[10]. They are regarded as real particles which are confined in baryons and mesons. Quarks are the only mass-bearing physical entities which cannot be detected in isolation in any experiment, now or ever.

When the production of a quark, like the top quark, is reported, it is always on the basis of the detection of traces of its theoretically known decay products[11]. In other words, when it is announced that a quark has been experimentally detected, what is meant is that its theoretically predicted decay products have been identified in the data from high energy accelerators.

One is tempted to draw an analogy here with the theological notion of *panentheism* by which the Divine is said to be present in every entity in the universe. But that Divinity cannot be directly perceived. This is true of quarks also. However, in the SM, quarks are not embedded in everything, only in hadrons[12].

Gluons: ***The strong interaction is mediated by gluons.***

As per quantum field theory, there is a field boson mediating the strong force among quarks. These field particles are known as *gluons*[13]. They correspond to the photons of the electromag-

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9 The rest-mass of J/Y is 3096.9 MeV/c^2. Its mean life is 7.2×10^{-21} s. In 1976 both Burton Richter and Samuel Ting received the Nobel Prize for this discovery.

10 In physics there are concepts like entropy, Hilbert space, and Lagrangian which have mathematical existence, but not physical reality. The quark is unusual in that it is believed to have physical existence, and yet cannot be observed.

11 The identification of quarks from the tracks they leave behind is a masterpiece of physics detective work. Thus, when the existence of the top quark was finally established in March 1995 in proton–antiproton collisions at Fermilab, the decay products included a top–antitop pair, which decay into two *W* particles and two *b* quarks. One *W* decays into a muon and a neutrino, the *b* quark into up and down quarks, which in turn decay into jets, as does the other *b* quark also. If there is a phase transition to a symmetry broken phase, quarks may exist as individual entities.

12 Theological parallels, though poetically interesting, should not be given ontological equivalence.

13 The name gluon, from glue, was also introduced by Gell-Mann who coined terms like quark, eightfold way, and strangeness. “Names are for fun. Why shouldn’t you be able to enjoy yourself?” he once said. However, these words (not being of Latin or Greek derivation, like proton, electron, and meson) need to be translated into other languages, rather than used as such.

netic field. Note, however, that photons do not carry any electric charge themselves: they merely cause the electromagnetic field. But gluons which mediate the force between the color charges of quarks also carry colors themselves. From group theoretic considerations it has been concluded that there are in fact eight kinds of color-characterized gluons[14].

One may wonder why it is impossible to split a proton into its component quarks in extremely high energy machines. This is because the force of attraction between quarks is not only very strong, but gets stronger and stronger as quarks are separated from one another. We may picture quarks as little balls connected to other such balls with extremely strong unbreakable springs. If we try to pull two of them apart, the force between them gets stronger and stronger. If the spring breaks, other gluon-balls appear at the broken ends.

In the framework of the SM then, the strong interaction between nucleons within the atomic nucleus is in fact a manifestation of forces between the quarks of which hadrons are made. The systematic mathematical analysis of strong interactions with color charges would correspond to the quantum electrodynamics of the electromagnetic interaction. Because this strong charge is described as color, this theoretical study is called quantum chromodynamics or QCD[15].

When quarks are very close (at high energies) the strong force loses its intensity. Thus when protons collide, for example at high energies, the quarks within them collide like billiard balls. We say that the strong coupling depends on energy[16]. At low energies the strength becomes enormously large, which is why quarks can never be separated out, even in principle. It is not surprising that protons and neutrons appear as fundamental (unbreakable) particles.

The Lepton Family and its Field Particles: ***Corresponding to the three quark pairs there are three lepton pairs with their own field particles.***

We are often struck by symmetries in the physical world. One such symmetry may be seen in the fact that just as we have three pairs of quarks which take part primarily in strong interactions, there are also three pairs of particles which do not take part in strong interactions. The particles are involved in weak interactions and (if charged) in electromagnetic interactions. The first of these had been recognized long ago. Indeed this was the first elementary particle to be

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[14] The need for eight types of gluons arises from the fact that there are three color-charges. It follows from the mathematical theory which takes into account the fact that quantum states are superpositions of states.

[15] From the Greek *chromos* for color, though that word refers literally to *color*. In technical jargon one would say that QCD is based on the special unitary group 3 or SU(3). It is a gauge theory that is Non-Abelian.

[16] This fact that the strength of the interaction becomes less as the energy increases is referred to asymptotic freedom. It is characteristic of QCD. This was a major discovery for which David Gross, David Politzer, and Frank Wilczek were awarded the Nobel Prize in Physics.

recognized as such: the negatively charged electron (e^-). Its companion is the antineutrino (ν_e*). Likewise, there are two other pairs: the muon (μ^+) and the muon neutrino (ν_μ); and the tauon (τ^+) and the tauon neutrino (ν_τ). All these six particles are collectively known as *leptons*[16].

Recall that in the framework of quantum field theory, a quantum aspect is associated with every fundamental interaction. Thus, the EM field has the photon and the strong field has gluons. From this point of view, there must be a particle aspect associated with the weak interaction also. Indeed such particles arise in the theoretical investigation of the weak field. Theory predicts that such particles should be enormously massive, carrying anywhere from 50 to 100 times the mass of the proton. A very large mass for a field particle implies that the range of action of the force is very short. In fact, the range of the weak interaction is of the order of 10^{-15} m or less. Theory also suggests that these particles must have a spin of 1 unit. They are thus vector bosons.

The massive vector bosons, which are the quantum aspects of the weak interaction, are called W^+, W^-, and Z^0 particles. The existence of the *W* particles, of which theoretical physicists did not have the slightest doubt, has been fully confirmed experimentally[17].

The Graviton: *One may picture a field particle for the gravitational field also.*

In the framework of quantum field theory one can envisage a particle aspect of the gravitational field. Such a particle is known as *graviton*. The graviton is similar to a photon and the gluon in being massless, but it is a spin-two boson. The spin two is related to the fact that, unlike with electric charges, there are no positive and negative mass. Photons do not electromagnetically interact with one another. But gravitons are mutually attractive. In this they resemble gluons. Theoretically gravitons can collide with one another. But the probability of this happening is unimaginable small. Therefore, it is simply impossible to detect such a collision even with the most powerful high-energy collider imaginable[18]. The force of gravity comes into play by the incessant exchange of virtual gravitons. Their interest lies primarily in making the physicist's worldview more complete and inclusive.

Coupling Constants: *The relative strengths of the fundamental interactions are reflected in their respective coupling constants.*

Every fundamental interaction is characterized by a parameter known as its coupling constant which is an intrinsic measure of its strength. Thus for example, in the case of gravitation, the

[17] The term lepton was introduced by Léon Rosenfeld in 1947.

[18] It is easy to envision such hypothetical particles from considerations of analogy, but the associated mathematical formulations are extremely complex. This is one reason why it has not been possible thus far to unify gravitation with the other fields.

magnitude of the force between two masses m_1 and m_2 depends on their distance of separation as well as on the gravitational constant G. Likewise, in the case of the electromagnetic interaction the force between two charges q_1 and q_2 depends on their distance of separation and on the Coulomb constant k. From other considerations it has been established that the coupling constant for the electromagnetic interaction is 1/137.

Now we may compare the gravitational force with the electrostatic force between two protons. This will be: Gm_pm_p/kq_pq_p which is of the order of 8.1×10^{-37}. From theoretical considerations it has been established that on this scale the coupling constant for the strong force is of the order of 1, while that for the weak force is between 10^{-6} and 10^{-7}.

It is a remarkable fact, seemingly a reflection of Nature's sense of humor, that gravitation is the weakest of all the fundamental interactions, yet it is the most sweeping space-wise, while the strongest of them all can barely exert itself beyond nuclear dimensions.

Fields at the Beginning: ***At the moment of the big bang there was but one single field.***

Theoretically it should be possible to develop a formalism in which all these fields appear as parts of just one unified field. This was how Maxwell unified the electric and the magnetic fields. Einstein and others attempted a similar synthesis of the electromagnetic and the gravitational field, but with little success. In the 1970s, physicists succeeded in unifying the electromagnetic and the weak forces. This is the so-called *electroweak theory*[19]. At energies of the order of 100 GeV the two fields merge into a single field. It should be emphasized that the standard model is not a unified theory in that it does not combine weak and electromagnetic forces into a single force which then breaks up into two separate forces. Rather it is a theory that describes weak and electromagnetic forces in a consistent manner through the mechanism of symmetry breaking. In this theory there are two coupling constants and not one as a truly unified theory should have.

Consider a body of water in a container. At ordinary temperatures it is calm and still. As the temperature rises the molecules agitate with increasing kinetic energy. As the temperature reaches the boiling point the water becomes more and more tumultuous. It boils frantically when it is sufficiently hot. The fundamental interaction fields behave in a somewhat similar way.

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[19] The history of the development of the electroweak theory for which Abdus Salam, Sheldon Glashow, and Steven Weinberg shared the Nobel Prize in 1979 is long and complicated. But in that labyrinth the fundamental path-breaking contribution of Robert Marshak and E C George Sudarshan (the so-called V–A theory) did not receive the recognition it deserved. For more on this, see, for example, Robert P Crease and Charles C Mann. *The Second Creation* (Ch. 11), Macmillan, NY, 1986.

Calculations show that the strengths of the three non-gravitational fields change in such a way that at extraordinarily high temperatures they have almost the same value. What this means is that within 10^{-35} s after the Big Bang those three forces were combined into one unified force. It is believed that after the so-called Planck time and a hundredth of a second there were two phase transitions. Above 10^{28} K there was this unified field. When the temperature cooled to 10^{28} K, the three forces separated out into two: the strong and the electro-weak. When the temperature further dropped to 10^{15} K, the weak and the electromagnetic fields separated into two distinct fields. In other words, at the very beginning there was only one fundamental force which gradually gelled into the four different fields that sway the cosmos today[20]. A crude analogy would be the following: Consider a crowd of people gathered in a huge hall to see a performance. When the show if over and they disperse, they separate out and become individual men and women, boys and girls.

Symmetry Breaking: **The physical world acquired its materiality as a result of a process called symmetry breaking.**

As the universe cooled down after the Big Bang it reached a near stillness: that is, the average fluctuations of the fields created were zero. So there was perfect symmetry. However, there was one field that settled down to a nonzero average value.

One analogy that is given sometimes is this: Consider a set of light taut strings vibrating violently because of the enormous energy they possess. When the strings lose their energies they settle down to states where they are all perfectly horizontal. Suppose now that one of the strings is slightly heavy, so when it stops vibrating it is not fully horizontal, but slightly hanging down. We may describe this situation by saying that in this case the symmetry has been broken. Such a field arose when the universe cooled down.

This is related to the question of why the universe is substantial rather than ethereal. That is to say, how did the elementary particles acquire the property of mass? This is a fundamental question for which an explanation was suggested by a number of theoretical physicists in mid-1960. Because the first paper on the subject was published by Peter Higgs, this theory is associated with his name. The central idea here is this: If there is a breaking of a global symmetry, there is in fact a massless particle for every symmetry that is broken. On the other hand, when a local symmetry is broken, there is a mass generated and this mass generation has come to be called the Higgs phenomenon. When a particle couples with a Higgs field in a particular manner, it acquires mass. In a crude way one might say that whenever a particle is

[20] To verify this we need to generate energy regimes that correspond to the initial stages of the universe. This calls for extremely powerful high energy accelerators.

linked to a Higgs field, it acquires a mass, just as when an object enters a pool of water it acquires wetness.

The interaction between the Higgs field and the particles is brought about by the field particle corresponding to it. It came to be called the Higgs boson because (like other field particles) it is subject to the Bose–Einstein statistics. In order to put into evidence the existence of this theoretically hypothesized particle we need to create an energy regime of an enormously high order. In high energy physics this can be achieved by accelerating protons to speeds approaching the speed of light and making them collide with one another. Evidence for the existence of the Higgs particle was apparently achieved in experiments at the Large Hadron Collider at CERN.

Another way of looking at this is that the Higgs field acts on quarks and leptons somewhat like a force of friction: It arrests their acceleration. The result of this is that these ultimate constituents of matter are endowed with what we call *mass*. In other words, if there was no Higgs field, ours would be a non-material world. The interpretation of the massiveness of fundamental particles as arising from the Higgs field which resulted from a symmetry-breaking at the genesis of the universe is one of the great discoveries of fundamental physics [21]. It is as close as we have gotten thus far regarding the ancient question: Why is there a physical world at all? The experimental confirmation (though not with 100% certainty) of the associated Higgs particle is regarded by many as yet another (if not the last) decisive confirming evidence for the validity of the Standard Model.

Brief Review of Fundamental Interactions: *The basic features of the causes of the phenomenal world may be summarized*.

The classical idea of force relates to pushes, pulls and friction that are clearly observable on our scale. Current physics tells us that all physical phenomena may be explained in terms of certain *fundamental interactions* or *fields*. To review what we have seen, the four fundamental interactions uncovered thus far can, as of now, account for every known event in the physical world.

We may look upon the fundamental interactions in terms of certain general properties. Let us first recall some general characteristics of all interactions, and then specify the particularities of each.

[21] The announcement was made that this was done on July 5, 2012. It became headline news all over the world. A comparable head-line catching news from the world of physics was when Einstein's General Relativity explanation of the motion of the perihelion of Mercury was observationally confirmed in 1919.

(a) Every interaction represents connections between different entities in the universe. Indeed, this is what makes them interactions. Interactions are responsible for every change occurring in nature, i.e., for all natural phenomena.

(b) Every interaction corresponds to a particular force field in nature. Thus we have the gravitational field, the electromagnetic field, the strong field, and the weak field.

(c) Every force field has a range. The range is either long, i.e., extending indefinitely; or short, i.e., within nuclear dimensions. The gravitational and the electromagnetic fields are long range, while the strong and the week fields are short range.

(d) The force field corresponding to every fundamental interaction has a quantum (particle) aspect. This is one of the basic results of *quantum field theory*. Thus, we have (in principle) the graviton for the gravitational field, the photon for the electromagnetic field, the gluon for the strong field, and the *W–Z* particles for the weak field. All field particles are bosons.

(e) Fundamental particles are of two kinds depending on their statistics: Fermions which have spins 1/2, 3/2, and bosons which have spins 0, 1, 2.

(f) Some fundamental particles experience force and others are carriers of force. The former constitute matter and may be bosons or fermions. They are normally observed to be massive (even neutrino is now expected to have a small mass not explained in the Standard Model). The carriers of force are known as gauge particles and can have spins 1 or higher. They can be massless or massive depending on whether the gauge symmetry is broken or unbroken. Photon and gluons are massless, but the weak gauge bosons are massive. In conventional symmetries these gauge particles are bosons (even the carrier of gravitational force, the graviton, is a boson with spin 2). However, there may be gauge symmetries which are fermionic as in supergravity where the gauge particle can be a spin 3/2 particle.

(g) Every interaction has a source: mass for the gravitational, electric charge for the electromag netic, and color charge for the strong. It turns out that there is no such thing as a weak charge. This is related to the fact that whereas there is conservation of mass, electric charge, and color charge, there is no such conserved entity in the case of weak interactions[22].

(h) Every interaction has a certain strength to which a numerical value may be attached on a comparative scale. Its measure is given by the coupling constant of the field.

(i) Every fundamental interaction plays an important role in the functioning of the physical universe. Thus, the gravitation ensures the stability through orbital motions of planetary, stellar,

[22] This is related to symmetries. The absence of a weak charge means that there is a broken symmetry here. For a clear non-mathematical discussion of these ideas see B A Schumm, *Deep Down Things: The Breathtaking Beauty of Particle Physics,* Johns Hopkins University Press, 2004.

and galactic systems. The electromagnetic field is responsible for the stability of atoms and the transformation of molecules: that is to say, for matter as we know it and for all of physical chemistry and biochemistry. Indeed its effects are the most directly experienced aspects of the physical world: heat, light, sound, and more. The strong interaction is responsible for the stability of nuclei, hence for the preservation of substances for long periods of time. Finally, the weak interaction is responsible for the decay of elementary particles, such as is found in the phenomenon of radioactivity.

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Our Readers Write ...

I am glad to see the second series '*Darshana* Jolts' by V V Raman in *Resonance* progressing so well.

I am sending this email only to make an observation concerning the remarks on page 700 of the July 2012 issue.Yukawa predicted his meson around 1935. The meson discovered by Anderson around 1937 was initially thought to be the Yukawa particle, but it soon became clear this could not be true. It later transpired that the Anderson particle is the mu meson (which had been predicted by Homi Bhabha), which has no strong interactions, while the Yukawa meson is the pi meson discovered by Cecil Powell around 1947.

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