Notes for THE LIGHTNESS OF BEING (2008), by Frank Wilczek

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Our new book, Frank Wilczek's The Lightness of Being, is mostly readable and occasionally quirky in its presentation of standard topics. He seems willing to use unconventional terminology unnecessarily, at least so it seems to me. A lot of the book will be familiar to some of us.

On p. 45-6, he introduces Heisenberg's uncertainty principle in a slightly unusual way. He seems to be saying that in an accelerator experiment, where position and time are precisely known, there must be a lot of uncertainty (and hence the possibility of large values) in the energy and momentum of some of the products. This seems to explain the indefiniteness of the values for the virtual particles. Does anyone have a better interpretation of this?

On p. 50, he points out that "asymptotic freedom" is not a particularly helpful phrase. But he does describe it fairly clearly on p. 47-51, as weakly bound up close and more tightly bound at greater distances. To me, "asymptotic freedom" implies the opposite - weakly bound at great distances. Oh well, sometimes bad names stick.

On p. 53-7, he uses this idea to describe quark confinement and quark jets. If quarks attract more strongly the farther they are apart, they won't get very far apart, i.e. they are confined in composite structures like mesons and baryons. If you hit one of those things hard enough, you might send two quarks flying out in opposite directions, which isn't supposed to happen. The motion against the large force diverts kinetic energy into more quark-antiquark pairs along the path of motion, which decay into still more debris. This causes streams of secondary particles in the two directions, called jets. The soft/hard radiation distinction is new to me. It refers to the fact that sometimes one of these isolated quarks will emit a gluon, which produces another jet of its own.

On p. 58-61, Wilczek gives us another introduction to symmetry. P. 63-69 introduce and compare QED and QCD. He doesn't emphasize it, but both of these theories rely heavily on more complex varieties of symmetry. The "charges" in QCD are usually called red, green, and blue. Wilczek ignores convention by calling them red, white, and blue. He also uses green and purple as the two charges (weak charge and hypercharge?) in the electroweak theory, which I don't recall seeing elsewhere.

On p. 69-72, he introduces global and local symmetry in the context of QCD color charge. In global symmetry of QCD, you can interchange the three colors freely, as long as you do it the same way everywhere, and nothing changes. But if you change them differently in different places, as required by local symmetry, your wave functions have abrupt changes at the boundaries of the regions. Since abrupt changes mean high energy density, your description of the system no longer matches reality. Just as in Schumm's book, this is repaired by adding the gluon fields to the system. They can be used to make the wave function well behaved again, despite the abrupt change in color definition. This is exactly what is required in local symmetry of color charge - color is only a matter of notation, even if you change notation arbitrarily from place to place. Pretty slick description.

With Chapter 8, the book gets more substantial. It never tries to be comprehensive, but his selected nuggets are more detailed, and often presented with a different perspective from that common in other books.

In Chapter 8, Wilczek introduces his concept of spacetime, which he unconventionally calls "The Grid". He regards it as an ether-like entity, with a built-in energy density, which appears to conform to special relativity in that this density does not change with relative motion. Fields of all sorts live in the Grid, and the most important one is the metric field, which gives it a local shape (curvature) by allowing distances and angles to be defined.

P. 79 gives an interesting comparison of Newtonian mechanics and special relativity. Both have perfectly good symmetries under translation, rotation, and boost (uniform velocity change). The difference is that the transformation that maintains the boost symmetry is different between them. The difference was not apparent in Newtonian mechanics, but it was in electromagnetism. Einstein's insight showed that mechanics was wrong and that it just had not been noticed yet.

In the p. 80s, there is discussion of the reality of ether, spacetime, fields, etc. It leaves me somewhat confused. But on p. 88-9, fields, convenient as a description, take on more reality as the theoretical and observational need for virtual particles becomes clear.

The next several pages about the QQbar condensate are completely new to me. Then on p. 94, he applies the idea to the electroweak charges. I have seen the superconductor idea of the W and Z bosons and the Higgs mechanism before, but this is a different way of talking about it. Does anybody know anything about this? Appendix B doesn't help much.

On p. 97, Wilczek introduces the metric field, which is an important feature of the description of spacetime. Mathematically, it is the "set of instructions for how to do geometry locally." What this means is that it takes some arbitrary coordinate system and allows it to be used to determine distances and angles. This may seem unnecessary, but in fact, it is the means used to describe the curvature of space. Remember that on a sphere, the sum of angles in a triangle is greater than 180 degrees. (Consider the triangle [North Pole, Gabon on the west coast of Africa at the equator, and Ecuador, on the west coast of South America at the equator.] This is an equilateral triangle with about 6000 miles on each side and three 90 degree angles. This can happen because the earth is not flat.) To calculate things like this, you need a metric field.

Wilczek wants to give the metric a physical existence. I don't know how well-founded or philosophical this is. Certain changes in the metric do give rise to gravity. If I remember correctly, moving a rigid body through certain metric changes will produce a gravity-like force on it. (Is this right?) If it is physical, then it is presumably subject to the uncertainty principle (p. 101 bottom). If this is true, then at the smallest scales, space cannot be perfectly uniform, but must be filled with all manner of peaks and ripples and bulges. That part, at least, is commonly accepted, although I have never heard a reason for it. Looking at the metric field as some kind of matter condensate (p. 103-4) seems to be going considerably farther.

On p. 105, he uses the phrase "Grid weighs" to introduce the concept of vacuum energy. This gives some credibility to spacetime having a physical reality (although not the metric field?). On p. 107, he introduces his "well-tempered equation." This is really just one form of an equation of state, giving the relation (in this case) between density and pressure. Eq. 1 could fairly be called the "equation of state for vacuum energy."

This particular "well-tempered" form of it has two properties that we would like to have: The energy density of empty space does not vary with the speed you travel through it, which is required by relativity (if it is indeed a physical thing), and the density does not vary as space expands or contracts. The latter property may soon be testable as supernova observations of the expansion of the universe improve.

On p. 109, Wilczek brings up the familiar conundrum of the huge difference between the apparent observed vacuum energy density and various theoretical estimates of it. The most often cited estimate is based on the virtual particle density of empty space (I think, I've never read a detailed description of it) which is cited as 10^120 times the observed value of dark energy. He gives a few other estimates with different values. As I said in the meeting recently, the important thing is not the specific number, but the huge difference between all of the estimates and the observed value. This is way bigger than anyone's idea of experimental error. Wilczek's thought that there could be cancellation between multiple contributions with different signs is interesting but speculative.

Chapter 9 is about making this view of "Grid" into a mathematical model and what can be learned from it. His perspective is that Grid, or spacetime and its features, is home to various fields that represent particles (and some other things too). Both real and virtual particles are fields that are solutions to their respective wave equations. These fields describe everything about the behavior of their particles. The addition of Feynman diagrams and their rules allows particle interactions to be described. At this level, real and virtual particles are very similar, with the main difference being that virtual particles need not obey all the usual rules about energy conservation, etc., but they can only exist for a very short time while participating in reactions involving real particles.

On p. 114-8, Wilczek introduces a mathematical notation for quantum states (state vectors; someone please correct me if I'm misusing terminology or mangling concepts), and shows how a very simple system rapidly acquires a large number of variables. These quantum states are superpositions of other quantum states, and can be represented as linear combinations of them in a form that is mathematically equivalent to a vector.

The example given is the spin direction of a small set of electrons. If you measure the direction of the spin of a single electron, you can only measure it with respect to a specific direction, and the answer has to be either that direction or the opposite one. Its state (as seen by a specific direction of measurement) is a superposition of the two cases, and the measurement will have a probability of turning out either way. (Measuring it forces it into one of the two possibilities, but that's another story. If you then measure it along another direction, you again get a superposition with definite probabilities.) This is represented by the last equation on p. 115. The up and down components can be regarded as basis vectors for describing the probabilities of measuring the spin on other directions. With more electrons, there are more possibilities. On p. 117, he uses this to explain entanglement. On p. 118, he describes a set of five qubits as having 2^5 (32) degrees of freedom. In the endnote on p. 250, he says it's really 31 (one less, for normalization), but they are complex.

These state vectors are probability amplitudes for various outcomes, should a measurement be made. A mathematical model of this type has to do all of its calculations in this environment of probabilities of outcomes in this very high-dimensional probability space. By Laplace's demon (p. 118), Wilczek means the old classical view that knowing the position and momentum of every particle is sufficient to predict a system's behavior with complete accuracy forever. Although still a very large computational problem, it is much smaller than the QM state formulation, and its promise of certainty is defeated. The appearance of virtual particles, and the possibility of non-uniformity of spacetime at small scales makes it even worse.

Pages 122-7 show how this type of model can be used to calculate the characteristics of composite particles. First you get a really big computer. You program it with space and time represented by very small discrete steps, rather than a continuum. "Empty" spacetime still has the quantum foam of virtual particles milling around, so that's the simplest meaningful situation. If we wish, we can start the model with some real particles in it. These are just part of the virtual particle fields that are already there, but they are not obligated to evaporate. The model runs just the same with these conditions. If, for example, we introduce two up quarks and a down quark with the right initial conditions, we find that this combination will persist forever. If the model is working properly, this stable combination will have all the properties of a proton. Or, we can introduce a down quark and an anti-strange quark in the correct configuration, and we see that it persists for a little while before decaying to something else. This is a K^0 meson. These show up as combinations of the fields of the constituent particles, and the model allows computation of various properties, such as mass, spin, and lifetime.

Figures 9.1-9.3 show the masses of a variety of particles that can be studied in this way. (Note that these are not two dimensional plots. They are several one dimensional plots (mass), arranged as columns of particles sharing the characteristic given on the horizontal axis.) The theory does not predict masses of fundamental particles. Figure 9.1 shows the measured masses. To make predictions of masses of these composite particles, we must make some assumptions about the masses to get started. Figure 9.2 shows three measured masses that are taken as definitive. With these, the others can be predicted. Figure 9.3 shows the predicted masses of the others, assuming the three postulated masses. The predictions match the observed values very well. This is a simple and limited demonstration of how computer simulations of particle wave functions in the Grid can be used.

While Ch. 9 is about (numerical) solutions of wave equations for particles in spacetime, Ch. 10 begins with a quote from Paul Dirac: "I feel I understand an equation, when I can anticipate the behavior of its solutions without actually solving it." This understanding is especially useful when the computational effort needed to produce solutions is so great. Simplified models and rules of thumb are helpful in gaining understanding the nature of solutions without fully solving each case. Wilczek points out three guiding principles that can be considered along with the wave equations for quarks, to explain how baryons have mass. First, a quark's color charge causes a disturbance in the fields that grows stronger with distance. Therefore, it takes energy to have quarks at a distance from each other. Second, this energy can be reduced by the proximity of another antiquark with opposite charge, so that their fields cancel. (Three quarks of different colors, making a color neutral triplet also cancel.) With exact superposition, there is exact cancellation of color charge fields, and zero energy in them. However, with the uncertainty principle, exact localization in position causes infinite (uncertainty in) momentum (and energy). (Note that large uncertainty necessarily includes the possibility of large absolute value. There's not that big a difference between two small numbers.) These two effects compete to minimize their energy contribution, since it is not possible for both to be zero. For stable particles, there is at least one compromise that works well enough that the particle does not decay. But the energy from these two effects is positive, and the third principle is that energy has mass, so these composite particles have mass from these two sources, even if the rest mass of the constituent particles is zero. This illustrates the theme of "mass without mass" that Wilczek wanted to show. He mentions in passing that a similar mechanism governs the size and structure of atoms. On p. 202, he states that these composite particles are the only cases where mass can be calculated from theory. The masses of the constituent fundamental particles are known only by measurement.

Chapter 12 is about simplicity and economy of mathematical models and theories. The goal is to get a lot of information from the theory, while minimizing the choices (input information) it requires to fit the data. Features that can be changed without effect may be superfluous. Too much arbitrary input information is suspect because with enough of it, a meaningless theory can be made to fit anything. Specificity of predictions is highly desirable, and predictions that disagree with observation are disqualifying. Predictions of previously unknown phenomena that turn out to be real are a big plus.

Chapters 13-16 consider aspects of the question of why gravity is so much weaker than the other interactions. Chapter 15 frames the question as "Why are nucleons so light". In Ch. 16, p. 156-7 Wilczek introduces Planck units, based on c, G, and h as universal constants of nature that determine the relationships between various fundamental physical conditions. Combining these three constants with their characteristic units in a way that gives units of mass, distance, and time, they can be made to form a basis for all physical units. Just as all units can be expressed as a combination of meters, kilograms, and seconds, they can also be expressed in terms of Planck distance, Planck mass, and Planck time. These are referred to as the fundamental units of the Planck scale, or Planck units.

On p. 158-9, Wilczek suggests that numerical values expressed in these units may be more tractable (closer to 1) than when expressed in other units. He acknowledges that this is an assumption, but in the case of the strong force, and hence the mass of nucleons, it seems to be true, with a value of 1/25. This is one of a variety of assumptions made about the Planck scale, and I'm not sure how well established they are. Beware of numerology.

In Part III, Wilczek makes his case for the unification of the three interactions of the standard model, and maybe gravity too. His approach is to show that the coupling strengths of the interactions converge at higher energy, as the interactions penetrate the clouds of virtual particles and reach the "bare" particles. To achieve this, it will be necessary to postulate an additional set of particles (p. 161).

The interaction energy that may achieve the unification of the interactions is speculated to be near 10^19 GeV (the Planck energy). This is about 10^15 times the LHC energy, so direct experimental observation is unlikely. Page 166 gives a nice analogy between the strong and electromagnetic forces, and how their short-range function holds nucleons or atoms together while the unbalanced residual force at slightly greater distances accounts for nuclear or chemical binding. The weak interaction is not so easily characterized. Does anyone know if there is an actual weak *force*, and how it is manifested?

On p. 167-8, identifies two loose ends to be dealt with later. They are the extreme weakness of gravity compared to the other interactions, and the non-zero mass of neutrinos. The latter requires the introduction of new particles.

On p. 172, Wilczek mentions that a "quirky copyist" may be involved in all of this. That's why I haven't discussed his unusual treatment of the standard model, which he calls the Core Theory. I think Fig. 17.2 (which he calls the Charge Account) and Wilczek's SO(10) model are widely recognized, if not fully accepted. Unfortunately, he doesn't explain these things much.

Chapter 18 gives a sketch of how he proposes the unification to happen. To preserve his proposed symmetry, the coupling strengths of the interactions should be the same. They aren't. But the observed coupling strengths are altered by the cloud of virtual particles filling spacetime. Therefore, at progressively higher energies, the interactions should become more and more "pure", unaffected by the virtual particles. This change of interaction strength with energy is called "running". Maybe as the interactions are measured without interference from virtual particles, they will converge. Fig. 18.2 shows how the three strengths run with energy. Wilczek doesn't say how these slopes are determined. I think there is some extrapolation from measurements made at the very low end of the energy scale way over to the right side of the plot. There may also be some theory-based extrapolation involved. Anyway, the lines do not converge.

In Ch. 20, Wilczek introduces supersymmetry (SUSY) to correct this deficiency in his unification theory. He does not describe exactly how this works, so I'll add my own interpretation as needed. SUSY introduces a new set of particles, one for each particle in the standard model, each with the same properties as its partner, except the mass is different, and the spin differs by 1/2. That makes each pair consist of one boson and one fermion. Each of a pair has the same electric, weak, and strong (color) charge. He says they are related in a way similar to the boost symmetry of special relativity, except that the velocity is confined to the tiny circular quantum dimensions of string theory (p. 187). These new particles and fields fit into his larger (SO(10)) symmetry (as well as some other candidates).

When this new symmetry is included in the field equations, there are more solutions, some of which represent the new supersymmetric particles. P. 186-7 give some examples of revised equations leading to new solutions, which in turn represent previously unknown fields and particles. He presumes that the new masses are all higher than the energy scale of existing accelerators, or some of them would have already been seen. These new fields, like the others, have quantum fluctuations, which manifest as virtual particles. That will change the screening effects, which changes how the reaction strengths depend on energy. This shows up as a change in slope of the lines in Fig. 20.1, possibly allowing them to converge. The slope changes above the mass/energy of the new particle. Since these are unknown, the lines might go anywhere, including to a convergence at 10^19 GeV. However, some of them should be fairly light and start to affect the slope at fairly low energy, and so might be seen with the LHC (p. 194). I think this is all speculative. Wilczek says the running of gravity's reaction strength can also be calculated, and it could converge to the same point. I don't know how definite the evidence for this convergence is, but the possibility of the lines changing slope as new virtual particles appear and screening changes seems quite plausible. This possible convergence of all four strengths at one point is taken as evidence that all of the interactions are unified at that energy, which is called Grand Unification. Various theories exist, with different symmetry groups and unification energies (10^16 to 10^19 GeV).

In Ch. 21, Wilczek identifies two major assumptions that go into this theory. One is that spacetime functions as a "multilayered, multicolored superconductor", i.e. that screening by virtual particles affects interaction strength. The other is that the tiny circular quantum dimensions exist and support supersymmetry, which could allow new particles to screen the interactions in such a way that they converge. The LHC may be able to test both of these assumptions. Another interesting possibility that could arise from this is that the lightest supersymmetric particle could be (nearly) stable and unable to interact with electromagnetic or strong forces. Dark matter could be made of such a particle. Wilczek claims (p. 196) that the amount of that particle left over after the big bang can be calculated, and is roughly the quantity needed.