THE BIG QUESTIONS IN ELEMENTARY PARTICLE PHYSICS

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Dedicated to Martinus J.G. Veltman, 1931–2021, In Memoriam

Whenever our basic understanding of the fundamental laws of physics improves, when more unified formalisms are uncovered, these advances are branded by subtle reformulations of the so-called Big Questions. More understanding comes with new questions, asked in a better way than before. When the renormalisation procedure for quantum field theories was finally unravelled, theoreticians realised that these gave new views on how the basic forces among elementary particles all could have a common, unified, origin. One elementary quantum field model stood out, which was dubbed the 'Standard Model', and the question was asked to what extent this model could describe all we know. Are there physical phenomena that suggest further improvement? Such questions could be asked to experimenters, but also from a purely theoretical point of view, one could ask what shortcomings the model has and what strategy should be followed to find better pathways. This paper briefly reviews some Big Questions of the past and asks how to use our deepest insights to rephrase the questions of the present.

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1. Introduction

With his strong personality, Martinus (Tini) Veltman has influenced many of his students, colleagues, peers and friends. Being smart and direct, his arguments were often quite to the point. If he found something to be important, then so it was.

He despised philosophy in science, and this was remarkable, as one of its closer friends was John Stewart Bell, who would later cause quite a stir in the field of science philosophy with his no-go theorems for hidden variables in quantum mechanics. And actually, Tini did cherish some philosophical concepts that he adhered to.

One of these was that purely mathematical arguments did not impress him at all, if he could not see why they would be important for our understanding of physics. One should not forget that physics is an experimental science. Elementary particle physics started with the observation of cosmic rays. Cosmic rays were understood as a steady flow of particles entering the atmosphere from outer space. If you set up a particle detector, you will hear it produce random sequences of clicks. Those clicks, that is what particles are. If you use different kinds of detectors under different circumstances, such as deep under ground, or on top of the Eiffel Tower, or near a particle accelerator, you will learn a lot about these particles. At low energies, the particles causing these clicks will be ionised atoms or molecules, but when they travel at high energies, or high speeds, they will be elementary particles. These are the basic constituents of all sorts of matter, including the atoms and molecules.

"What's in that box?", was the title of his nomination speech [1], April 1967, at the occasion of his appointment as Professor of Theoretical Physics, at the University of Utrecht. At that time, the known elementary particles were holding some deep secrets, resembling firmly closed boxes. The only hope to unravel these, seemed to be by shaking these boxes hard enough. New particle accelerators were being built in Europe and in the United States with the aim of having particles collide as hard as possible, allowing physicists to study the resulting debris, again consisting of elementary particles.

2. Quantum Field Theory

Being the tiniest constituents of matter, elementary particles must obey the same laws as atoms and molecules, and that means that they move in accordance with quantum mechanics. When we try to shake them up as hard as we can, this means that they must be aimed at each other with maximal amounts of kinetic energy per particle. These energies relate to the particle masses according to Albert Einstein's famous equation $E = mc^2$. If the kinetic energies E are chosen to be high when compared with the mass m of a particle, this particle may break apart to produce other particles. This implies that colliding particles may form multi-particle clusters, and understanding exactly what happens is then far from straightforward. How do we begin to attempt mastering such configurations?

One imagines that particles may be controlled by force fields, and these fields may obey field equations. Such situations are known in theoretical physics: sound, light, and also tension strengths in materials all obey field equations. Quantum mechanics ordains that vibrating fields carry energy that is partitioned in energy quanta. Realising this, it becomes tempting to relate the elementary particles to such quanta of energy. The question then really becomes: *How can we find out what these field equations are?* That, we will have to do by shaking these boxes.

A particle with electric charge will generate an electric current when it moves. Particles may carry other kinds of cargo when they move, and so there may exist various kinds of currents. It is possible to imagine that currents produce fields, much like the electric and magnetic fields generated by electric currents. The field equations controlling the strengths of such fields would be much like Maxwell's equations, which control electric and magnetic fields. The field quanta carried by these Maxwell fields were among the first elementary particles known: the photons, or, the carriers of light. Scientists considered the currents particles could generate, and imagined these to be the fields, which must satisfy equations: *current algebras*.

Like tennis balls, particles may possess *spin*. Different kinds of particles were known to spin differently. Pions and kaons were known not to spin at all, or, their spin is 0. They could be imagined to behave as charges (more precisely: a field that creates or annihilates a pion, can be equated to the divergence of a current [2]). Other particles, such as the ρ and A particles have spin 1, like the currents themselves, or perhaps they are more like the fields of these currents. Investigators attempted to see some systematics here. The field equations should link all particles with currents and force fields.

Steinberger [3] had noticed that if pions are assumed to interact with nucleons, to account for the attraction between like nucleons, one could also calculate how neutral pions, through creation and annihilation of virtual protons, would annihilate into 2 photons. This calculation matched the observed $\pi^0 \rightarrow 2\gamma$ decay quite well, but then there was a problem, since this decay did not agree with the simplest current algebras that Sutherland and Veltman [2] had proposed.

It was Bell who, together with Jackiw [4], and independently Adler [5], had noted that the conservation of the pion current would be spoiled by quantum effects, and the word 'anomaly' was coined for this. Adler, Bell and Jackiw had discovered that the mathematical procedure of *renormalisation* required an asymmetric treatment for decaying pions, in such a way that not only pions and nucleons are associated with a particular kind of current called 'axial current', but the divergence of this current must also get a contribution from photons. Not only the mathematics told them about this, and the experimental physicist Steinberger, not realising that he had been using renormalisation theory, had indirectly confirmed the anomaly, but Nature itself also seemed to agree with the math here, since the calculations of the neutral pion decaying into photons, agreed numerically quite well with the experimental observations.

For Tini this was a surprise. Nature *does* care about mathematics. When I arrived as an undergraduate student who needed to do some basic research in theoretical physics, he gave me 'anomalies' as a subject to study. I hardly knew quantum field theory then, and all I could do was to check the calculations and agree that there was some mystery here, a mystery that would show up whenever fermionic particles that differ from their mirror image contribute to algebraic currents. One thing I had learned was that mathematics is important for theoretical physics.

What are the field equations that control the behaviour of the fundamental particles? It was now obvious that currents must play a role. There were three kinds of interactions that appeared to be important. One was the forces caused by electric charges, their currents, and their magnetic fields. Great progress had been made from around 1930 to around 1950. It was satisfying to learn that numerous experiments could be carried out to confirm that electro-magnetic forces acting on charged and neutral particles could be calculated extremely precisely.

It became evident that there exist other forces. The second force was the strong force. Many particle species react very strongly on the presence of these forces, which made it easy to study their effects experimentally, but very hard to understand theoretically what is happening. Again, mathematics was needed: the symmetry structures of these forces could be mapped. This subject was well-known in mathematics as 'Lie group theory'. Veltman preferred the way it was taught by theoretical physicists. The elementary particles sometimes obeyed the laws and sometimes did not. We wanted to adopt the optimal way to describe all this.

The strong forces obey strict symmetry laws, but these symmetry laws are the reason why an important class of particles are immune: the leptons. These particles owe their existence to other, much weaker forces that make them observable in experiments. The weak forces also have symmetries, but they differ from the strong force. It appeared that weakly interacting particles generate a special type of weak currents. This current showed some resemblance to electric currents. What was going on?

It is tempting to describe the history of elementary particle physics as a succession of experimental discoveries and theoretical constructions that seem to be almost inevitable and obvious, but they were not that at all. There were no road signs telling investigators where to look and how to argue. They had to learn how to recognise the different particles, how to arrange the species and varieties like plants and animals. How do these particles originate, how do they interact and how do they decay; which categories are there and where do we look for new features? The subject of this paper is to explain the successes of the past, and to arrive at indications on how to go forward now. There is a community of experts who know exactly where humanity has been successful, and they have determined where to look next.

There is also a colourful mix of amateur scientists who are convinced that we missed many other possibilities for further research, but being unaware of what is already known, with great accuracy, reduces their chances for success almost to zero. The reason for bringing up the existence of all sorts of dead alleys in our science is that there are weaknesses and imperfections even in the professional lines of the story, mainly because some areas of research are inaccessible to experimental verification. History of science shows long periods of stagnation where voids in our overall picture had been filled with phantasies that seemed to be obvious at the time, but were badly in need of repair. Not only amateurs but also the professionals (to a much lesser extent but still) may be misled by their beliefs.

In the mid 20^{th} century, elementary particle physics was not suffering much from such problems. New possibilities for experiments became available, and new topics of mathematical science had been revealed. In 1954, Yang and Mills published [6] a great new piece of insight they got: *Maxwell's equations for the electro-magnetic fields, could be generalised.* One could add different currents, and their associated fields, so that new particles, would emerge, resembling photons, but carrying electric charges themselves. Their model was based on a more general set of Lie groups than plain electromagnetism. Veltman urged that his students should read this paper by Yang and Mills, and when I asked "Why?", his response was: "I do not know, but it looks important". And so it was, even though the 'new photons' the theory suggested, did not look like anything known; photons of this sort could almost certainly not exist. The reason why Veltman thought it was important was that the new currents resembled very much the currents that seemed to play such an important role in the weak interactions.

Numerous clever experiments and theoretical deductions had indicated that particles somewhat like the Yang–Mills photons, could very well exist, and explain the observed weak interactions, but there was an important complication. Moving with the speed of light, the Yang–Mills photons had to be assumed to be massless, whereas the particles responsible for the weak force had to carry a large amount of mass. It is tempting now to name the question that had to be investigated: *where does this mass come from?* But this is not how people argued at that time; rather, they concluded that the Yang–Mills theory just was inappropriate.

The question was answered, but not immediately recorded as such, when Brout and Englert [7] and independently Higgs [8], as well as a group at the Imperial College in London [9], proposed a mechanism for an apparent breakdown of local symmetries. This effect replaces the Yang–Mills photon with a boson that was exactly the one needed to understand the weak interactions.

Veltman was interested in a related but different question. Knowing how anomalies can ruin beautiful theories, he wanted to know how the procedure of renormalisation should be applied when photons such as the Yang–Mills particles were replaced by bosons with mass [10]. By doing the calculations very accurately, he discovered that this does *not* work.

The discovery of the correct theory for describing the weak interactions was made by asking a better question: *How can we introduce a particle spinning like a photon, but carrying mass, in such a way that the theory can be renormalised?*

This was the question that could be answered by discovering that only a Yang–Mills theory combined with the BEH mechanism leads to the kind of particles needed to describe the weak interactions, while at the same time an extra, spinless particle enters the scene, the Higgs particle. Without this particle, whose existence had been described and predicted by Higgs [8], renormalisation would fail.

One essential ingredient in Veltman's analysis was a feature of the particle propagator functions that enabled him to cut Feynman diagrams in pieces, the 'cutting rules' [11]. The Feynman propagator $\Delta^{\mathrm{F}}(k)$ for a massive particle in momentum space k is usually written as

$$\Delta^{\mathrm{F}}(k) = \frac{-i}{k^2 + m^2 - i\varepsilon} \quad , \tag{2.1}$$

$$\text{in position space } x : \quad \Delta^{\mathrm{F}}(x) = \int \mathrm{d}^4 k \, \mathrm{e}^{ik\cdot x} \, \Delta^{\mathrm{F}}(k) \quad , \tag{2.2}$$

where ε is an infinitesimal positive number indicating how the integral (2.2) must be chosen to be on a contour that avoids the pole (The variables k and x are 4-vectors in Euclidean space, where $k \cdot x = \vec{k} \cdot \vec{x} - k^0 x^0$). The propagator for a particle on-shell is

$$\Delta^{\pm}(k) = 2\pi \, \delta\left(k^2 + m^2\right) \, \Theta(\pm k^0) \, ; \qquad \Delta^{\pm}(x) = \int \mathrm{d}^4 k \, \mathrm{e}^{ik\cdot x} \, \Delta^{\pm}(k) \, . \tag{2.3}$$

Here, $\Theta(x)$ is the Heaviside step function. These on-shell propagators obey in x space,

$$\Delta^{+}(x) = (\Delta^{-}(x))^* \, ; \qquad \Delta^{+}(x) = \Delta^{-}(-x) \, . \tag{2.4}$$

The cutting rules state that these propagators are related as follows:

$$\Delta^{\mathrm{F}}(x) = \theta\left(x^0\right) \Delta^{+}(x) + \theta\left(-x^0\right) \Delta^{-}(x) \quad \text{and} \tag{2.5}$$

$$\Delta^{F\,*}(x) = \theta\left(x^0\right) \Delta^{-}(x) + \theta\left(-x^0\right) \Delta^{+}(x) \, . \tag{2.6}$$

One easily proves this by performing the contour integration in the complex k^0 plane. Equations (2.5) and (2.6) imply that, due to Lorentz invariance, Δ^{F}, $\Delta^{\mathrm{F}\,*}$, Δ^+ and Δ^- are all equal when x is outside the light cone. Because of the on-shell properties of $\Delta^{\pm}(k)$ integrations over $\Delta^{\pm}(k)$ often show no ultraviolet divergence, so that equations (2.5) and (2.6) are very useful in renormalising a theory. Remember however that, in momentum space, $\theta(x^0)$ behaves as a factor $-i/(2\pi k^0 - i\varepsilon)$, which may still lead to divergences.

3. The Standard Model

Renormalisation is a necessary ingredient whenever a theory describes interaction as a perturbation expansion. In other branches of physics, perturbation theory is just a technical device for performing calculations where the exact equations are too cumbersome. In particle physics, the situation is not quite the same. When calculating weak interaction processes, it is not clear whether 'exact equations' exist at all. The perturbation method was discovered, and renormalisation is a part of this. In principle, one might have thought that 'exact equations', whatever they are, will not require handling infinite expressions, asking for extra constraints just to keep the infinities under control.

It was originally thought that the *strong* interactions should not depend on such procedures, since the perturbation expansion diverges right from the beginning. But when 'asymptotic freedom' was discovered [12], it became clear that the ultraviolet region of the strong interactions also depends on perturbation expansions. The strong interactions were also found to be described by a Yang–Mills system, but without a BEH mechanism. One generally assumes that the ultraviolet domain of a theory determines the course of the interactions in all other domains as well.

The question *How do we sum the perturbation terms, or is there another way to obtain the exact equations for all interactions?* is correctly posed but it seems to be not so urgent. We can arrange the diagrams in such a way that diagrams calculated using perturbation theory determine with a satisfactory accuracy how the elementary particles will interact under practically all circumstances, as if we *nearly have the 'ultimate theory' at our fingertips.*

But this is not true for many reasons. First, the perturbation expansions are still formally divergent, so that we still do not quite understand what the equations are at the most fundamental level. Secondly, there is one force that can only be taken into account at the most rudimentary level: gravity. The gravitational force cannot be included in an optimal way; we return to this shortly. The third reason for concern is that there appear to be phenomena at a very large distance scale in the universe: dark matter and dark energy. These require extensions of what we know: new particles or new theories or both.

Besides that, the interactions that are pretty neatly understood leave us with the impression that there should be more. Thus, as is usually the case in science, we still have questions that need to be answered.

Before returning to these questions, it is important to make an abbreviated list of what we do have. *Electromagnetism* is now a special case of the Yang–Mills theories, a force based on the Lie group U(1). It is understood very well, in the sense that calculations can be carried out up to more than a dozen decimal places, where we can check the results with equally impressive experimental techniques.

The *weak force* is now well understood as an extension of electromagnetism in terms of a Yang–Mills theory with $\mathrm{SU}(2)\otimes\mathrm{U}(1)$ as its gauge group. The electromagnetic forces are then understood as generated by a U(1) subgroup of this theory. Finally, the strong force is an independent Yang–Mills system based on SU(3).

The matter fields consist of only one complex doublet of scalar fields, the Higgs field, in the representation algebra of $\mathrm{SU}(2)\otimes\mathrm{U}(1)$, and a threefold of Dirac fields in one $3\otimes 2_{\mathrm{L}}$ and two $3\otimes 1_{\mathrm{R}}$ representations of the full group, referred to as the 'three generations'.

This is a (very brief) summary of the 'Standard Model' of the elementary particles [13]. Somewhat surprisingly, the newest particle accelerator, LHC at CERN, has not produced anything new as far as we know, although as this is being written, a few possible glimpses are being studied [14].

4. Beyond the Standard Model

The fact that the Standard Model (SM) worked so well was a surprise for many. For one thing, many investigators claimed that quantum mechanics is incompatible with special relativity. Does this mean that there is something wrong with quantum field theory (QFT)? Veltman taught his students that this claim only comes from philosophers — there seems to be nothing wrong with quantum field theories. The validity of special relativity follows from the cutting rules, see end of Section 2. He did not tell us that it was his friend John Bell [15–17] who had come with powerful — but philosophical — arguments that something was wrong here. Veltman advised just to ignore these claims, and he was almost right, as will be explained later.

Already in the 1970s, researchers asked questions as to how to proceed from here. It is quite clear that the Standard Model cannot cover everything that may take place in the universe. It only explains what happens as long as collision energies of elementary particles do not significantly exceed a few TeV. We have no way to tell what there will be to add. In the 1970s, this boundary was much lower, and it was expected that the Standard Model would break down beyond 100 GeV or so. Thus, finding no clear new signal at all, was the biggest surprise delivered by the new generation of particle accelerators.

What did we expect?

We know that the gravitational force, most accurately described by the theory of General Relativity, is only covered at the most elementary level. In a sense, we can add perturbative corrections, by handling gravitation as the exchange of gravitons. This works up to a point: this perturbation expansion is not renormalizable and, partly for that reason, fails completely at the Planck energy,

$$E_{\rm Planck} = \sqrt{\hbar\, c^5/G_{\rm N}} = 1.22 \times 10^{16}\ {\rm TeV}\,, \tag{4.1}$$

where $G_{\rm N}$ is Newton's gravitational constant.

This is too far away to be accessible by experiment. However, it was argued that the group structure, and in particular the fermionic representations of the group SU(2)⊗ U(1)⊗ SU(3) suggested a natural further 'unification' into the group (SU(5), or better still, SO(10). In SO(10), the fermions might be arranged in remarkable multiplets forming a 16 representation of SO(10), which is indeed a spinorial representation of the same kind as the 4-dimensional multiplets they form in the Lorentz group, SO(3,1).

If we assume that a Brout–Englert–Higgs mechanism would break the symmetry down into the Standard Model group, this would have to happen at energies $\mathcal{O}(10^{-3})$ times $E_{\rm Planck}$, a number obtained by extrapolating the SM to higher energies, at which the strong interactions as well as the weak and electromagnetic ones would neatly match.

The numbers appear to match even better if we add the concept of *supersymmetry* to this scenario. According to this theory, there will be symmetry relations between fermionic and bosonic particles. The known fermionic particles do not match with any of the known bosonic particles to form supermultiplets, but this is expected to happen, and it should happen at energies that *can* be reached experimentally. However, in spite of extensive searches at the highest possible energies, the missing fermions and bosons have not been detected at all.

What is needed is further guidelines to follow. The theories considered above just use the observed symmetry structure of the Standard Model. Indeed, this is the most important lead we have, but, unfortunately, the energies accessible to experimental research are still way too far separated from the Planck energy, where all particles and forces should join to form a single, solid construction. We should search for further principles on which we can base our theories.

Perhaps the most promising approach is superstring theory. Regarding all existing elementary particles as pieces of strings, one can try to arrange the observed particles into known structures produced by these theories.

This is easier said than done. String theories produce symmetries and multiplet representations of these symmetries that show some resemblance to the SM. From the 1970s, this theory developed quite far, but one problem seems to be that many of the symmetry structures in the SM are broken, and it is not understood how symmetry breaking takes place in string theories.

Returning to Veltman, he has always criticised string theories as being too mathematical. But the most important warning he gave concerns the fact that ideas offered in string theory could not possibly be checked by experiments. One often expects that the stringy nature of particles will only become evident near the Planck scale. How do we know whether this theory is on the right track at all? What evidence do we have that strings have anything to do with our world? String theorists responded that string theory naturally explains several things, such as the existence of gravitational forces and the notion that particles form bosons and fermions forming representations of gauge groups. But the Standard Model shows numerous detailed structures that have been precisely determined in experiments, but that could not be explained within the terminology of strings.

The situation with other approaches to quantum gravity is not any better. We have Loop Quantum Gravity, an approach starting from connection equations with closed loops, and simplicial quantum gravity, taking space and time in tiny pieces that are locally flat. Needless to say, attempts such as all of the above must be encouraged, but, as yet, they have in common that they are based on fairly wild guesses that leave us at a loss on what we should try next. What is really needed is a *systematic* approach. Basically, the starting point was that there is something missing in our present understanding. Let us fill the gaps with something.

One feature that nearly all attempts tried until today have in common, is the way quantum mechanics has been used as a frame to start from. We have Hilbert space, and we have states in this Hilbert space. The question is, how should we characterise these states, and next, what strategies should we follow to guess the quantum evolution law. Eventually, that evolution law should be controlled by a Schrödinger equation. Are there constraints on this that we have overlooked?

Here, I have a suggestion that can be directly derived from philosophical arguments in physics. Quantum mechanics has always been treated as being a fundamental departure from classical logic. This, we claim, can be disputed. Quantum mechanics was discovered experimentally, but it could have been discovered by pure, mathematical thinking. Suppose that the evolution operators for elementary particles do not only involve differential equations but also finite permutations of states. In a way, we can say that this is supported by experiments: muons can be permuted into μ-neutrinos, pions into pairs of photons, and so on.

Mathematicians have learned to investigate the group of permutations and their subgroups using *linear representations*. In this doctrine, all elements of a group are written as matrices acting on finite or infinite vector spaces in complex space. Usually, these matrices are unitary. One derives properties such as the dimensionality of subgroups, using vector algebra. In mathematics, this is just technology, but in physics we call this quantum mechanics.

This technology is very general, one can apply it for all sorts of transformations, including the orbits of classical objects following some equation of motion. What this means is that the distinction between quantum mechanics and classical logic may not be as absolute as is usually taken for granted.

This would be an absolute departure from Bell's theorem [15–17]. Bell however, used philosophical assumptions that would apply when statistics is used to derive approximations. The representation algebra only applies when the exact theory is analysed. The exact theory should include every step in a measuring process, so that Bell's observers, 'Alice' and 'Bob' cannot decide what to observe using their 'free will'. This is where one can find the origin of the violation of Bell's theorems.

In this particular case, a more accurate philosophical study would be adequate, but since all theories we ever worked with in the past were approximations, we have no experience in working with exact theories.

This is where our basic physical insights could improve. We must learn to understand how to apply unitary representation theory, as a new generation of quantum mechanical doctrines, for model building. What one ends up with is a class of models that could be studied more precisely: the *cellular automaton theories* [18]. A cellular automaton is a system that works with arrays of cells, with identical digital data in each cell. The evolution law should tell us how every cell updates its data depending on the data in the nearest neighbouring cells. This is the kind of systems to which unitary representation theory applies. Note that the cellular automata referred to here evolve by following completely classical logical laws. Quantum mechanics enters as a device, not a new theory that affects our notion of 'reality'.

This leads to new 'Big Questions', which contain purely mathematical ingredients that we should be able to work out. The first Big Question here is how a cellular automaton, on which, for the time being, we impose the constraint that it be time reversible, can be mapped onto quantum field theories. This may sound incredible, but actually, the existence of such mappings should be manifest.

All particles for which we know the associated fields, have masses that are very low compared to the Planck mass, see Eq. (4.1). Therefore, the radial component of the Higgs field must be a Goldstone boson. Its mass being as light as it is, must mean that we have here a very good but not exact symmetry, which is spontaneously broken. What needs to be done is to identify this symmetry in a cellular automation.

Next, we have the gauge fields. They represent local symmetries, and therefore we should identify exact local symmetries in the automaton. The data in the automaton all move so fast that the values they take are invisible at large distance scales. However, there is a number of exceptions: binary symmetries, presumably also approximative, and related to the Higgs particle symmetry. The binary symmetries generate fermionic fields. The fact that they interact with the Goldstone/Higgs symmetry should be an indication as to how these fermionic modes all relate.

In short, what is called the Standard Model now, is a representation of the (exact and approximative) symmetry transformations in the cellular automaton, and we should be able to compute how the local symmetries are related to the global one. Today we do not know how to do such calculations, but we have not really tried.

It is interesting to note that the cells in the automaton should be fast fluctuating. Representation theory tells us that these will all occupy the lowest energy states, which are the only states we can detect today [19]. It is via these states that quantum mechanics emerges.

This would only be the beginning of renewed efforts to find the theory at the basis of the Standard Model. We know the symmetry structures, we know that there is a global symmetry that is very slightly broken, and there are various types of local as well as binary symmetries of which we also know how they should be connected,

Finally, interwoven in these questions is the structure of space and time themselves, and in particular their symmetry properties. This we derive from Special and General Relativity. Again, we know the equations but it will be a difficult and vast problem to decipher these.

The nice feature of the systems that we may have to study is that, quite possibly, they are finite and discrete at the Planck scale. If we can distil models with the right symmetry, the *constants of nature* will be calculable.

Anyone can ask Big Questions, but it is not easy to ask questions that would suggest new pathways leading to real progress of our understanding. A notable example is the set of questions asked in connection with superstring theory. The notion of superstrings, equipped with totally standard procedures regarding quantum mechanics, is often used as a starting point. One question frequently asked is how to incorporate black holes in the picture. Since classical gravity for sure admits solutions that appear to behave as the most compact objects possible given their weight, it is asked how to describe these in the known string language. Of course, such questions are legitimate, but since I now have seen how quantum mechanics can be incorporated smoothly into equations that respect classical logic, my preference goes towards the use of such insights. One obtains unique views of what a black hole really is.

Veltman would just smile when these topics are brought up. He believed neither in string theory nor in black holes. And quantum mechanics? Just consult the experimental results and do the math, would have been his advice.

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