THE LIMITS OF OUR IMAGINATION IN ELEMENTARY PARTICLE THEORY

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ABSTRACT

The author attempts to identify the obstacles that are standing in the way of further progress in our theoretical understanding of the world of quantised elementary particles. Our own evolutionary history may be as relevant to this question as the actual structure of the laws of physics.

Keywords: Intuition, Evolution, Patterns, Logic, Obstacles.

1. INTRODUCTION

Fifty years ago, Physics had reached a marvellous degree of perfection. The atom was cracked, it had been revealed to consist of a tiny nucleus with very light, negatively charged particles orbiting around it, and moreover the rules governing their motion had been uncovered: they were extremely accurately described by the laws of Quantum Mechanics.

And yet this was only the beginning of an equally successful period of further discoveries: after the discovery of the pion [1], a plethora of new subnuclear particle species were found [2], and many of these were discovered to possess an internal structure, they are composed of quarks, kept together by gluons. An essential step was made in the early '70s: the determination of the *complete set* of all possible renormalizable field theories. In a relatively short period of time, one choice from this

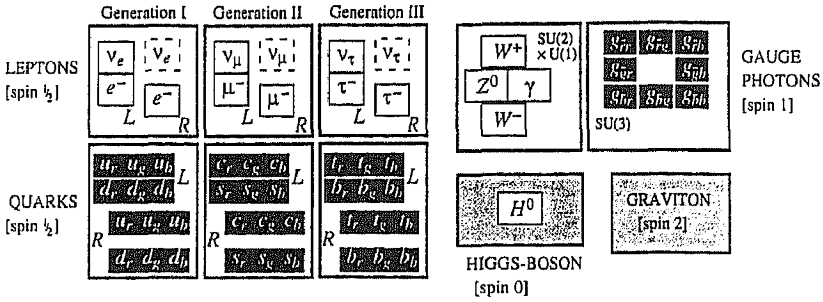

Fig. 1. Sketch of the Standard Model.

set was identified as being able to reproduce the experimental observations extremely precisely [3]: the *Standard** *Model.*†

Ever since the later '70s, physicists have been ready for the next step. We want to go beyond the Standard Model. We would like to insert supersymmetry and to quantise the gravitational force. We came with "Superstring Theory" [4], enriched it with membranes, generalised into D-branes [5], and expect all this to condense into "M-theory".

Yet, as far as our description of the real world is concerned, these theories are still idle, and very little tangible progress has been made since 1984. Central themes of this exposé are the following: the human mind has been able to penetrate deeply into the truths of quantum elementary particle physics. Can this be explained? And what then is standing in the way of further progress today?

To answer these questions, one has to understand the physical world as well as the human mind.

To begin with the latter, we now know that it took shape in accordance with the forces of evolution. Natural selection has given to the human mind the ability, for instance, to make bows and arrows, better than other races could. The Neanderthalers, for example, must have become extinct for this reason. But then, one may ask, "What do bows and arrows have in common with elementary particles?" Indeed, it must be that those aspects of logical reasoning that bows and arrows have in common with elementary particles, have been decisive in our recent successes.

To illustrate such biological arguments further, I will make a digression into what should be called "the Standard Model of Biology", a theory that explains evolution in terms of elementary processes at the molecular level. [6]

* Since this construction was actually very special, I would have preferred to replace "Standard" by "Universally Accepted".

† In modern particle physics, there is a tendency to interchange the words "Model", and "Theory". Of the many models used in theoretical physics, the Standard Model is one of the few genuine theories. Historically, it started out as being just a model.

2. EVOLUTION. THE BEGINNING OF LIFE

In this section, a summary is given of the insights into how life on this planet may have started. It is mixed a bit with my own non-professional ideas on the subject. Inaccuracies are to be attributed to the author.

Instead of 50 years, let us go back in time a couple of billion years. An apparently inconspicuous planet was orbiting an apparently inconspicuous star, and it had only just solidified. Volatile matter had escaped from its interior and had formed an atmosphere and oceans, above a crust consisting of continents which were continuously moving with respect to each other due to internal convection currents. Numerous exotic chemical reactions occurred at its surface, producing, among others, many different organic substances. These may have accumulated in numerous mud pools at the coasts and near rivers, constantly changing, not only by the action of rain and ocean water, but also by volcanic activity, and perhaps meteorite impacts. ‡

So-far, these phenomena may have been common on many such planets. But, during what might have been a window of only a couple of million years, an extremely improbable combination of circumstances may have brought about a miraculous accident. [8] Most if not all of the details of these events are still shrouded in mystery, both for biologists and for chemists. I imagine it could have been something like this. [6]

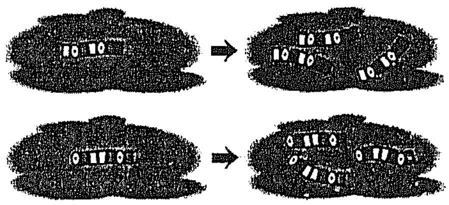

Fig. 2. The beginning of life.

a) A chain consisting of a given sequence lands in a pool, catalysing the formation of many other chains identical to the first. *b*) A different chain would produce different off-spring.

The mud pools contained tiny molecular units which, with some effort, could be chemically bound into chains. The first chains were not long, and they were rare. The miraculous chemical condition was, that if any kind of chain accidently landed into a newly formed mud pool, it would calalyse the formation of many more chains, and these other chains would tend to consist of the same sequence of units as the original. § See Figure 2.

‡ In the scenario that will be sketched here, many chemical substances are required to exist in such high concentrations that experts prefer to think of more violent environments than an ordinary, peaceful "mud pool". [7]

§ It is rather unlikely that the first chains were anywhere nearly as complex as modern *DNA* molecules.

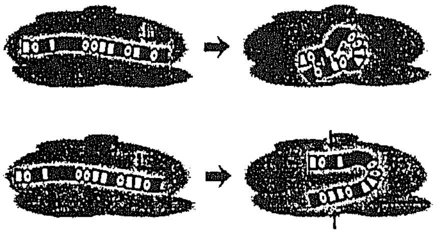

Fig. 3. Genes expressing forms.

a) A chain folding in such a way that units pair up, due to attractive forces between equal units. Unlike units repel each other. *b*) A single change of a subunit could disable the chain to make this particular form (other shapes might still be possible).

The chemical properties of a chain molecule may in a very delicate way have depended on its composition. See Figure 3. Here, we depicted what happens if like units attract. In the (more likely) case that *unlike* units attract, the situation is more complicated to imagine. Whatever the exact forces are, certain chains would roll up into sturdy structures, while others would not do that, or form different structures. From these shapes it may have depended how molecules were transported from one mud pool to the next, and how quickly they disintegrated. This way, the competition between the chain molecules would have begun. The molecules transported information. They became the first genes. Whichever gene managed to multiply and spread fastest, would have become the dominant form. The war between the genes continues to this day and is called "evolution". It is my impression that the conditions necessary to get evolution started are so special that it would amaze me if it has happened at all on many more planets in the entire universe. The chemical reactions needed to form the required molecules from abiotic material are known, but presently it is not at all understood how the chemicals involved could ever have reached the concentrations required [7].

Fig. 4. Cells form membranes.

a) Membrane formation. *b*) form organisms.

More was needed. The mud pools must also have contained molecules with one water-attracting end and one water repelling end. Such molecules tend to form membranes [9] (see Fig. 4). The original mud pools may have been obliterated with freely floating membranes. Miraculously again, the gene-molecules managed to manipulate the membranes. In Fig. 4b, a gene has built itself a house. Richard Dawkins [6] refers to these houses as "survival machines", and they served exactly the same purposes as our houses do today. Their forms and their organisation slowly evolved. Clearly, these cells made these genes much more immune against desiccation and attack from outside. Hundreds of millions of years later, the cells must have started to agglomerate to form organisms, and they slowly took the shapes of all living beings familiar to us today. All these forms, however, were nothing but tactical survival machines enabling the genes to multiply and defend themselves more efficiently.

3. THE HUMAN MIND

I skip a couple of intermediate steps, and return to the scene of just 5×10^6 years ago. Among the numerous different kinds of gene-survival machines, some of the genes had managed to fabricate things we call "primates". They were monkeys. Some of their cells had specialized into information processing, and they are called "brains". It is important to note what these brains could and what they could not do.

The extreme agility monkeys had in jumping from branch to branch and tree to tree, was obtained by learning processes. They imitated their parents. By that time, the most advanced monkeys may also have learned how to make and use the simplest tools such as branches to obtain food, defend themselves, etc. They copied the behaviour of others.

Monkeys were also quite able to recognise patterns – to some extent. They could distinguish edible things from poisonous or dangerous ones, and so on. This extremely complicated mental process is a beautiful accomplishment of evolution.

But what monkeys were very bad at, was logical reasoning and arguing. They could not add two and two together and draw conclusions. The ability to do this had to wait until they had evolved into homo sapiens.

Next, let us look at the situation 50 000 years ago. People knew how to throw rocks at each other, but also how to use them to build things. They used branches not only to obtain food but also to build houses, and weapons such as bows and arrows. Moreover, people could *experiment*, and elaborate new ideas. This enabled them to control fire, and they gave new delightful shapes to rocks, turning them into patterns they could recognise elsewhere in life. It is called "art". By this time, people had learned how to calculate and to anticipate: put snake poison on your arrowheads to make these more deadly, cultivate plants and animals, etc.

Whereas the previous section explained that all these developments are entirely due to evolutionary processes at the molecular level, the conclusion of the present section is also revealing.:

- Our ability to *copy* the achievements of our predecessors is milions of years old.
- Even older is our ability to recognise patterns and shapes.
- But our familiarity with *logical reasoning* has a much more recent origin, a couple of thousands years ago.

Therefore: *copying is easy for us; logical reasoning is very difficult.*

Remark added in print: the reader should *not* conclude that copying things is an inferior procedure; quite to the contrary, it is very powerful, and often the only choice we have. We have to use this ability of ours as best as we can, searching for things to copy whenever we do not know how to proceed. But in the mean while, we should realise that doing physics also requires solid reasoning, and that we, humans, are bad at it; we must learn to improve our ability to reason.

Our reasoning is full of flaws. Much of the progress of modern physics is due to the detection of flaws in our reasoning that had escaped from our attention for decades or even centuries. Einstein's relativity theory is a prime example of this. It had not been realised before that our notions of space and time had to be revised. If we look further back, say 500 years, we recognise bigger gaps in the logical explanations of physical phenomena at that time. And then a property of the human mind shows up that you might be surprised to hear about from a scientist: humans *love* logic! The proof of this is, that whenever a gap in our understanding shows up, we fill the gap with surrogate logic. I propose to call this surrogate logic *magic*. Its definition is:

Magic is make-belief logic without any proof, from observations or otherwise.

There are many examples of magic, even in the modern world:

- Fairy tales. When the logic of the real world is too difficult to explain to our children, we replace it by a kind of magic that they do understand, but the logic is false.
- Myths. Achilles was a hero in Greek mythology. During his childhood, his mother Thetis dipped him in the river Styx, by which he became invulnerable, except for the part of his heel where his mother held him. At that spot, he was eventually killed. It sounds logical, but it isn't logic from real life.
- Many of the world's religions also make use of magic.
- Superstitions, astrology, are all based on magic.

When our logic fails us, explanations are invented. What thunder and lightning were, was not known by the Germanic tribes of ancient times, so they made up the explanation: angry gods are riding over the cloud tops with their wagons, throwing fire at each other and towards those on the ground.

4. MODERN PHYSICS

There are also examples of magic in physics. Quantum mechanics is an important example. The laws themselves are constructed with extremely precise logic, but there is a gap: what is the reality behind the laws? This gap is filled with magic. The existence of "many worlds", the role played by "consciousness", do not follow from quantum mechanics, but physicists are unhappy with the fact that we simply do not know what the underlying reality is.

I do not place myself above all this; I also need to speculate about reality. Instead of soft notions such as "many worlds", or "fuzzy logic", my belief is that there is a rock-solid, concrete and merciless reality behind the quantum mechanical laws of physics. It is entirely deterministic, but we do not understand these laws at all. All we have is rules of dealing with the statistics. It is usually argued that the violation of Bell's inequalities implies the impossibility of a deterministic reality. This conclusion, however, requires the assumption that an observer has a "free will" in choosing whether to measure, say, the x-component or the y-component of a spin. But we know that this so-called free will is also determined by laws of physics. In Aspect's experiment, it is replaced by harmonic oscillators, hardly an example of free will. Physicists have not yet accepted the idea that observers, even our own brains, are controlled by laws of physics, not by free will. I should hasten to add that my arguments are insufficient by far to resolve the problems of interpreting quantum mechanics. The true answers are still unknown.

New developments in physics require that:

1. a *pattern* is recognised in a group of physical phenomena;
2. the *structures* in this pattern are analysed;
3. by solid *reasoning* the logical coherence in these structures is explained;
4. and then the complete *laws* are formulated.

Point (3) here does not have to be the most difficult stage, as long as we have examples from previous theories that we can copy. In that case, the developments quickly follow each other, but when new procedures are required, there may be an obstruction.

Famous examples in recent physics are the revolutions around 1900. Maxwell's wave theory of light had been based on copying the description of waves on an ocean, but the genius of Albert Einstein was needed to show to us a flaw here: the analogon of the ocean, the "ether", should be disposed of.

In 1927, the genius of Dirac was needed to deduce a new equation for the electron, and to conclude from that the existence of antiparticles (positrons).

During the period 1950 – 1968, a lot happened in theoretical physics, but, at least in elementary particle physics, there was no breakthrough in our understanding. Quarks had been proposed, but it was then argued that they do not exist. Here, one was copying Einstein (you don't *see* the ether, so you must conclude that it does not exist!). Renormalizable quantum field theories existed, but they were thought to be wrong. Here, Dirac was copied (if there is an inconsistency in your equations, replace them by something else!)

In the early 1970s, new reasoning gave us the exact place that renormalisable gauge theories have in particle physics. It is amusing to observe what happened when the Weinberg-Salam-Ward model was recognised as being a good candidate for the weak and electromagnetic interactions: many copies of the model were proposed, with little changes here and there. [10] They all turned out to be wrong; the original scheme was the best.

When the new field of non-Abelian gauge theories was opened up, many new topics for study became available. The importance of topologically non-trivial fields was discovered, such as vortices, monopoles, and instantons. They play an essential role in the quark confinement mechanism, so we learned that quarks and gluons are real, even thought they are confined. The concept of "duality", a reciprocal relationship between different theories began playing an important role, but it had been copied from statistical physics.

Simultaneously, string theory arrived. It was originally intended to be a model for hadrons. Although it successfully explained the linearly rising Regge trajectories in the hadron spectrum, it was eventually replaced by QCD, which explains the same features much more accurately. Yet, string theory exhibited so much interesting mathematical structure, that copies of it began being used as candidates for more fundamental theories of the basic forces.

5. STRING THEORY

Many results from previous theories could be copied: the algebra of states, the structure of Feynman-like diagrams of something that looks like a perturbation expansion, the essential role of various topological structures such as the p-branes, and dualities of various sorts. The complexity of the associated mathematics is impressive, and it is not my intention to criticize the research that led to the present understanding of these intricate structures. But we hear the word 'magic' just a trifle too often, and indeed there are many logical gaps. They are filled with what is usually called 'intuition'. Superstring theory is often suspected to 'be' (read: 'lead to') an exact universally valid theory for all fundamental interactions. This suspicion is based on the following observations:

i) String theory is better than renormalizable: it is *finite.*

ii) String theory naturally contains a *gravitational force.*

iii) String theory has *no free parameters.*

Suggestive as these results are, certain comments are of order:

ad *i*): The theory is finite *order by order in the perturbative expansion.* In practice, this situation is not much better than what we have in ordinary quantum field theories. The entire expansion still diverges. This, to be sure, is a problem that is also fully present in quantum field theories. Quantum electrodynamics does not allow calculation of $g-2$ for the electron with an accuracy better than a number of the order of $\exp(-C/\alpha)$. Even QCD, the celebrated theory for the strong interactions, though asymptotically free, nevertheless suffers from this problem; its mathematical foundation is less than perfect[‖]

ad *ii*) Therefore, space-time is curved. Yet 'string perturbation theory' starts out with a flat (or with fixed curvature) background space-time. This leads to trouble in the formulation of the theory. It is founded on very weak logic.

ad *iii*) But there are many possible 'vacuum states'. The theory is too weakly formulated to enable us to distinguish between these. If, following Linde [11], the only distinction can come from an anthropic principle, then the labels of these vacuum states effectively serve the same function as a coupling constant.

Exerting the most rigorous logic is imperative here, and indeed, here the logical line is difficult and treacherous. My own impression is that string theory cannot be anywhere close to the ultimate theory, although it may well contain important information about our world. As it is the case with renormalizable quantum field theories, string theory may possibly function as a model for a certain regime of the physical world, but not for the whole world.

Presently, we see a strong inclination towards the use of abstract mathematics (following Dirac's successful example), the use of various types of duality (following successes in statistical physics and lattice gauge theories), and the use of large N limits of matrix theories (which had been successful in Quantum Chromodynamics, in particular in two dimensions), and this led to a

‖ Lattice QCD is usually assumed to be rigorously founded, but if one wants to *prove* uniqueness of the amplitudes and the spectrum, one hits upon the difficulty that the vacuum state is not well enough known. Here also, no criticism is intended for the important work on lattice QCD.

doctrine called M-theory.

Even the most fanatic adherents of these ideas admit that they are based on intuition, not on solid reasoning. The gaps appear to be filled by magic. What is happening here? On what is this intuition based? Is it something in our genes? Rather than criticizing these developments too much, I remind the reader that up till the present our genes have been extremely helpful, so perhaps this is the way to go. But it is not based on logic.

6. BLACK HOLES. CONCLUSION

There must be considerable gaps in our understanding of both General Relativity and Quantum Mechanics, in particular where these theories overlap. The best strategy appears to be the frontal attack: what are the strongest possible gravitational fields? What are the states with the highest possible energy or energy density? Thus one is led to investigate the black hole and its relation to quantum mechanics.

The advantage of using black holes as *Gedankenlaborator*, is that they can easily be visualised. They are ordinary objects, much like bows and arrows. Given the fact that our capacity at logical thinking is weak, our best chances for success are here. In contrast, strings, and their effects on the metric, are exotic, and M-theory appears to defy our common sense. Our intuitions in this domain of physics are likely to be wrong – mine certainly are.

A promising result of quantum black hole theory, obtained soon after Hawking's discovery of their particle emission properties, is that the amount of *information* that can be posited on the black hole horizon, is precisely known: one bit of information for every $0.724 \times 10^{-65}\ \mathrm{cm}^2$. Thus, it appears that the physics of quantum black holes will be the physics of information processing. It is tempting to speculate that all of physics at the Planckian distance scale is nothing but a precisely defined manipulation prescription for bits of information. It is the physicist's task to unravel the rules.

Quite generally, history has shown to us that the road towards the truth can be quite complex. It is sometimes discovered by very intuitive reasoning, sometimes by applying the severest logic. What is needed is a large community of *different* theorists, and experimentalists with different styles and techniques, large scale and small scale, approaching the problems from different angles. The most successful avenue will become the highway of the future.

Evolution in physics will be as merciless as evolution in biology, and equally erratic. Not always those who may seem to be the best equipped will get their way. The true obstacle is often the point where new logical reasoning is required, and the appeal to magic is to be avoided.

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