Seeking inspiration from the Standard Model
in order to go beyond it

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Abstract

We look at various features of the Standard Model with the purpose of exploring some possibilities of how to seek physical laws beyond it, i.e. at even smaller distances. Only parameters and structure which are not calculable from the Standard Model is considered useful information. Ca. 90 bits of information contained in the system of representations in the Standard Model are explained by four reasonable postulates. A crude estimate is that there is of the order of \( \sim 2 \times 10^2 \) useful bits of unexplained information left today. There are several signs of the fact that the Standard Model is a low energy tail of a more fundamental theory (not yet known). However, some worries are expressed as concerns how far the exploration of the physics beyond the Standard Model can proceed - if we are to be inspired from these \( \sim 2 \times 10^2 \) bits alone.

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1 Introduction

It is a wonderful fact, and we should not forget to appreciate it, that the collaborative activities here on our planet - which take place roughly $\sim 10^{17}$ seconds after the “big bang” - have been able to design experiments creating physical conditions which are substantially removed from the natural energy scales on earth. So far we have been able to set up experiments which can give information about the extreme physical conditions in the universe back to approximately $\sim 10^{-10}$ seconds after big bang!

Moreover, a set of (mathematical) regularities which account for the observed behavior of Nature under these extreme conditions (with energies of the order of $\sim 10^{11}$ eV per microscopic degree of freedom) have been found and are compactly described in the generally accepted Standard Model of the electroweak and strong interactions.

Questioning [1] whether we will be able to identify a set of principles which captures how Nature operates at even earlier times, i.e. at even higher energy, it is worthwhile to speculate how to be guided towards such principles?

The situation is today that theoreticians (the creators of the Glashow Salam Weinberg Ward model and QCD, i.e. of the Standard Model) have caught up with experiment to such an extent that making further theoretical progress is up to the problem that there is very little information about the laws of Nature which is not - in principle - explained by this Standard Model. So we have to make careful use of the little information yet left unexplained.

2 The Standard Model (input and output)

The Standard Model provides not only detailed perturbative - and even some nonperturbative results - of specific processes but explains also many general features such as symmetries. For example we may indeed consider the following features derivable from the Standard Model:

1. Parity, charge conjugation, and time-reversal symmetry for strong and electromagnetic interactions.

2. Chiral symmetry and hereunder approximate flavour-symmetries (due to the smallness of some quark masses), e.g. isospin and Gellman-SU(3) symmetry for strong interactions. Conservation of baryon B and lepton number L and especially B-L are derivable with a high accuracy (at low temperature).

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1By unexplained we here mean unexplainable in terms of predictions from the Standard Model itself, i.e. we do not count the huge amount of hadronic data, say, which we today think are explainable entirely within the Standard Model itself, though requiring nonperturbative techniques with are beyond present abilities.

2Provided, though, that the theta-term coefficient $\Theta_{QCD}$ of QCD is very small.
3. Custodial symmetry

Besides many symmetries, a lot of parameters in e.g. atomic or nuclear physics are derivable from the Standard Model (think e.g. of a parameter like Rydbergs constant $Ry = \frac{me^4}{2\hbar^2}$ in atomic physics or the decay rates for super-allowed transitions in nuclei).

However, some features must be imposed at the outset. These features rather defines the Standard Model - they cannot be derived from it. We could call them “input” into the Standard Model. Some of these features concerns symmetries, e.g.:

1. 3+1 dimensional Poincaré invariance.

2. Gauge symmetry under the gauge Lie algebra $U(1) \times SU(2) \times SU(3)$ or, better, Lie group $S(U(2) \times U(3))$.

3. The fermion Weyl particle representations with its repetition in three generations (families), cf. table 4.

4. The Higgs or Higgs-replacement is doublet with $y/2=1/2$.

Not so transparently related to symmetries are the general principles of quantum mechanics and quantum field theory (and renormalizability) which is also to be considered input structure into the Standard Model. In addition to these input principles there are a number of unexplained parameters:

- 3 lepton masses, 6 quark masses, 3 gauge coupling constants, the expectation value of the Higgs field $<\Phi>$, 1 topological angle (close to zero), 4 quark mixing angles, i.e. all in all of the order of 19 external (unexplained, but already measured) parameters or so.

There are also a few not yet measured parameters which are only accessible through cosmology — if at all — or through better accelerators: The Higgs mass, the weak topological angle, $\Theta_{SU(2)}$, and to some extent even the top mass.

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3Custodial symmetry is the extra $SU(2)$-symmetry of the Higgs-field physics arising from the fact that the Higgs-field potential $V(|\phi|^2)$ and the Higgs-field kinetic term are invariant under $O(4) \sim SU(2) \times SU(2)$ symmetry - considering the two-component Higgs-field 4 real components transforming as a four-vector under $O(4)$ - while it is only the one of these $SU(2)$’s which is identified with the Glashow-Salam-Weinberg (GSW) $SU(2)$ gauge group. The remaining $SU(2)$ is the custodial symmetry group.

4Note, that often only very little of the Standard Model is used in the derivation of such parameters in atomic or nuclear physics. Remember that the “Standard Model” has absorbed in it quantum mechanics, Q.E.D., the Maxwell equations etc. so we can consider e.g. Bohr’s formula to be a consequence of it.
### Representation of Standard Model

#### Matter Fields

| $U(1) \times SU(2) \times SU(3)$ representation $(y/2, I_W, a)$ | $1^{st}$ family | $2^{nd}$ family | $3^{rd}$ family |
|---|---|---|---|
| $(1/6, 1/2, 3)$: $q_L \overset{CP}{\sim} (\bar{q})_R$ | $(u_r, u_y, u_b)_L$ | $(c_r, c_y, c_b)_L$ | $(t_r, t_y, t_b)_L$ |
| $(-2/3, 0, 3)$: $(\bar{u})_L \overset{CP}{\sim} u_R$ | $(\bar{c}_r, \bar{c}_y, \bar{c}_b)_L$ | $(\bar{t}_r, \bar{t}_y, \bar{t}_b)_L$ |
| $(1/3, 0, 3)$: $(\bar{d})_L \overset{CP}{\sim} d_R$ | $(\bar{s}_r, \bar{s}_y, \bar{s}_b)_L$ | $(\bar{b}_r, \bar{b}_y, \bar{b}_b)_L$ |
| $(-1/2, 1/2, 1)$: $\left( \begin{array}{l} \nu \\ l \end{array} \right) \overset{CP}{\sim} \left( \begin{array}{l} \bar{\nu} \\ \bar{l} \end{array} \right)$ | $e^+$ | $\mu^+$ | $\tau^+$ |
| $(1, 0, 1)$: $(l^+)_L \overset{CP}{\sim} l^-_R$ |
| $(1/2, 1/2, 1)$: | | |

Table 1: This table lists all the 15 irreducible representations of left handed Weyl fields in the Standard Model, the representation structure being denoted as an ordered triple in the left column. The first item of this triple $(y/2, I_W, a)$ is the weak hypercharge in the normalization, often called $y/2$, the next is the weak isospin $I_W$, and the third is the dimension of the associated irreducible representation of the color $SU(3)$-group with an underlining, the anti-triplet is denoted $\bar{3}$. The lower indices $r, y$ and $b$ refer to the three colors “red”, “yellow” and “blue”. The upper index $c$ denotes that it is not exactly the flavour indicated by the symbol but the Cabibbo-rotated one which goes together with the associated quark-flavour of the 2/3-charged quark. The Higgs field is written with “?” to denote that it may not exist.

Charge-parity conjugation will give the representations, as indicated in the table, through the relations:

$q_L \overset{CP}{\sim} (\bar{q})_R, (\bar{u})_L \overset{CP}{\sim} u_R, (\bar{d})_L \overset{CP}{\sim} d_R, \left( \begin{array}{l} \nu \\ l \end{array} \right) \overset{CP}{\sim} \left( \begin{array}{l} \bar{\nu} \\ \bar{l} \end{array} \right)$ and $(l^+)_L \overset{CP}{\sim} l^-_R$
2.1 Why and how to measure the information content in the Standard Model?

How long can theoretical physicists go beyond the Standard Model without new progress in experimental physics? This is measured by the amount of information in the structure and parameters in the Standard Model not yet explained. Any proposal for a theory beyond the Standard Model would namely have to defend its truth by explaining some of this information.

But how shall we measure, more quantitatively, this information? If we want to teach contemporary particle physics to a layman or an alien, we will explain that it is described by a gauge theory, what the gauge group is, which representations is used and finally the value of the external parameters. But, prior to that, we will also have to teach him general physics, and the concepts necessary to define a gauge field theory etc. This process would require a huge amount of information, or text-bits, and such a number can not be of interest for the purpose of estimating the scientific value of a model in theoretical physics.

Rather the tables below may be viewed as a kind of “shopping guide” which the reader may find useful when buying a “model of everything” or a “model behind”. The scientific value of such models is given, then, by the number of bits they are able to explain. The price of a model is, in this analogy, the number of bits required to define it.

As a terrifying example of explaining a presumably negative number of bits one may mention the “world machinery” model described in \[6\] set up to explain the 3 bits of the space-time dimension, using a rather involved set of model assumptions, representing a number of bits which is complicated to evaluate, but most likely is greater than 3.

As a less terrifying example we may mention some work by S. Dimopoulos, L.J. Hall, S. Raby and A. Rasin \[11\]. In a scheme taking over a Gorgi-Glashow supersymmetrized SU(5) G.U.T., or rather SO(10) scheme, they postulate some operators responsible for the mass matrices and yield so remarkable agreements with experimental masses and mixings that it looks, at first, as being able to explain 30 bits! (they explain 13 parameters from 7 input parameters).

To bring the concepts in theoretical physics, e.g. the concepts defining the Standard Model, in contact with daily language (and ultimately with elementary elements of perception) is a very complicated task. The outcome of such an exercise will depend on the cultural context in which we develop physics. Besides, if we were able to rewrite the entire Standard Model into the form of an text-string consisting of elements of language (words) in direct contact with elementary perceptual experiences, the Standard Model would look so complicated that its beauty and simplicity would be hidden. Somewhat analogously, a simple and beautiful program written in Pascal looks horribly complicated if written in terms of “machine language”.

However, by closer inspection it turns out that about four bits of the information has been fitted into their scheme by inserting zeroes in the mass matrices (strongly) inspired from the already known experimental numbers. Moreover, a place where a larger amount of adjustment could potentially have sneaked in is in selecting the composite operators involving several successive exchanges of 45’s and intermediate fermion propagators. These
Let us sketch how we may crudely define - i.e. in a somewhat arbitrary way - the number of “bits” needed in setting up a model as the Standard Model, i.e. the amount of information contained in the input structure and input parameters needed to specify the model.

We take this number of bits of unexplained information to be given by

\[ \log_2 \left( \frac{\text{Number of models with parameter-system which have similar or less amount of complexity}}{\text{the same model with different values of the parameters provided these parameters deviate more than the present experimental uncertainty}} \right) \]  

(2.1)

But what do we mean by a model which have a complexity comparable to that of the Standard Model? In fact, this is a very complicated question for which we will not offer an exhaustive analysis here. It may not have an objective answer (unaffected by some theoretical bias).

Premature considerations of the difficulty of varying some (sub)structure and yet obtain a well defined class of models (thus necessarily keeping other structure fixed) may also be found in sec.3.3 in [7].

Here, we consider a very restricted class of models - models which only deviate from the Standard Model in details⁷ - and count as separate models the same model with different values of the parameters provided these parameters deviate more than the present experimental uncertainty. Talking about the models of same or lower degree of complexity we really have in mind to restrict ourselves to consider quantum field theories, so that we just have to consider as possible those models which are obtained by specifying a gauge Lie algebra (that can easily be a direct product of several simple ones - as it is the case for the Standard Model) and a system of representation for particles/fields of various spins.

It is important - but somewhat of an arbitrary choice - that we do not include more complicated representations and Lie algebras nor larger parameter values than those appearing in the Standard Model itself. The reason for this (somewhat arbitrary) convention in the definition of the number of unexplained bits of information (to be listed in our tables) is that there would otherwise be the problem that there are eventually infinitely many Lie algebras, infinitely many possible - usually reducible - representations and infinitely many possible parameter values - also if one consider values deviating by less than the experimental uncertainty as identical values (so we really count the number of uncertainty intervals). Even after the suggestion of this principle for counting “bits” the exact implementation in the various cases, Lie algebra, Lie group, system of representations, dimensions etc. still involve a bit of arbitrary choices. Especially, we shall include what we call ansätze lead to Clebsch-Gordan-coefficient-like factors. These factors are though of order one and rational - but they may still represent a fitting of discrete parameters. A crude estimate shows that there will only be of the order of 30-22-4= 4 bits left as the truly explained information, but even that might be quite suggestive of at least some truth being there. See [11] for the more general features really explaining the agreement.

⁷ In fact, we only vary the gauge Lie algebra, the representations of it and the space-time dimensionality.
“order of magnitude information” for those parameters for which a priori (though theoretically prejudiced) expectations exists (usually from dimensional arguments).

**Distance measure to a “theory of everything”**
A “theory of everything” (T.O.E.), with the word “everything” taken in an elementary strict sense, contains zero bits of unexplained information! One could in principle build up a distance measure, counting (a lower estimate of) the number of unexplained “bits”. How far is a given model $T$ from being a T.O.E.?  

$$||T - T.O.E.|| = \left( \text{# of unexplained bits of information} \right)$$  \hfill (2.2)

We shall see that the Standard Model is at least $\sim 2 \times 10^2$ bits away in distance (a number which grows with the increasingly precise measurements) from a “Theory of Everything”!

We remark, that the number of bits we are able to arrive at are lower estimates, both because of our conventions of not counting models which are more complicated than the Standard Model, and because we are anyway not able to take into account the possible models (simpler or more complex) that we are not able to even think about.

### 2.2 Amounts of unexplained information in the Standard Model (our definitions)

For a quantity - a parameter - $k$ for which there is no special expectation w.r.t. order of magnitude, and which is (presently) measured with an uncertainty $\Delta k$ we define the amount of (unexplained) information contained in such a parameter (yet to be explained) to be

$$\log_2 \frac{k}{\Delta k}. \hfill (2.3)$$

If there is an order of magnitude expectation - usually on grounds of dimensional arguments - we suggest to take into account the information in measuring the order of magnitude of the ratio of the quantity $k$ to the expectation called $scale$ (which is only defined up to a factor $e = 2.7..$, say), by imagining that the numerical value of the logarithm $|\ln(k/scale)|$ following our convention could have been smaller but not larger in a “simpler model”. Since $scale$ is only defined order-of-magnitudewise it can not be significant if $k$ by has the same value as $scale$ to better than, say, a factor $e$. The total amount of information in the measured value of the parameter $k$ is therefore

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8If there were really no quantity of the same dimension to compare with the value would be useless for making theories, but we imagine using $c = G = \bar{h} = 1$ to define our unit system; cf. footnote in section 2.3.
taken to be
\[
\log_2 \frac{\max \left\{ 1, |\ln \frac{k}{\text{scale}}| \right\}}{\Delta \ln k} \simeq \log_2 \frac{\max \left\{ 1, |\ln \frac{k}{\text{scale}}| \right\}}{\Delta k/k} = \log_2 \frac{k}{\Delta k} + \max \left\{ 0, \log_2 |\ln \frac{k}{\text{scale}}| \right\} .
\] (2.4)

The second term in this expression is what we call “the order of magnitude information”
\[
\left( \text{order of magnitude information} \right) = \max \left\{ 0, \log_2 |\ln \frac{k}{\text{scale}}| \right\} .
\] (2.6)

When several similar quantities such as the quark masses all deviate in the same direction (by being smaller say) from the expected scale, the Higgs expectation value in vacuum \(< \phi >_{\text{vac}}\), we shall presumably rather refer these parameters to each other and only one of them to the a priori scale \(< \phi >_{\text{vac}}\); i.e. our expected scale for a quark mass goes down once we know that another quark (or lepton) is surprisingly light. By this convention we minimize the amount of order of magnitude information to be listed in our table.

Consider, as an example, the parameter \(\Theta_{QCD}\) for which it is only known that \(\Theta_{QCD} < 10^{-9}\). It must be counted as having an experimental uncertainty equal to the value so there is only order of magnitude information in the smallness of \(\Theta_{QCD}\). The expected value (since it is an angle between 0 and \(2\pi\)) is of the order of \(\Theta_{QCD} \sim 1\). Therefore there is \(\sim \log_2 \ln(10^9) \sim 4\) bits of order of magnitude information (which is also a substantial amount of order of magnitude information carried by only one parameter).

**Standard Model - parameter information (cf. table 2)**

For the weak scale \(< \phi >_{\text{vac}}\) itself \(< \phi >_{\text{vac}} \sim 246 \text{ GeV}\) one often takes the expected scale to be the Planck energy scale with the motivation of the prejudice that this is the “most fundamental” scale to use. Even for dimensionless quantities such as the fine-structure constants one should look for some “natural” unit to find the scale to be used. However, since we take double logarithm “\(\log_2 \ln\)” in (2.6) it does not matter much what we use for the scale, say the typical critical fine-structure constant \(\alpha \sim 1/20\) or just simply \(\alpha \sim 1\).

Because of confinement the very concept of a quark mass is not so clean. One must distinguish the “constituent quark mass” defined as being the one used in the nonrelativistic quark model(s) and the “current algebra quark mass” - which is the one most directly connected to the Yukawa couplings. The latter is determined from the breaking of the chiral symmetry caused by this current algebra mass and reflects itself as a nonzero mass to the approximate Nambu-Goldstone bosons \(\pi, K\) and \(\eta\). It is the current algebra

\footnote{However, there may very well be new physics at much lower scales, for example, say, of the order of \(\sim 10^2 - 10^3 \text{TeV}\), from which \(< \phi >_{\text{vac}}\) arises.}
Table 2: Estimated information in the parameters of the Standard Model. The * for the 5 bits of order of magnitude information for the weak scale $<\phi>$ indicate that it is an upper estimate which corresponds to the commonly asserted - though debatable - theoretical prejudice that the Planck scale, or G.U.T. scale say, is the natural expected scale of “any phenomenon” - and thus also of the weak scale.

masses or, rather, the related Yukawa couplings which are to be thought of as parameters, “input parameters”, of the Standard Model. Because of the uncertainties in the techniques of extracting these numbers (= current algebra masses) from QCD it is presumably fair to say that they are not determined better than to say three significant digits on base two or say one significant digit on base ten ($2^3 \sim 10$). For the heavy quarks similar uncertainties appear although the technique of estimating the masses is somewhat different from that for the light quarks.

**Standard Model - discrete information (cf. table 3)**

Table 3 shows the discrete information in those input features of the structure of the Standard Model for which alternatives are easy to imagine. (For example we do not count the possibilities of exchanging the principles of quantum mechanics with something else).

The estimated amount of information in the gauge Lie algebra expresses that there are of the order of $\sim 2^6$ Lie algebras with rank less than or equal to that of the Standard Model ($S(U_2 \times U_3) \simeq U(1) \otimes SU(2) \otimes SU(3)$ has rank four).

The item “Higgs representation” contains log₂ of an estimate of the number of representations smaller than or equal to the actual Higgs representation. The dimension and signature 3+1 is one possibility between the possibilities 0+0, 1+0, 2+0, 1+1, 3+0, 2+1, 4+0, 3+1, 2+2, which
Table 3: Listing of information for various types for discrete settings in the structure of the Standard Model. The first column with numbers shows the information unexplained before we introduce the four assumptions listed in table 4 (section 3.2 below). The last column gives the unexplained numbers after this explanation has been taken into account.

| Standard Model - discrete information | Before understanding | After understanding |
|--------------------------------------|----------------------|---------------------|
|                                      | Weyl representations | Weyl representations |
| Gauge Lie group                      | 6                    | 8                   |
| Weyl representations                 | 92                   | 0                   |
| Higgs representation                 | 6                    | 4                   |
| 3 + 1 dimensions                     | 3                    | 3                   |
| Spin distribution                    | 8                    | 6                   |
| Total                                 | 115                  | 21                  |

makes up 9 possibilities (using our convention of not counting larger numbers than those in the Standard Model) and thus they contain \( \log_2 9 \approx 3 \) bits. The item “Spin distribution” is supposed to count the information in how many fields (or particle types) we have with different spin. In this connection we take into account that a massless photon or Yang Mills particle is so different in spin structure from a massive spin 1 that it should be counted as a different possibility. In this item is also included the information that there are 3 generations. How we arrive at the item “Weyl representations” is best explained in connection with the table 4, but really the main point is to count \( \log_2 \) of the number of ways 15 irreducible representations can choose between the \( 13 \cdot 2 \cdot 3 = 78 \) possibilities for having \( y/2 = -1, -5/6, -2/3, -1/2, -1/3, -1/6, 0, 1/6, 1/3, 1/2, 2/3, 5/6, 1; \) weak isospin \( I_W = 0, 1/2; \) and the color \( SU(3) \) representation being \( 1, 3 \) or \( \overline{3} \). \( (15 \cdot \log_2 78 = 93 \) bits). One of the 93 bits corresponds to the knowledge of weak interactions coupling to left handed quarks and leptons rather than to right handed quarks and leptons, and that particular bit is therefore not meaningful without an a priori standard (convention) - which do not exist - for what is left and right.

2.3 Some remarks about the very little amount of unexplained information in gravitation theory

We restrict attention to the Standard Model and - essentially - ignore gravity which is the other branch of laws of physics which is well established today. Compared to the Standard Model the situation with respect to the number of parameters and structure measured in gravity is that there is strictly speaking only one properly measured parameter - the Newtonian gravitational constant - and one parameter you would expect to be able to measure with present accuracy, the cosmological constant \( \Lambda \). In Planck units, the
expectation $\Lambda \sim 1$ (i.e. $scale \sim 1 \ m_P^4$) would be the natural scale for the cosmological constant (and such values are achieved in many quantum gravity models). However, the measured value is less than $10^{-120} m_P^4$. Thus, if we extended our counting of unexplained bits to include gravity, the cosmological constant would - in much analogy to $\Theta_{QCD}$ - represent no unexplained genuine measurement information since its measurement uncertainty is still as large as the quantity itself, but a lot of unexplained order of magnitude information $\sim \log_2 \ln(10^{120}) = \log_2(120 \cdot 2.3) = \log_2 276 \sim 8 \text{ bits}$ corresponding to the cosmological constant problem: Why is the cosmological constant so exceedingly small compared to a priori expectations?

One might formally count $\log_2 (G/ \triangle G) \sim 13 \text{ bits}$ as the content in the Newtonian gravitational constant, but from a model building point of view one must accept some dimensionful quantities - just to set the scale$^{10}$. The measurement of such quantities is then not really useful in model building except in putting the scale for the other quantities. Having used the gravitational constant for defining the unit system we cannot also count it as carrying information.

In total we thus essentially only get the 8 bits of the cosmological constant puzzle from gravity yet to be explained. The theory of gravity is also structurally already so elegant that very little information is needed to specify the model and presumably only of the order of a couple of discrete information bits are as yet unexplained: The graviton is spin 2 but could say a priori have had less spin and perhaps have had all helicities. In all we thus have of the order of $\sim 8 + 2 = 10 \text{ bits}$ more than described above by including gravity.

We note, that since there are so few bits to explain within the theory of gravity itself the scientific value of some “quantum gravity” theory almost unavoidably has to be measured by the amount of predictive power it has concerning data which do not deal with gravitation theory itself, i.e. it has to predict data which lie outside of gravitation theory! For example, if the “quantum theory of gravitation” is able to predict some of the 19 unexplained parameters of the Standard Model (of the electroweak and strong interactions) then the “quantum gravity” theory may be justified (and gain some belief) this way.

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10 Explicitly, we need the measurement of three dimensionful quantities in order to set a standard by which we measure for example length, time and mass (and it is then a profound fact - the validity of this fact requires a bit of reflection - that the dimensions of all other quantities in physics, e.g. the quoted $\sim 19$ parameters of the Standard Model, may be expressed in terms of these three standard units). The three dimensionful quantities are often selected to be the Newtonian gravitational coupling constant $G$, the velocity of light $c$ and the Planck constant $\hbar$. Thus, we can not include the measurements of $G$, $c$ and $\hbar$ - in our table 2 - as useful parameter information since the function of these parameters, by choice, merely is to inject a scale into the entire system of parameters of the Standard Model.
2.4 Information from cosmology? (thermal equilibrium phases are strong “cosmological filters”)

Including cosmology in the considerations of seeking beyond the Standard Model we may have some more data at our disposal - even with today's accelerators and measurements. We have the Hubble expansion rate (extremely crudely) and the background radiation temperature - the famous $3^0\ K$ radiation, really $2.75^0\ K$ - and some primordial abundances. Most informative are presumably possible correlations and fluctuations over space of say the temperature (COBE results) and the distribution and motions of galaxies.

In cosmology we really see the big bang physics through an extremely cloudy filter! It is to be hoped - of course - that this may turn out not completely to be the case - in view of the foreseeable limitations in our abilities of putting substantially more than present energies $\sim 100 GeV$ on a single elementary particle.

It appear to us, that if thermal equilibrium phases are reached at certain stages in the evolution of the universe then only very little information of the physics that went on before that phase can reach us today. It is difficult for a signal to survive through an equilibrium phase. Basically only conserved quantum numbers survive, like baryon and lepton numbers and energy. If the thermodynamic equilibrium is not reached globally, there may survive some information in the correlations or, rather, in the spatial variations in the densities of these conserved quantities (and the temperature).

3 Which information in the Standard Model is most inspiring?

It is of interest to identify (in retrospect) those features in the disciplines of classical mechanics (macroscopic bodies), solid state physics, atomic physics and nuclear physics, say, which point towards some regularities at the energy level above (cf. the quantum staircase) and try that way to develop intuition and more “general principles” for how to search for underlying structure.

An inspiring way to start is presumably to identify those features which are not yet understood, and among them, single out the most surprising ones

\[11\] Thermal equilibrium phases are reached in several evolutionary stages of the early universe. For example, thermal equilibrium phases in the formation of quark-gluon plasma at energy scales $\sim GeV$ are, presently, contemplated to be reached within $fm/c \sim 10^{-23} \text{seconds}$ whereas the corresponding phase in the Universe has a time span of the order of $10^{-5} \text{seconds}$. So there is a lot of time to form thermal equilibrium phases of quark-gluon plasma during the cooling of the universe!

Also, the plasma of charged electrons and charged nuclei has a lot of time to reach thermal equilibrium w.r.t. atomic physics degrees of freedom before the transition from plasma to a gas of neutral atoms takes place (approximately $\sim 10^5 \text{years}$ after big bang). In addition to conserved quantum numbers such as baryon number, lepton numbers and electric charge only the number of each type of primordially produced nuclei survives this equilibrium.
(“mysteries”) as the most inspiring. Two forms of surprises are:

1. Paradoxes
2. Dimensional surprises

(1) Paradoxes: A true paradox has a potential of giving an important hint that something is wrong somewhere. The attempt to cure such a paradox is therefore a good starting point for guessing intelligently some underlying structure. Cf. the paradox (in the end of last century) of the ultraviolet catastrophe in black body radiation (leading to the Planck hypothesis) and the paradox of why the orbits in the atom do not fall into the center, leading to Niels Bohrs hypothesis of “stable quantum states” (by which Bohr in the same go killed around $\sim 4$ bits by explaining the Rydberg constant as the combination $\frac{m_e e^4}{2\hbar^2}$).

As an example of a paradox, existing today, one could perhaps point to the non-regularizability of the chiral Weyl particles in the Standard Model (c.f. discussion and references in [6, 8]). Another paradox might be that it is most likely not possible to make the cut off go to infinity (non-perturbatively) in electrodynamics. Quantum Electro Dynamics is not renormalizable at the non-perturbative level, in the sense that according to [10] one can find various physical quantities varying with the cutoff for given renormalized coupling and mass. Since the Standard Model contains a $U(1)$ group (with similar properties as electrodynamics) this paradox is very likely also shared by the Standard Model.

(2) Dimensional surprises: If a given phenomenon in Nature occurs with a strength (for example, with a transition amplitude in quantum mechanics) which is much smaller - or, perhaps, even vanishes - relative to what we expect on dimensional grounds it signals interesting underlying principles.

Two well known examples (by now well understood) illustrates this point:

- The vanishing of the monopole mode (which is the first one would expect to dominate on purely dimensional grounds with no understanding of the underlying physics) in the electromagnetic dipole radiation and the vanishing of both the monopole and dipole modes (the first contributing mode is the quadrupole) in gravitational radiation carry signals of the symmetry structure of electromagnetism and general relativity (and are explained e.g. in terms of the helicity structure of the respective force carriers, the photon and the graviton).

- An example of a strongly suppressed transition amplitude (relative to what we should expect from dimensional analysis) which involve more de-

\[ \text{[12]} \]This relation has been confirmed by the later decimals arriving due to the better measurements since Niels Bohrs times. So today this relation explains more than 4 bits. Due to relativistic corrections $\sim \alpha^2$ the simple Bohr relation should however not be true to better than $\sim 10^{-4}$ corresponding to $\sim 13$ bits of predictive precision.

\[ \text{[13]} \]A rescue may be to embed the Standard Model in some grand unified theory in which asymptotic freedom is ensured, although the presence of (a) Higgs field(s) may continue to present a problem.
tailed knowledge of the structure of the Standard Model is the smallness (but verified existence) of neutral flavour changing currents. Such currents have a suppression factor

$$\sim \sin \Theta \cos \Theta \left( \frac{m_c^2 - m_u^2}{m_W^2} \right)$$

due to the clever cancellations between the generations (GIM-mechanism) in the Standard Model.\[14\]

“Neutral flavor changing currents” is a wonderful example of getting inspiration from a feature which is surprisingly suppressed relative to expectations from dimensional arguments. In the sixties, when only three quarks $u, d, s$ were known, there was no mechanism (known) to suppress the neutral flavour changing current. It guided Glashow (and Björken) to predict a new quark — $c$.

3.1 Unsolved problems and “mysteries” - Which are the most important?

While the above examples are by now explained within the Standard Model itself, let us now proceed to identify similar - but totally unexplained - “puzzles” or “mysteries” of the Standard Model which may very well give valuable hints of structure (e.g. symmetries) beyond the Standard Model.

Some of the input parameters of the Standard Model have in fact quite strange values (they are examples of what we call “dimensional surprises” and they carry correspondingly a large amount of “order of magnitude information” in table 2):

- $\Theta_{QCD}$ is zero with great accuracy ($\Theta_{QCD} < 10^{-9}$) while it “ought” to be of order of $\pi$ or so, since rotational angles are in the compact set $[0, 2\pi]$. Note that the corresponding angle for the $SU(2)$ group, $\Theta_{SU(2)}$, is not measured.

- The smallness of quark and lepton masses relative to the weak interaction scale $< \phi >_{\text{vac}}$ or the Fermi constant $G_F$, say. This could point to some approximative symmetries (and associated conserved quantum numbers), cf. sec.3.4.

- The large generation gaps in the fermion masses (i.e. presumably in the Higgs Yukawa couplings).

- Why is the Higgs-scale (the scale of weak interactions say) so exceedingly low compared to the Planck-scale or to some grand unification scale, say, in case such a unification should exist?\[14\]

\[14\] In fact, it is very hard to compete with the Standard Model - when it comes down to constructing an underlying model which gives the same suppression factor. For example, “technicolor models” have difficulties in reproducing this suppression factor.
• If we include gravity, why is the cosmological constant \( \Lambda \) so exceedingly small (or zero)?

As an example of a mystery a widely announced example is the interpretation of quantum mechanics.

Let us now turn to some examples - mainly our own - in which we claim to look fairly unprejudiced (straightly) at the data - i.e. the parameters and structure of the Standard Model itself.

### 3.2 First observation: Only little information is stored in the representation system of the fermions

It is to be expected that it is easier to extract inspiration from the structural information (discrete information) than from the numbers (the parameters), which need more model building to become inspiring, and among the former the information in the Weyl fermion representations which contain around 90 \( \text{bits} \) seems promising to attack at first glance. However, we shall see that with a few rather reasonable assumptions, listed in table 4, we can explain essentially all these 90 \( \text{bits} \).

• **Mass protection.** One observation, seen from table 1, is the constraint of “mass protection” which implements the constraint that under no circumstances do we find both an irreducible representation and its charge conjugate. That is, when we for example find left handed dsb-antiquarks with the representation \( (y/2 = 1/3, I_W = 0, a = 3) \) then we do not find the charge conjugate representation \( (y/2 = -1/3, I_W = 0, a = 3) \). Now, the crucial observation is to note, that these two representations allow together a mass term

\[
\sim m\psi_r^T C^T \psi_r + h.c.
\]

that does not make use of the Higgs breaking of the gauge group. At more fundamental scales there may very well be particles which are not mass protected. Such particles would have a mass corresponding to the typical mass scale of the theory at the more fundamental scale. This could be of the order of some hundred \( TeV \) (or even of the order of the Planck scale, we might speculate). The fact, that the Standard Model obeys this “mass protection rule” tells us presumably that it is a low energy tail of whatever is the more fundamental theory. It only contains those particles that are protected from getting “normal masses” (from the point of view of the theory beyond). From

\[15\] Note, that the very large number of bits, \( \sim 90 \text{bits} \), contained in table 4, is due to the large number (45) of particles and the fact that each particle could in principle have a different representation. If we impose the constraint that we have a system of three generations with identical representations the above number of bits would reduce roughly by a factor of 3.

It should be emphasized, also, that some of our estimates of the number of bits in table 4 are somewhat crude.
Information in the representation system

| Small representations | Anomaly constraints | Mass protection | Charge quantization | Information left | Excluding handedness |
|-----------------------|---------------------|-----------------|---------------------|-------------------|---------------------|
| •                     |                     |                 |                     | 93                | 92                  |
| •                     | •                   |                 |                     | 58                | 57                  |
| •                     |                     | •               |                     | 91                | 90                  |
| •                     | •                   | •               |                     | 56                | 55                  |
| •                     |                     |                 | •                   | 55                | 54                  |
| •                     | •                   | •               | •                   | 19                | 19                  |
| •                     |                     | •               | •                   | 45                | 44                  |
| •                     | •                   | •               | •                   | 1                 | 0                   |

Table 4: Table showing how various combinations of the four assumptions mentioned in the text reduce the amount of information contained in the representation system (cf. table 1) of the matter fields (fermions) in the Standard Model. The numbers represent the information content measured in bits which is not explained by the combination denoted by the •’s. The true numbers are in the right handed column of numbers (as described in the text).

the point of view of the Standard Model and from an experimental point of view, however, these “normal” masses are huge!

- **Charge quantization.** Another “observation”, which we may extract from table 1, is a fact which we simply have put in for phenomenological reasons\(^{16}\): All particles in the Standard Model has to obey a charge quantization rule which is a generalization of the well known Millikan charge quantization rule,

\[
Q = -\frac{t}{3} \pmod{1} \quad \text{or equivalently} \quad \frac{y}{2} + \frac{d}{2} + \frac{t}{3} = 0 \pmod{1} \quad (3.7)
\]

where \(y/2\) is the weak hypercharge, \(d\) denotes “duality” which means \(d = 1\) for weak isospin \(I_W\) being half-integer, and \(d = 0\) for \(I_W\) integer, while \(t\) is triality for the color representation meaning that \(t\) modulo 3 counts the number of triplet representations \(\mathbf{3}\) needed to build up a representation from which the representation in question can be extracted. E.g. triality is 1 for the triplet \(\mathbf{3}\) and 0 for the singlet \(\mathbf{1}\), whereas for the anti-triplet \(\mathbf{\bar{3}}\) it is \(-1 = 2 \pmod{3}\).

O’Raifeartaigh and L. Michel\(^{16}\) have argued that the information in this quantization rule can be packed into the requirement that the representations of the Standard Model be representations (truly and not only ray-representations) of the group \(SMG = S(U(2) \times U(3)) \subset SU(5)\) which

\(^{16}\)This fact, which is the charge quantization rule, was known long before the Standard Model was constructed and was rather implemented - than predicted - in the construction of the Standard Model.
is specified as
\[
\begin{pmatrix}
  u_{11} & u_{12} & 0 & 0 & 0 \\
  u_{21} & u_{22} & 0 & 0 & 0 \\
  0 & 0 & v_{11} & v_{12} & v_{13} \\
  0 & 0 & v_{21} & v_{22} & v_{23} \\
  0 & 0 & v_{31} & v_{32} & v_{33}
\end{pmatrix}
\]
\[u \in U(2), \quad v \in U(3) \quad \text{and} \quad \det u \cdot \det v = 1\].

The information of the charge quantization is thus compactly packed (with use of fewer unexplained bits) by saying that this is the Standard Model group, instead of just the Lie algebra. Since there are naturally more groups than Lie algebras up to a given rank or a given dimension of the group, there are a couple of more bits of information in knowing the group than the algebra; 8 for the group while only 6 for the algebra, say. The \(8 - 6 = 2\) bits invested pay off by explaining around 37 to 55 bits (cf. table 3). So using the group is a strong scientific progress compared to using the algebra.

- **Anomaly constraints.** Even if a quantum field theory at the classical level seems to be gauge invariant, there can be anomalies quantum mechanically. This means that it is indeed not gauge invariant: It has gauge anomalies! An intuitive idea about what happens when one has anomalies may be achieved by thinking of the anomaly resulting from pumping Weyl particles up from the Dirac sea, which has infinitely many particles, so the Dirac sea can remain intact even after pumping up some particles\(^{17}\). In this way it seems that some particles have been produced, or if pumped down have been destroyed. If the particle(s) in question carry gauge charge such an effect will spoil gauge invariance. This thread to gauge invariance is circumvented in the Standard Model by a very sophisticated cancellation between the particles of different types being pumped up and down: their charges are chosen so cleverly that the net gauge charge being pumped up (minus the amount pumped down) is just zero for all the types of gauge charge under all the possible field configurations. In four dimensional space time the anomalies arise in perturbation theory from triangle diagrams with Weyl-particles going around the triangle loop. Gauge bosons are attached to the three corners of the triangle. For each choice of the three gauge bosons which couple via such a triangle diagram the contribution to the anomaly from the full system of Weyl fermions in the model must cancel in order that it shall not develop true breaking of the gauge symmetry. A model as the Standard Model will only remain consistently gauge invariant at the quantum level provided these cancellations take place, and that imposes severe restrictions on the system of Weyl representations. Imposing these necessary conditions for the consistency thus reduces the number of allowed Weyl representation systems and thus the amount of bit information yet to be explained. There are always trivial solutions obtained by imposing parity or

\(^{17}\) This is the effect of the infinite hotel: the hotel is infinite - it has infinitely many rooms - but it is full. Now there come one guest more, and indeed he can find place: he gets number 1, the guest there is then moved to room number 2, and guest in room number 2 is moved to 3, and so on. In the infinite hotel this procedure works satisfactorily.
charge conjugation invariance, but that would be totally forbidden by the requirement of “mass protection”. Under the anomaly requirements needed for consistency is also the Witten discrete anomaly and the mixed anomaly. The former says that there must be an even number of weak isospin doublets ($I_W = 1/2$), and the latter comes from the requirement that the interaction with the gravitational field must not cause gauge symmetry violation. It implies that the summation over all the Weyl particles in the model of the weak hypercharge $y/2$ should be zero.

The anomaly constraints - which mathematically are expressed as 6 different algebraic constraints - are indeed a very powerful set of constraints. Note from table 4 that removing the anomaly constraints from the Standard Model makes it possible to construct of the order of $\sim 2^{45}$ models (instead of one).

- **Small representations.** With the three assumptions above concerning the system of Weyl particle representations there are actually no solutions with lower representations than those in the ordinary generations in the Standard Model. In this sense we can claim that the Weyl fermion representations in the Standard Model are remarkably small! By the assumption of small representations in the table we simply mean that we only have allowed representations of “size” (dimension and or charge) up to that occurring in the Standard Model. Since we - anyway - by our convention only consider the small representations in our counting of bits, we actually do not relax this assumption when we compute the number of bits yet to be explained.

The column “excluding handedness” means the number of bits after we have taken into account that there is no true physical difference between a model and the parity reflected model. If the number of bits in the two columns do not deviate by the usual one bit, it is because most of the models involved in the counting respect parity invariance so the counting is not changed by counting parity conjugate only for one.

It is remarkable that imposing these four rather reasonable assumptions: “mass protection”, “no anomalies”, “charge quantization”, and “small representations”, we end up with only one model with 15 representations, namely the Standard Model itself. Really, one can only construct models with these assumptions in which the Weyl fermions occur in “generations” of the same irreducible representations as in the Standard Model (listed in table 1). Since we then have a number of irreducible representations which is divisible by 5 the assumptions above even explain approximately two bits of the information listed under “spin distribution”.

In the column “After understanding Weyl representations” we have in table 3 presented the numbers of bits left unexplained after the understanding in terms of the four assumptions above about these Weyl representations.
3.3 Extracting information from the gauge group - Why is the gauge group so “skew”?

A relatively unbiased way of storing the information of the gauge group $SMG = S(U_2 \times U_3)$, the 8 bits, is an observation connected to the quantity $\chi = (\log q)/r$, which we have defined \[4\] for all compact (potential gauge) groups. For the Standard Model group ($SMG$) the quantity $\chi(SMG) = (\log 6)/4$ is larger than for any other group, except that it takes just the same value for the cartesian products $SMG \times SMG \times \ldots \times SMG$ of the standard model group a number of times with itself. The quantity $q$ here is roughly associated with the charge quantization rule(s) deduced from the group in question and counts how many times smaller the quanta for the Abelian charge(s) you can get by allowing the particles to couple to the semi-simple part of the gauge group than by not allowing that. The information about physics to extract from the remarkable largeness of this $\chi$ in Nature’s choice may stand as a bit of a challenge to be found out, although some stability or robustness of a group with high $\chi$ may be dreamt in a gauge theory which is speculated to have quenched randomness like an amorphous medium.

A somewhat related property to this high-$\chi$-property is the property that the Standard model group is remarkable by its relatively low number of automorphisms and “generalized automorphisms” (somewhat a concept invented for the purpose; essentially some simple homomorphism)! This principle of “skewness” \[4\] can - a bit favorably interpreted - also be said to single out the Standard Model group as the “most skew” of the groups up to dimension 19. (I.e. taking into account groups containing up to 19 gauge bosons).

With our convention of not counting the bigger groups the principle of skewness should only be required to single out the Standard Model group among groups up to dimension 12 (in fact, it singles out the Standard Model group up to dimension 19) and thus we can say that it explains the 8 bits for the groups and replace it by “the principle of skewness” together with a couple of bits telling the details of defining the concept of “generalized automorphisms” and about how to include in counting the infinitely many inner automorphisms in order to really make the SMG win the competition of being skewest.

3.4 Are the generation gaps a signal of underlying approximative symmetries?

A most striking feature of the quark and lepton masses is that they are very small - by a few orders of magnitude - compared to the scale of masses $\sim 100 \text{ GeV}$ (expected from the Standard Model) coming from the Fermi-constant. Moreover, the scale of the masses for the three generations of quarks and leptons differs (also) by orders of magnitude. These mass gaps and the smallness of the masses may suggest that there shall exist at some level beyond the Standard Model - some approximately *conserved* quantum numbers (i.e. symmetries) being different for right and left handed compo-
nents of the fermions in a way varying from generation to generation. We have recently looked for schemes \[12\] in which such quantum numbers are \textit{gauged}. Something in the direction of repeating the Standard Model group for each generation could be helpful (although the fact that the top quark mass is much higher than the \(\tau\) and the \(b\) masses constitutes a problem). At least it is suggested \[12\] that some new quantum numbers exist which take on different values for different generations.

3.5 Why do we live in 3+1 dimensions? (only \(\sim 3\) bits of information)

There are several attempts to explain why we should have 3 spatial dimensions (c.f. \[9\] and references therein). In particular, emphasis have been made as concerns the lack of stability of motion in a Coulomb - or Newtonian - potential, if the space dimension were higher than three. Mostly a single time dimension is presupposed rather than being explained, but Jeff Greensite \[9\] and also ourselves \[6, 7\] seek to attack that bit of information which tells about the signature of the metric of space time. We (ourselves) point out that just for the Weyl-equation in four space time dimensions all linearly independent matrices \(-n^2\) of them, when the Weyl field has \(n\) components - are used \textit{just once each} in the Weyl-equation\[18\]. That is to say that the requirement

\[
n^2 = \begin{cases} 2^{d-2} & \text{for } d \text{ even} \\ 2^{d-1} & \text{for } d \text{ odd} \end{cases} = d
\]

apart from a trivial solution \(n = d = 1\) implies that the dimension is \(d = 4\). Requiring the Weyl equation to come from a \textit{real} action leads then to the signature \(3 + 1\) or \(1 + 3\).

As pointed out to us - recently - by Dharam Ahluwalia at Los Alamos, the space dimensionality three is also \textit{the} dimension in which the number of rotation generators equals the number of Lorentz boost generators (= the number of space dimensions).

3.6 The values of the coupling constants

The definition of the finestructure constants \((\alpha_1, \alpha_2, \alpha_3)\) contain a factor \(4\pi\) which depends on conventions: \(\alpha = g^2/4\pi\). In order to tell whether a finestructure constant is small or big we need to compare it with something that is a constant of the same type (so as to avoid to make notation dependent searches for regularities). A proposal \[13\] for making a comparison to what is again finestructure constants is to use the \textit{multicritical} couplings - obtained from the study of lattice gauge theories (Monte Carlo calculations) - for the same group, and to avoid the problem of the dependence on the

\[18\] Strictly speaking the Weyl equation is not defined in odd dimensions. In that case we therefore just talk about what should rather be called the Dirac equation.
scale $\mu$ of the “running” couplings we compare the coupling constants at the Planck scale\footnote{Note, that the effective gravitational coupling constant $\sim G\mu^2$ runs with the scale $\mu$ for trivial reasons, since $G$ has dimension $m^{-2}$, and is - by definition of the Planck scale - of order 1 just at the Planck scale. If in some sense the gravitational coupling constant would be “multicritical”, it would be at the Planck scale, if we assume that the critical value for $G\mu^2$ is of order $\sim 1$.}
\[
\frac{\alpha_{U(1)\text{crit}}}{\alpha_1(\mu_{\text{Planck}})} = 6, \quad \frac{\alpha_{SU(2)\text{multicr.}}}{\alpha_2(\mu_{\text{Planck}})} = 3, \quad \frac{\alpha_{SU(3)\text{multicr.}}}{\alpha_3(\mu_{\text{Planck}})} = 3. \quad (3.9)
\]

The non-Abelian couplings yield the two numbers 3 with such an accuracy that about 1.5 bits tell that they are integers. A toy model has been constructed \footnote{We thank Dr. Lawrence Hall concerning this point.} which involves the group $G = SMG \times SMG \times SMG$ at the Planck scale and which arrives at the relations \footnote{We thank Dr. Lawrence Hall concerning this point.} in a natural way.

We remark\footnote{We thank Dr. Lawrence Hall concerning this point.} that in supersymmetric $SU(5)$-G.U.T. one also have that the value of the $SU(5)$ coupling constant, at the G.U.T. or Planck scale, is rather near the multicritical value,
\[
\alpha_5(\mu_{\text{Planck}}) \text{ or } \alpha_5(\mu_{\text{GUT}}) \approx \alpha_{SU(5)\text{multicr.}}. \quad (3.10)
\]

and thus the principle of (multi)criticality of coupling constants appears to have at least two chances of “hitting”.

Note, that there is only little “order of magnitude” surprise in the values of the coupling constants. That is, whereas the quark masses, or the strong angle $\Theta_{\text{QCD}}$, say, are surprisingly small the values of the coupling constants $\alpha_1, \alpha_2, \alpha_3, \alpha_G \sim 1$ are all of the expected “order $\sim 1$” at the Planck scale provided one takes into account that the natural unit of a finestructure constant is of the order $\sim 1/20$ (which are the critical or multicritical values).

4 Some final remarks

Briefly stated, we have proposed a way to count in bits the information content in various parts of the Standard Model (its structure and parameters). Our counting may be useful in evaluating the “explanatory power” (in terms of bits) of attempts to guess physics beyond the Standard Model: A fundamental model has to explain more bits than the number of bits which are required to define it.

We have considered some possibilities of going beyond the Standard Model - using the unexplained structure and parameters of the Standard Model as the only source of “experimental inspiration”.

It is, at present, hard to get experimental data which \textit{directly} probes how Nature operates at energies substantially above $\sim 100 GeV$ (per particle) - up to which energy scales the Standard Model (of the electroweak and strong interactions) operates so successfully.
It is hard to create such experimental data here on earth. Moreover, cosmological data are up to the problem that only little information survives - when the universe reach thermal equilibrium phases (this appears to be the case in many stages in the evolution of the universe!). In each local region of space where thermodynamic equilibrium is reached, basically only conserved quantum numbers survive, like energy, baryon and lepton numbers and the separate types of isotopes (if it is cold enough). All other information reach the “heat death”, cf. sec. 2.4.

If we can not obtain direct (i.e. supported by experiments) information about how Nature operates beyond $\sim 100\ GeV$ we are thus forced to attempt to guess - from purely theoretical considerations - about how Nature might be constructed at such higher energies and we have to base such guesses solely on the information contained in the parameters and the structure of the Standard Model itself.

It appears, that it is important to read as closely as possible “what is to be read” in the Standard Model - and try to identify paradoxes and mysteries from which to be inspired (in order to try to go beyond).

How much of physics at Planck scales, say, are we able to predict from controlling physics at $\sim 100\ GeV$ scales?

It is fair to say, that there is no sufficiently simple candidate today of a fundamental model which offers an understanding of the numerical values of the 19 parameters and the structure of the Standard Model. It is, however, logically possible that not only one but several different models (some of them simple, some of them more complicated, most of them very complicated?) could be constructed which all have the Standard Model as the infrared limit and in that case it is not possible - lacking the guidance from experiments performed in a dialogue with Nature - to choose between the many possible fundamental models.

However, it is also logically possible, that one particular model is so extraordinary simple that we find it a miracle that it exists (and explain the Standard Model). In this case we would be tempted to believe it. (See, also, discussions in S. Weinberg [1]).

A sufficiently simple principle explaining a miraculously large number of parameters or features of the Standard Model could also deserve to be believed.

In order to be guided towards such principles we have in this article tried to to read the Standard Model w.r.t. its structure and parameters, in particular we have - as an exercise - tried to measure quantitatively: How much information is there to be inspired from in the Standard Model?

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$^{21}$Note, that cosmic radiation which hits earth (here Nature itself — most likely pulsars? — functions as an accelerator) contains particles which are very energetic (up to $\sim 10^{10}\ GeV$ per particle has been observed). The possibility of using this radiation for doing particle physics is strongly limited by the low luminosity of the high energy part of the spectrum.

$^{22}$The viewpoint that many models operating in the “ultraviolet” may lead to the same “infrared” physics have been pursued in the project we call random dynamics, cf. e.g. Froggatt & Nielsen [3] and references therein.
It is presumably impossible to measure the simplicity of a model or principle unbiased, i.e. without theoretical prejudices. Nevertheless we have attempted to measure simplicity in terms of bits and found — with rather natural conventions — the information content in the Standard Model (parameter system and structure) to be of the order of $2 \times 10^2$ bits. Bits were assigned to the knowledge of the 19 external parameters, the gauge Lie algebra, its representation system, and (a few bits to) the dimension of space time, $3+1$. Some parts of the structure of the Standard Model is very difficult to translate into “bits” of information — How many “bits” of information is there in the principle of Lorentz invariance? — Thus, somewhat arbitrarily, we stopped before assigning bits to the principles of Lorentz invariance and quantum mechanics. It is not sufficiently clear which alternatives to these principles we should consider. We have also not counted the principle of gauge symmetry, but indirectly some bits related to it were included in assigning bits to the number of particles with different spin and *helicity*.

Despite the arbitrariness of the measure we believe that the number contains some truth about how close theoretical physics is to catching up with experiment.

The $\sim 2 \times 10^2$ of unexplained information in the Standard Model is very little as compared to the amounts of unexplained information in other periods of the history of physics. For example the large amounts of hadronic resonances and scattering data which were collected in the sixties, say, make up much more information than $2 \times 10^2$ bits - but are now believed to be *in principle* understood in QCD.

With this limited amount of unexplained experimental data available it is necessary to use the precious bits with care and make sure, when proposing a model, that it explains a positive amount of information. We have made several attempts, some are reported in sec.3.2-3.6, to find principles that could explain some bits of the unexplained information in the Standard Model. Most of these principles or explanations, however, cost more bits than they explain.

Of the $\sim 3 \times 10^2$ bits of information in the Standard Model, which we find in a first calculation (cf. section 2.2), the $\sim 90$ bits from the Weyl representations and a couple of bits from the information on the numbers of particles are explained by four rather reasonable assumptions “mass protection”, “no anomalies”, “charge quantization” and “small representations” and gets compactified to only two bits by describing the gauge group instead of the Lie algebra. Thereby we get down to the already mentioned $\sim 2 \times 10^2$ bits.

If we accept the explanation [{4}] of the resulting gauge group as the winner in the game of the largest $\chi$ we convert the 8 bits of the group into whatever we take the $\chi$-concept to “cost” (that could though easily be more than 8 so that it would not pay). The finestructure constants from multicriticality [{13}] at first glance explains of the order of 15 bits (three numbers with 7% accuracy), but again the price may be higher, since these predictions require the rather complicated group $SMG \times SMG \times SMG$ at the fundamental (Planck)
level. Unless we, somehow, argue that a cross product of a single group with itself several times is especially simple the cost in bits would be appreciably bigger than three times that for $SMG$ itself, i.e. $3 \cdot 8 = 24$, so it would not pay. Again the attempt [12] to fit the quark and lepton mass spectra does not pay; it starts out with a rather low reduction in unexplained information, since it only explains the fact that there are hierarchies but it does not predict any detailed numbers - except after fitting lots of parameters. Hall et al. [11] is more promising starting out by explaining both couplings, masses and mixing angles (constituting an information content around $\sim 30$ bits. Even if only of the order of four are left - arrived at by subtraction of the information content in the input structure - this is quite impressive already). If we could combine with the bits by claiming the GUT SU(5) coupling multicritical, we might gain two bits, say, minus again the price for stating multicriticality (which may though hardly pay for only one parameter).

More generally, in seeking the inspiration, we have pointed towards the more surprising features such as (1) the genuine paradoxes and (2) surprising parameter values on grounds of dimensional arguments (cf. section 3).

Both from the finestructure constant story with the group $SMG \times SMG \times SMG$ and from the generation gaps there appears the suggestion that different generations must have different quantum numbers at the more fundamental level.

Are there any signals appearing from several features of the Standard Model?

A very important signal is: Standard Model is just the low energy tail of an underlying theory!

All particles we know are very special in the sense that they have no fundamental mass terms in the Lagrangian. They are all mass-protected by the same gauge symmetry - and can only get non-zero masses through the Weinberg-Salam Higgs mechanism. This mass protection is seen from the following two features of the Standard Model:

| Standard Model information | Before understanding Weyl representations | After understanding Weyl representations |
|----------------------------|-------------------------------------------|----------------------------------------|
| Real parameters           | 155                                       | 155                                    |
| Discrete parameters       | 115                                       | 21                                     |
| Total                     | 270                                       | 176                                    |

Table 5: Resume of our counting of the measured but unexplained information in the Standard Model. The first column does not utilize the explanation given in section 3.2.

23 If we restrict attention to the principle itself (without detailed models) of having extra mass protecting quantum numbers that idea may be so simple that even the tiny amount of fitting explanation and the explanation of the big mass ratios is indeed enough to give a positive gain!
1. The “mass protection” (cf. section 3.2) observed concerning the Weyl representations: There is no occurrence of a representation and its charge conjugate.

2. Of the 13 bosons of the Standard Model the 12 of them are gauge bosons (mass protected) and one of them is a Higgs particle. In fact, we have only seen mass-protected particles! (the Higgs particle has not been observed yet) Why do we not see particles which have a fundamental mass in the Lagrangian? When Nature has this possibility to construct a massive particle why should it then only use the Higgs-mechanism? A natural explanation is that Nature indeed uses this possibility of giving particles fundamental masses, but such masses becomes so large that we have not yet seen them.

Among the particles with fundamental masses there are presumably both scalar fields, vector fields (?), fermions etc. To a scalar field with a fundamental mass there can be associated a group of “mass protected” particles which then get masses of the order of magnitude of the mass of the scalar field (functioning as a “Higgs” field). All the particles in the Standard Model, i.e. all the particles we have seen until now, belong to only one such group. They are all associated to only one scalar field. This suggests that we are looking at a very isolated group of particles on the mass axis. This group simply is the group associated with the lightest scalar field (one of them has to be the lightest!).

All this suggests that the Standard Model is the low energy tail of a more fundamental theory.

Pointing in the same direction is the non-perturbative inconsistency [10] of QED and thus presumably the Standard Model. This enforces the existence of a physically existing cut-off, i.e. the Standard Model has to be regulated by some other more fundamental theory at some higher energy scale.

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24E.g., the most natural explanation for only seeing those Weyl representations that describe massless particles is that the other representations (pairs which are the charge conjugate of each other, i.e Dirac representations) also exists but their particles are too heavy to be seen. Note, that this also constitutes a sort of explanation of parity violation: If the weak interactions were parity invariant, then mass terms for the fermions would be allowed, and since we only look at the low energy tail of the theory we would not see them.
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