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Does the Higgs Mechanism Exist?

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This paper explores the argument structure of the concept of spontaneous symmetry breaking in the electroweak gauge theory of the Standard Model: the so-called Higgs mechanism. As commonly understood, the Higgs argument is designed to introduce the masses of the gauge bosons by a spontaneous breaking of the gauge symmetry of an additional field, the Higgs field. The technical derivation of the Higgs mechanism, however, consists in a mere re-shuffling of degrees of freedom by transforming the Higgs Lagrangian in a gauge-invariant manner. This already raises serious doubts about the adequacy of the entire manoeuvre. It will be shown that no straightforward ontic interpretation of the Higgs mechanism is tenable since gauge transformations possess no real instantiations. In addition, the explanatory value of the Higgs argument will be critically examined.

1 A Short Historical Introduction

In 1961 Sheldon Glashow presented the first $SU(2) \times U(1)$ gauge theoretic model for the electroweak interaction. The model was based on a straightforward application of the gauge principle: the idea that in order to fulfil the requirement of invariance of the fundamental Lagrangian under local gauge transformations (of the considered symmetry), one needs an inhomogeneous coupling term. Mathematically, the usual derivative is to be replaced by an appropriate gauge covariant derivative ($\partial_\mu \rightarrow \partial_\mu + iqA_\mu$ for U(1) for instance).[1] Yet, the gauge potential term that thus occurs does not include a mass and so a straightforward application of the gauge principle leads to massless gauge bosons only. Since the weak interaction has short range, it was clear that the gauge bosons were required to be massive. At that time, this could have been seen as a sign that demanding gauge invariance is to proceed on the wrong track, and that the idea of extending the gauge principle to symmetries higher than U(1)—discovered only half a decade earlier by Yang and Mills—is not fundamental. On the other hand it was also known that gauge symmetry was seemingly vital for the construction of renormalizable quantum field theories (QFTs). There was thus a tension between the requirement of massive exchange particles for the weak interaction and the renormalizability of an appropriate QFT, a tension that Glashow could not dissolve within his early work.

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By 1964, Peter Higgs and also Brout, Englert, and Kibble extended the work of Goldstone on spontaneous symmetry breaking to gauge theories. But they did not apply their framework to any phenomenologically relevant model. This was first done by Abdus Salam and Steven Weinberg in 1967 and 1968 for Glashow's $SU(2) \times U(1)$ electroweak model. The key idea was that $SU(2) \times U(1)$ gauge symmetry is an exact, but "hidden" symmetry, and that masses can be generated "dynamically" by spontaneous symmetry breaking. Salam and Weinberg succeeded in completing a framework which indeed dissolves the above-mentioned tension between massive exchange particles and renormalizability. This framework is the well-known Standard Model's *GSW electroweak theory* based on $SU(2) \times U(1)$ gauge symmetry—its first impressive experimental confirmation was the discovery of weak neutral currents in 1973 at CERN. Thus, the GSW theory implements the existence of massive exchange particles, the weak W- and Z-gauge bosons, as well as massive leptons by means of the now widely-known "Higgs mechanism": the "spontaneous breaking of a gauge symmetry."

The enormous importance of GSW can perhaps be measured by the succession of Nobel prizes "induced" by it. In 1979 the prize was awarded to "GSW" themselves (Glashow, Salam, Weinberg); next, after the 1983 discovery of W- and Z-bosons at CERN, Carlo Rubbia and Simon van der Meer were awarded the 1984 Nobel prize for their leadership of the experiments; and finally Gerard 't Hooft and Martinus Veltman were honoured in 1999 for their mathematical proof in the early 1970s, by which the renormalizability of spontaneously broken gauge theories was theoretically established.

Parts of the 1979 Nobel lectures show the importance of the idea of the Higgs mechanism within the GSW theory and its conceptual understanding not only by the common physicist but also by the leading figures. Glashow, for instance, writes:

> In pursuit of renormalizability, I had worked diligently but I completely missed the boat. The gauge symmetry is an exact symmetry, but it is hidden. One must not put in mass terms by hand. The key to the problem is the idea of spontaneous symmetry breakdown ... Salam and Weinberg ... first used the key. (Lundqvist 1992, 498)

And Weinberg continues along the same lines:

> Higgs, Kibble, and others ... showed that if the broken symmetry is a local, gauge symmetry, like electromagnetic gauge invariance, then although the Goldstone bosons exist formally, and are in some sense real, they can be eliminated by a gauge transformation, so that they do not appear as physical particles. The missing Goldstone bosons appear instead as helicity zero states of the vector particles, which thereby acquire a mass. (Lundqvist 1992, 545)

We will see in a moment how the detailed derivation of the Higgs mechanism works. To be sure, there is nothing wrong with the mathematics of it, but on closer inspection of the "mechanism" it will become clear that a deeper conceptual understanding of the formalism is not at all as obvious and as straightforward as most presentations, notably textbook presentations, of the Higgs mechanism usually pretend. For instance—and as the alert philosophy of physics reader will certainly have noticed already—the status of the symmetries in question, gauge symmetries, is in fact a non-empirical or merely conventional one precisely in the sense that neither global nor local gauge transformations possess any real instantiations (i.e. realizations in the world). Rather their status is comparable to the status of coordinate transformations (the status of gauge symmetries will be addressed in detail in Sec. 3.1). How is it then possible to instantiate a mechanism, let alone a dynamics of mass generation, in the breaking of such a kind of symmetry? Suspicions like this should raise philosophical worries about the true ontological and explanatory story behind the Higgs mechanism.

Although in recent times interest in spontaneous symmetry breaking (SSB) within philosophy of physics has risen, no one has yet scrutinized the Standard Model Higgs mechanism in the particular direction just indicated. Some authors, e.g. Castellani (2003), Kosso (2000) and Morrison (2003), are interested in the epistemological status of a "hidden" symmetry and in whether and how one is justified in building physical models on unobserved symmetries. While this is certainly an interesting topic, these authors nevertheless consider SSB scenarios in various branches of physics mainly on a par—and this, as we will see, is a serious misunderstanding. Chuang Liu in a series of papers carefully analyzes and compares the various sorts of SSBs that play a role in classical physics (Liu 2003), quantum statistics (Liu and Emch 2005), and condensed matter as well as particle physics (Liu 2002). In this latter paper Liu correctly emphasizes some important disanalogies between the concept of SSB in the well-known ferromagnet model on the one hand and in particle physics on the other hand, which we will also discuss, but he unfortunately does not delve into the important question of the meaning of breaking a conventional gauge symmetry. John Earman (2003, 2004b) perhaps comes closest to our particular suspicion when he writes:

> As the semi-popular presentations put it, "Particles get their masses by eating the Higgs field." Readers of *Scientific American* can be satisfied with these just-so stories. But philosophers of science should not be. For a genuine property like mass cannot be gained by eating descriptive fluff, which is just what gauge is. Philosophers of science should be asking the Nozick question: What is the objective (i.e. gauge invariant) structure of the world corresponding to the gauge theory presented in the Higgs mechanism? (Earman 2004b, 1239)

Indeed, how can any physical mechanism arise from the breaking of a merely conventional symmetry requirement? (Similarly, one would not think that any physics flows out of the breaking of coordinate invariance!—Again this will be addressed in detail in Sec. 3.1.) Earman himself unfortunately only touches on the issue without really answering it.[2] We are in fact left here with a series of pressing questions still in the air. In what sense, we may ask, are Goldstone bosons "real" (à la Weinberg)? In what sense are the masses of the particles truly "dynamically generated"? What exactly is the predictive and explanatory power of the Higgs mechanism? And, finally, does this very mechanism "exist" at all?

2 The Higgs Mechanism

2.1 Ferromagnetism as a Case of SSB

Before we delve into the Higgs mechanism, it will be instructive to take a look at ferromagnetism first as *the* paradigm case of SSB. This is all the more useful since almost any presentation of the Higgs mechanism stresses the supposed analogy between the Higgs case and the ferromagnet. By way of contrast, it will be our concern to point out the crucial disanalogies between the two cases.

In Heisenberg's well-known model from 1928, a ferromagnet is construed as an infinite array of spin-$\frac{1}{2}$ magnetic dipoles, where spin-spin interactions between neighbours tend to align the dipoles. Obviously, the model shows complete symmetry under spin rotations and the microscopic Lagrangian is therefore SO(3)-invariant. At high temperatures, thermal oscillation in the ferromagnet will lead to randomized domain-like spin correlations at all length scales. The ferromagnet therefore shows no macroscopic magnetization; this is true at least in the absence of an external field, whereas the ferromagnet behaves in the high temperature regime as a paramagnet.

Below a critical point, the Curie temperature, the ferromagnetic tendency of the dipoles to align prevails over the thermal fluctuations. We obtain a phase transition by means of an SSB of the SO(3) rotation symmetry. In the low-temperature regime the ferromagnet will show a spontaneous macroscopic net magnetization.

2.2 Some General Remarks on SSB and QFT

As suggested by the ferromagnet case, SSB is generally characterizable as a scenario where the Lagrangian (or equations of motion) of a physical system possesses a symmetry that is not obeyed by the states of the system (solutions of the equations of motion). In particular, the energy ground state appears to be asymmetric. This may at first seem odd since it clashes with a rather evident principle, known as Curie's principle, stating that the asymmetries in the effects must be found in the causes (or, conversely, that the symmetries in the causes must be found in the effects).[3] But of course the actual breaking of, for instance, the dipole rotations of the ferromagnet will in fact be caused only by an ever so small asymmetry in the spin-spin alignments. Moreover, the new ground state of the system after SSB has taken place shows a degeneracy such that the system after SSB plus the total set of degenerated ground states retains the initial symmetry of the system before SSB.

Our presentation in the two following sections 2.3 and 2.4 will discuss the Higgs (toy) model on the "classical" level of Lagrangians only, without delving into the technicalities of a proper QFT analysis. This may at first seem inappropriate. For in the case of QFT the ground or vacuum state degeneracy is intimately connected with the disturbing property of unitarily inequivalent representations of the canonical commutation relations of the field operators—a direct consequence of the fact that QFT systems are modelled as systems with an infinite number of degrees of freedom. There is therefore no unique QFT vacuum; any representation may be associated with its own vacuum state, all of which unitarily—and, hence, supposedly physically—inequivalent. This then raises all the worries about Curie's principle again, and, what is more, the particular occurrence of SSBs in QFTs seems to be a direct consequence of the fact that the symmetries in question cannot be unitarily implemented.

Pressing as these worries are, they will nevertheless not be of our concern here (as should be clear from the introduction already). The main focus of our analysis lies on the particular *gauge symmetry aspect* of the Higgs argument—and the main premise of our argument will be that a gauge symmetry is merely conventional and that it can therefore not be considered the source of a real physical mechanism. This aspect can very well be brought to light on the Lagrangian level already. Since our crucial arguments can be given from such a less complicated point of view, we need not delve into QFT matters.

Another worry could be that even in the ferromagnet case it is necessary to model the system in the thermodynamic limit of infinitely many dipoles in order to obtain a phase transition—and that in this respect the analogy with the Higgs mechanism is greater than assumed above. While this is a technical question that deserves a rigorous technical discussion (see, for instance, Ruetsche 2006), the question whether, in this respect, there exists an analogy or not does not nevertheless touch upon the clear disanalogy between the ferromagnet and the Higgs case as far as the difference in the nature of the considered symmetries is concerned. And it is, again, only this latter aspect on which we will focus.

Hence, whether or not a genuine Higgs mechanism can finally be built on a rigorous QFT approach circumventing the problem of unitarily inequivalent representations and whether or not one day the infinity limes will conceptually be well understood, it is in no case acceptable to claim that the breaking of a merely conventional gauge symmetry plays a crucial role in establishing such a mechanism. Since this, however, seems to be the case in present accounts, it is legitimate and perhaps necessary to focus on just this single gauge symmetry aspect of the Higgs argument.

2.3 The Higgs Mechanism in the $U(1)$ Toy Model

It is easiest to get the idea of the Higgs mechanism by considering the $U(1)$ theory as the simplest model. This toy model includes all the relevant features and allows us to keep track of the argument structure more easily than in the physically relevant model of the electroweak $SU(2) \times U(1)$ gauge theory. Our presentation follows the one in Halzen and Martin (1984, Chap. 14.6–14.9).

We start from a Lagrangian with a complex scalar field $\phi = -\frac{1}{\sqrt{2}}(\phi_1 + i\phi_2)$ and coupled gauge field $F^{\mu\nu}$:

$$\mathcal{L}' = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + |(\partial_\mu - iqA_\mu)\phi|^2 - \mu^2|\phi|^2 - \lambda|\phi|^4. \tag{1}$$

The first two terms are kinetic, the last two describe a potential $V(\phi) = \mu^2\phi^*\phi + \lambda(\phi^*\phi)^2$. We consider only the case $\lambda > 0$, where the ϕ-field is self-interacting because of the ϕ^4-term. From the two possibilities for the sign of μ^2, the case $\mu^2 > 0$ simply leads to the theory of a massive scalar field analogous to the Klein-Gordon-Lagrangian $\mathcal{L}_{KG} = \frac{1}{2}(\partial_\mu\varphi)(\partial^\mu\varphi) - \frac{1}{2}m^2\varphi^2$. But here we are interested in the case $\mu^2 < 0$. This case shows two distinctive features: we get a negative mass term μ, and $V(\phi)$ is no longer a simple parabola but possesses energy minima with $\frac{\partial V}{\partial \phi} = 0$ at $\phi = \pm v$, where $v := \sqrt{\frac{-\mu^2}{\lambda}}$. More precisely, $V(\phi_1, \phi_2)$ now has the form of a "Mexican hat" with $\phi_1^2 + \phi_2^2 = v^2$ over the (ϕ_1, ϕ_2)-plane. In other words, in the energetically favoured state, the ground state, the global and local $U(1)$ symmetry is broken.

Now the first decisive step follows. We rewrite ϕ as a field expansion of the vacuum state:

$$\phi = \frac{1}{\sqrt{2}}(v + \eta + i\xi) \tag{2}$$

with real η, ξ. This ansatz clearly violates $U(1)$; after inserting (2) into (1) we get

$$\begin{aligned}\mathcal{L}'' \;=\;& -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}q^2v^2A_\mu A^\mu + \frac{1}{2}(\partial_\mu\eta)^2 + \frac{1}{2}(\partial_\mu\xi)^2 \\ & -v^2\lambda\eta^2 - qvA_\mu\partial^\mu\xi + \mathcal{O}(\text{fields}^3).\end{aligned} \tag{3}$$

What is the particle content of $\mathcal{L}''$? Obviously we get a massive real scalar field η, a massless ξ-field, and a massive vector field A_μ. The existence of a massive vector field is exactly our goal, and the existence of the massless boson field is predicted by the *Goldstone theorem*: For any generator of a symmetry that is broken in the ground state there exists a massless scalar Goldstone boson. In solid state physics, for instance, such Goldstone bosons are known as energy modes like phonons, plasmons, spin waves, etc.

Let us now compare the degrees of freedom of $\mathcal{L}'$ and $\mathcal{L}''$. Originally, A_μ as well as ϕ had two degrees of freedom, there are four physical degrees of freedom in $\mathcal{L}'$ altogether. In $\mathcal{L}''$, however, we seem to have $1+1+3=5$ degrees of freedom. But this is impossible, since we can hardly change the physical content of our theory by merely transcribing it. It turns out, indeed, that the degree of freedom of the Goldstone boson is unphysical insofar as it can be made to disappear by a suitable gauge. To see this we may rewrite (2) in polar coordinates

$$\phi = \frac{1}{\sqrt{2}}(v+H)e^{i\frac{\theta}{v}} \tag{4}$$

and choose the particular gauge

$$A_\mu \rightarrow A_\mu - \frac{1}{qv}\partial^\mu \theta \tag{5}$$

in $\mathcal{L}'$. This is the second decisive step, since now we get independence of θ; and finally

$$\begin{aligned}\mathcal{L}''' \;=\; & -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}q^2v^2A_\mu A^\mu + \frac{1}{2}(\partial_\mu H)^2 + \lambda v^2 H^2 \\ & -\lambda v H^3 - \frac{1}{4}\lambda H^4 + \frac{1}{2}q^2 A_\mu A^\mu H^2 + q^2 v A_\mu A^\mu H. \end{aligned} \tag{6}$$

From this it becomes apparent that we are indeed only dealing with a theory of a real scalar field, the Higgs field H with mass $m_H = \sqrt{2\lambda}v$, and some vector field A_μ with mass $m_A = qv$. The redundant degree of freedom of the Goldstone boson is in fact absorbed into the longitudinal polarization of the gauge boson. It is precisely this transcription of degrees of freedom—because of the non-invariance of the ground state—which is usually called the “Higgs mechanism”.

2.4 The Higgs Mechanism in the Electroweak Model

The more complex model of the GSW electroweak theory considers a Higgs mechanism which starts in the Goldstone mode from an $SU(2)$ doublet ϕ with $2 \cdot 2 = 4$ degrees of freedom and a gauge coupling to three massless vector bosons $\mathbf{W}_\mu$ corresponding to the generators of SU(2) and one massless vector boson B_μ corresponding to the generator of U(1), which means $4 \cdot 2 = 8$ degrees of freedom for the vector fields and twelve degrees of freedom in toto.

In the Higgs mode we go over to three massive vector bosons W_+, W_-, Z_o, that is $3 \cdot 3 = 9$, one massless photon γ with two and one massive Higgs scalar H with one degree of freedom, altogether again twelve degrees of freedom.

In the full-blown model, the Higgs mechanism is also used to generate the lepton masses. It is, however, not necessary for the purposes of this paper to delve into the details of this application, since it is really the same logic applied to another case.

3 A Threefold Analysis

We start our threefold analysis (as regards the ontological, explanatory and heuristic value of the Higgs model) with three observations. Needless to say, all these observations apply both to the U(1) toy as well as to the electroweak model.

First observation: all three considered Lagrangians are mathematically equivalent in the sense that they belong to a different choice of variables and gauge

$$\mathcal{L}' \sim \mathcal{L}'' \sim \mathcal{L}'''. \tag{7}$$

More precisely, from $\mathcal{L}'$ we go over to $\mathcal{L}''$ by rewriting the field variable ϕ in terms of v, η and ξ according to (2), which does, however, lead to a spurious degree of freedom. This gauge freedom is removed by the transcription (4) instead of (2) for ϕ, now written in terms of v, H and θ, together with the particular gauge fixing (5), by which the transition from $\mathcal{L}'$ to $\mathcal{L}'''$ is accomplished. From this observation the suspicion immediately arises that the whole "mechanism" consists in a mere shuffling of degrees of freedom!

The second observation is that all three Lagrangians are in fact invariant under U(1) and that the symmetry is "broken" not on the level of the Lagrangians, but only on the level of their ground states.

The third observation is that indeed the first Lagrangian $\mathcal{L}'$ with parameter choice $\lambda > 0$, $\mu^2 < 0$ does not allow for any quick, literal interpretation, since here we are facing the obscure case of a ϕ-field with imaginary mass μ.

The second observation already demonstrates the reason why some authors prefer the terminology of "hidden symmetry" instead of "SSB" (e.g. O'Raifeartaigh 1979). Given our remarks in Sec. 2.2 that the system after "SSB" plus the set of ground states retains the initial symmetry of the system before "SSB", this is certainly conceptually far more precise. The third observation may perhaps be questioned from a rigorous QFT point of view (see below), and so it will be in particular the first observation together with the conventional status of gauge symmetries which eventually undermines the prospects of an ontological picture of the Higgs mechanism.

3.1 Ontology of the Higgs Mechanism?

As already mentioned in Sec. 2.1, it is a widespread view that the SSB of the Higgs mechanism is of the same kind as in the case of spontaneous magnetization in the ferromagnet. One is then tempted to regard the Higgs mechanism as a dynamic evolution, a real process in time with a dependence on temperature (e.g. Linde 1979; cf. also Huggett 2000, 633, and Balashov 2002, Sec. 4). The following passage from a panel discussion of the 1996 Boston University Conference on the Conceptual Foundations of Quantum Field Theory highlights this:

> Huggett: What is the mechanism, the dynamics for spontaneous symmetry breaking supposed to be? ... I mean isn't this a dynamic evolution, something that happens in the history of the universe?
>
> Coleman: Oh, it happens with temperature, yeah. Typically at high temperature you're very far from the ground state but the density matrix or whatever has the symmetry. Have I got it right, Steve? You were one of the first to work this out.
>
> Weinberg: Yeah, it doesn't always happen, but it usually happens.
>
> Coleman: Yes, typically at high temperatures the density matrix has a symmetry which then disappears as the temperature gets lower. But that's also true for ordinary material objects. ... it's the same thing. The difference between the vacuum and every other quantum mechanical system is

> that it's bigger. And that's from this viewpoint the only difference. If you understand what happens to a ferromagnet when you heat it up above the Curie temperature, you're a long way towards understanding one of the possible ways it can happen to the vacuum state. (Cao 1999, Chap. 26)

Without doubt, the ferromagnet's SSB allows a straightforward realistic interpretation: the observable change of the macroscopic net magnetization. In this case we *do* have a real dynamic process in time with a phase transition at Curie temperature and with a real instantiation of the underlying symmetry: the rotational degrees of freedom of the elementary magnetic dipoles of the ferromagnet.[4] But nothing like that holds in the case of the Higgs mechanism's SSB, as the following three objections show.

First, the transition from the Goldstone mode to the Higgs mode cannot be understood as a real process in the world, because of our third observation: the impossibility of a realistically interpretable particle content of $\mathcal{L}'$. A typical handwaving argument at this point could be that we may nevertheless consider the Goldstone regime portrayed by $\mathcal{L}'$ as real, since the ϕ^4-term is dominating the imaginary mass term of order ϕ^2, which means that the latter may simply be neglected at the high energies prevalent in the early cosmos. While such an argument is at best satisfying from a pragmatic and instrumentalist perspective, it still leaves open the ontological question of an appropriate interpretation of physical entities with imaginary masses.[5]

One has to admit, however, that our way of presenting this objection is in a sense based on an all too naive view of interpreting Lagrangians. From a more rigorous quantum field theoretic perspective the definition of mass depends on the definition of the ground state of the theory—and it is the whole point about the Higgs mechanism that $\mathcal{L}'$ doesn't give us the "true" ground state. But this only underlines our overall suspicion of $\mathcal{L}'$ from the more elaborate viewpoint of QFT.

A second objection concerns the reality of the Goldstone bosons (recall Weinberg: "Goldstone bosons ... are in some sense real"). In the case of the ferromagnet the Goldstone bosons indeed exist as long-range spin oscillations, but the application of the Goldstone theorem in the case of a *gauge symmetry* leads to spurious, unphysical degrees of freedom, which can be transformed away by our conventional choice of gauge. There simply seems to be no sense in which Goldstone bosons can be given a realistic interpretation (recall again Earman: "... a genuine property like mass cannot be gained by eating descriptive fluff, which is just what gauge is").

This point is directly connected with the third, most important objection against the analogy between the ferromagnet and the Higgs case, and thereby against any ontological picture of the Higgs mechanism. Whereas in the case of the ferromagnet SO(3) is instantiated by real rotations of the dipoles, *quantum gauge transformations possess no such real instantiations.* This was already highlighted in the introduction: neither global nor local unitary gauge transformations are observable, the status of gauge symmetries is a non-empirical and merely conventional one.

A few explanations are in order here. The conventional nature of the choice of gauge should be clear. Also, in view of global quantum gauge transformations, the claim about their non-observable or non-empirical status is certainly uncontroversial, since it is well-known that the expectation value $\langle \hat{A} \rangle = \frac{\langle \psi | \hat{A} | \psi \rangle}{\langle \psi | \psi \rangle}$ of a quantum observable $\hat{A}$ is invariant under $\psi \rightarrow \psi e^{i\chi}$. Perhaps this is not immediately clear for local quantum gauge transformations $\hat{U}(x) = e^{i\chi(x)}$. For here one might argue that, for instance, the eigenvalue p

of the momentum operator $\hat{p}_\mu = -i\partial_\mu$ for a plane wave $\psi = e^{ipx}$ changes for a locally phase transformed wave $\psi' = \hat{U}\psi$ into $p + \partial_\mu \chi(x)$—and that this is a physically significant change. To see the fallacy of this argument, consider the wave function $\Psi(x) = \langle x|\phi\rangle$ in the position representation $|x\rangle$, where the $\{|\phi\rangle\}$ span an abstract Hilbert space. Here, one immediately sees that a proper understanding of local gauge transformations $|x'\rangle = \hat{U}|x\rangle$ is in terms of changes in $|x\rangle$, i.e. merely conventional changes in the position representation. And, of course, such changes affect all Hilbert space operators $\hat{O}' = \hat{U}\hat{O}\hat{U}^+$ as well. In the above example we must therefore use the appropriate covariant momentum operator $\hat{p}'_\mu = \hat{U}\hat{p}_\mu\hat{U}^+$, which in application to ψ' leads again to eigenvalue p. This demonstrates the non-empirical nature of local gauge transformations (cf. Healey 2001, Brading and Brown 2004, Lyre 2004).

On the positive side, to characterize a theory as a gauge theory with gauge group G means to single out the form of the field strength interaction tensor, defined in fibre bundle terms as the curvature tensor of the appropriate G-connection. Here of course the analogy between gauge transformations of a particular group G and coordinate transformations ends: while it must in principle be possible to give a coordinate covariant formulation for *any* physical theory (rendering the principle of general covariance in one specific sense physically insignificant), the claim that a certain interaction field exists in nature and that, as such, a particular gauge group G applies is of course physically significant. Nevertheless, by analogy with coordinate transformations, the G-transformations themselves conform to nothing more than conventional changes of a fibre bundle representation and do not possess any real instantiations.[6]

To sum up: the three negative results—no real instantiations of imaginary masses, no real instantiations of Goldstone bosons, and no real instantiations of gauge transformations—provide a clear answer to our overall question: no ontological picture of the Higgs mechanism seems tenable; the possibility of an as yet undiscovered process or a mechanism supplemented to the exposition given in sections 2.3 and 2.4 notwithstanding. But as far as the exposition in 2.3 and 2.4 is concerned, the Higgs mechanism "does not exist".

3.2 Explanatory Value of the Higgs Mechanism?

Once an ontic interpretation of the Higgs mechanism is blocked, it seems natural to ask further for the epistemic and explanatory value of the hypothesis. After all, the Higgs mechanism was introduced to explain the masses of the elementary particles. Is such a goal reached?

We are obviously facing a rather misleading terminology again. It is, at first, well known that the Higgs model does not allow one to predict the individual values of the particle masses (but only certain ranges because of general boundary conditions such as the applicability of renormalization procedures and the like). But also a more general explanation of masses, let alone of the nature of mass, is hardly given. On the contrary: our ontological analysis has clearly shown that the masses are not "dynamically generated" in any literal or realistic sense—the particular values are rather put in by hand as free parameters of the GSW Lagrangians $\mathcal{L}'_{GSW}$ to $\mathcal{L}'''_{GSW}$.

But let us consider the number of parameters of the GSW model. In the Goldstone mode we count the two coupling constants g and g' of $SU(2) \times U(1)$ and two further parameters μ and λ of the Higgs potential, i.e. four parameters in total. In the Higgs mode we have again the two coupling constants g and g' together with three masses: m_H

of the Higgs as well as M_W and M_Z of the weak bosons. These five parameters, however, depend in a particular manner on the Weinberg angle θ_W:

$$e = g \sin\theta_W = g' \cos\theta_W \tag{8}$$

and

$$M_W = M_Z \cos\theta_W . \tag{9}$$

From these relations it becomes clear that we are effectively dealing with only four parameters, as one would expect from the Goldstone mode, yet the dependency relation (9) is frequently considered a *prediction* of the model—and this looks like a considerable explanatory strength of the Higgs mechanism.

But here again objections have to be raised. Already from the empirically known V-A structure of the electroweak current the relation (8) is required as well as the particular mixing of states, in which the neutral gauge boson fields A_μ and Z_μ must be written. The mixing of g and g' (i.e. $\theta_W \neq 0$) leads to a theory in which $SU(2)$ and $U(1)$ are linked in a non-trivial manner, the requirement $\theta_W \neq 0$ then induces (8) and (9). The dependency relations are in this way directly built in to the mathematical structure of $\mathcal{L}'''_{GSW}$. The final upshot of the whole discovery history of GSW, however, was that under the condition of constructing a renormalizable theory, it was mandatory to have the non-trivial symmetry mixing and, hence, to get dependencies in the form of (8) and (9). This fact shows the supposed explanatory value of GSW in a new light, since even if one were to construe GSW from scratch one could, under the condition of renormalizability, derive $\mathcal{L}'''_{GSW}$ directly without the detour through the Higgs mechanism. The empirical validity of the relations (8) and (9) is after all only an indicator of the empirical appropriateness of the Higgs mode Lagrangian—nothing less, but certainly also nothing more.

3.3 Heuristic Value of the Higgs Mechanism

We seem to be left with a disastrous result: nothing is explained by the Higgs mechanism at all! Within the context of justification considered so far, we were not able to single out any convincing argument in favour of the conceptual idea of the Higgs mechanism. But certainly—given the predominance of the Higgs story in the literature—*there must be something to it.* What could this something be? The answer lies in the context of discovery.

As already outlined in the introduction, the Higgs mechanism was obviously an important heuristic tool for reconciling gauge symmetry and renormalizability in the 1960's (recall Glashow: "I completely missed the boat..."). Moreover, from a heuristic perspective every physicist will immediately support the view that $\mathcal{L}'_{GSW}$, the Lagrangian from which the GSW-Higgs model takes its starting-point, has a far "simpler" mathematical structure than $\mathcal{L}'''_{GSW}$. That is to say, it is almost impossible to invent or to discover $\mathcal{L}'''_{GSW}$ from scratch. It is, instead, more than convenient to have some "guiding story" leading from $\mathcal{L}'_{GSW}$ to $\mathcal{L}'''_{GSW}$. And this is all the more true insofar as $\mathcal{L}'''_{GSW}$ seems to describe an essential trait of reality.

The Higgs mechanism as the guiding story leading from $\mathcal{L}'_{GSW}$ to $\mathcal{L}'''_{GSW}$ within the context of the early discovery of GSW certainly had its overwhelming heuristic value, as the quotations in the introduction show. And it is also true that, from a purely mathematical point of view, $\mathcal{L}'_{GSW}$ is written down in a far more tractable representation than $\mathcal{L}'''_{GSW}$. But at the end of the day this is only a matter of mathematical representation.[7]

From the physical point of view and given the devastating analysis in the last two sections we could—or actually should—introduce the GSW model by writing down $\mathcal{L}'''_{GSW}$ directly.

The upshot is that the Higgs mechanism had its heuristic value only within the context of discovery, whereas within the context of justification this very "mechanism" should rather be considered a kind of *Wittgensteinian ladder*: once $\mathcal{L}'''_{GSW}$ is introduced we may without further ado forget about its heuristic derivation.

4 Conclusion

We have clearly seen that what the Higgs mechanism is all about is a mere reshuffling of degrees of freedom. It certainly does not describe any dynamical process in the world—no ontic interpretation of the Higgs mechanism is tenable, since neither imaginary mass particles, nor GSW Goldstone bosons, nor quantum gauge transformations have any real instantiations in nature. The whole story about the "mechanism" is just a story about ways of representing the theory and fixing the gauge. We have also seen that no concrete physically explanatory value of the Higgs mechanism within the context of justification can be pointed out, but rather a heuristic value within the early context of discovery of GSW.

Needless to say, on the other hand, our exclusively conceptual analysis does not involve any direct arguments against the possible existence of the as yet undetected Higgs boson: $\mathcal{L}'''_{GSW}$ may very well describe reality, after all this is a purely empirical question. In fact, given the strong empirical evidence for GSW, we must definitely assume that the Higgs boson exists. It intimately belongs to the structure and predicted particle content of the theory, as most clearly revealed by an interpretation of the kinetic terms and mass terms in $\mathcal{L}'''_{GSW}$ (bearing in mind footnote 7). And this is what GSW and its empirical evidence commits us to. But GSW does not commit us to a story, called "Higgs mechanism", that pretends to deliver a dynamical picture about how the predicted particles come into being.

Perhaps our critical analysis may have an impact on the power of persuasion of $\mathcal{L}'''_{GSW}$ regarding a deeper understanding of the nature of mass. It has often been pointed out that the Standard Model has too many free parameters, including all the mass values of the elementary particles. Our analysis certainly makes the seemingly ad hoc character of the GSW model even more transparent. Where, if not from $\mathcal{L}'_{GSW}$ and the supposed spontaneous breaking of a gauge symmetry, does the *structure* of $\mathcal{L}'''_{GSW}$ arise from?

We will learn—should the Higgs boson one day be found—that $\mathcal{L}'''_{GSW}$ indeed describes an essential trait of reality. In the light of our critical analysis of the Higgs mechanism, this raises a series of fundamental questions. Why does the Higgs field occur in nature together—in one package, so to speak—with the other particles of the GSW theory? What, if at all, is the true connection between the Higgs field and the masses of the particles, if it is not a story about the breaking of a gauge symmetry of the ground state of $\mathcal{L}'_{GSW}$? These questions are undoubtedly fascinating questions, but also undoubtedly questions about the physics beyond the Standard Model and, as such, an open task to physics, not to philosophy.

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Notes

[1] Of course this well-known recipe does not entail the existence of a non-zero interaction field (compare footnote 6). The logic of the gauge argument has been unfolded by several authors in recent years; cf. Brown (1999), Lyre (2001) and Martin (2002).

[2] A reaction on Earman certainly worth reading and tentatively in spirit with the present paper, though not as decisive as we are concerning ontological consequences, is Smeenk (2006). Chris Smeenk and I wrote our papers independently and only discovered certain similarities in our views only after a recent meeting at a conference.

[3] The original source is Curie (1894); for a systematic discussion of the status of Curie's principle see for instance Chalmers (1970). In a recent paper, Earman (2004a) addresses the principle's connections to QFT—thereby repeating his worries about the Higgs mechanism as already expressed in his quote in the introduction.

[4] It is not necessary to delve into any sophisticated philosophical debate about realism here. We simply use a minimal and, perhaps, commonsensical notion of physical reality, where physical quantities are considered to be connected with observable consequences—and we take this notion, for the purpose of this discussion, as an unproblematic notion.

[5] One might, perhaps, speculate about the introduction of new physical principles here—for instance a new variant of the "Cosmic Censorship", where Nature forever hides imaginary masses from our eyes. But nothing like that has been worked out by anyone yet.

[6] From all the above the logic of the gauge principle should also become clear: the demand of local gauge invariance prompts the introduction of a covariant derivative $D_\mu = \hat{U}\partial_\mu \hat{U^+}$. In the usual textbook presentations (e.g. Halzen and Martin 1984, 316), however, the gradient of the phase is written in terms of a vector field, where also the dimensions of a charge come in: $\partial_\mu \chi(x) = -qA_\mu(x)$. This suggests a reading of the covariant derivative $D_\mu = \partial_\mu + iqA_\mu(x)$ as if the existence of a gauge potential A_μ were enforced. But one must be aware of the fact that a thus introduced potential is, in fibre bundle terminology, a *flat connection* only. That is to say the physically significant curvature tensor, the derivative of the connection, is still zero. Whether, in fact, a particular curvature or gauge field interaction tensor is non-zero and is as such realized by nature, is of course an *empirical input* and cannot be dictated by demanding local gauge invariance (see footnote 1 and references therein).

[7] A further note of clarification: the reader might perhaps be puzzled by our claims about the equivalence of the three Lagrangians on the one hand and the impossibility of a direct realistic interpretation of $\mathcal{L}'$ as opposed to $\mathcal{L}'''$ on the other hand. There seems to be a tension between our first and third observation in the beginning of section 3. And indeed, observation three hinges on stressing a "quick and literal" interpretation of the particle content of a Lagrangian by simply looking at the mass terms. On the basis of our analysis we may now of course say that such a quick and literal interpretation of $\mathcal{L}'$ cannot directly be gained, but is rather indirectly revealed by the direct interpretation of $\mathcal{L}'''$.

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