[Accepted for Publication in *Studies in History and Philosophy of Modern Physics*]

The Construction of the Higgs Mechanism and the Emergence of the Electroweak Theory

Interdisciplinary Centre for Science and Technology Studies (IZWT)
University of Wuppertal
Gaußstr. 20
42119 Wuppertal, Germany
karacak@gmail.com

Abstract

I examine the construction process of the Higgs mechanism and its subsequent use by Steven Weinberg to formulate the electroweak theory in particle physics. I characterize the development of the Higgs mechanism to be a historical process that is guided through analogies drawn to the theories of solid-state physics and that is progressive through diverse contributions from a number of physicists working independently. I also offer a detailed comparative study that analyzes the similarities and differences in these contributions.

1. Introduction

The concept of "spontaneous symmetry breaking" (SSB) as used in (relativistic) quantum field theory was inspired from the vacuum-structure of the Bardeen-Cooper-Schrieffer(BCS) theory of superconductivity in solid-state physics.[1] As physicists Yoichiro Nambu[2] and Giovanni Jona-Lasinio[3] once remarked, the integration of SSB into the theoretical framework of quantum field theory illustrates a case of "cross-fertilization" between solid-state physics and particle physics through the sharing of a physical concept. The integration process of SSB has been discussed in

[1] Barden et al. 1957; see also Bogoliubov 1958 for its re-formulation.
[2] Nambu 2009.
[3] Jona-Lasinio 2002.

a joint paper[4] by Laurie Brown and Tian Yu Cao, which has also accounted for the emergence of SSB as a physical concept and its early use in solid-state physics. What constitutes the final step in this integration process is the construction in the sixties of what is today referred to as "Higgs mechanism" in the literature of modern physics. This was achieved through diverse contributions from different physicists working independently. Even though the aforementioned paper by Brown and Cao is very helpful and thorough in many respects, it does not engage in a detailed examination of the similarities and the differences that exist between the approaches taken in these contributions.[5] Nor does it discuss their convergence to the Higgs mechanism as well as to the formulation of the electroweak theory by Steven Weinberg in 1967. All these *as-yet-unaddressed* historical issues call for a critical study of the development of the Higgs mechanism that is currently missing from the literature of history and philosophy of modern physics.[6] In the present paper, I shall undertake a detailed *comparative* study of the works that contributed to the development of the Higgs mechanism. Moreover, in parallel to this discussion, I shall also trace the development of the electroweak theory as the *unified* theory of electromagnetic and weak forces.

The plan of the present paper is roughly as follows. In Section 2, I shall give a short summary of the failure of the V-A theory of weak interactions. In Section 3, I shall dwell on Glashow's work on a unified theory of weak and electromagnetic forces. I shall also discuss the zero-mass problem of the Yang-Mills theory and how it plagued Glashow's work. In Section 4, I

---

[4] Brown & Cao 1991.

[5] See Brown and Cao 1991, p. 234, where *only* the names of the physicists whose works contributed to the Higgs mechanism are mentioned and their works are cited in Footnote: 65.

[6] The literature of history and philosophy of modern physics concerning SSB is of relatively recent origin. Most works have dealt with the philosophical aspects of this concept; whereas very little attention has been paid to its historical examination. Philosophical studies of the Higgs mechanism include, e.g., Kosso 2000; Earman 2003, 2004a, 2004b; Liu 2003; Morrison 2003, Castellani 2003, Liu & Emch 2005; Smeenk 2006; Lyre 2008; and Struyve 2011.

shall examine in detail the construction process of the Higgs mechanism that solved the zero-mass problem. In Section 5, I shall describe the formulation of the electroweak theory by Weinberg on the basis of the Higgs mechanism. Finally, in Section 6, I offer a comparative assessment of the contributions that led to the construction of the Higgs mechanism.

2. The failure of the V-A theory of weak interactions

In 1956, two Chinese physicists, Tsung-Dao Lee and Chen-Ning Yang, proposed that, unlike in strong and electromagnetic interactions, "parity conservation"[7] might be violated in weak interactions.[8] The following year, this proposal was confirmed by a team of experimental physicists[9], and Lee and Yang were jointly awarded the 1957 Nobel Prize for physics. The "V-A theory" was formulated in 1958 as an attempt to explain the parity violation discovered in weak interactions.[10] However, it was soon understood that the V-A theory gave certain unrealistic predictions about weak interactions at high energies and that, more importantly, it was *not* a renormalizable[11] theory; greatly precluding its acceptance by the physics community. Motivated by these problems, an important modification was introduced into the V-A theory; it was suggested[12] that just like the electromagnetic interaction was described in terms of the exchange of a photon in the theory of quantum electrodynamics, the weak interaction might be represented not as a point interaction, as in the original V-A theory, but rather as the exchange of gauge

---

[7] In quantum mechanics, "parity" transformations refer to the inversions of coordinate-axes in the form $\mathbf{r} \rightarrow -\mathbf{r}$. The conservation of parity states that the field equations describing a quantum mechanical system remain unchanged under parity transformations.
[8] Lee &Yang 1956.
[9] Wu et al. 1957.
[10] Feynman & Gell-Mann 1958 and Marshak & Sudarshan 1958.
[11] A theory is said to be "renormalizable" if all divergences, or infinities, in observable physical quantities—such as cross section and decay rate—it yields are removable by a redefinition of coupling constants and re-scaling of fields.
[12] Lee & Yang 1960.

bosons (also called “vector mesons”)—often referred to as “intermediate vector bosons” (IVBs)—for which there was no experimental evidence whatsoever.[13]

Even though the IVBs were postulated on the ground of an analogy drawn from quantum electrodynamics, there were significant dissimilarities between the photon and IVBs. First, unlike the photon, as required by the theoretical structure of the V-A theory, the postulated IVBs must exist in two charged states, namely, positive and negative states. Second, the IVBs were postulated to be massive particles, ensuring the short-range behavior of the weak force. However, the requirement that the IVBs be massive yielded divergent perturbation series, bringing back again the problem of renormalization. Therefore, the attempt to re-formulate the V-A theory on the basis of the IVBs did not lead to any better understanding of the physics of weak interactions.

Despite the dissimilarities mentioned in the above paragraph, there were significant similarities between the way the electromagnetic force was treated in quantum electrodynamics and the way the weak force was treated in the modified V-A theory. In both of these theories the force under consideration is mediated by vector bosons. Also, in both of these theories, the strength of the force is represented by a universal coupling constant. A year before the formulation of the V-A theory, in 1957, Schwinger had published a paper where, based on these similarities, he had for the first time introduced the IVBs and proposed that they, together with the photon, could be seen as the members of the same family of particles, namely of an “isotopic” triplet of vector fields.[14] He had then conjectured that two oppositely charged fields mediate weak interactions and that the neutral field is the photon field mediating the

---

[13] Note that, as shall be seen in what follows, the IVBs were first introduced by Schwinger in 1957 prior to the formulation of the V-A theory.
[14] Schwinger 1957.

electromagnetic force. In other words, Schwinger had proposed to treat the weak and electromagnetic forces to be different manifestations of the same force represented by a single universal coupling constant.

3. Glashow's theory: a partially correct approach to the unification of electromagnetic and weak forces

In 1961, Sheldon Lee Glashow, a doctoral student of Schwinger's at Harvard, wrote a paper[15] where he elaborated on the ideas presented in Schwinger's 1957 paper and proposed a unified theory of weak and electromagnetic forces on the basis of the "gauge principle".[16] Let me now very briefly touch upon what this principle amounts to in relativistic quantum field theory.[17] The gauge principle requires that the Lagrangian of the theory display both Lorentz invariance and "local" gauge invariance. The principle of Lorentz invariance states that the mathematical form of the field equations of the theory remains invariant under the Lorentz transformations. On the other hand, the principle of local gauge invariance refers to the invariance of the Lagrangian under a group of transformations (called "gauge group") that are space-time dependent; while the "global" gauge invariance refers to the invariance of the Lagrangian under transformations that are the same at every point in space-time. According to the gauge principle, global gauge invariance of a free matter field theory can be extended to local gauge invariance by introducing into its Lagrangian an interaction term consisting of the coupling of the matter field to a gauge vector field. The local gauge invariance entails that there exists a local conservation law corresponding to a physical quantity, which is called the "gauge invariant" quantity of the theory.

[15] Glashow 1961.
[16] Philosophical discussions of this concept can be found in Lyre 2001, Martin 2002, Healey 2007 and Guay 2008.
[17] For an introduction to relativistic quantum field theory, see, e.g., Brown & Harre 1988, Teller 1995, Cao 1999 and Kuhlmann et al. 2002.

Quantum electrodynamics[18] was the first theory of particle interactions whose formulation was based on the gauge principle. It was also demonstrated in the late forties that it was a renormalizable theory.[19] In quantum electrodynamics, the gauge field is the photon field and the Lagrangian has U(1) local gauge invariance, the gauge invariant quantity being the electric charge.

After the formulation of quantum electrodynamics, Chen-Ning Yang and Robert Mills generalized the gauge principle to interactions represented by non-Abelian gauge groups, i.e., gauge groups whose generators do not commute with each other.[20] In the literature of quantum field theory, the term "Yang-Mills theory" is now used as a generic name to refer to *non-Abelian* quantum field theories adhering to the gauge principle. In the Yang-Mills theory, the imposition of local gauge invariance (together with Lorentz invariance) requires gauge vector bosons—i.e., quanta mediating gauge forces—to be massless.[21] Technically, this is due to the fact that in quantum field theory mass terms, which are quadratic in fields (not containing derivatives), are *not* gauge invariant.[22] Thus, any quantum field theory of Yang-Mills type should contain no mass terms quadratic in gauge fields (not containing derivatives) in its Lagrangian if it is to be gauge invariant.[23] However, all experimental evidence indicates that the only massless gauge vector boson is the photon that mediates the electromagnetic force. This difficulty is commonly referred to as the "zero-mass problem" of the Yang-Mils theory.[24]

[18] For a comprehensive historical study of the construction of quantum electrodynamics, see, e.g., Schweber 1994.
[19] Renormalization is an important constraint in formulating a gauge theory; see, e.g., t' Hooft 2005. For a philosophical discussion of this concept, see, e.g., Teller 1988, Cao & Schweber 1993 and Huggett 2002.
[20] Yang&Mills 1954. For an introduction to the Yang-Mill theory, see; e.g., Moriyasu 1983 and Healey 2007.
[21] A formal proof can be found in Moriyasu 1983, ch. 4.
[22] To see this, see, e.g., Moriyasu 1983, p. 52.
[23] A formal proof can be found in Moriyasu 1983, ch. 4.
[24] See, e.g., Cao 2010, p. 143, for a discussion of this problem in historical context.

The formulation of Glashow's 1961 theory proceeded through an analogy to quantum electrodynamics. On the basis of previously mentioned similarities between the weak and electromagnetic forces, Glashow proposed that the weak force, like the electromagnetic force, could be regarded as a gauge force and that these two forces could be unified under a gauge theory of Yang-Mills type. In analogy to quantum electrodynamics, for the description of weak interactions, he considered "weak isospin"[25] to be a gauge invariant quantity and the symmetry group associated with this conserved quantity to be SU(2). Furthermore, as part of this analogy, following Schwinger proposal in his 1957 paper, Glashow postulated that the weak force is *mediated* via the exchange of the IVBs, just like the electromagnetic force is mediated via the exchange of a gauge boson, namely, the photon.[26] However, Glashow was already aware of the zero-mass problem of the Yang-Mills theory; i.e., the problem of how to represent the photon and IVBs under a *fully* gauge symmetric Lagrangian. In a paper[27] published in 1959, Glashow had proposed to avoid the zero-mass problem by using the concept of "partial symmetry", to which I shall now briefly allude. Glashow's main goal in this paper was to deduce "a new and less restrictive criterion" for the renormalizability of vector boson interactions, which at that time were believed to be *non-renormalizable* in most cases, if strict conservation laws were applied. The way Glashow defined the concept of "partial symmetry" and the associated concept of "partial conservation law" in his 1959 paper can be summarized as follows. The part of the Lagrangian containing the mass terms of the theory can be separated from the kinematic and interaction parts of the Lagrangian. As explained above, if the Lagrangian is fully gauge symmetric under a group of transformations, then there must correspond to it a conserved

[25] "Weak isospin" symmetry is the spin symmetry associated with the IVBs.
[26] For a philosophical discussion of the "analogical reasoning" that led to the construction of the electroweak theory, see Kosso 2000.
[27] Glashow 1959.

current. However, if *only* the kinematic and the interaction parts of the Lagrangian, but *not* the part containing the mass terms, are gauge invariant under a symmetry group, then this symmetry is called a "partial" symmetry, and accordingly the Lagrangian under consideration is called a "partially symmetric" Lagrangian. As a corollary, the current corresponding to partial symmetry is not conserved, but satisfies a "partial conservation law". Glashow concluded his 1959 paper by asserting that certain vector boson interactions would be renormalizable if the strict conservation law was dropped and the "partial conservation law" was maintained.

The novelty in Glashow's theory was the introduction of the *compound* gauge symmetry group SU(2)xU(1) to be the gauge group of weak and electromagnetic interactions. Glashow took into account *only* the "electron-type" leptons[28] and considered an important empirical fact regarding those particles; namely, that there exist two "left-handed" electron-type leptons, namely, the left-handed electron-type neutrino $\nu_{e,L}$ and the left-handed electron e_L, and one "right-handed" electron-type lepton, namely, the right handed electron e_R.[29] He also introduced what is called "weak hypercharge" which is denoted by Y and related to electronic charge Q through the Gell-Mann—Nishijima—Nakano relation[30]: $Q = T_3 + (Y/2)$, where T_3 stands for the third component of "weak isospin". This led him to the conclusion that $\nu_{e,L}$ and e_L form an isotopic doublet under the group $SU(2)_L$ which represents the invariance of "weak isospin", and that forms a singlet under the group $U(1)_h$ which represents the invariance of weak hypercharge; thereby yielding together the four-parameter compound symmetry group $SU(2)_L \times U(1)_h$.[31] In

[28] A *lepton* is a spin-1/2 elementary particle that interacts through electromagnetic, weak and gravitational forces, but does not interact through strong force.
[29] In particle physics, a particle is called "right-handed" if its spin direction is the same as the direction of its motion; otherwise it is called "left-handed".
[30] Gell-Mann 1956, Nakano & Nishijima1953.
[31] Here, the subscript "L" signifies that only the left-handed component of the particle participates in the interaction. And, the subscript "h" denotes "hypercharge". So, the $U(1)_h$ symmetry, which represents the conservation of weak

Glashow's theory, $SU(2)_L$ gauge group calls for the existence of the four IVBs: one *triplet* consisting of one positive, one negative and one electrically neutral vector boson for the $SU(2)_L$ symmetry group, namely, in Glashow's notation, Z_1, Z_2, Z_3, respectively, and one neutral *singlet*, which Glashow denoted by Z_S.

The next step in the formulation of Glashow's theory was how to give mass to the IVBs. This step was achieved by adding explicit mass terms into the Lagrangian. However, this procedure, often called "explicit symmetry breaking", was already known to destroy the gauge invariance of any theory of Yang-Mills type and thus render it *non-renormalizable*.[32] As previously stated, this is due to the fact that mass terms are quadratic in fields (not containing derivatives) and thus are not gauge invariant. However, it is to be recalled that in his 1959 paper Glashow argued that if the Lagrangian was taken to be partially gauge symmetric and accordingly if a partial conservation law was adopted, then the theory under consideration might be renormalizable. Having introduced *explicit* mass terms—i.e., terms quadratic in *Z* fields—into the Lagrangian, Glasgow properly arranged them so as to yield the following super-positions of the fields Z_3 and Z_S : $Z_{\mu,3}\cos\theta + Z_{\mu,S}\sin\theta$ and $Z_{\mu,S}\cos\theta - Z_{\mu,3}\sin\theta$, where the angle θ represents the ratio of the relative strengths of the triplet and singlet interactions of the IVBs and the index μ runs from 1 to 3. Here, Glashow observed that the former is associated with a massive particle, which he called the neutral massive vector boson B_μ, and that the latter is associated with a massless field A_μ, which he identified to be the photon field. Glashow interpreted this result to indicate the existence of neutral weakly interacting currents.[33] Given that at the time Glashow formulated his theory there was no experimental evidence whatsoever indicating the existence of

hypercharge, should not be confused with the U(1) symmetry which represents the conservation of charge in quantum electrodynamics.

[32] See Komar & Salam 1960.

[33] Glashow 1961.

neutral currents and that all weak interactions were believed to be charged, the above result should be seen as a novel *qualitative* prediction of Glashow's theory.

The above discussion suggests that the prediction of weak neutral currents is a consequence of both SU(2)xU(1) group structure and the introduction of the explicit mass terms into the Lagrangian. However, Glashow's 1961 theory failed to give any *quantitative* predictions with regard to the masses of the IVBs, and those masses remained arbitrary in the theory.[34] Due to the absence of definite predictions, Glashow's theory did not attract much attention from the relevant physics community.[35] There was yet another reason behind this lack of interest. A number of physicists[36], prominently Abdus Salam, demonstrated that Glashow's theory was not renormalizable. These physicists mathematically established that any quantum field theory of Yang-Mills type is renormalizable *only* if it is exactly gauge invariant, and if there corresponds to this exact invariance a *strict* conservation law. This result was contrary to Glashow's assertion that partial conservation law was not required for renormalization.

Summarizing, in the early sixties, attempts to construct a successful theory of weak interactions were beset by the zero-mass problem of the Yang-Mills theory. This problem was vigorously investigated during the first half of the sixties, and it was eventually solved on the basis of the concept of "spontaneous symmetry breaking" (also referred to as "spontaneous

---

[34] A very similar model of electromagnetic and weak interactions was proposed by Salam and Ward in a paper published in 1964 (Salam & Ward 1964). Like Glashow, Salam and Ward acknowledged that neutral massive IVBs were needed for a unified description of electromagnetic and weak interactions, and by simply assuming the difference between the weak and electromagnetic coupling strengths, they derived exactly the same SU(2)L x U(1)h group structure for the unified description of weak and electromagnetic forces as the one already derived by Glashow in his 1961. Strangely enough, even though Salam and Ward cited Glashow's 1959 paper about renormalizability, they did not cite his 1961 paper where he offered his unified theory of electromagnetic and weak interactions.

[35] According to the "Science Citation Index" data, over the course of seven years between the years of 1961 and 1967, Glashow's 1961 paper was cited only once each year; two of these citing publications were co-authored by Glashow himself.

[36] See, e.g., Salam 1960, Kamefuchi 1960 and Salam 1962.

breakdown of symmetry"[37]). In what follows, I shall examine the important developments that led to the solution of the zero-mass problem.

4. The construction process of the "mass-generation" mechanism

The concept of SSB is used in physics to characterize the situation in which a certain symmetry associated with a physical system is lost when the system goes into a "ground state" (also called "vacuum state") that does not possess the original symmetry of the system. The concept was first introduced into the context of relativistic quantum field theory by the works of Yoichiro Nambu[38]. Using the formalism of quantum field theory, Nambu provided a quantum field theoretic elucidation of the BCS theory of superconductivity, where the *original* derivation of the *Meissner effect* was not gauge invariant. The Meissner effect is the phenomenon that below a critical temperature magnetic field is expelled from a superconductor's surface, and that it can only penetrate a very small length.[39] According to the BCS theory, the Meissner effect results from the formation of the electron pairs called "Cooper pairs"[40]. In the above-cited papers, Nambu demonstrated that the *Ward identity*[41] holds true in the case of the Meissner effect and

[37] The term "spontaneous breakdown of symmetry" is due to Baker & Glashow 1962.
[38] Nambu 1960a, 1960b. See Brown & Cao 1991 for a detailed discussion of Nambu's work on SSB.
[39] This effect was first reported by Walther Meissner and Robert Ochsenfeld in a paper jointly published in 1933; see Meissner & Ochsenfeld 1933.
[40] In solid-state physics, the term "Cooper pair" denotes an electron-pair that has equal and opposite spins. The interaction between the Cooper pair electrons are taken to be mediated through "phonons", which are conceived to be massless and spinless energy excitations resulted from the vibrations of ions in a lattice. The wave-function of a Cooper pair has a long-range phase coherence, and this destroys the U(1) phase invariance, which is a global invariance. For details, see e.g. Weinberg 2005, vol. II, ch. 21. For future reference, it is also important to note that in solid-state physics the interaction between the Cooper pairs is taken to be mediated by what are called "phonons" which are defined to be both massless and spinless energy excitations. For details, see e.g., Kittel 2005.
[41] In QED, the Ward identity is a statement of current conservation as a consequence of local gauge invariance; it reads: $\mathbf{k}_\mu M^\mu(k) = \mathbf{0}$, where the four-vectors represent respectively the momentum of the photon involved in a

that thereby local gauge invariance is saved by virtue of the existence of phonon states (also called "collective states").

Inspired by the similarities among the field equations of Dirac's electron theory and Bogoliubov's reformulation of the BCS theory of superconductivity[42], Nambu, together with Giovanni Jona-Lasinio, constructed an elementary particle model (of nucleons and mesons) [43]—to be later called the Nambu-Jona-Lasinio model—that displays SSB analogous to the one in the BCS theory of superconductivity. In this model, based on an analogy drawn from the BCS theory, Nambu—Jona-Lasinio suggested that the nucleon mass is acquired through a similar mechanism of SSB in which an energy gap arises in a superconductor. The Nambu—Jona-Lasinio model also showed that, within the mathematical framework of quantum field theory, the concept of SSB could be used to describe a situation where the Lagrangian of a physical system, as well as its associated field equations, is fully symmetric under a continuous internal symmetry group, but the ground state (or vacuum state) does not possess the *very* same symmetry. According to quantum mechanics, the ground-state for a physical system is typically *unique* and defined to be the state having the minimal energy. If there are multiple minimal-energy states, the ground state is defined to be a linear superposition of all these states. However, there are cases in which the ground-state of the system becomes *degenerate* (i.e., non-unique)—the situation called "vacuum degeneracy"—namely, that, there exist multiple minimal-energy states differing from each other by their non-vanishing values of certain operators. In such a situation,

scattering process and the scattering amplitudes for that scattering process. See, e.g., Peskin and Schroeder 1995, sec. 7.4.
In quantum field theory, the following is called the Ward identity:, where the vectors represent respectively the propagation and polarization directions of the gauge vector field. Note that the Ward identity is a statement of current conservation as a consequence of *local* gauge invariance. See, Peskin & Schroeder 1995, p. 160.
[42] Bogoliubov 1958. In his Nobel Lecture, Nambu says: "The formal similarity of the Bogoliubov-Valatin equation to the Dirac equation naturally led me to transport the BCS theory to particle physics." See Nambu 2009.
[43] Nambu & Jona-Lasinio 1961a, 1961b.

the invariance (uniqueness) of the ground-state under the symmetry transformation of the system is lost when the system is initially taken to be in one of those minimal-energy states. Therefore, the condition of SSB is tantamount to the condition of the non-invariance of the ground-state.[44]

The approach underlying the Nambu—Jona-Lasinio model was subsequently used by other quantum field theorists to formulate dynamical models of elementary particles.[45] What was common to all these dynamical models was that the masses of the elementary particles were generated via a mechanism of SSB of the internal symmetry of the Lagrangian describing the gauge interaction under consideration. Yet, in all these models, the mechanism of SSB also brought about the generation of unwanted massless scalar bosons, for which there was no experimental evidence whatsoever.

In 1961, Jeffrey Goldstone conjectured that the SSB of a continuous symmetry in a Lorentz-covariant Lagrangian brings about massless (scalar) zero-spin bosons—often called "Goldstone bosons".[46] A year later, several proofs of this conjecture were presented in a joint paper[47] by Goldstone, Salam and Weinberg, and subsequently Goldstone's conjecture was elevated to the status of a theorem, which has come to be referred to as the "Goldstone theorem".[48] This led, among the quantum field theorists, to the *supposition* that massless scalar bosons would be an *inevitable* consequence of all dynamical models of the Yang-Mills theory; thereby presenting a *supposed* dilemma which can be expressed as follows. The only way to solve the zero-mass problem and give mass to gauge bosons is through the SSB of the original gauge symmetry of the Lagrangian. However, in this way, one encounters the difficulty posed by

[44] For a comprehensive quantum field-theoretic treatment of spontaneous symmetry breaking, see, e.g., Cheng & Li 1984, Chapter 8, and Peskin & Schroeder 1995, Chapter 20.
[45] See, e.g., Baker & Glashow 1962, Suzuki 1963, Byrne et al. 1965.
[46] Goldstone 1961. Note that the same result was presented in the same year in Nambu & Jona-Lasinio 1961a. Also, see Nambu 1960a for a similar result in the context of superconductivity.
[47] Goldstone et al. 1962.
[48] See Guralnik et al. 1968 for an extensive discussion of the Goldstone theorem.

the Goldstone theorem—often referred to as the "Goldstone zero-mass difficulty"—namely that, the existence of massless scalar bosons for which there is no experimental evidence. Therefore, either the gauge principle is wrong and should be abandoned, or the idea of SSB should be given up instead. However, for the Yang-Mills theory, neither way is promising.

Instead of giving up either the gauge principle or the idea of giving mass to gauge quanta via a mechanism of SSB, the resolution of the Goldstone zero-mass difficulty was sought in doubts about the validity of the Goldstone theorem. The first explicit objection against the general validity of the Goldstone theorem came in 1963 from a solid-state physicist, namely, Philip Anderson. Before I dwell on how Anderson tackled the Goldstone-zero mass difficulty, in the ensuing discussion, I shall allude to Schwinger's work from which Anderson took his cue.

In a series of two papers[49] published in 1962, Schwinger argued that "the gauge invariance of a vector field does not necessarily imply zero mass for the associated particle if the current vector coupling is sufficiently strong". Schwinger's argument was based on his observation that in relativistic quantum field theory local gauge invariance does not preclude gauge quanta to be massive, if the vacuum polarization tensor[50] has a pole (i.e., singularity) at momenta $p^2 = 0$.[51] Schwinger demonstrated that the existence of such a pole is possible if the current-vector coupling is sufficiently strong. He illustrated this argument in a two-dimensional (one time and one space dimensions) model of quantum electrodynamics where the polarization tensor develops a pole at $p^2 = 0$; thereby the photon acquires mass. Schwinger was not able to devise a mechanism through which gauge quanta of the Yang-Mills theory could acquire mass.

[49] Schwinger 1962a, 1962b.

[50] Note that the vector polarization is required to be transverse in order to guarantee gauge invariance. This result is due to the Ward identity; for a formal proof see, e.g., Peskin & Schroeder 1995, p. 160.

[51] For a derivation of this result, see, e.g., Peskin & Schroeder 1995, p. 245-246.

However, as the above discussion indicates, he anticipated the very idea underlying the mass generation mechanism, namely, that gauge bosons could acquire mass through current-gauge field coupling.

This idea of Schwinger was taken up by Anderson in his paper of 1963. In this paper, Anderson contended that the treatment of the Meissner effect by the free-electron gas theory[52] in solid-state physics was a *non-relativistic* example illustrating Schwinger's suggestion. The free-electron theory accounts for the Meissner effect in the following way: due to the interaction with the external magnetic field, longitudinally polarized massless phonons mediating between the Cooper pair electrons inside a superconductor turn into massive plasmons[53], whose longitudinal and transverse components are composed of respectively a phonon and a photon mediating the (electro) magnetic field. In quantum field theoretic language, this in turn means that the photon appears to have acquired "mass", due to its acquired longitudinal polarization state, and as a result, the magnetic force behaves like a short-range force inside the superconductor.[54] Anderson regarded massless phonons, which have appeared inside a superconductor as a result of SSB of local gauge invariance, as zero-mass Goldstone bosons. Upon this, he suggested that just like in the case of the Meissner effect where massless phonons become the longitudinal components of massive plasmons after interacting with photons, under sufficiently strong current-gauge vector field coupling, in the case of the Yang-Mills theory the Goldstone bosons would become the longitudinal components of massive gauge bosons. Incidentally, it is worth noting that what Anderson suggested here closely echoes today's semi-popular presentation of the mass

[52] See Nozieres & Pines 1958.
[53] In solid-state physics, a "plasmon" is defined to be a collective excitation of the free-electron gas in a metal. For details, see, e.g., Kittel 2005.
[54] In solid-state physics, this phenomenon is commonly referred to as the "Anderson mechanism". See, e.g., Zee 2010, p. 264.

generation mechanism.[55] According to this, the mass-generation mechanism consists of a reshuffling of degrees of freedom; namely, a massless gauge field, which has two degrees of freedom due to its two transverse polarization states, and a Goldstone boson, which has only one degree of freedom due to its longitudinal polarization state, combine so as to form a massive gauge field, which has three degrees of freedom due to its both transverse and longitudinal polarization states. In short, Anderson was convinced that "[t]he Goldstone zero-mass difficulty is not a serious one, because [it] can probably [be cancelled] off against an equal Yang-Mills zero-mass problem."[56] And, he went on to suggest that "the only mechanism … for giving the gauge field mass is the degenerate vacuum type of theory, in which the original symmetry is not manifest in the observable domain."[57] Therefore, Anderson's conviction was that the Goldstone theorem did not in fact pose a dilemma for the Yang-Mills theory, contrary to what it was generally supposed to do.

However, Anderson's argument was an analogy argument from solid-state physics, and the demonstration of its validity within the theoretical framework of the Yang-Mills theory awaited contributions by a number of physicists. A year later, Abraham Klein and Benjamin Lee took up Anderson's suggestion within the theoretical framework of quantum field theory. They showed that, in non-relativistic field theories, first, " [t]here exists no general proof, independent of model and method of calculation, which establishes the existence of zero-mass particles in field theories with spontaneous breakdown of symmetry[, and second, t]here are nevertheless classes of such field theories wherein zero-mass particles do occur in consequences of the broken

[55] See, e.g., Zee 2010, p. 264.
[56] Anderson 1963.
[57] Ibid.

symmetry."[58] The original analysis presented by Klein and Lee was restricted to non-relativistic theories; but they conjectured that the BCS theory was not the only theory in which the Goldstone theorem was evaded, and that relativistic models of fundamental interactions that displayed SSB but that did not contain massless bosons were also possible. Walter Gilbert objected to this proposal and argued that since the Goldstone theorem was applicable only in Lorentz-covariant theories, the absence of massless scalar bosons in non-relativistic theories should be interpreted as a consequence of the *inapplicability* of the theorem, rather than as a consequence of its failure.[59]

Peter Higgs criticized Gilbert's proof by arguing that there was a *loophole* in the Goldstone theorem that might allow the avoidance of massless scalar bosons in certain relativistic gauge theories.[60] Higgs showed that the Goldstone theorem would break down in a class of *non-manifestly* Lorentz-covariant gauge theories that use the "radiation gauge"[61] (also known as the "Coulomb gauge"), on the condition that the conserved currents associated with the generators of the internal gauge group were coupled to gauge fields. Note that Lorentz covariance is said to be "manifest" if causality principle, which takes the speed of light to be the maximum attainable physical speed, is not violated. Moreover, Lorentz covariance is manifest under the Lorentz gauge condition, but not under the radiation gauge. In a follow up paper[62], without specifying any gauge condition, Higgs examined the breakdown of the U(1) gauge

[58] Klein & Lee 1964.
[59] Gilbert 1964.
[60] Higgs 1964a. In this paper, Higgs also noted that this class of theories would still be Lorentz-covariant but not manifestly Lorentz-covariant, as was shown by Schwinger 1962c.
[61] For future reference, the conditions: $\vec{\nabla} \bullet \vec{A} = 0$ and $\vec{\nabla} \bullet \vec{A} + \frac{1}{c^2}\frac{\partial \phi}{\partial t} = 0$ are called respectively the *radiation gauge* and the *Lorentz gauge* (in vacuum). And, under the electromagnetic U(1) gauge transformation, $A_\mu \to A_\mu^{'} = A_\mu - \partial_\mu \chi,$ where χ is an arbitrary scalar function.
[62] Higgs 1964b.

symmetry in the simple case of a classical (*unquantized*) gauge theory (namely, classical electrodynamics). To this end, he considered the following the U(1) globally symmetric Lagrangian: $L = -\frac{1}{2}[(\partial_\mu \varphi_1)^2 + (\partial_\mu \varphi_2)^2] - V(\varphi_1{}^2 + \varphi_2{}^2)$, where *V*, and φ_1 and φ_2 denote respectively the potential energy and the real scalar fields. He coupled the conserved current of the above Lagrangian to a U(1) gauge-symmetric field A_μ to obtain the following U(1) locally symmetric Lagrangian:

$$\begin{aligned} L' = &-\frac{1}{2}(\partial_\mu \varphi_1)^2 - \frac{1}{2}(\partial_\mu \varphi_2)^2 + eA_\mu[(\partial_\mu \varphi_1)\varphi_2 - (\partial_\mu \varphi_2)\varphi_1] \\ &-\frac{1}{2}(eA_\mu)^2(\varphi_1{}^2 + \varphi_2{}^2) - V(\varphi_1{}^2 + \varphi_2{}^2) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}, \end{aligned} \tag{1}$$

where the third term represents the coupling of the conserved current of L with the gauge field A_μ, and *e* is a dimensionless coupling constant. Higgs demonstrated that if one chose (without loss of generality of the solutions of field equations) the vacuum-state values of the real scalar fields as $\varphi_1 = 0$ and $\varphi_2 = \varphi_0 =$ *constant*, this would spontaneously break U(1) local gauge symmetry of L'. He also derived the associated field equations as:

$$\partial^\mu \{\partial_\mu (\Delta\varphi_1) - e\varphi_0 A_\mu\} = 0, \tag{2a}$$

$$\{\partial^2 - 4\varphi_0^2 V''(\varphi_0^2)\}(\Delta\varphi_2) = 0, \tag{2b}$$

$$\partial_\nu F^{\mu\nu} = e\varphi_0\{\partial^\mu\ (\Delta\varphi_1) - e\varphi_0 A_\mu\}. \tag{2c}$$

By the introduction of new variables:

$$\begin{aligned} B_\mu &= A_\mu - (e\varphi_0)^{-1}\partial_\mu(\Delta\varphi_1), \\ G_{\mu\nu} &= \partial_\mu B_\nu - \partial_\nu B_\mu = F_{\mu\nu}, \end{aligned} \tag{3}$$

he put Equations (2a) and (2b) into the following forms, respectively:

$$\partial_{\mu} B^{\mu} = 0, \qquad (4a)$$

$$\partial_{\mu} G^{\mu\upsilon} + e^2 \varphi_0{}^2 B^{\mu} = 0. \qquad (4b)$$

Higgs noted that Equations (4a) and (4b) jointly describe vector waves whose quanta have a mass of $e\varphi_0$. He also noted that the right side of Equation (2c) is proportional to the conserved current, expressed in Equation (2a), which is linear in vector potential and thus gauge invariant. Therefore, Higgs was able to show that, as a result of symmetry breaking, the gauge field acquired mass, while gauge invariance was maintained. Higgs further noted that Equation (2b) describes scalar waves whose quanta have a mass of $2\varphi_0\{V''(\varphi_0^2)\}^{1/2}$; revealing an important aspect of the mass-generation mechanism, namely, that it brings in the theory a massive scalar boson. In Higgs words:

> It is worth noting that an essential feature of the type of theory which has been described in this note is the prediction of incomplete multiplets of scalar and vector bosons. It is to be expected that this feature will appear also in theories in which the symmetry-breaking scalar fields are not elementary dynamic variables but bilinear combinations of Fermi fields. (Higgs 1964b)

Moreover, in the same paper, Higgs remarked that in the absence of current-vector field coupling, i.e., $e = 0$, Equations (2a) and (2c) describe respectively zero-mass scalar and vector bosons. The latter in turn means that in the absence of current-vector coupling the Goldstone field decouples from the gauge field and the latter becomes massless. Upon these results, Higgs remarked that "as a consequence of [the coupling between scalar and gauge fields], the spin-one quanta of some of the gauge fields acquire mass; that is, the longitudinal degrees of freedom of the particles (which would be absent if their mass were zero) go over into the Goldstone bosons when the coupling tends to zero."[63] This led him to conclude that "[t]his phenomenon is just the relativistic analog of the plasmon phenomenon to which Anderson has drawn attention [in his 1963 paper]."[64]

Independently of Higgs' work[65], the SSB of the U(1) local gauge symmetry in the same Lagrangian model was examined in a joint paper by François Englert and Robert Brout. Unlike Higgs, they directly followed Schwinger's approach in his 1962 papers and offered a quantum field theoretic treatment of the SSB of the U(1) gauge symmetry by using the radiation gauge, thereby without destroying the manifest Lorentz covariance of the theory. They reached essentially the same qualitative result as Higgs did, namely, that when the conserved current of the theory couples to a gauge field, the gauge boson associated with the gauge field acquires mass as a result of SSB of gauge symmetry. [66] To this end, in particular, they calculated the vacuum polarization tensor for the gauge field as:

$$\pi_{\mu\nu}(p) = (2\pi)^4 ie^2[g_{\mu\nu} < \varphi_1 >^2 - (p_\mu p_\nu / p^2) < \varphi_1 >^2], \qquad (5)$$

[63] Higgs 1964b.
[64] Ibid.
[65] Indeed, chronologically speaking, both in terms of the receipt date by the journal and the publication date, Englert and Brout's paper preceded those of Higgs's. Englert and Brout's paper was received by *Physical Review Letters* on June 26 1964, and was published on August 31, 1964. On the other hand, Higgs' first paper was received by *Physics Letters* on July 27 in the same year, and was published on September 15, 1964. Higgs' second paper was received by *Physical Review Letters* on August 31, 1964, and it was published on October 19 in the same year. In this second paper, Higgs cited Englert and Brout's 1964 paper by footnoting that he obtained the same results as those reached by Englert and Brout. We also know that at the time Englert and Brout wrote their 1964 paper, they did not have any contact with Higgs (author's personal communication with Englert, December 19, 2009). The following passage from a recent paper by Higgs explains how he could cite Englert and Brout's paper in his second paper prior to the publication date of Englert and Brout's paper.

> My revised paper was accepted by Physical Review Letters, but the referee drew to my attention a paper which had been received a month earlier. This was the paper by Englert and Brout (based on research which had preceded mine), which discussed the 'Higgs mechanism' in much greater generality than mine had done. Our papers were somewhat complementary; Englert and Brout had studied the tree approximation to the vector field propagator in spontaneously broken gauge theories by Feynman diagram methods, whereas I had started from classical Lagrangian field theory.
> When I met Nambu for the first time twenty years later, he revealed that he had been the referee of both papers. (Higgs 2007)

[66] Englert & Brout 1964.

where $<\varphi_1>$ stands for the vacuum expectation value of one of the components of the scalar field which was added to the Lagrangian to break the symmetry, namely, $<\varphi\ >=(\varphi_1+i\varphi_2)$, with the phase chosen: $<\varphi\ >=<\varphi^*>=<\varphi_1>/\sqrt{2}$. Note that the above vacuum polarization tensor is transverse, i.e., $\pi_{\mu\nu}p_\nu=0,$ and that it has a pole at $p^2=0$. Here, while the former result means that gauge invariance is maintained after SSB, the latter indicates that, according to the result derived by Schwinger, the gauge field acquired mass. Moreover, drawing on a result previously derived by Nambu and Jona-Lasinio[67], namely, that the Goldstone boson is an intermediate state of zero mass associated with a pole at $p^2=0$ in the Ward identity, Englert and Brout concluded that, given that the massless gauge boson has no longitudinal polarization, the second—purely longitudinal—term in the above vector polarization tensor is solely due to the Goldstone boson appearing as a result of SSB of local gauge symmetry. Englert and Brout interpreted this result as pointing to a mechanism of mass-generation, according to which the Goldstone field appearing as a result of SSB of local gauge symmetry, which causes the second term in the above polarization tensor, gets absorbed into the massless gauge field; thereby lending longitudinal polarization thus mass to the gauge boson.[68]

At this point, it is also worth noting that both Higgs and Englert and Brout demonstrated that in the case of the SSB of local gauge symmetry the Goldstone fields survive in the theory as

[67] Nambu & Jona-Lasinio 1961a, 1961b.

[68] Incidentally, it is worth mentioning that, based on their work in 1964, Englert and Brout, in a joint paper with Thiry in 1966, suggested, without providing any rigorous formal proof, that the Yang-Mills theory with mass generated by SSB would be renormalizable[68]. As I shall briefly touch upon in the next section, Martinus Veltman and Gerard t' Hooft later elaborated Englert and Brout's approach, which was based on the Ward identity, to formally prove the renormalizability of the Yang-Mills theory with spontaneous symmetry breaking (See Englert et al. 1966). It is worth pointing out that even though Englert and Brout's approach was essential to the proof that the Yang-Mills theory remained renormalizable after SSB, it was not considered for renormalization by others until Veltman and t' Hooft considered it in the early seventies.

longitudinal polarization modes of massive gauge fields; thus indicating that they represent intermediate states in the vacuum polarization.

Yet, the aforementioned works by Higgs and by Englert and Brout were incomplete in important respects. Higgs's analysis of SSB was based on a classical treatment of fields. Without giving any quantum field theoretical treatment, Higgs merely conjectured that the same result would hold true also in *quantized* field theories with larger symmetry groups. Also, he did not use the Lorentz gauge that was essential to the general validity of the Goldstone theorem. Englert and Brout, unlike Higgs, offered a quantum field theoretic account of spontaneous symmetry breaking; however their treatment did not offer a complete analysis of the entire mass spectrum of the model under the SSB of the U(1) local gauge symmetry.

In a jointly written paper[69], Gerald Guralnik, Carl Hagen and Tom Kibble analyzed SSB in the model previously studied by Englert and Brout and by Higgs. Unlike Englert and Brout who calculated the vacuum polarization tensor by using the first order perturbation theory to show the massiveness of the gauge field after the SSB of local gauge symmetry, Guralnik and co-authors, like Higgs, using the variational principle, derived the field equations from the Lagrangian and thereupon concluded that "[t]he two degrees of freedom of [the gauge field] combine with [the scalar field introduced into the Lagrangian to break the gauge symmetry so as] to form the three components of a massive vector field."[70] However, again, the mass-spectrum Guralnik and co-authors derived was *incomplete*; because they had discarded the higher (than first) order interaction terms. As a result, they interpreted the mass-spectrum as consisting of a massive gauge vector boson and a massless scalar boson. However, at that time, they failed to notice that this massless particle would have had mass, if the higher order interaction terms had

[69] Guralnik et al.1964.
[70] Ibid.

been taken into account. As a result, unlike Higgs, no suggestion was made by Guralnik and co-authors that the mass generation mechanism would bring in the theory a massive scalar boson.

In a paper published in 1966, Higgs offered a *quantum field theoretic* treatment of the mass generation mechanism he had provided in his 1964b paper and substantiated all his previous results. He was finally able to demonstrate that Anderson's argument held also true in relativistic field theory; thus meaning that Anderson mechanism had a relativistic analog in quantum field theory. It is worth pointing out that Higgs also substantiated an important result that he had previously reached in his 1964b paper (see Equation (2b) and the related remarks above); namely, that the mass-generation mechanism entailed the existence of a massive scalar boson, which would later be referred to as the "Higgs boson".[71] This result means that the mass-generation mechanism solves the zero-mass problem by invoking a scalar field—later to be called the "Higgs field"—for which there is no evidence whatsoever. Moreover, the mass generation mechanism brings in an *unknown* scalar boson, associated with the postulated scalar field, for which, again, there is no evidence whatsoever. it is to be noted that while the mass generation mechanism enabled the Yang-Mills theory to get rid of the unwanted Goldstone bosons, it confronted it with another *as-yet-undetected* scalar field and an associated scalar boson.[72]

At this point, it is worth noting that even though Guralnik and co-authors reached the same result as Higgs and as Englert and Brout regarding the way the gauge field acquires mass, they did not interpret those results as contradicting the Goldstone theorem, but rather as

[71] Higgs 1966. In this paper, like Guralnik and co-authors, Higgs also asserted that the Lorentz gauge would be inconsistent with the canonical commutation rules, and as a result of this, the Higgs mechanism could not be consistently implemented in the Lorentz gauge.
[72] On July 4, 2012, CERN announced that a new particle consistent with the characteristics of the Higgs boson was detected in the ATLAS and CMS experiments; see the press release at the URL: http://press.web.cern.ch/press/PressReleases/Releases2012/PR17.12E.html

indicating its *inapplicability* in the radiation gauge.[73] Their consideration was that if the Lorentz gauge was not imposed on the Lagrangian (as in the radiation-gauge electrodynamics investigated by Higgs), then it would not possess manifest covariance which was essential to the proof of the Goldstone theorem.[74] In such a case, they argued, the existence of a local conservation law for the current of the gauge theory, i.e., $\partial_\mu J^\mu = 0$, would not *necessarily* imply the time independence of the charge $Q_i = \int J_i(\vec{x},t)\, d\vec{x}$, i.e., the global conservation of the charge, as required by the gauge principle, and this would in turn preclude the possibility of applying the Goldstone theorem. This meant, according to Guralnik and co-authors, "a departure from the assumptions of the [Goldstone] theorem, and a limitation on its inapplicability which in no way reflects on the general validity of [its] proof"[75], leading them to suggest that the mass generation mechanism would not be said to have solved the mass-problem if it were to be implemented in the radiation gauge. They also contended that the mass-generation mechanism would not be consistently implemented in the Lorentz gauge, as the canonical commutation relations would be inconsistent with the Lorentz gauge.

This important step was taken up by Kibble in a paper[76] published in 1967, where he re-considered the Lagrangian model previously examined by Higgs, by Englert and Brout and by Guralnik and co-authors. Kibble established two main points. First, contrary to the previous assertions made by both Higgs and Guralnik and co-authors, he demonstrated that quantum field theory allowed the mass generation mechanism to be consistently implemented also in the Lorentz gauge formalism with results identical to those obtained in the radiation gauge

[73] Guralnik et al. 1964.
[74] Goldstone et al. 1962.
[75] Guralnik et al. 1964.
[76] Kibble 1967.

formalism. Second, Kibble considered the same Lagrangian model for an arbitrary non-Abelian gauge group of arbitrary dimensions and demonstrated that the mass-generation mechanism was generalizable to models having non-Abelian gauge groups. In particular, Kibble mathematically demonstrated:

> If all the currents associated with a broken non-Abelian symmetry group are coupled to gauge vector fields, the number of massless vector bosons remaining in the theory is just the dimensionality of the subgroup of *unbroken* symmetry transformations. In particular, if there are no unbroken components of the symmetry group, then no massless particles remain.[77]

Given that the gauge symmetry group SU(2) associated with weak interactions was non-Abelian, the above result was crucial in that it indicated the possibility that the mass generation mechanism could also serve to solve the zero-mass problem standing in the way of a unified field theory of electromagnetic and weak interactions. This was how things stood in 1967, and now the challenge was to construct a realistic model of electromagnetic and weak interactions on the basis of the mass generation mechanism.

5. Weinberg's formulation of the electroweak theory

Soon after the publication of Kibble's paper, the idea that gauge fields might acquire mass through the mass-generation mechanism without destroying gauge invariance was taken up by Weinberg in a paper published in 1967 to construct a unified field theory of electromagnetic and weak interactions.[78] The opening paragraph of this now seminal three-page paper indicates the

[77] Ibid.
[78] Weinberg 1967.

chief difference between the approaches of Glashow and Weinberg to the unification of electromagnetic and weak interactions:

> Leptons interact only with photons, and with the intermediate boson that presumably mediate weak interactions. What could be more natural than to unite these spin-one bosons into a multiplet of gauge fields? Standing in the way of this synthesis are the obvious differences in the masses of the photon and intermediate [vector bosons], and in their couplings. We might hope to understand these differences by imagining that the symmetries relating the weak and electromagnetic interactions are exact symmetries of the Lagrangian but are broken by the vacuum. However, this raises the specter of unwanted massless Goldstone bosons. This note will describe a model in which the symmetry between the electromagnetic and weak interactions is spontaneously broken, but in which the Goldstone bosons are avoided by introducing the photon and intermediate-boson fields as gauge fields. [79]

Unlike Glashow who believed that "[partial symmetry] is the only sort of symmetry which could relate the massive IVBs to the massless photon"[80], Weinberg was convinced that the Lagrangian of a gauge theory that would represent both electromagnetic and weak interactions should remain *exactly* gauge invariant in order for its renormalizability not to be destroyed. In this sense, Weinberg viewed the mass generation mechanism to be the right tool that would establish the link between the vector fields associated with the electromagnetic and weak interactions.[81] Therefore, Weinberg's had a two-step proposal: the first step involved the determination of a gauge group that is relevant to both weak and electromagnetic interactions, and accordingly, the

[79] Ibid.
[80] Glashow 1961.
[81] The difference between the coupling strengths of the electromagnetic and weak interactions is due to the empirical fact that the IVBs are massive, while the photon is massless.

second step consisted of the formulation of a Lagrangian with exact gauge symmetry and of the SSB of this exact symmetry via the mass-generation mechanism.

With respect to the first step above, Weinberg considered exactly the same gauge group—namely, $SU(2)_L \times U(1)_h$—Glashow used in his 1961 paper. Again like Glashow, he considered only the *electron-type* leptons and, for their mathematical representations, he constructed a left-handed doublet: $L = [\frac{1}{2}(1+\gamma_5)]\begin{pmatrix}\nu_e \\ e\end{pmatrix}_L$, which consists of a left-handed neutrino and a left-handed electron, and a right-handed singlet: $R = [\frac{1}{2}(1-\gamma_5)]e_R$, which consists of a right-handed electron. Weinberg noted that neither $SU(2)_L$ symmetry nor $U(1)_h$ symmetry and thus the compound $SU(2)_L \times U(1)_h$ symmetry remained *entirely* unbroken in nuclear interactions, and that the only "unbroken" gauge symmetry (also called "exact" symmetry) was the U(1) gauge symmetry of electromagnetism representing the conservation of the electronic charge in nuclear interactions. Hence, what Weinberg needed was a SSB of the compound symmetry $SU(2)_L \times U(1)_h$ down to $U(1)_{em}$, i.e., the electromagnetic U(1) gauge group. With respect to the second step stated above, Weinberg considered the following Lagrangian which is symmetric under the chosen gauge group:

$$
\begin{aligned}
L = &-\frac{1}{4}(\partial_\mu \vec{A}_\nu - \partial_\nu \vec{A}_\mu + g\,\vec{A}_\mu \times \vec{A}_\nu)^2 - \frac{1}{4}(\partial_\mu B_\nu - \partial_\nu B_\mu)^2 - \bar{R}\gamma^\mu(\partial_\mu - ig' B_\mu)R \\
&- L\gamma^\mu(\partial_\mu ig\,\vec{t} \bullet \vec{A}_\mu - \frac{i}{2}g' B_\mu)L - \frac{1}{2}\left|\partial_\mu \varphi - ig\vec{A}_\mu \bullet \vec{t}\,\varphi + \frac{i}{2}g' B_\mu \varphi\right|^2 \\
&- M_1{}^2 \varphi^* \varphi + h(\varphi^* \varphi)^2 - G_e(\bar{L}\varphi R + \bar{R}\varphi^* L)
\end{aligned}
\tag{6}
$$

The first two terms in the above Lagrangian describe the interactions due to gauge fields which, following Glashow's proposal in his 1961 paper, Weinberg introduced as

$\vec{A}_\mu = (A_\mu^1, A_\mu^2, A_\mu^3)$ and B_μ. Here, the former three correspond to the generators of SU(2)L and the latter to that of U(1)h, and while and are respectively taken to be respectively positively and negatively charged, andare taken to be both electrically neutral. Also, note that at this level vector fields are all massless, as required by the gauge principle. The third and fourth terms concern the interactions between leptons and gauge bosons. The fifth term reflects the idea of spontaneous symmetry breaking, and it represents the coupling between gauge fields and scalar field φ (often referred to as the "Higgs field"), which is represented by a spin-zero doublet:

$\varphi = \begin{pmatrix} \varphi^0 \\ \varphi^- \end{pmatrix}$, and which Weinberg added to the Lagrangian in order to generate the spontaneous breakdown of SU(2)L x U(1)h symmetry down to U(1)em.[82] The sixth and seventh terms are the potential terms associated with the Higgs scalar field. And, the final term, which describes "Yukawa coupling" between leptons and the Higgs field, was added to the Lagrangian by Weinberg to generate the electron mass.

An important technical feature of the Lagrangian Weinberg considered was that it could be re-organized by making the following identification, which had already been used by Glashow in his 1961 theory. Namely, the fields A_μ^1 and A_μ^2 can be linearly superposed so as to yield the following positively and negatively (electromagnetically) charged fields: $W_{\mu\pm} = \frac{1}{\sqrt{2}}(A_\mu^1 \pm iA_\mu^2)$. Similarly, A_μ^3 and B_μ can be linearly superposed so as to yield the following neutral spin-one fields: $Z_\mu = \left(1/\sqrt{g^2 + g'^2}\right)(gA_\mu^3 + g'B_\mu)$ and $A_\mu = \left(1/\sqrt{g^2 + g'^2}\right)(-g'A_\mu^3 + gB_\mu)$, where g and g' stand respectively for the coupling

[82] The scalar field Weinberg added to the Lagrangian was a scalar doublet in the form *Ø=(Ø0, Ø-).*

constants of the fields $\vec{A}_\mu$ and B_μ.[83] It is possible to recast these relations into the following forms: $A_\mu^3 = A_\mu sin\theta + Z_\mu cos\theta$ and $B_\mu = A_\mu cos\theta - Z_\mu sin\theta$, where $sin\theta = g'/\sqrt{g^2 + g'^2}$ and $sin\theta = g/\sqrt{g^2 + g'^2}$, and θ is known in the physics literature as the "Weinberg angle", or the "weak mixing angle"[84]; because it represents the "mixing" of the electromagnetic and weak gauge fields.[85]

The next step, in accordance with the mass-generation mechanism, was to "break" the gauge symmetry of the Lagrangian and generate masses for gauge bosons. To this end, Weinberg fixed the vacuum expectation of the so-called "Higgs field" to a non-vanishing value: $\varphi = \lambda\begin{pmatrix}1\\0\end{pmatrix}$, where λ is a constant. As a result of SSB, the first four terms of the Lagrangian remain unchanged, while the rest takes the following form:

$$-\frac{1}{8}\lambda^2 g^2[(A_\mu^1)^2 + (A_\mu^2)^2] - \frac{1}{8}\lambda^2(gA_\mu^3 + g'B_\mu)^2 - \lambda G_e\bar{e}e \tag{7}$$

Note that the resulting Lagrangian differs from the original one only by terms quadratic in fields; indicating that vector fields have acquired mass as a result of SSB. The last term above indicates that the electron has acquired a mass of λG_e. By using the above identifications, one can observe that the first term above can be written as: $(\lambda g/2)^2\, W_\mu^+\, W_\mu^-$, indicating that the field $W_\mu^\pm$ has acquired a mass of $M_{W_\mu^\pm} = \lambda g/2$. Similarly, the middle term above can be put into the form:

---

83 Here, "A_μ" is a newly introduced vector field and should not be confused with the field $\vec{A}_\mu = (A_\mu^1, A_\mu^2, A_\mu^3)$ associated with the generators of SU(2)L.

84 In fact, such a "mixing" angle was first introduced by Glashow in his 1961.

85 Note that in the original paper Weinberg did not use the above notation, which seemed to me more appropriate here to state the experimental predictions of Weinberg's theory.

$\lambda'^2/4\ (g^2+g'^2)\,Z_\mu Z_\mu$, indicating that the Z_μ field has acquired a mass of M_{Z_μ} = $(\lambda/2)\sqrt{g^2+g'^2}$. By using the above relations, it is easy to see that $M_Z = M_W/cos\theta$. In the resulting Lagrangian, there is no term quadratic in the field A_μ , meaning that, unlike the fields $W_\mu^\pm$ and Z_μ , the field A_μ did not acquire mass as a result of the SSB of local gauge symmetry. Weinberg identified the field A_μ to be the photon field, as this was empirically known to be the only massless gauge field.

At this point, it is to be noted that in order to be able to derive testable results from the above mass terms, one needs to specify the numerical values of the coupling constants. To this end, Weinberg considered the part of the final Lagrangian that corresponded to the *charged* interaction between leptons and gauge bosons. By substituting Fermi's weak-interaction coupling constant G_F for g, Weinberg equated the low-energy limit of that interaction term to that of the V-A theory, which had been experimentally well confirmed in that regime. This yielded the numerical value of the expectation value of the Higgs field as λ ~ 246 GeV. Note that the electroweak theory does not determine the mass of the associated scalar boson, which has come to be referred to as the "Higgs boson".

Subsequently, Weinberg considered the part of the final Lagrangian that corresponded to the *neutral* interaction between leptons and gauge bosons. Picking up the particular term that represented the coupling of the electromagnetic current with the photon field A_μ, Weinberg identified—as should be done according to quantum electrodynamics—the constant in front of that particular term, namely $g\ sin\theta$, as the electronic charge *e*. In this way, Weinberg was able to relate the coupling constants of the fields $\vec{A}_\mu$ and B_μ to the electric charge *e* through the

Weinberg angle, namely, $e = g\, sin\theta = g'\, cos\theta$. These also enabled Weinberg to establish the numerical values of the masses of the IVBs as: $M_W = 38.5/sin\theta$ GeV, and $M_Z = M_W/cos\theta$. Note that, as in Glashow's 1961 theory, the existence of weak neutral currents is also predicted by Weinberg's theory. It is also to be recalled from the previous discussion that in Glashow's theory the masses of IVBs mediating weak interactions were left *arbitrary*. In this respect, Weinberg's theory gives more definite predictions; in his theory the masses of the IVBs were also predicted. But all quantitative predictions were dependent upon the exact determination of the numerical value of the Weinberg angle.

Summarizing the above considerations, there are two essential ingredients in Weinberg's electroweak theory. The first is the SU(2)xU(1) group structure that underlies the theoretical structure of the electroweak theory; it mathematically represents the weak and electromagnetic interactions of leptons. Note that in quantum field theories of Yang-Mills type it is the gauge symmetry group that completely fixes the number of gauge fields as well as their associated vector bosons responsible for mediating the interactions between elementary particles, thereby determining the dynamics of interactions through the Lagrangian. Therefore, one can regard the compound symmetry group SU(2)xU(1) to be the theoretical element that lends unifying power to Weinberg's theory. It determines a common dynamics for the weak and electromagnetic interactions of leptons, as opposed to distinct and separate gauge symmetry groups associated with different field dynamics.

The second essential ingredient of the electroweak theory is the mass-generation mechanism that accounts for how the IVBs acquire mass, while the photon remains massless. Recall that in Glashow's theory, this is in no way explained. In this theory, the mass terms for the IVBs are put into the Lagrangian by "hand" and this procedure leaves the masses of the IVBs totally *arbitrary*. It also destroys gauge invariance and thus renormalizability of the gauge theory. By contrast, in Weinberg's theory, why the IVBs are massive while the photon is not is explained by the mass-generation mechanism; according to which, the IVBs acquire mass through interaction with the Higgs field, but the photon does not undergo an interaction with the Higgs field and as a result it stays massless. Again, contrary to Glashow's theory, in Weinberg's theory, the masses of the IVBs are not arbitrary but rather *constrained* by the way their corresponding gauge fields interact with the Higgs field; the masses acquired by the IVBs are determined by the interactions they undergo with the Higgs field. This suggests that it is primarily the mass-generation mechanism that lends to Weinberg's theory both the explanatory and predictive powers, which Glashow's theory lacks. However, what is left unexplained in Weinberg's theory is the origin of the Higgs field that is necessary for the mass-generation mechanism. Let me note in passing that this aspect of Weinberg's theory has been sharply criticized over the years by both physicists and philosophers of science.[86]

Before I close this section, I would like to mention that the issue of renormalization was left open in Weinberg's 1967 paper. Towards the end of this paper, Weinberg briefly alluded to this issue and remarked:

> Is this model renormalizable? We usually do not expect non-Abelian gauge theories to be renormalizable if the vector-meson mass is not zero, but our Z_μ and W_μ mesons get their mass from the spontaneous breaking of the symmetry, not from a mass term put in at the beginning.[87]

Weinberg's theory did not attract much attention from the relevant physics community until t' Hooft, in 1971, proved that gauge theories of Yang-Mills-type were renormalizable, not only

[86] See X, for a discussion of these criticisms (the reference for this work is suppressed for "peer review").
[87] Weinberg 1967.

with massless fields[88] but also with massive fields in which gauge bosons acquire mass through the mass generation mechanism.[89] This motivated Weinberg to derive the experimental consequences of his theory concerning weak-neutral currents. Soon after t' Hooft's renormalization proof, in 1972, Weinberg published a paper predicting the expected amount of neutral-current types of events in semi-leptonic processes.[90] These developments, especially the renormalizability proof, aroused great interest among the experimental high energy physicists[91]; because renormalizability for a quantum field theory means that it is free of any unphysical divergences that make all of its existing predictions worthless.[92]

The aforementioned predictions of Weinberg's theory were tested throughout the years. First, its prediction concerning the weakly interacting neutral currents was tested and confirmed by Hasert et al. in the now famous "Gargamelle" experiment at CERN in 1973.[93] Second, the Weinberg angle was measured throughout the years by using different techniques in a number of experiments[94] with improved accuracy, and its numerical value was established as 30°, according to which Weinberg's theory yielded the masses of the IVBs as $M_W \sim 80$ GeV and $M_Z \sim 91$ GeV. *W* and *Z* bosons were detected in the first "underground experiments" UA1 and UA2 conducted in 1982-1983 at CERN[95], and their masses were measured quite close to the values predicted by Weinberg's theory. The electroweak theory's prediction concerning the Higgs field and the

---

[88] 't Hooft 1971a.
[89] 't Hooft 1971b. Note also that a more elaborate proof of the renormalizability of the Yang-Mills theory was later provided by Veltman and t' Hooft in a joint paper published in 1972; see t' Hooft & Veltman 1972.
[90] Weinberg 1972
[91] As mentioned in Galison 1987, this is also illustrated in the rapid increase in the number of citations Weinberg's 1967 paper received during the years 1967 to 1971: 1967, 0; 1968, 0; 1969, 1 (not 0 as incorrectly given in Galison 1987, as well as in Coleman 1979 to which Galison refers), 1970, 1; 1971, 4; 1972, 64; 1973, 162. As in Coleman 1979 and Galison 1987, the "Science Citation Index" data are used in the present paper.
[92] See especially Pickering 1984 and Galison 1987 for a detailed historical treatment of the reception of the electroweak theory by the experimental physics community and of the period during which its predictions were tested.
[93] Hasert et al.1973.
[94] For instance, Prescott et al. 1978, and Fanchiotti & Sirlin 1990.
[95] Arnison et al. 1983.

associated Higgs scalar boson is currently under test in the Large Hadron Collider (LHC) experiments conducted at CERN.[96]

6. Conclusions: A Comparative Assessment of the Contributions Leading to the Construction of the Mass-Generation Mechanism

In this final section, by taking stock of the previous conclusions, I shall offer a comparative analysis of the works that contributed to the construction process of the mass-generation mechanism. The first point I shall point out is that the historical process in question was guided by analogies drawn to the theories of solid-state physics, namely, the BCS theory of superconductivity and the free-electron gas theory. The previous discussion has shown that the incorporation of SSB as a method of mass-generation mechanism into the theoretical framework of relativistic quantum field theory was conducive to the solution of the zero-mass problem of the Yang-Mills theory. Remember that this incorporation process was achieved through a model of elementary particles (i.e., of nucleons and mesons) that was constructed jointly by Nambu and Jona-Lasinio within the context of relativistic quantum field theory on the basis of an analogy drawn to the "energy gap" structure in the BCS theory of superconductivity. This analogy, which I shall call the "superconductivity analogy", states that the way nucleons and mesons acquire mass can be accounted for in relativistic quantum field theory by a mechanism of SSB analogous to the one that leads to the formation of energy gap in the BCS theory of superconductivity. This indicates that the content of the superconductivity analogy has an important "heuristic" value in the sense that it underscores the significance of SSB for the zero-mass problem of the Yang-Mills theory. A similar view was also expressed by Jona-Lasinio as follows: "The strict analogy with BCS made the physical mechanism leading to the spontaneous symmetry breaking quite

[96] For details, see Quigg 2008 and references therein.

transparent and [it] was understood by the elementary particle [physics] community."[97] It is to be noted here that by way of the superconductivity analogy the method of SSB already used in solid-state physics was transferred into the context of particle physics and used as a method to solve a conceptual problem—namely, the zero-mass problem—for which it was not originally designed. These and previous considerations suggest that Nambu's work and his joint work with Jona-Lasinio played a crucial role, albeit indirect, in the construction of the mass-generation mechanism in that they provided SSB with a quantum field theoretical foundation and thereby elucidated its significance for the solution of the zero-mass problem of the Yang-Mills theory.

Schwinger (1962) deserves to be credited with being the first to anticipate the key idea underlying the mass-generation mechanism, namely, that gauge bosons could acquire mass through sufficiently strong current-gauge field coupling. However, Anderson's 1963 paper, which relied on Schwinger's 1962 paper, made the first concrete proposal for the solution of the zero-mass problem of the Yang-Mills theory. Remember that the zero-mass problem is a two-fold problem; one aspect concerns how to give mass to gauge bosons through SSB in a way consistent with the gauge principle, and the other aspect concerns how to eliminate from the gauge theory the undesirable Goldstone bosons resulting from SSB. As the above discussion has shown, Anderson recognized that, under the condition of strong current-vector field coupling suggested by Schwinger, the above seemingly contradictory aspects of the zero-mass problem were indeed reconcilable and would cure each other in the Yang-Mills theory.

We have seen that Anderson drew on an analogy to the treatment of the Meissner effect by the free-electron gas theory to illustrate Schwinger's claim that under the condition of sufficiently strong current-gauge field coupling the Goldstone zero-mass difficulty would be

[97] Jona-Lasinio 2002.

evaded in the Yang-Mills theory in the same way it was evaded in the treatment of the Meissner effect by the free-electron gas theory. That is to say, Anderson's argument by analogy suggested that the pattern of explanation offered by the free-electron gas theory with regard to the Meissner effect—namely, that under sufficiently strong current-gauge field coupling the Goldstone and the Yang-Mills gauge bosons combine so as to become massive particles—would hold true also in cases of the Goldstone zero mass difficulty in particle physics. We have seen that this analogy was pursued by Higgs to demonstrate that the mechanism Anderson had suggested in solid-state physics had a counter-part in relativistic quantum field theory. Therefore, by means of the analogy drawn to the free-electron gas theory, an explanation pattern already used in solid-state physics was adapted into quantum field theory to solve an analogous difficulty in particle physics.

Remember that, in quantum field theory, a *globally* symmetric free field Lagrangian (i.e., symmetric under global gauge transformations) can be turned into a *locally* symmetric one (i.e., symmetric under local gauge transformations) by coupling its conserved current to a gauge field.[98] Therefore, Anderson's suggestion in his 1963 paper can be taken to point out that the massless Goldstone bosons can be evaded by promoting global invariance to local gauge invariance by way of coupling to the conserved current. This is exactly the point where the focus in the debate concerning the status of the Goldstone theorem shifted from global symmetry to local symmetry and thus to the SSB of the latter in the Yang-Mills theory. As has been discussed earlier, the physicists who followed Schwinger's and Anderson's suggestions investigated the validity of the Goldstone theorem and sought for a solution of the zero-mass problem within the context of elementary particle models exhibiting SSB of *local* gauge symmetry.

[98] See Cheng & Li 1984, sect. 8.1.

We know from the earlier discussion that during the course of the solution of the zero-mass problem of the Yang-Mills theory Schwinger's and Anderson's suggestions were first appreciated and taken up at around the same time by Higgs and by Englert and Brout. The discussion in the previous section has revealed that these physicists followed different routes to reach the same qualitative result; namely, that as a result of SSB of local gauge symmetry in a Lagrangian where the gauge field is coupled to a conserved current the otherwise massless gauge field acquires mass. While Higgs' approach was based on the variational principle for the derivation of the field equations associated with the mass spectrum of the Lagrangian after SSB, Englert and Brout's approach was based on the (first-order) perturbation theory for the derivation of the vector polarization tensor as well as the Ward identity associated with the gauge field after SSB.

There was yet another important difference between the approaches taken by Higgs and by Englert and Brout. In their 1964 paper, Englert and Brout investigated whether gauge quanta could acquire mass through SSB of *local* gauge symmetry under the condition of sufficiently strong current-vector field coupling. Their most important achievement in this paper was that they showed how the zero-mass problem would be solved through the mass-generation mechanism and that this mechanism required a *synthesis* of the gauge principle with the concept of SSB through current-gauge vector coupling. As has been mentioned earlier, they showed for the first time that the Goldstone boson field appearing as a result of SSB could be conceived as constituting the longitudinal polarization mode of the gauge field and thereby providing the associated gauge boson with mass without destroying the gauge invariance of the theory. On the other hand, in Higgs' 1964a paper, we do not see such a synthesis yet; rather, in this paper, Higgs speaks of how the Goldstone bosons would be avoided in the radiation gauge under the sufficiently strong coupling condition, and in this sense he does not, at least directly, address the zero-mass problem, i.e., how to explain the way gauge bosons acquire mass in the Yang-Mills theory. It is only in his 1964b paper that Higgs tackles this problem and is able to show that under the condition of sufficiently strong current-vector coupling not only the Goldstone theorem would be avoided but also vector bosons would acquire mass through SSB of local gauge symmetry in a way consistent with the gauge principle. That is to say, it is only in his 1964b paper that Higgs established the aforementioned synthesis that would lead him to the construction of the mass-generation mechanism. Moreover, in this paper, as has been previously discussed, Higgs, for the first time, put forward *unequivocally* the prediction that one of the consequences of the mass-generation mechanism would be a massive scalar boson, which is today referred to as the "Higgs boson." This is an important feature of the mass-generation mechanism that lacks in Englert and Brout's 1964 paper as well as in Guralnik and co-authors's 1964 paper.

No doubt, Englert and Brout's 1964 paper and Higgs' 1964 and 1966 papers hold a very important place in the construction process of the mass-generation mechanism. However, two key contributions made possible the general application of the Higgs mechanism in quantum field theory. The first was Guralnik and co-authors' two-fold contribution that involved: first, the derivation of, albeit incomplete, the mass-spectrum associated with the mass generation mechanism, and, more importantly, second, the recognition that the mass generation mechanism formulated in the radiation gauge would violate the global conservation law and thus the gauge principle—which is essential to the Goldstone theorem; indicating that it would not serve to evade the consequence of the Goldstone theorem. Therefore, Guralnik and co-authors' work was important especially for clarifying the *theoretical* implications of the mass-generation mechanism that pertained to the Goldstone theorem, and thus for revealing the necessity of a *manifestly* covariant formulation of this mechanism if it were to solve the zero-mass problem in a way consistent with the gauge principle.

The second key contribution was Kibble's three-fold contribution that consisted of the mathematical demonstration of: (1) the consistency of the mass-generation mechanism with the Lorentz-gauge, and thus with manifest covariance; (2) the generalization of the mechanism to Lagrangian models with *non-Abelian* gauge groups; and (3) the derivation of the pattern of SSB underlying the mass-generation mechanism and its relation to the mass-spectrum. It is to be noted here that both Higgs and Guralnik and co-authors had dismissed (1); and (2) and (3) had not been investigated before. The significance of Kibble's contribution lies in that it established for the mass-generation mechanism a general quantum field-theoretic framework that was necessary for its general applicability to a wide range of Lagrangian models over and above the U(1) toy model of electrodynamics previously considered by Higgs, by Englert and Brout as well as by Guralnik and co-authors. In this respect, as has been discussed in the previous section, Kibble's contribution also paved the way to the construction of the electroweak theory.

The discussion in this final section suggests that no single work *by itself* was sufficient to establish all the essential features of the mass-generation mechanism in its full generality. Rather, it suggests a historical process of theoretical construction during which different contributions complement each other while exhibiting rather diverse approaches to the construction of the mechanism. Hence, rather than suggesting a "true father" for the mass-generation mechanism of the Yang-Mills theory, the discussion in this paper allows us to regard it as the joint product of a number of contributions from different physicists during the years between 1962 and 1967.

References

Aitchison I. J. R. and Hey A. J. G. (2003): *Gauge Theories in Particle Physics*, Bristol: Adam Hilger.

Anderson P.W., (1963): “Plasmons, Gauge Invariance, and Mass”, *Physical Review*, 130:439.

Arnison G. et al., (1983): “Experimental-Observation of Isolated Large Transverse Energy Electrons with Associated Missing Energy at Square-Root-S=540 GeV”, *Physics Letters B*, 122:103.

Baker M., and Glashow S.L., (1962): “Spontaneous Breakdown of Elementary Particle Symmetries”, *Physical Review*, 128:2462.

Bardeen J. et al., (1957): “Theory of Superconductivity”, *Physical Review*, 108:1175.

Bogoliubov, N. N., (1958): “A new method in the Theory of Superconductivity I”, *Soviet-Physics JETP*, 7:41.

Brout R. and Englert F., (1999): “Spontaneous Symmetry Breaking in Gauge Theories: a Historical Survey”, in *Proceedings of the International Europhysics Conference on High Energy Physics*, Jerusalem, Israel, 19-25 August. 1997, edited by D. Lellouch D. et al., Springer, Berlin.

Brown L. M. and Cao T.Y., (1991): “Spontaneous Breakdown of Symmetry: Its Rediscovery and Integration into Quantum Field Theory”, *Historical Studies in the Physical and Biological Sciences*, 21: 211.

Brown H. R. and Harre R., (eds.), (1988): *Philosophical Foundations of Quantum Field Theory*, Oxford: Clarendon.

Byrne N., et al., (1965): “Breakdown of Unitary Octet Symmetry in a NonLinear Spinor Model of Elementary-Particle Theory”, *Physical Review*, 139B:918.

Cao T. Y. and Schweber S. S., (1993): "The Conceptual Foundations and Philosophical Aspects of Renormalization Theory", *Synthese*, 97:33.

Cao T. Y., (1997): *Conceptual Developments of Twentieth Century Field Theories*, Cambridge University Press.

________ (1999): *Conceptual Foundations of Quantum Field Theory*, Cambridge University Press.

_________ (2010): *From Current Algebra to Quantum Chromodynamics: A Case for Structural Realism*, Cambridge University Press.

Castellani E., (2003): “On the meaning of symmetry breaking”, in K. A. Brading and E. Castellani (eds.), *Symmetries in Physics: Philosophical Reflections*, p. 321, Cambridge: Cambridge University Press.

Cheng T. and Li L., (1984): *Gauge Theory of Elementary Particle Physics*, Oxford University Press.

Coleman S., (1979): “Nobel Prize”, *Science*, 206:1290.

Darden L. and Maull L (1977): “Interfield Theories”, *Philosophy of Science* 44:43.

Earman J., (2003): “Rough guide to spontaneous symmetry breaking”, in *Symmetries in Physics: Philosophical Reflections*, edited by Brading K. and Castellani E., p. 335, Cambridge University Press.

_________ (2004a): “Curie's principle and spontaneous symmetry breaking”, *International Studies in the Philosophy of Science* 18:173.

_________ (2004b): “Laws, symmetry, and symmetry breaking: Invariance, conservation principles, and objectivity”, *Philosophy of Science* 71:1227.

Englert F. and Brout R., (1964): “Broken Symmetry and Mass of Gauge Vector—Mesons”, *Physical Review Letters*, 13:321.

Englert F., et al., (1966): “Vector Mesons in Presence of Broken Symmetry”, *Il Nuovo Cimento*, 43A:244.

Feynman R.P. and Gell-Mann M. (1958): “Theory of the Fermi Interaction”, *Physical Review*, 109:193.

Fanchiotti S. and Sirlin A., (1990): “Accurate Determination of Sin 2-Theta-W()”, *Physical Review D*, 41:319.

Galison P., (1987): *How Experiments End*, University of Chicago Press.

Gell-Mann M., (1956): “The Interpretation of the New Particles as Displaced Charged Multiplets”, *Il Nuovo Cimento*, 4:848.

Gilbert W., (1964): “Broken Symmetries and Massless Symmetries”, *Physical Review Letters*, 12:713.

Glashow S. L., (1959): “The Renormalizability of Vector Meson Interactions”, *Nuclear Physics*, 10:107.

___________ (1961): “Partial Symmetries of Weak Interactions”, *Nuclear Physics*, 22:579.

Goldstone J., (1961): “Field Theories with Superconductor Solutions”, *Nuovo Cimento*, 19:154.

Goldstone et al., (1962): “Broken Symmetries”, *Physical Review*, 127:965.

Guay A., (2008): “A Partial Elucidation of the Gauge Principle”, *Studies in History and Philosophy of Modern Physics*, 39:346.

Guralnik G. S., et al., (1964): “Global Conservation Laws and Massless Particles”, *Physical Review Letters*, 13:585.

________________ (1968): “Broken Symmetries and the Goldstone Theorem,” in *Advances in Particle Physics*. Vol. 2, edited by Cool R. L. and Marshak R. E., New York: Interscience, p. 567.

Hasert, F. J. et al., (1973): “Observations of Neutrino-Like Interactions without Muon or Electron in Gargamelle Neutrino Experiment”, *Physics Letters B*, 46: 138.

Healey R., (2007): *Gauging what's real: the conceptual foundations of contemporary gauge theories*, Oxford University Press.

Higgs P., (1964a): “Broken Symmetries, Massless Particles and Gauge Fields”, *Physics Letters*, 12:132.

_______ (1964b): “Broken Symmetries and Masses of Gauge Bosons”, *Physical Review Letters*, 13:508

_______ (1966): “Spontaneous Symmetry Breakdown without Massless Bosons”, *Physical Review*, 145:1156.

_______ (2007): “Prehistory of the Higgs boson”, *Comptes Rendus de Physique*, 8:970.

Huggett N., (2002): “Renormalization and the Disunity of Science”, in *Ontological Aspects of Quantum Field Theory*, edited by Kuhlmann M., et al., World Scientific Publishing.

Jona-Lasinio G., (2002) “Cross Fertilization in Theoretical Physics: the Case of Condensed Matter and Particle Physics”, *Highlights of Mathematical Physics*, edited by Fokas A., et al., p. 143, published by American Mathematical Society.

Kamefuchi, S., (1960): “On Salam’s Equivalence Theory in Vector Meson Theory”, *Nuclear Physics*, 18:691.

Kibble T. W. B., (1967): “Symmetry Breaking in Non-Abelian Gauge Theories”, *Physical Review*, 155:1554.

Kittel C., (2005): *Introduction to Solid State Physics*, Wiley.

Klein A. and Lee B.W., (1964): “Does Spontaneous Breakdown of Symmetry Imply Zero-Mass Particles”, *Physical Review Letters*, 12:266.

Komar, A., and Salam A., (1960): “Renormalization problem for vector meson theories”, *Nuclear Physics*, 21:624.

Kosso P., (2000): “The Epistemology of Spontaneously Broken Symmetries”, *Synthese*, 122:359.

Kuhlmann M. et al., (eds.), (2002): *Ontological Aspects of Quantum Field Theory*, World Scientific Publishing.

Lee T.D. and Yang C.N. (1956): “Parity Nonconservation and a Two-Component Theory of the Neutrino”, *Physical Review*, 104:254.

____________________ (1960): “Implications of the Intermediate Boson Basis of the Weak Interactions: Existence of a Quartet of Intermediate Bosons and Their Dual Isotopic Spin Transformation Properties”, *Physical Review*, 119:1410.

Liu, C., (2003): “Spontaneous symmetry breaking and chance in a classical world”, *Philosophy of Science* 70: 590.

Liu, C., and Emch G. G., (2005): “Explaining quantum spontaneous symmetry breaking”, *Studies in History and Philosophy of Modern Physics* 36: 137.

Lyre H., (2001): “The Principles of Gauging”, *Philosophy of Science*, 68:S371

________(2008): “Does the Higgs Mechanism Exist?”, *International Studies in the Philosophy of Science* 22: 119.

Marshak R. and Sudarshan G., (1958): “Chirality Invariance and the Universal Fermi Interaction”, *Physical Review*, 109:1860.

Martin C., (2002): "Gauge Principles, Gauge Arguments and the Logic of Nature", *Philosophy of Science*, 69:S221.

Maudlin T., (1996): “On the unification of physics”, *Journal of Philosophy* 93:129.

Meissner W. and Ochsenfeld R., (1933):"Ein neuer Effekt bei Eintritt der Supraleitfähigkeit". *Naturwissenschaften*, **21**: 787–788
Moriyasu K., (1983): *An Elementary Primer for Gauge Theory*, World Scientific: Singapore.

Morrison M., (2003): “Spontaneous Symmetry Breaking: theoretical arguments and philosophical problems”, in *Symmetries in Physics: Philosophical Reflections*, edited by Brading K. and Castellani E., p. 347, p. 3, Cambridge: Cambridge University Press.

Moriyasu K., (1983): *An Elementary Primer for Gauge Theory*, World Scientific: Singapore.

Nakano, T. and Nishijima, N., (1953): “Charge Independence for V-particles”, *Progress of Theoretical Physics*, 10:581.

Nambu Y., (1960a): “Quasi-Particles and Gauge Invariance in the Theory of Superconductivity”, *Physical Review*, 117:648.

_________ (1960b): “Axial Vector Current Conservation in Weak Interactions”, *Physical Review Letters*, 4:380.

_________ (2009): “Nobel Lecture: Spontaneous symmetry breaking in particle physics: A case of cross fertilization”, *Review of Modern Physics*, 81:1015.

Nambu, Y., and Jona-Lasinio G., (1961a): “Dynamical Model of Elementary Particles based on an analogy with Superconductivity I”, *Physical Review*, 122:345.

___________________________ (1961b): “Dynamical Model of Elementary Particles based on an analogy with Superconductivity II”, *Physical Review*, 124:246.

Nozieres P. and Pines D., (1958): “Electron Interaction in Solids. General Formulation”, *Physical Review*, 109:741.

Peskin M.E. and Schroeder D.V., (1995): *An Introduction to Quantum Field Theory*, Westview Press.

Pickering A., (1984): *Constructing quarks: a sociological history of particle physics*, University of Chicago Press: Chicago.

Prescott C.Y. et al., (1978): “Parity Non-Conservation in Inelastic Electron-Scattering”, *Physical Letters B*, 77:347.

Struyve W., (2011): “Gauge Invariant Accounts of the Higgs Mechanism”, *Studies in History and Philosophy of Modern Physics*, 42: 226-236

Quigg C., (2008): “The Coming Revolutions in Particle Physics”, *Scientific American*, February, 46.

Salam, A., (1960): “An equivalence theorem for partially gauge–invariant vector meson interactions”, *Nuclear Physics*, 18:681.

_________ (1962): “Renormalizability of gauge theories”, *Physical Review*, 127:331.

_________ (1968): “Weak and electromagnetic interactions”, in *Elementary Particle Theory: Relativistic Groups and Analyticity (Nobel Symposium No. 8)*, edited by N. Svartholm (Almquist and Wiksell, Stockholm), p. 367.

Salam, A., and Ward J.C., (1964): “Electromagnetic and Weak Interactions”, *Physics Letters*, 13:168.

Salmon, W.C., (1989) *Scientific Explanation and the Causal Structure of the World,* Princeton, NJ: Princeton University Press.

Schweber, S. (1994): *QED and the Men Who Made It*, Princeton University Press.

Schwinger, J. (1957): "A Theory of Fundamental Interactions", *Annals of Physics,* 2:407.

___________ (1962a): "Gauge Invariance and Mass", *Physical Review*, 125:397.

___________ (1962b): "Gauge Invariance and Mass. II", *Physical Review*, 128:2425.

___________(1962c): "Non-Abelian Gauge Fields. Relativistic Invariance", *Physical Review,* 127:324.

Smeenk, C., (2006): "The Elusive Higgs Mechanism", *Philosophy of Science* 73: 487.

Suzuki M., (1963): "Remarks on the Superconductor of Models of Elementary Particles", *Progress of Theoretical Physics,* 30:138.

t' Hooft, G., (1971a): "Renormalization of Massless Yang-Mills Fields", *Nuclear Physics B,* 33:173.

__________ (1971b): "Renormalizable Lagrangians for Massive Yang-Mills Fields", *Nuclear Physics B,* 35:167.

__________ (2005): "Renormalization of Gauge Theories", in *The Rise of the Standard Model: Particle Physics in the 1960s and 1970s,* edited by von Hoddeson L., p. 179, 1997, Cambridge University Press.

t' Hooft G. and Veltman M., (1972): "Regularization and Renormalization of Gauge Fields, Nuclear Physics B 44:189.

Teller P., (1988): "Three problems of Renormalization", in *Philosophical Foundations of Quantum Field Theory*, edited by Brown H. R. and Harre R., p. 73, Oxford: Clarendon.

________(1995): *An Interpretative Introduction to Quantum Field Theory,* Princeton University Press.

Veltman M., (1997): "The Path to Renormalizability", in *The Rise of the Standard Model: Particle Physics in the 1960s and 1970s,* edited by von Hoddeson L., p.145, 1997, Cambridge University Press.

Weinberg S., (1967): "A model of Leptons", *Physical Review Letters*, 19:1264.

___________ (1972): “Electromagnetic and Weak Masses”, *Physical Review Letters,* 29:388.

___________ (2005): *The Quantum Theory of Field*s, vol. 2., Cambridge University Press.

Wu C. S. et al., (1957): “Experimental Test of Parity Conservation in Beta Decay”, *Physical Review,* 105:1413.

Yang C. N. and Robert M., (1954): “Isotopic spin conservation and a generalized gauge invariance”, *Physical Review* 96: 191.

Zee A., (2010): *Quantum Field Theory in a Nutshell,* Princeton University Press.