Yoichiro Nambu and the Concept of Apparent Vacuum: A Stepping Stone to Spontaneous Symmetry Breaking

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The processes of discovery and concept formation are as mysterious as they are intriguing. In this article, they give a sketch of Yoichiro Nambu's long path toward the concept of spontaneous symmetry breaking focusing on the pivotal role played by his notion of "apparent vacuum". This is instrumental to draw the original analogical correspondence between the vacuum of quantum field theory and solid matter, which, transforming over time in its use and purpose, enables Nambu to arrive at the concept of spontaneous symmetry breaking. From this historical episode they draw a methodological lesson and emphasise the broad cultural influences that conditioned the conceptual development.

1. Introduction

The expression "apparent vacuum" sounds to the laymen oxymoronic, not to say nonsensical: how can a vacuum be "apparent" and void have a quality? Does it refer to a vacuum that behaves like a physical medium, or maybe to a physical medium that behaves like vacuum? To the particle physicist, with some imagination this expression-concept might possibly sound more allusive, and intriguing, but without further explanation, it remains no less cryptic and obscure. As we will argue, the concept of apparent vacuum acted as an essential nexus in the path towards spontaneous symmetry breaking, arguably one of the key ideas in the physics of the last century. In the sense given to it by its inventor, the Japanese physicist Yoichiro Nambu, an apparent vacuum designates a solid medium that can be treated in the same way as the vacuum of quantum field theory.

A fundamental concept in both the standard model of elementary particles and in the physics of solids, spontaneous symmetry breaking describes the emergence of nonsymmetric states (e.g., the ground states of a physical system) from a symmetric law in a large variety of physical systems—including the majority of those which undergo a phase transition, from crystals to ferromagnets. At first, Nambu had called this theoretical possibility "hidden symmetry," and later on rechristened it "self-consistent breakdown of symmetry." The former denomination was motivated by the fact that, as he had discovered, the symmetry of the law is "hidden" in the ground state, i.e., it appears broken when considering only the individual ground state, but conserved when considering the system on the whole (the ground state *plus* the single-particle excitations and the collective excitations). The qualification "self-consistent" in the later denomination derived from the approximation method that Nambu had used to compute the physical parameters whose nonzero value determined the symmetry breaking. The modern denomination "spontaneous symmetry breaking (or breakdown of symmetry)" appears for the first time in a paper by Baker and Glashow.[1]

Among the systems whose behaviors can be interpreted in terms of spontaneous symmetry breaking, we find superconducting media and, somewhat counterintuitively, also the vacuum of quantum field theory—the ground state whose excitations represent elementary particles. As diverse "substances" as they may appear, both the superconductor and the vacuum were the first "media" found to undergo a spontaneous symmetry breaking and to owe to that their distinctive behavior. In fact, their joint action was instrumental to the very formation of that notion: having brought to light the relation between three characteristic features of superconductivity (the energy gap, the collective excitations/plasmons, and a ground state which violates gauge symmetry), Nambu recognized that an analogous relation may hold between the mass of nucleons, the pions, and a vacuum state violating chiral symmetry. In a path ascending from the particular to the universal, these two instances were conceptualized in terms of spontaneous symmetry breaking.[2]

2. Plasmas, Nuclei, Superconductors, and the Quantum Vacuum

Far from being the exclusive result of a sudden illumination, the analogy drawn by Nambu between the physics of superconductors and the physics of vacuum, and the relation between such seemingly disparate substances, were the fruit of a decade-long path, the roots of which I argue lay in the concept of apparent vacuum. As there is though no trace of the latter in the finished construct of spontaneous symmetry breaking, it was only through a historical investigation that I discovered its role as keystone of Nambu's speculative arch. Delving into Nambu's archival papers, I came across a letter of reply that David Pines sent to him on

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October 23, 1952.[3] In that letter, Pines refers to some "apparent vacuum".

> [...] *I am very interested in your approach to the plasma problem.* [...] *It might well be that your approach will be a much more powerful one in this area* [the nuclear problem]. *Your idea of treating the filled Fermi sea as an apparent vacuum is a particularly appealing one.*

With some trepidation I set out to find Nambu's original letter in the yet unsorted archival papers of Pines at the University of Illinois. With the thrill that small and big discoveries give us, I found the letter.[4] To my satisfaction, therein Nambu articulates the idea of apparent vacuum and, building on it, lays out his own reformulation of the collective description of the plasma medium that Pines and David Bohm had recently given.[5]

> *I was suggested by your articles* [...] *to examine the* [collective] *oscillations of the plasma as a preliminary to many important problems, such as the properties of nuclei, superconductivity and superfluidity, origin of solar noise, Heaviside layers, origin of cosmic rays, and theory of discharge. The essential idea of my treatment is the same as yours, but I make use of the recently developed ideas of quantum electrodynamics: interaction representation and renormalization.*

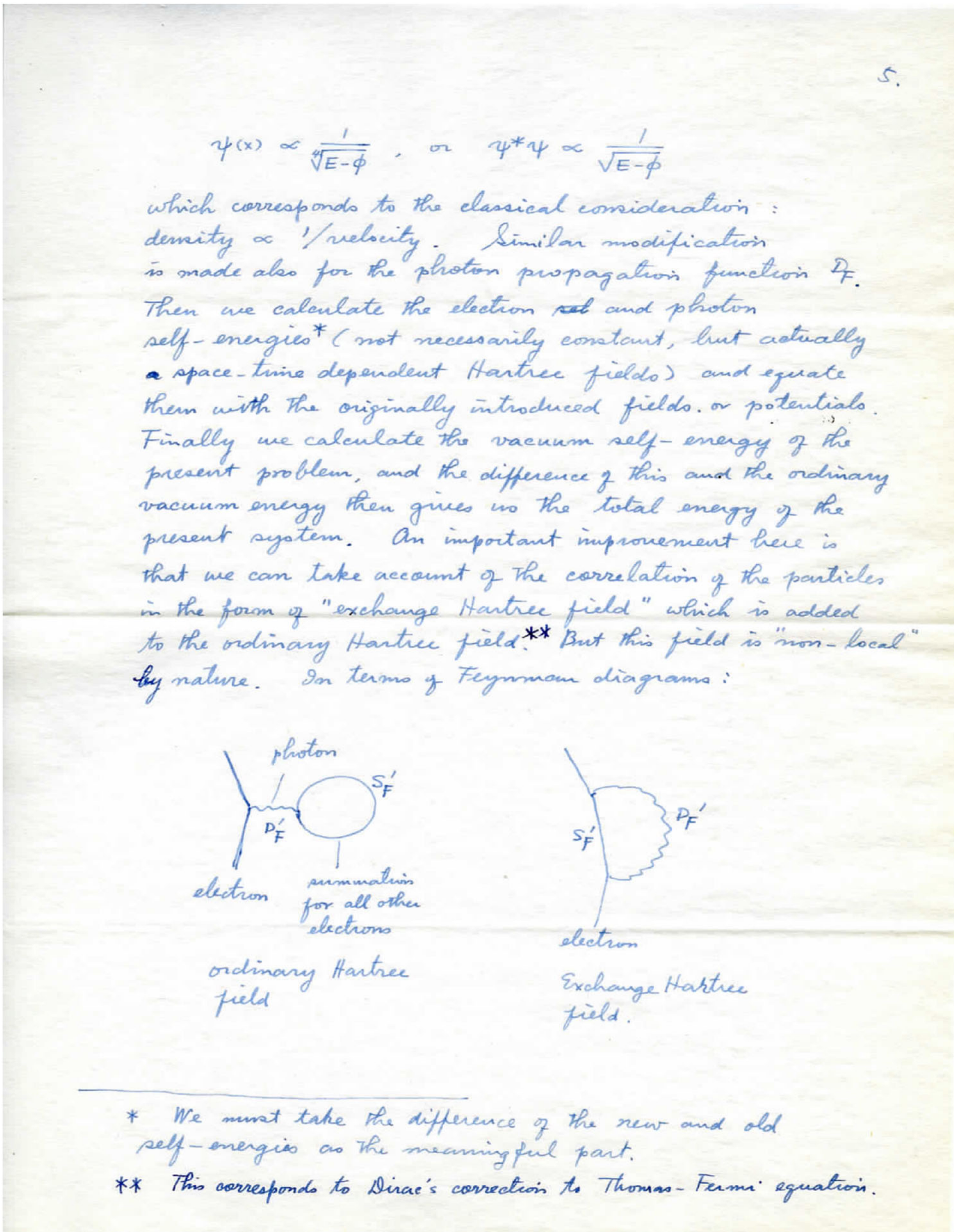
After a concise exposition of his ideas, Nambu adds below:

> *A more elegant way to look at the idea here* [...] *is to look at the state in which all levels up to the Fermi energy are occupied as an apparent "vacuum".*

In a nutshell, Nambu's trick is to regard the plasma medium "above" the quantum vacuum—i.e., occupying the states of finite positive energy up to the Fermi energy—as a "second" vacuum (which he refers to as apparent vacuum). The plasma seen as such an apparent vacuum gives an *additional* self-energy to the photons and electrons as compared to when they are in vacuum, and its effect can be then accounted for by going over to a new interaction representation and renormalizing a "second time" the already dressed electrons and photons. In other words, in this picture the renormalized properties of the electrons and photons of the plasma are the result of both the interactions with the virtual particles of the vacuum medium—already included in the dressed electrons and photons—and the many-body interactions with the other real electrons and photons populating the apparent vacuum. Differently from the self-energy due to the former interactions (calculated perturbatively), the calculation of the additional self-energy required the use of a suitable nonperturbative approximation method. Nambu adopted the self-consistent mean-field method previously elaborated by Hartree and Fock, cleverly using the eponymous potentials to work out what he called "self-consistent self-energies" for the electrons and photons. These are defined as the respective self-energy terms ($\psi\bar{\psi}$ for the electron field ψ, AA for the photon field A) each with a Hartree–Fock potential as its coefficient. Determining the two coefficients self-consistently, these (linear and one-particle) additional self-energy terms are used to replace the two-particle nonlinear scattering processes that each photon or electron on average undergoes with all the others in the plasma—represented by the Compton and Møller scattering terms of the form $\psi\bar{\psi}\, AA$ and $\psi\bar{\psi}\psi\bar{\psi}$, respectively—allowing to absorb them in the respective particles' properties.

Through the device of the apparent vacuum and the use of a mean-field approximation method, the formal fully fledged structure of quantum electrodynamics and its mathematical tools, then recently developed for the vacuum, were extended to treat the plasma (and any solid for that matter). If the formulation given by Nambu provided the same results of Bohm and Pines' collective description, its advantage was that it made more integral use of the field theoretical framework, systematically extending the Feynman–Dyson formulation, its physical picture and tools (the Green's functions), to real media. The result was a framework which treated fermions and bosons on the same footing and expressed the change in particles' properties more naturally by taking the particle perspective of Feynman and Dyson, rather than using the Schwinger–Tomonaga formulation as done by Bohm and Pines. Later on, upon its application to superconductors, these features of Nambu's formulation would turn out fundamental to discover the relation which lays at the core of spontaneous symmetry breaking (see ref. [2] for details).

The reformulation of plasmas that Nambu exposed to Pines was further refined and generalized into a "collective description of many-particle systems" in a paper co-authored with Toichiro Kinoshita—one of Nambu's fellows in Japan who like him had meanwhile emigrated to the US.[6] This paper was meant to treat, among other many-body problems, also the challenging problem of nucleons and mesons in the nucleus, which had been obsessing Nambu and had occupied the minds of the Japanese physicists for years. The hoped-for application to nuclei would however remain unfulfilled, and the long and technical paper co-authored with Kinoshita would pass practically unnoticed and uncited. Lying unutilized for a few years, that mathematical framework, in an unanticipated exaptation, came in handy to Nambu in 1960 to elegantly reformulate the microscopic theory of superconductivity proposed in 1957 by John Bardeen and collaborators.[7] Although the theory gave a complete and empirically adequate explanation of superconductivity, it predicted the existence of a superconducting ground state that violated gauge symmetry. This was a nonnegligible issue for a theory which claimed to account for the electromagnetic properties of superconductors. In those circumstances, Nambu's collective description unfolded its full potential. Enabling to easily integrating into it the theorems on gauge-invariance already developed in the context of quantum electrodynamics (see ref. [2]), the reformulation shows how the symmetry-breaking superconducting gap necessarily implies the emergence of symmetry-restoring collective excitations, revealing thus that gauge symmetry in superconductors is in fact not violated but only "hidden" (**Figure 1**). Such connection would then be transposed to particle physics, and thereby generalized, by drawing a series of analogical correspondences: between the superconducting ground state and the vacuum, the former's apparent violation of the gauge symmetry and the latter's apparent violation of the chiral symmetry, the "gapped" quasiparticles (elementary excitations of the superconductor) and the massive elementary particles (elementary excitations of the vacuum) as well as between the respective collective excitations.[8]



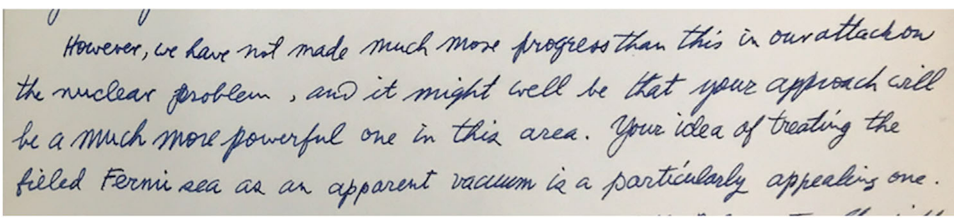
5.

$$\psi(x) \propto \frac{1}{\sqrt{E-\phi}}, \quad \text{or} \quad \psi^*\psi \propto \frac{1}{\sqrt{E-\phi}}$$

which corresponds to the classical consideration: density ∝ 1/velocity. Similar modification is made also for the photon propagation function D_F. Then we calculate the electron ~~sel~~ and photon self-energies* (not necessarily constant, but actually a space-time dependent Hartree fields) and equate them with the originally introduced fields or potentials. Finally we calculate the vacuum self-energy of the present problem, and the difference of this and the ordinary vacuum energy then gives us the total energy of the present system. An important improvement here is that we can take account of the correlation of the particles in the form of "exchange Hartree field" which is added to the ordinary Hartree field.** But this field is "non-local" by nature. In terms of Feynman diagrams:

* We must take the difference of the new and old self-energies as the meaningful part.

** This corresponds to Dirac's correction to Thomas-Fermi equation.



However, we have not made much more progress than this in our attack on the nuclear problem, and it might well be that your approach will be a much more powerful one in this area. Your idea of treating the filled Fermi sea as an apparent vacuum is a particularly appealing one.

Figure 1. Two excerpts taken from the correspondence from Nambu to Pines (top) and Pines to Nambu (bottom). The latter contains the cue which set me to hunt for the former, where Nambu expounds the idea of "apparent vacuum" and his reformulation of Bohm and Pines' collective description of the plasma medium. (Top panel) Reproduced with permission. Copyright 1952, University of Illinois Archives. (Bottom panel) Reproduced with permission. Copyright 1952, Hanna Holborn Gray Special Collections Research Center, University of Chicago Library.

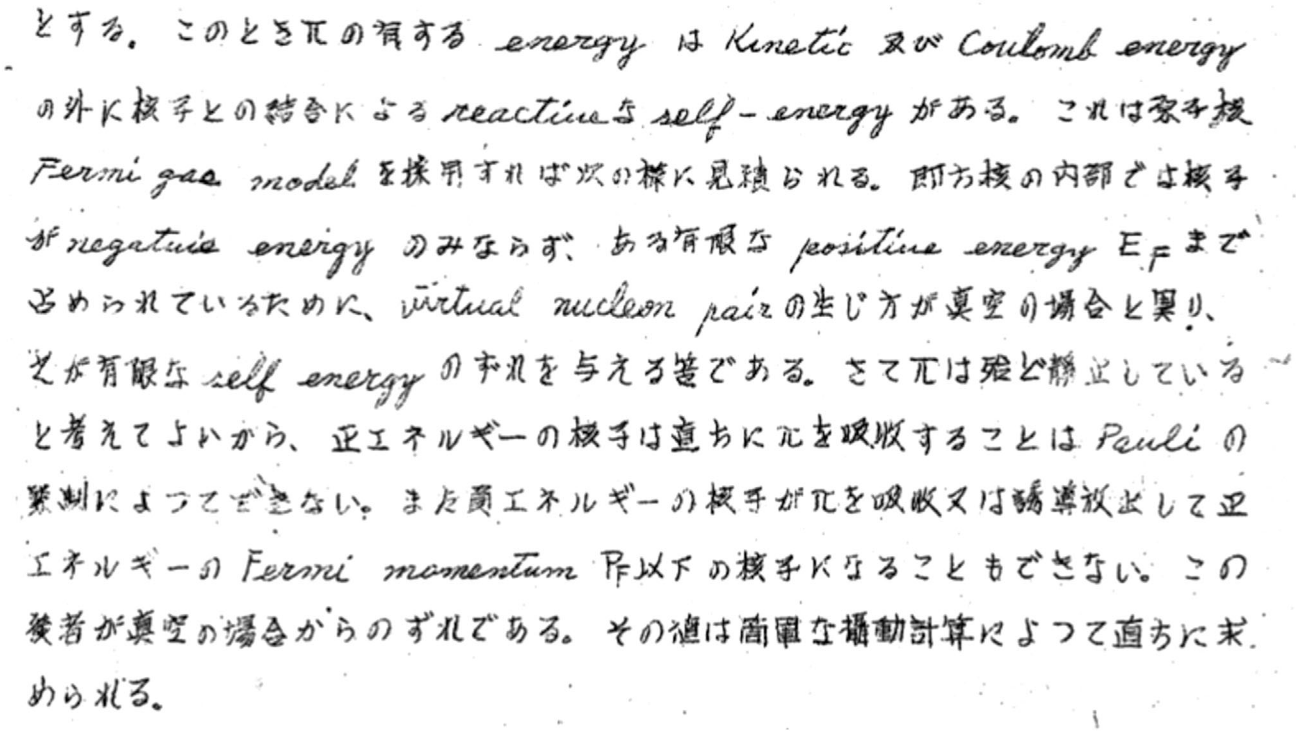

とする。このときπの有する energy は Kinetic 及び Coulomb energy
の外に核子との結合による reactive な self-energy がある。これは原子核
Fermi gas model を採用すれば次の様に見積られる。即ち核の内部では核子
が negative energy のみならず、ある有限な positive energy E_F まで
占められているために、virtual nucleon pair の生じ方が真空の場合と異り、
それが有限な self energy のずれを与える筈である。さてπは殆ど静止している
と考えてよいから、正エネルギーの核子は直ちにπを吸収することは Pauli の
禁制によつてできない。また負エネルギーの核子がπを吸収又は誘導放出して正
エネルギーの Fermi momentum P_F 以下の核子になることもできない。この
後者が真空の場合からのずれである。その値は簡単な摂動計算によつて直ちに求
められる。

Figure 2. An excerpt from Nambu 1950's handwritten communication on *Soryushiron Kenkyu*. The sentence in the middle reads "[...] because nucleons in a nucleus occupy not only negative energy but also a finite positive energy E_F, the virtual nucleon[-antinucleon] pair appears differently than in vacuum. This will give a finite deviation of self-energy from the vacuum case." Reproduced with permission. Copyright 1950, Soryushiron Kenkyu.

2.1. The *Ursprung* of the Concept of Apparent Vacuum

Let us return for a moment to Nambu's letter to Pines in order to trace the concept of apparent vacuum back to its deeper roots. As written in the letter, Nambu conceives of his collective description as a framework to treat a variety of physical systems beside the plasmas, including nuclei and their properties. As I found out, it is indeed in connection with the latter that the idea of apparent vacuum had originally appeared, in an embryonal form, in a handwritten communication sent to the informal physics journal *Soryushiron Kenkyu* (literally "Particle theory research") in April 1950.[9]

This communication, along with the notebooks of the period, revealed that the apparent vacuum had been conceived in the context of Nambu's search for a new formalism, inspired by solid-state physics, to treat nucleons and mesons in the nucleus relativistically, and with the aim of finally providing a sound basis to the meson theory of nuclear forces—proposed 15 years earlier by Hideki Yukawa but found to be empirically inadequate. With this aim in mind and in a situation where the physics community was abandoning the meson theory of nuclear forces,[10] in that brief communication Nambu set out to estimate the effect of the atomic nucleus on the virtual processes of a pion (a.k.a. pi-meson) immersed into it. The key point of the argument is that, as he writes, from the point of view of the pion surrounded by the nuclear medium, "nucleons occupy not only negative energy, but also a finite positive energy E_F (Fermi energy)." This apparent vacuum "above" the vacuum proper, Nambu argued, physically prevents some of the virtual nucleon-antinucleon excitations generated by the pion. This translates into a modification of the pion self-energy as compared to when the pion is immersed just in the vacuum medium. On that occasion, Nambu compares the situation to a dielectric medium whose presence alters the dielectric properties of the underlying vacuum and, by analogy, calls the apparent vacuum a "di-mesic" medium (**Figure 2**).

Although this first tentative application to nuclear systems assumes the nucleus as a simple degenerate Fermi gas, it already contains the key premise of all the subsequent developments. Such premise consists in considering many-body systems as apparent vacua whose effect on a particle can be incorporated in the particle's self-energy. This simple analogical device opened the way to employing concepts, methods, and theorems developed in quantum electrodynamics for the vacuum, to model plasmas and superconductors. This brought to the formulation of the notion of spontaneous symmetry breaking in the context of the latter, and later on enabled to transpose that notion to the vacuum itself, thereby leading to the realization that the vacuum is more akin to a complex medium than a featureless and symmetric one. In this chain of successive enablements, the concept of apparent vacuum was the first link.

2.2. A Final Reflection: Nambu's Lesson of Method

The concept of apparent vacuum might remind some readers of Paul Dirac and the eponymous Sea. This is indeed the right key to interpret that concept and Nambu's original inspiration for his simple model of nuclear matter. In 1929, Dirac had been led by the mathematics of his relativistic wave equation to assume that the vacuum is physically *filled* with negative-energy electrons. In other terms, the quantum vacuum acted like a degenerate Fermi gas from which, by the action of a photon, electrons could be removed to occupy a positive energy state. In the years to come, a fully fledged quantum electrodynamics would replace the idea of removal and occupation from/of the vacuum with the more abstract creation and annihilation operators. Along with that, Dirac's picture of the vacuum as a Fermi gas and the mechanism of generation of the virtual pairs implied by it became unnecessary and sank into general oblivion. Such an oblivion, however, did not concern Nambu, who exploited that disused construct anew by re-elaborating and repurposing the vacuum-solid analogy at its core. He did so by leveraging two elements. First, he used the analogical "equation" in the opposite direction and for a purpose different from Dirac's—translating the effects of solids into the language of quantum field theory. Second, he reintroduced it in the meanwhile mutated context of quantum field theory, and thus by combining it with the concepts and tools that had been developed in the meantime. In this way, an existing theoretical object, constructed by Dirac with a purpose in mind, was given a new use and purpose by Nambu and enabled in his hands a new unforeseen development. Drawing an analogy with the world of living organisms and borrowing a concept from the realm of evolutionary biology, we may regard Nambu's as a novel *affordance*.[11]

As a comprehensive historical analysis reveals, this affordance arose, at least partly, from the concurrence of a few heterogenous elements: Nambu's education in Tokyo, which had induced in him an interest in solid-state physics,[12] and the different course that Dirac's picture took among some Japanese physicists, a course influenced by their tendency to produce concrete representations of the abstract objects as well as the "substantialistic" philosophy promoted by the Yukawa-Sakata school (see refs. [2] and [13]). In light of these elements, one should then read the otherwise enigmatic remark that Nambu would make many years later on how "under the influence of the Yukawa-Sakata school" he had always regarded "Dirac's assumption of the filling of the negative energy states in the vacuum" not as "a mathematical trick but a reality."[14] The story here reveals the sense of these words. The apparent vacuum betrays and epitomizes this *Denkkollektiv*-specific practice of representation, or *Denkstil*, which had arisen in connection with the appropriation of modern physics in Japan. In hindsight, it is tempting to see Nambu's visualization, first of solid matter as extension of the vacuum and later on the vacuum as solid (superconductive) matter, as the first manifestation of his "synesthetic" thinking: that compresence of abstract and concrete analogs of the same object, which would show up then again in other contexts. "[...] he did not seem to make logical connections but associations" recollects one of his students, and later a collaborator of his, "halfway through a talk, a string would become a vortex and then a flux tube."[15] It is in terms of superconductivity and lines of force and field that Nambu was seeking—as in a Glass Bead Game—to think of a highly abstract concept like a string, searching in the former objects for new affordances to exploit.

This episode illustrates how giving new use to an already existing, and in fact disused, theoretical construct germinated into a novel and productive conceptualization. This new use was owed at least partly to the distinct way of thinking, elaboration, and approach of some Japanese physicists to questions and objects of a European-born discipline like quantum mechanics. The apparent vacuum belongs to that class of concepts which act as pegs along the path to the construction of a theory, leaving no visible sign in what ends up being constructed, and immortalized. In retracing that historical path, we uncover where these pegs were placed, how they assisted the climb, and what their local logic was. All of a sudden, Nambu's logic of discovery becomes then clear and the oxymoronic apparent vacuum begins to make sense.

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Conflict of Interest

The author declares no conflict of interest.

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