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SYMMETRIES AND ASYMMETRIES IN PHYSICS

Between symmetry and asymmetry: spontaneous symmetry breaking as narrative knowing

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Abstract

The paper presents a historical-epistemological analysis of the notion of "spontaneous symmetry breaking", which I believe today provides a template for conceiving the relationship between symmetry and asymmetry in physics as well as in other areas of the natural sciences. The central thesis of the paper is that spontaneous symmetry breaking represents an instance of "narrative knowing" in the sense developed by recent research in history and philosophy of science (Morgan and Wise (eds) SI narrative in science, Studies in history and philosophy of science, 2017a). Spontaneous symmetry breaking is best understood as a hybrid narrative comprising formulas, verbal statements, images, and at times also other media. This flexible notion can be deployed in different variations, allowing to explain a broad range of non-symmetric phenomena or models as resulting from (not necessarily observable) processes of loss of symmetry. I will support this thesis by first analysing in detail the way in which spontaneous symmetry breaking, and in particular electroweak symmetry breakdown, are presented in today's physics textbooks and reference works, and then by reconstructing the emergence of the hybrid construct from the late 1950s until the 1970s, when spontaneous symmetry breaking definitively established itself as a key physical notion.

Keywords Spontaneous symmetry breaking · Narrative knowing · History of high energy physics · Higgs mechanism

1 Introduction

Symmetry and asymmetry are notions whose importance for today's fundamental physics can hardly be overestimated. As witnessed equally well by research papers, textbooks and popular science writing, physicists today regard symmetries, i.e. math-

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ematical invariances, both as an especially fruitful heuristic tool for investigating micro-physical phenomena and as an epistemologically privileged instrument to understand observable and unobservable structures of nature. At the same time, they underscore how fundamental symmetries more often than not manifest themselves as what is variously characterized as “approximate”, “broken” or “hidden” symmetries, and which I shall in general refer to as asymmetries.[1]

Some philosophers believe that symmetries may even provide a basis for an ontology, while on the other hand debates have started on how far theorists’ faith in symmetries as a guideline for research may have gone beyond the limits of a fruitful scientific methodology (Brading et al. 2017). In the present contribution I will not address these topics, but rather engage in a historical-epistemological investigation of the mutual relationship between symmetry and asymmetry as it emerged during the second half of the twentieth century. More precisely, I will focus on the notion of “spontaneous symmetry breaking”, which emerged in elementary particle physics in the 1950s and ‘60 s and eventually came to be regarded as applying well beyond the limits of that discipline. I believe that it today provides a template and an overarching framework for conceiving the relationship between symmetry and asymmetry not only in physics, but also in other areas of the natural sciences. Investigating the present and past of this notion therefore provides an ideal entry point for shedding light on the historical epistemology of symmetry and asymmetry.

The central thesis of this paper is that spontaneous symmetry breaking is today best characterized as a multi-media narrative comprising formulas, verbal statements, images, and at times also other media. As is usual for narrative structures, spontaneous symmetry breaking is flexible and can be spelled out in different variations depending on the specific context. Thanks to this adaptability, spontaneous symmetry breaking allows to interpret a broad range of phenomena and models lacking symmetry as resulting from processes of loss of symmetry, thus making it possible to deploy heuristic and rhetoric strategies connected to symmetry despite its factual absence. In this way, the epistemic status of both symmetry and asymmetry is enhanced. Spontaneous symmetry breaking can be regarded as an example of “narrative knowing”, an epistemic strategy which has become increasingly common in theoretical physics since the late twentieth century (Borrelli 2012; Morgan and Wise 2017a, b; Wise 2004a, b).

After having introduced the notion of narrative knowing (Sect. 2), I will state and comment the main theses of this paper (Sect. 3). I will then argue for my theses in a series of steps. First of all I will analyse how the generic notion of spontaneous symmetry breaking is presented today in scientific and philosophical literature, showing how these presentations display constitutive narrative character (Sects. 4 and 5). I will then discuss how, in manuals of theoretical physics, one specific implementation of that narrative, i.e. the spontaneous breakdown of electroweak symmetry in the Standard Model, functions as a narrative explanation for particle masses (Sects. 6 and 7). Using the terminology introduced by historian Norton Wise (2004a, b), I will claim that spontaneous symmetry breaking provides a “growing explanation” of particle masses, because it narrates how they emerge in a (fictive or real) time.

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[1] Although in principle distinctions between asymmetry, broken symmetry and lack of symmetry might be made, as we shall see, in the case of high energy physics the three notions have today become mutually entangled.

The emergence of spontaneous symmetry breaking is today often projected back at least to the early twentieth century, connecting it to Heisenberg's work on ferromagnetism (e.g. Brading et al. 2017; Brown and Cao 1991; Morrison 2003). In fact, as we shall see, the concept of spontaneous symmetry breaking only emerged in the early 1960s in context of particle physics thanks to a cross-fertilization with work on superconductivity, and was only later on regarded as comprising ferro-magnetism and other solid state phenomena. I will offer a historical-philosophical reconstruction of how various constructs comprising mathematical formulas, verbal statements and visual elements and involving symmetry and asymmetry emerged in the 1950s and early '60 s, and came to form a network of meanings associated to what would later become spontaneous symmetry breaking (Sects. 8–11).

The historical reconstruction is not an expendable add-on to the analysis of present notions of spontaneous symmetry breaking, but should be seen as providing in its turn a "growing explanation" for it. From today's perspective, the elements bound into the notion of spontaneous symmetry breaking may appear somehow arbitrary, and even misleading. Realizing how they individually emerged and eventually came together and entered the shared knowledge tradition of physics leads to a narrative historical understanding of why those specific features are there and how the notion proved so successful and long-lived despite its fragmentary, and even incoherent character. Therefore, this case study is also an example of how historical understanding is a necessary complement to a logical-mathematical analysis of physical notions.

2 Narrative knowing: a short introduction

Narratives may play different roles in scientific practices. Among the most studied ones is the way stories serve as rhetoric devices to convincingly present results, models or arguments and build up authority, and how more or less accurate historical narratives of institutions and past practitioners foster unity in a discipline and define its identity (Azzouni et al. 2015; Blume and Leitgeb 2015; Brandt 2009; Morgan and Wise 2017a). More recently, attention has focused on the constitutive epistemic role of narratives in processes of knowledge construction in the natural sciences as well as in other cultural spheres. The latter role of narratives has often been dismissed by philosophers of science, who tend to see a clear-cut difference between (however defined) rational, deductive reasoning and epistemic constructs based on story-telling (Morgan and Wise 2017a, p. 1; Roth 2017). In particular, theories and models in the mathematical-physical disciplines are usually regarded as coherent constructs which can be analysed in logical-mathematical terms. Although it is often recognized that, in practice, not all theoretical structures conform to this ideal, it is usually assumed that this is only a temporary situation. This attitude mirrors the tendency of theoretical physicists to disregard in their research practice the strict prescriptions of mathematical rigour and vaguely assume that, eventually, rigorous versions of their procedures will be found which validate all their previous results.[2] This attitude is particularly evident in today's microphysics, where, during the last decades, theories have increasingly often taken the form of hybrid constructs in which mathematical elements are

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[2] I have discussed this issue in some detail in Borrelli (2012, pp. 201–202, pp. 211–212).

combined with other medial strategies, like words, diagrams or images (Borrelli 2012, 2015b, 2017a; Wise 2004b).

This development was noted early on by Stephan Hartmann, who argued that the acceptance and use of models in nuclear and high energy physics cannot always be understood purely in terms of empirical adequacy or logical-mathematical deduction from a theory: In some cases, models may establish themselves primarily because they are associated to what Hartmann calls "a good story" (Hartmann 1999, p. 344). According to Hartmann, the story associated to a model helps it become established against competition because physicists perceive it as providing a physical understanding that formalism alone does not offer. Does this mean that stories constitutively contribute to the construction of physical meaning? Hartmann remains quite vague on this point. He clearly draws a line between the formalism of a model and its interpretation, on the one hand, and the story, on the other hand, stating: "a model is an (interpreted) formalism + a story" (Hartmann 1999, p. 344). Therefore the model as a whole is not a narrative, yet it includes a story. Does the story only provide a rhetoric and didactic help, or is it as essential at the formalism for understanding? Hartmann admits: "it is […] very difficult to explicate how a model and its story exactly provide understanding", leaving open the option that stories might indeed constitutively contribute to the construction of physical meaning. Hartmann never developed further his reflections on the topic, so it remains unclear whether he was generally questioning the assumption that physical notions, models and theories can always be fully analysed in logical-mathematical terms.

Michael Stöltzner has recently deployed a more restrictive version of Hartmann's stories in a paper about modes of scientific explanation (Stöltzner 2017). While admitting that stories can fulfil an explanatory function in high energy physics and agreeing with my view that they may even contain mathematical elements, Stöltzner underscores that their role is only to "justify the application" of the formalism, and that models may nonetheless be "formally subsumed under a theory", so that the mathematical elements contained in stories are somehow separate from those of models (Stöltzner 2017, p. 443).[3] More specifically, Stöltzner distinguishes the practice of theoretical particle physicists into mathematically well-defined procedures (among which he counts renormalization), and some "lore" that may be rhetorically employed to justify the use of those practices:

> [P]article physicists construct models by setting up a Lagrangian figuring all the basic fields, which is worked upon by a series of well-established procedures that may yield other fields and physically observable features. Some of these procedures are mathematically well-defined, among them renormalization, while others are closer to the above-mentioned community-based lore that reflects previous successful explanatory practices, and allows a unified treatment of several models by means of a simple argument pattern. All of them are mathematical at face-value, but while renormalization can be justified by a

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[3] Stöltzner incorrectly presents the notion that stories may include mathematical elements as a difference to my own work, overlooking the fact that I had expressed precisely this idea in the same paper which he quotes, where I characterize the naturalness problem as "a hybrid narrative combining words, formulas, numbers and analogies" (Borrelli 2015a, p. 69).

> formal proof that needs no story, the others partly rely on stories about how to operate this argument pattern. The rhetorical employment of such a story—for instance if scientists disagree whether a certain idealization is justified—does not minimize its role as an explanatory ideal (Stöltzner 2017, pp. 443–444).

In conclusion, although Stöltzner's stories justify the use of models, they never contribute to the construction of physical meaning, which is only attached to traditional formalism of quantum field theory. Thus, Stöltzner attempts to deploy the notion of narrative in high energy physics, while at the same time holding on to the ideal that theoretical constructs in the exact sciences fundamentally have logical-mathematical character. Yet precisely in view of the multiform character of theoretical practices, which both Hartmann and Stöltzner acknowledge, it appears necessary to set aside that ideal and engage with the possibility that theoretical constructs may take the form of multi-medial narratives which cannot be analysed only in logical-mathematical terms. This is the position I take and will back up with an analysis of spontaneous symmetry breaking.

Before going further, however, it is necessary to discuss how the term "narrative" should be understood here. There are among narratologists and literary scholars various elaborate definitions of narrative, but researchers working in science and technology studies usually adopt a minimal definition characterizing narrative as a series of at least two events connected in a sequence in such a way as to implicitly or explicitly suggest causality, agency and more in general an event (Abbott 2014; Borrelli 2019). The sequence is usually temporal, although it need not relate to lived, experienced time. This definition only concerns form, and says nothing about content. Narratologists often distinguish between "factual" and "fictional" narratives, yet this distinction has been criticized as problematic, especially as far as the natural sciences are concerned (Brandt 2009; Schaeffer 2013). In the present paper I will not address this issue, both because it is not relevant for my main thesis and because I, too, do not regard the categories of factual and fictional as appropriate to this case.

The idea that narratives may have an epistemic role in research practice has been a subject of discussion in the philosophy of history since the late twentieth century, in connection with the works of Arthur Danto, Hayden White and Paul Ricoeur, who suggested that historians construct a narrative out of their source material to reach historical understanding (Jaeger 2009). This of course does not imply that historical accounts are fictional or arbitrary, but simply that an "objective" historical account modelled after the ideals of the natural sciences is not possible and that narrative meaning-making is a part of historical understanding. Interestingly, authors arguing for narrative knowing in historiography often present knowledge in the natural sciences as a template for non-narrative, "objective" understanding. Yet scientific objectivity is a historically and culturally situated ideal (Daston and Galison 2010), and in the last decade scholars from the humanities, and even some practising scientists, have noted how no clear-cut distinction between scientific knowledge and story-telling obtains. A significant example is an essay collection on the roles narratives in mathematics (Doxiadēs and Mazur 2012). In that volume, mathematician Michael Harris states that "mathematics is narrative" (Harris 2012, p. 138), claiming that mathematical theorems are more than mere collections of valid logical inferences. Through a comparison between man-made proofs and a hypothetical fully automated one performed by an android, Harris argues that the latter one may be true, but cannot be mathematical because it lacks the narrative element provided by the human mathematician: “From the android’s point of view, any valid inference ends with a theorem, and it is only the programmer’s invisible hand that chooses where to switch off the machines and affix a Q.E.D. to the end of the last completed line” (Harris 2012, p. 137). Thus, for Harris, a mathematical theorems seems to be the emplotment of a logical inference. Of course, this claim is highly debatable and depends on how “theorem”, “proof” and “narrative” are defined, but it shows how logical-mathematical expositions and story-telling may be nearer to each other than usually assumed.

While theorems are a somehow surprising candidate for narratives, more plausible ones can be found in the life sciences, where rigorous mathematical theories are the exception and not the rule. The most detailed and path-breaking study in this sense is Gillian Beer’s monograph *Darwin’s plots. Evolutionary Narratives in Darwin, George Eliot and Nineteenth-century Fiction* (1983). Beer convincingly argues that Darwin could only conceive and express his theory of evolution by creating a new, multi-layered narrative construct. Darwin’s evolution theory could be understood by following small stories of competitions and selection playing out in lived time which connected to a broader, overarching narrative comprising individuals and species and extending over dimensions of time well beyond the limits of human experience. The evolutionary narrative which Darwin created employing the literary strategies of his age was in turn taken up by authors of his time, especially George Eliot and Thomas Hardy, and eventually became so entrenched in modern culture, that it is for us today an unproblematic explanatory pattern employed well beyond the biological sphere.

Mathematical theorems and evolution theory are just two examples of the many ways in which narratives may play a constitutive role in the production of scientific knowledge. During the last years, various authors have brought forward case studies supporting this claim, and in particular Mary Morgan and Norton Wise present a broad range of research results on this topic in a special issue devoted to narrative science and narrative knowing (Morgan and Wise 2017a). Their aim is not to formulate any general theory of narrative knowing, but rather to highlight some common features between different case studies, leading philosopher and historians of science to keep into account the epistemic role of narratives in their investigations. They convincingly argue for the constitutive epistemic role of narratives in science “knocking aside some oft-made, simple, or stereotypical, assumptions about there being a fundamental opposition between narrative and science” (Morgan and Wise 2017b, p. 1). Morgan and Wise explain how narratives are able to connect fragmentary elements like mathematical formulas, verbal statements, computer simulations, diagrams or images into a hybrid, but meaningful whole which provides the basis for the production of new knowledge. Case studies detail the different ways in which this narrative unity functions in scientific practice, and the one most relevant for the present study is how narratives represent the coming-to-be in time of the epistemic object which scientists are studying, for example a molecular bond or the evolution of a population (Rosales 2017; Wise 2017). The time dimension involved need not coincide with lived time, as we saw in the case of mathematical proof, but still constitutes a temporal dimension in which the epistemic object studied “grows”, acquiring a given set of features.

Wise had already analyzed this kind of narratives in an essay collection on "growing explanations" (Wise 2004a) and in later work (Wise 2011). The term growing explanation refers to a saying in the life sciences that, to know an organism, you have to grow it. Wise compares the growing of an organism to the narrative presentation of how a phenomenon unfolds in time (Wise 2004b). On the basis of a broad range of case studies he convincingly argues that, during the second half of the twentieth century, scientific explanations have increasingly often taken the form of such "historical" narratives. He suggests that this development may be linked to the increasing use of computer algorithms which have to be dynamically run to provide information about the target system, and more in general to the rise of sciences dealing with complex systems, whose behavior cannot be explained by reductionist approaches. Wise expounds his idea of narrative knowing using the example of snowflakes (Wise 2011, pp. 360–367, 2017, pp. 74–75). There is as of today no microscopical model of snowflake growth, but in the last decades computational models have been able to simulate it in an empirically successful way making use of algorithms which cannot be seen as corresponding to actual micro-physical processes. These computations "explain" the formation of snow crystals in a historical narrative by visualizing the steps of their growth rather than by providing a reduction of the process to some fundamental laws. It is an instance of narrative knowing, in which the epistemic object is understood through a hybrid narrative which lets it unfold in time.

While narrative knowing may be connected to the use of computing, it can also be linked to the employment of non-rigorous mathematical techniques, especially as far as contemporary high energy physics is concerned (Borrelli 2012, 2015a, b; Galison 2004; Wise 2011). As we saw above, already Hartmann had suggested that "stories" may have an epistemic function, albeit a somehow limited one, and his ideas provided the starting point for my own reflections on narratives in high energy physics. Going beyond Hartmann's approach by combining it with Morgan and Wise's work, I do not draw a line between formalism, interpretation and story, and rather regard theoretical constructs as multi-medial narratives. In the following pages I will ague that spontaneous symmetry breaking is a scientific notion that can be known only by following its unfolding in time. Different phenomena and theories characterized as spontaneous symmetry breaking may be linked to different versions of the overarching narrative which comprises mathematics, words and more. Thus, in the apparently purely logical-mathematical realm of theoretical physics a similar situation obtains as the one Alirio Rosales describes when speaking about theories in evolutionary biology:

> Theories are composed of multiple interacting components: models, diagrams, different kinds of mathematical formalisms, and so on. I argue that some theories have narratives as essential components. In some theories, narratives function as integrating devices of the mathematical components: they hold them together as pieces in the investigation of the same complex process (Rosales 2017, p. 22).

3 The main theses of this paper

In the previous section a notion of narrative knowing has been sketched which will serve as a heuristic tool in trying to unravel the relationship between symmetry and asymmetry in contemporary physics. To provide an orientation for the readers I will now state and briefly comment upon the main claims of the paper. As already noted, the working hypothesis which partly motivates this work is that the relationship between symmetry and asymmetry in contemporary physics is in large measure shaped by the notion of spontaneous symmetry breaking as a "tertium quid" mediating between the two poles of symmetry and asymmetry. This working hypothesis will not be put to test in the paper, but hopefully the results of the present analysis of spontaneous symmetry breaking will provide a basis for future studies in that direction. As to the key theses of the paper, they can be summarized in three points building upon each other:

1. The notion of spontaneous symmetry breaking has in today's physics (and possibly in other sciences) a prominent, but rather ambiguous status. Although it is labelled at times as a phenomenon and at times as a mathematical construct, none of the two characterizations is actually well-defined. More precisely:
    - 1.a. Spontaneous symmetry breaking is often described as a phenomenon manifesting itself in different physical systems. Examples often mentioned are ferromagnets (transition between magnetized and demagnetized state), a rod balancing on its tip and suddenly falling down in one direction, superconductors (transition between normal and superconducting behaviour), and elementary particles (transformation of massless particles into massive ones). Beyond the reference to these exemplars, though, an overarching physical characterization of spontaneous symmetry breaking is lacking.
    - 1.b. Spontaneous symmetry breaking is also characterized as a mathematical construct. Different mathematical expressions and models are referred to as implementations of spontaneous symmetry breaking: the Higgs model, the Ising model, or any symmetric equation with asymmetric solutions. Yet here, too, an overarching definition connecting all these structures is absent. This rather technical issue will be dealt with more in detail in Sect. 5.
2. Spontaneous symmetry breaking is best characterized as a multi-medial, time-based narrative which comprises mathematical formulas, verbal statements, images, and at times also other media. This hybrid composite is kept together by an overarching narrative connecting the diverse elements into a story which has to be followed step by step to understand what spontaneous symmetry breaking is, and eventually deploy it as an explanation in specific contexts. Therefore, spontaneous symmetry breaking can be regarded as an instance of narrative knowing and serves as a "growing explanation" in various scientific contexts.
3. In its basic form, spontaneous symmetry breaking connects two mathematical expressions, a symmetric and an asymmetric one, by means of a verbal statement on how the one transforms (itself) into the other. Thank to this narrative, the asymmetric formula can be conceived as resulting from a now-lost, symmetric one. If it were not embedded in the narrative, the final formula would displays the same

> mathematical properties, but could not be understood as an instance of spontaneous symmetry breaking. Observable transitions can be associated to this narrative (e.g. ferro-magnetism, superconductivity), but a system can be characterized as having gone through spontaneous symmetry breaking even if the (allegedly) symmetric state was not, and possibly could not, be observed, as in the case of mass generation by way of the spontaneous breakdown of electroweak symmetry.

To support these theses, in the first part of my paper I will provide a review of how spontaneous symmetry breaking in general (Sects. 4 and 5) and the breakdown of electroweak symmetry in particular (Sects. 6 and 7) are presented today by philosophers of science and scientists. I will show how these presentations display the features of narrative knowing as expounded in Sect. 2. In the second part of the paper (Sects. 8–11) I will step back in time and show how the various elements of today's narrative of spontaneous breakdown of electroweak symmetry and relevant mass generation emerged and combined between the late 1950s and the 1960s, to give rise to the narrative construct spontaneous symmetry breaking.

4 The elements of the narrative of spontaneous symmetry breaking

Let us start the discussion with a verbal characterization of spontaneous symmetry breaking. Among the many descriptions which can be found in popular, philosophical and scientific literature, I choose the quite clear and straightforward one from a widely used academic resource: the *Stanford Encyclopaedia of Philosophy*. In the article "Symmetry and symmetry breaking" by Katherine Brading, Elena Castellani and Nicholas Teh we read:

> Spontaneous symmetry breaking (SSB) occurs in a situation where, given a symmetry of the equations of motion, solutions exist which are not invariant under the action of this symmetry without any explicit asymmetric input (whence the attribute "spontaneous"). A situation of this type can be first illustrated by means of simple cases taken from classical physics. Consider for example the case of a linear vertical stick with a compression force applied on the top and directed along its axis. The physical description is obviously invariant for all rotations around this axis. As long as the applied force is mild enough, the stick does not bend and the equilibrium configuration (the lowest energy configuration) is invariant under this symmetry. When the force reaches a critical value, the symmetric equilibrium configuration becomes unstable and an infinite number of equivalent lowest energy stable states appear, which are no longer rotationally symmetric but are related to each other by a rotation. The actual breaking of the symmetry may then easily occur by effect of a (however small) external asymmetric cause, and the stick bends until it reaches one of the infinite possible stable asymmetric equilibrium configurations (Brading et al. 2017).

This passage begins with a verbal statement on symmetric equations having asymmetric solutions, to which in principle various mathematical examples might be attached. That statement is however immediately connected to a time-based narrative, in which readers are walked though a detailed description of how a simple system (a vertical stick under pressure) goes from a symmetrical to an asymmetrical state. The verbal description makes the transition from symmetry to asymmetry understandable by building upon the readers' everyday experience, their knowledge of mechanics and their physical intuition. We note how the ambiguous choice of words leaves the agency behind the breakdown largely undetermined. At the beginning it is stated that a "spontaneous" breakdown occurs without "any explicit asymmetric input", while in the end an "asymmetric external cause" is present, albeit characterized as "however small", thus suggesting that the initial instability of the system in some sense actively participates in giving rise to the "spontaneous" symmetry breakdown.

This ambiguous, time-based narrative is not a special feature of the *Stanford Encyclopaedia* article, but is found in one form or the other in all definitions of spontaneous symmetry breaking, albeit in more or less complex technical form. Such characterizations always contain similar elements, namely:[4]

(a) descriptions of physical systems which display both a "symmetrical" and an "asymmetrical" state in observable sense, such as a ferro-magnet acquiring or losing residual magnetization, or a rod balancing on its tip and then falling down. Although these examples are helpful, many instances of spontaneous symmetry breaking are not characterized by an observable loss of symmetry. For example, in superconductivity and in electroweak symmetry breaking the loss of symmetry can only be appreciated when looking at mathematical models and not at phenomena;

(b) simple mathematical models which may be employed to formalize systems such as those in (a). The most common example is a one-dimensional double-well-potential y(x), whose formula and graphic representation are shown in Fig. 1. This potential represents both mathematically and visually a situation in which a system can "slide" from an unstable, symmetrical equilibrium state (the maximum) to a stable, asymmetrical one (one of the two minima);

(c) verbal statements which fill up the gaps between the other elements. Among these statements, particularly important is the use of the term "spontaneous", whose historical origin we shall discuss later on. Calling the symmetry breakdown "spontaneous" characterizes the symmetry as both present, since it spontaneously acts, and absent, since it is broken down. A further story often told is that laws of nature are expressed by symmetric equations that can have both symmetric and asymmetric solutions, and that physical systems may somehow move from the first to the second ones. Since such statements are made also in cases where equations cannot even be written down, let alone solved (e.g. Weinberg 1996, p. 163), they should not be mistaken for straightforward mathematical arguments. A related narrative is the one describing how the ground state of a system (or the "vacuum" for quantum fields) is not unique, leading to a symmetry breakdown in observable phenomena when the vacuum changes. In all of these statements, the temporal element is central for the understanding: systems move from symmetric

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[4] The following overview is compiled on the basis of the following texts: Castellani (2003), Brown and Cao (1991, pp. 215–217), Cheng and Li (1984, pp. 141–151, pp. 240–247), Earman (2003), Itzykson and Zuber (1980, pp. 519–526, pp. 540–549, pp. 612–616), Kibble (2015), Mandl and Shaw (1984, pp. 279–289), Morrison (2003), Weinberg (1996, pp. 163–165) and Zee (2010, pp. 223–230).

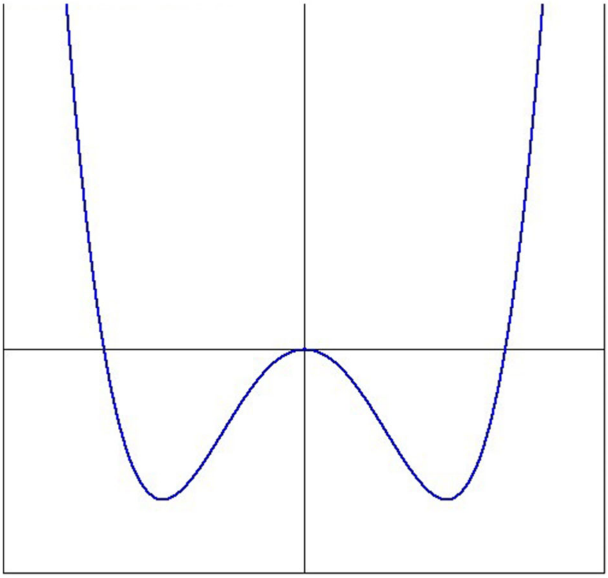


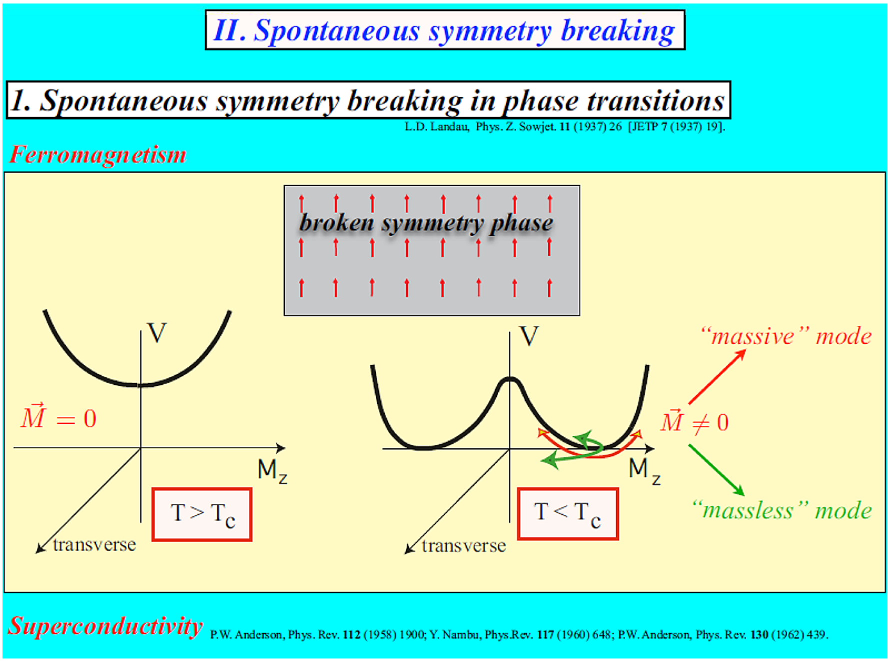
Fig. 1 The shape of the double-well potential. The diagram can be seen as representing the fomula $y(x) = -ax^2 + bx^4$, with a, $b > 0$. In this case $a = 2$ and $b = 0.5$

> to asymmetric solutions, and the vacuum changes or is transformed by some agency, for example the Higgs field, as we shall see later on.

A very effective means of combining the different kinds of elements (physical exemplars, mathematical models, verbal statements and images) is seen in Fig. 1. As already noted, the picture can be seen as an exact graphical representation of a mathematical function, which in turn models a mechanical system. At the same time, the image can also be perceived as a qualitative sketch of a physical situation in which a ball may slide along hills and valleys. Finally, as we shall see later on, the mathematical model can be associated with quantum-field-theoretical versions of spontaneous symmetry breaking, such as the Higgs mechanism. An example of how these different representational functions are superimposed and combined is found in the slides of the Nobel prize Lecture by François Englert, who shared with Peter Higgs the 2013 Nobel for the discovery of the Higgs mechanism (Fig. 2). Englert's slide may suggest to expert and non-expert readers that rigorous mathematical constructs underpin it. However, although many mathematical models can be associated to the elements in the slide, no closed, rigorous definition of spontaneous symmetry breaking exists, as we shall see in the next section.

5 Spontaneous symmetry breaking: the mathematical side

What about the mathematical side? Why should we not regard spontaneous symmetry breaking as based on some very complex overarching mathematical structures which



II. Spontaneous symmetry breaking

1. Spontaneous symmetry breaking in phase transitions

L.D. Landau, Phys. Z. Sowjet. **11** (1937) 26 [JETP 7 (1937) 19].

Ferromagnetism

Superconductivity P.W. Anderson, Phys. Rev. **112** (1958) 1900; Y. Nambu, Phys.Rev. **117** (1960) 648; P.W. Anderson, Phys. Rev. **130** (1962) 439.

Fig. 2 A slide from François Englert's Nobel Lecture on the "Brout–Englert Higgs mechanism". Here, various images, formulas, words and references to physical systems stand side by side, implementing the narrative of spontaneous symmetry breaking (Englert 2013, Copyright© François Englert)

only a few theorists can actually understand? The answer is that a careful perusal of the specialistic literature fails to deliver any traces of such a construct.[5]

Indeed, some mathematical physicists have given precise and coherent mathematical definitions of what they believe should be referred to as "spontaneous symmetry breaking", but these definitions fail to cover all cases which are generally regarded as instances of spontaneous symmetry breaking—and in particular the Higgs mechanism often does not fall under that term (e.g. 't Hooft 1997, p. 196 note 15; Strocchi 2008, especially pp. 193–195). Franco Strocchi has offered a mathematical definition for spontaneous symmetry breaking according to which no transitions from a massless to a massive universe is possible (Strocchi 2008, pp. 9–11, pp. 115–122). Thomas Kibble wrote in his article on "Spontaneous symmetry breaking in field theory" in the *Encyclopaedia of Mathematical Physics* that "It is somewhat ironic that the most famous example of a spontaneously broken gauge theory [i.e. the Higgs mechanism] probably does not, strictly speaking, exhibit a symmetry-breaking phase transition!"

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[5] I list here once again all the reference works, papers and textbooks in physics and philosophy where I have endeavoured to find an overarching definition of spontaneous symmetry breaking: Castellani (2003), Brown and Cao (1991), Cheng and Li (1984), Earman (2003), Itzykson and Zuber (1980), Kibble (2006, 2015), Liu and Emch (2005), Lyre (2008), Mandl and Shaw (1984), Morrison (2003), Peskin and Schroeder (1995), Strocchi (2008), 't Hooft (1997), Weinberg (1996) and Zee (2010). It may be also noted that, should such a definition exists, it would most probably be quoted by recent physics texts, given the great and growing importance of priority claims among physicists.

(Kibble 2006, p. 203). Significantly, in the *Encyclopaedia of Mathematical Physic*s no overarching entry on spontaneous symmetry breaking exists, but only a series of articles or topical remarks on spontaneous symmetry breaking discussing how that notion may (or not) be defined in various specialistic fields.

Philosophers of science have tried to shed light on the matter by focussing on the strictly mathematical aspects of the spontaneous breakdown of symmetry, and in particular asking about the legitimacy of verbally interpreting the breakdown of electroweak symmetry as a process of mass generation (Liu and Emch 2005; Earman 2003, 2004; Lyre 2008; Morrison 2003; Stöltzner 2017; Struvye 2011). While these philosophical studies usually come to the conclusion that such interpretations should be discouraged, perhaps their most important result has been to show how there is no single, coherent mathematical structure allowing to fully grasp the various meanings which scientists associate with spontaneous breakdown of symmetry in general and of electroweak symmetry in particular. Despite these indications, most philosophers of science remain convinced that a logical-mathematical analysis may solve the issue, and choose not to acknowledge that the present hybrid construct of spontaneous symmetry breaking appears to function quite well as a theoretical structure in scientific research. For example, in his recent overview of philosophical discussions on the Higgs mechanism, Stöltzner admits that no overarching mathematical framework exists which is capable of rigorously subsuming all instances of spontaneous symmetry breaking (and particularly none within algebraic quantum field theory), but at the same time states that "the most convincing explanation of SSB in particle physics can be given within algebraic QFT" (Stöltzner 2017, p. 451).

Instead, I will argue that in this, as in other cases, the primary focus on logical-mathematical structures does not allow to grasp the full scope of contemporary scientific discourse. This approach is problematic because it presupposes a parasitic relationship between mathematical and verbal (or visual) aspects of theoretical practice, with the former representing by themselves scientific knowledge and the latter providing only an interpretation for it. In short: words allegedly need formulas, but not the other way round. On the contrary, analyses of the present situation, such as those quoted above, suggest that the relationship should be seen as a symbiotic one, where words and formulas are inextricably entwined with each other (as well as with other elements) to produce scientific knowledge (Borrelli 2012, 2015b). In this particular case, the verbal, and at times also the visual, component is essential for constructing the time-based narrative without which mass generation and electroweak symmetry breakdown would not be understandable. In conclusion, if physicists today wish to regard a broad array of models and phenomena as instances of spontaneous symmetry breaking, for example to explain the origin of particle masses in quantum field theory, then they can only do so by deploying a general notion of spontaneous symmetry breaking which has a hybrid narrative character and cannot be analysed purely in logical-mathematical terms. Of course, physicists are not forced to use that notion, if they are ready to give up its explanatory and heuristic power, but it is a fact that they have so far not chosen to give it up, and have instead endowed it with a prominent role in their research practices. It is therefore of great philosophical interest to take a closer look at this epistemic constellation, using as an example the spontaneous breakdown of electroweak theory.

6 Electroweak symmetry breaking in theoretical physics manuals: verbal descriptions

In this section and in the next one I will analyse in some detail how the spontaneous breakdown of electroweak symmetry and the relevant generation of particle masses are presented in physics textbooks, which have a seminal role in shaping the way in which future generations of scientists will do research (Kaiser 2005a). My aim is to show how the generic narrative of spontaneous symmetry breaking is implemented in a specific case. Since the topic is technically non-trivial, in this section I will for simplicity discuss only how electroweak symmetry breaking and mass generation are presented verbally. In the next section, I will discuss how the verbal statements are combined with mathematical and visual elements to form a hybrid narrative explanation of mass generation. Let us start from the manual by Michael Peskin and Daniel Schroeder (1995), which is one of the most widely used textbooks of quantum field theory. There, we read:

> This mechanism, by which spontaneous symmetry breaking generates a mass for a gauge boson […] is now known as the *Higgs mechanism*. […] the scalar [i.e. Higgs] field that causes spontaneous breaking of the gauge symmetry is an important ingredient in the structure of the Glashow-Weinberg-Salam [i.e. electroweak] theory (Peskin and Schroeder 1995, p. 692, pp. 715–716, italics in the original).

In this passage the scalar Higgs field is explicitly identified as the agent that “causes” spontaneous symmetry breaking, which in turn “generates” the mass of many—and possibly all—particles. Accounts in other textbooks may differ from the one quoted above in the precise identification of the agency to which masses are due, but all of them verbally describe how massless particles are transformed into massive ones in a time-based process which is characterized as a “mechanism”. Let us now consider a few more examples:

> We now apply the Higgs mechanism to this model [a massless model] to generate non-vanishing masses for the $W^{\pm}$ and the Z^0 bosons, and we shall see how this also enables us to to introduce lepton masses (Mandl and Shaw 1984, p. 289).

> The imposition of local [gauge] symmetry implies the existence of massless vector particles. If we want to avoid this feature of the gauge theory and obtain massive vector bosons, the gauge symmetry must be broken somehow. […] We may contemplate the possibility of spontaneous symmetry breaking of the symmetry […] This remarkable phenomenon […] is commonly referred to as the *Higgs phenomenon* (Cheng and Li 1984, pp. 240–241, italics in the original).

> We started from a system describing […] a massless gauge field. After spontaneous symmetry breakdown, we have […] one massive vector field […] This is the phenomenon discovered by Englert and Brout and by Higgs (Itzykson and Zuber 1980, p. 614).

Since the initial, symmetrical theory contains massless scalar particle which are not present any more in the final one, electroweak symmetry breaking is at times described as a sort of particle cannibalism, with particles "eating" a massless boson and so becoming massive:

> The role of the [massless] Goldstone boson in the Higgs mechanism is intricate, and seems mysterious at this level of the discussion. [...] It is tempting to say that the gauge boson acquired its extra degree of freedom by *eating* the Goldstone boson (Peskin and Schroeder 1995, p. 692, italics in the original).

> This phenomenon of a massless gauge field becoming massive by eating a Nambu–Goldstone boson was discovered by numerous particle physicists and is known as the Higgs mechanism (Zee 2010, p. 264).

In conclusion, although the wording may vary, all quoted statements convey the same message: masses are not an inborn, invariable property of particles, but are rather the result of a "generation" going hand in hand with a spontaneous breakdown of gauge symmetry. The whole terminology is time-based: symmetry is not already broken, but breaks down, mass is generated or acquired, and massless particles disappear or are eaten by other particles. Although the massless phase of particles has never been (and probably cannot ever be) observed, this description is no pure metaphor, as scientists sometimes claim of their fancy verbal descriptions, since the picture is clearly characterized as a feature of nature (a "mechanism", a "phenomenon" being "discovered") and also put on the same footing as observed transitions in condensed matter physics, as we shall see presently.

Thus, students are presented in textbooks with the scientific knowledge that particle masses emerge in some physical process in which spontaneous symmetry breaking, the Higgs mechanism and disappearing bosons feature prominently. The agency behind the process remains ambiguous, as it is variously ascribed by stating that the Higgs "gives mass" to other particles, that particles "eat" each other or that symmetries "spontaneously" break down. The narrative offers readers both a description and an explanation of the existence (and possibly the value) of particle masses which motivates them to regard the Higgs boson as worthy of further investigation. Here I am using the term "explanation" descriptively, in reference to today's particle physics community: As will be discussed more in detail later on, the idea that masses are in need of being explained emerged in high energy physics during the 1950s, and has since then become a widely shared belief in the community. It is not my intention or interest to discuss whether masses should or not be regarded as in need of explanation in a general sense, but rather to analyse how spontaneous symmetry breaking is presented as a (narrative) explanation for the origin of mass in present literature. The narrative is no window-dressing, but the core of the matter, as I shall endeavour to show in the next sections.

7 Electroweak symmetry breaking in Peskin and Schroeder's *Introduction to quantum field theory*

Having discussed the verbal elements of the narrative of electroweak symmetry breaking, let us now look at its mathematical components. We shall do this by following the way in which electroweak symmetry breaking is introduced in the manual by Peskin and Schroeder (1995). In Part One of their book Peskin and Schroeder introduce the basics of quantum field theory, and in Part Two they begin by stating a formal analogy between quantum field theory and condensed-matter physics which, although admittedly not rigorous, "adds to our reserve of knowledge a completely new source of intuition about how field theory expectation values should behave" (Peskin and Schroeder 1995, p. 294). This relation is later invoked to verbally introduce spontaneous symmetry breaking:

> The closest formal analogue to a scalar field theory was seen to be the continuum description of a ferromagnet or some other system that allows a second order phase transition. This analogy raises the possibility that in quantum field theory as well it may be possible for the field to take a non-zero global value. As in the magnet, this global field might have a directional character, and thus violate the symmetry of the Lagrangian. In such a case, we say that the field theory has a *hidden* or *spontaneously broken* symmetry. We devote this chapter to this mechanism of symmetry violation (Peskin and Schroeder 1995, p. 347, italics in the original).

Thus, spontaneous symmetry breaking is introduced by referring to the observable transition of a ferromagnet between magnetized and non-magnetized state or other observable phase transitions. A "global field" is mentioned as an analogous to the magnetic field, and presented as the agency which "violates" symmetry. Both transitions are presented as a special case of a more general, but fully unspecified "mechanism". The authors then go on to explain how "spontaneous symmetry breaking is a central concept in the study of quantum field theory", saying that "it plays a major role in the applications of quantum field theory to Nature" (Peskin and Schroeder 1995, p. 347). Here they mention "applications" in statistical mechanics, weak interactions, strong interactions and the search for unified models of fundamental physics. These are very different phenomena and mathematical structures which are bound together by the narrative of spontaneous symmetry breaking.

After the verbal introduction, a simple mathematical model is presented as example of spontaneous symmetry breaking (Peskin and Schroeder 1995, p. 348). The model ("linear σ-model") is a classical field theory containing a field φ with N components with an N-dimensional version of the double-well potential seen in Fig. 1, whose minimum obtains for:

$$\varphi_{\mathrm{i}}(\mathrm{x}) = 0 \,\mathrm{for}\, \mathrm{i} \neq \mathrm{N}, \quad |\varphi_{\mathrm{N}}(\mathrm{x})|^2 = \mathrm{v}^2$$

Peskin and Schroeder note how the Lagrangian is invariant for rotations of φ in N-space ($\varphi \rightarrow -\varphi$ for the one-component case) and then make a change of field variables:

$$\pi_i(x) = \varphi_i(x) \text{ for } i \neq N, \quad \sigma(x) = \varphi_N(x) - v.$$

When written in terms of the new fields, one (but only one!) minimum of the potential obtains when all N components of the field are equal to zero. Moreover, the redefined Lagrangian is not invariant for an N-rotation of (π, σ). The authors state that the original symmetry is "no longer apparent" and that the one-component model "is the simplest example of a spontaneously broken symmetry" (Peskin and Schroeder 1995, p. 348). The example also shows how the "spontaneous" symmetry breakdown can be linked to mass generation: in the original Lagrangian, the field φ was massless, but the reshuffled Lagrangian contains a term of the form $-\ 1/2\ \mu^2\ \sigma^{\ 2}$ (with μ a constant): a mass term! The π components, however, remain massless and, as Peskin and Schroeder explain, they are an example of the massless "Goldstone bosons" often accompanying spontaneous symmetry breaking (Peskin and Schroeder 1995, pp. 351–352). There is of course little mystery in the apparent symmetry loss here: the original symmetry is still there, but is more difficult to see, because the model is written in terms of the new variables (π, σ). On the other hand, the Langrangian was never invariant with respect to a N-rotation of the new fields, so no symmetry was lost. Moreover, the "spontaneous" transformation has been brought about by an aptly chosen change of variables performed by the scientists.

There is noting new in the remarks I just made, and both philosophers and mathematical physicists have often complained that such "simple examples" are in fact very misleading from a mathematical point of view. However, if we regard spontaneous symmetry breaking as a hybrid construct, it becomes clear why these examples offer a fitting means to express the spontaneity narrative: the symmetry of the "old" fields is not broken, but is not there in terms of the "new" fields. Although the change was here done by hand, the exemplar of ferro-magnetism has already been put into place to suggest that the "reshuffling" of variables at least approximately stands for a physical transition. The suggestion is not mathematically underpinned, neither here nor elsewhere in the volume, but the general effect is what counts—and is what Peskin and Schroeder obtain. The passage from one set of fields to another appears at this level still as a purely formal choice, but its key physical significance is revealed when the fields are quantized, because only when quantizing with respect to the reshuffled fields massive particles appear (Peskin and Schroeder 1995, pp. 352–388). In the quantum case, the value of a field at the minimum becomes its "vacuum expectation value". Peskin and Schroeder explain that, in the quantum case, there is no function which allows that value to be computed, and then proceed to use the mathematical analogy between quantum field theory and solid state physics (here a magnetic system) to show that the double-well potential provides a mathematical and visual means to conceive spontaneous symmetry breaking also for quantum systems (Peskin and Schroeder 1995, pp. 364–369).

Having set the stage of spontaneous symmetry breaking with simpler cases, the authors introduce the Lagrangian of electroweak interactions, and go through the whole reshuffling procedure here, too, to argue that the Higgs field spontaneously breaks electroweak symmetry and generates mass terms for itself and other particles (Peskin and Schroeder 1995, pp. 689–727). This is the Higgs mechanism where, as we saw above, the Goldstone bosons are "eaten" by the vector bosons. In conclusion, Peskin and Schroeder first verbally introduce spontaneous symmetry breaking through the example of the ferro-magnet and by the formal analogy between solid state physics and particle theory. After that, they discuss a simple mathematical model, associating spontaneous symmetry breaking with the reshuffling of a field variable and to the double-well potential. Finally, they embed the simple model in the more complex theory of electroweak forces. The transition between symmetry and asymmetry in electroweak interactions appears thus due to a change of variables performed by the physicists, yet assimilated to the case of the ferromagnet. Thus they implicitly suggest, but do not explicitly claim, that in the case of particle physics, too, the change of variable of the Higgs field can be seen a stand-in for some physical agency bringing about the loss of symmetry, as happens for ferromagnets. It is important to underscore this point because, should we discard the time-based narrative linking by means of the Higgs field the initial, symmetric model to the final, asymmetric one, there would be no reason any more to introduce the symmetric starting point at all. One would then be left only with the non-symmetric model, e.g. the Weinberg-Salam Lagrangian, which is empirically successful, yet does not allow to explain masses as resulting from a now-hidden symmetry of particle forces. Without the historical narrative of how spontaneous symmetry breaking and mass generation obtained, masses remain unexplained. In Wise's terms, masses need to be grown to be explained.[6]

The narrative of electroweak symmetry breaking and mass generation is a complex, hybrid construct in which the reshuffling of a scalar field (the Higgs field) takes up a central, if obscure, physical significance. It is this significant which motivates physicists to regard the Higgs boson as linked to the origin of mass, and therefore worth special study. Without the narrative, much motivation for theoretical and experimental research would be lost. To better understand its features, it will be useful to "grow" its explanation by sketching the key steps of its historical emergence, which coincide with the earliest unfolding of spontaneous symmetry breaking as a more general notion.

8 Spontaneous symmetry breaking's unfolding I: hidden symmetries of nature

From the late 1940s onward, an increasing number of particles exhibiting a broad range of masses and interaction properties were observed, prompting physicists to regard first mass differences, and later on mass in general as something in need of explanation, so that the question of the 'origin of mass' became an increasingly important focus of theoretical research.[7]Various schemes were proposed to account for particle masses and it was in this context that mathematical invariances (exact or approximate) became

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[6] I wish to remind readers that, as discussed in Sect. 5 above, there is at present no overarching mathematical framework for spontaneous symmetry breaking which includes the Higgs mechanism, so that the narrative employed by Peskin and Schroeder cannot be seen as a didactic simplification of some refined mathematical argument.

[7] For an overview of the development of particle physics in the 1950s and '60s see (Brown et al. 1989). For a more specific, detailed discussion of spontaneous symmetry breaking and of the quest fot the 'origin of mass' see (Borrelli 2015c).

increasingly important as a guideline for physical research (Borrelli 2015d, 2017b, 2017c). Slowly, the idea established itself that a small number of distinct fundamental particle interactions existed which could be distinguished from each other both by their relative strength (strong, weak, middle-strong…), and through their invariance properties with respect to transformation of space–time variables and of additional degrees of freedom relevant in micro-physics, such as "isospin". One factor which prompted the interest in symmetries was the realization in 1956–1957 that left–right symmetry, which had so far been regarded as an exact invariance of all fundamental physical laws, was in fact broken by weak interactions. Soon after this discovery two theoretical works appeared which proposed sketchy, but highly influential models of how the laws of nature might be characterized by symmetries which are not manifest in observable phenomena. One model was due to Werner Heisenberg, the other one to Julian Schwinger.

In collaborations with a number of other authors, Heisenberg developed the idea that observed interactions displaying different degrees of invariance could be derived from a single symmetric theory of (unobservable) spinor fields (Dürr 1993). The symmetry reduction ("Symmetrieverminderung") between fundamental equations and phenomena was due to an asymmetric, degenerate vacuum state. Starting from the remark that it was common knowledge that symmetric equations could have asymmetric solutions, Heisenberg assumed that the equations ruling the behaviour of the elementary spinors had more than one minimum energy solutions ("ground level"), and that none of them was symmetric. Each of the solutions corresponded to a different, asymmetric vacuum state:

> It is in no way clear from the beginning that there must be a state "vacuum" possessing all symmetry properties of the initial equations. […] If it turns out to be impossible to construct a symmetrical "vacuum" state, this fact can only be intuitively interpreted in the sense that the asymmetrical ground level is not properly a vacuum, but rather a "world" state which constitutes the basis for the existence of elementary particles.[8]

In Heisenberg's theory the vacuum/world state was endowed with isospin or other particle properties, which could be "detached" ("entzweigt") and attached to a particle (Dürr et al. 1959, pp. 446–447). In a similar way, quantum numbers of decaying particles could "reattach" to the vacuum. Thus, the vacuum/world state took active part in particle phenomena, although it could never be directly observed. The transformations of the vacuum manifested themselves as asymmetries of particle properties, although the whole system (particle + vacuum) remained always symmetric. The narrative of the asymmetrical vacuum/world generating observed asymmetry was central to Heisenberg's theory, but he was never able to fully underpin it with mathematical

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[8] "Es ist keineswegs vom vornerein sicher, daß es auch einen Zustand "Vakuum" geben muß, der alle Symmetrieeigenschaften der Ausgangsgleichung besitzt. […] Wenn es sich als unmöglich erweist, einen voll symmetrischen Zustand "Vakuum" zu konstruieren, so kann dies anschaulich wohl nur so gedeutet werden, daß es sich bei dem unsymmetrischen Grundzustand nicht eigentlich um ein Vakuum, sondern um einen Zustand "Welt" handelt, der die Grundlage für die Existenz der Elementarteilchen bildet" (Dürr et al. 1959, p. 446).

models.[9] Thus, the vacuum/world story cannot be regarded as an "interpretation" of some mathematical structure, but is rather an independent element of a hybrid knowledge construct. The asymmetry of phenomena could be understood in Heisenberg's model only by following step by step their emergence from the activity of the vacuum, so that we can speak of a time-based narrative construct.

While Heisenberg developed his theory of the asymmetric vacuum, Schwinger, too, proposed that the observed variety of symmetries and asymmetries in particle interactions might derive from an underlying, fully symmetric theory. He wrote:

> We suppose that the various intrinsic degrees of freedom [of particles] are dynamically exhibited by specific interactions, each with its characteristic symmetry properties, and that the final effect of interactions with successively lower symmetry is to produce a spectrum of physically distinct particles from initially degenerate states (Schwinger 1957, p. 407).

The term "dynamically" expresses a key element of Schwinger's approach: the notion that, through the process of renormalization, "dynamical" effects would lead to the appearance in the renormalized Lagrangian of terms which were absent from the initial one.[10] Schwinger conceived these effects as in principle computable through perturbation theory, although he did not offer any example of such computations. Schwinger spoke in this sense of a "dynamical invariance property" and a "dynamical origin of mass" (Schwinger 1957, p. 408, p. 415). The latter was particularly important, as he assumed that all particle masses should be regarded a products of an "unknown physical agency" (Schwinger 1957, p. 411). However, since Schwinger did not underpin this verbal statement with a computation of "dynamical" effects, we should regard his theory as a hybrid, narrative construct combining mathematical steps with verbal statements expressing a time-based process.

To represent the dynamical connection Schwinger employed a field ($\Phi_{(0)}$) with charge, spin and isospin equal to zero, possibly associated with an as-yet-unobserved, unstable "σ meson". Schwinger verbally (and only verbally!) argued that, since $\Phi_{(0)}$ had the same quantum numbers as the state of minimum energy, i.e. the vacuum, it could formally have a value different from zero also in that state. Interaction of other fields with $\Phi_{(0)}$ could then lead through further unspecified "dynamical" effects to the appearance of terms not originally present in the Lagrangian. These terms broke some of the initial symmetries, and Schwinger noted that "thus a suitable μ-meson mass constant might emerge" (Schwinger 1957, p. 423). Thus, the scalar field let mass "emerge", taking up the role of the "unknown physical agency" Schwinger had evoked earlier on to explain mass. No mathematical procedure was associated to this verbal statement: the only formulas which appeared were the various terms

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[9] A central tenet of Heisenberg's view was that physically significant predictions could not be obtained from that theory using perturbative expansions, but only by means of nonperturbative techniques. Such nonperturbative tools, however, still largely had to be developed, and this constituted the main problem of Heisenberg's approach.

[10] The term "renormalization" indicates a procedure necessary to extract finite prediction from perturbative computations in quantum field theory. In those computation divergent integrals appear which have to be formally subtracted following a mathematically non-rigorous, yet carefully defined procedure of "renormalization" which was developed around 1950 contemporary but independently by Richard Feynman, Julian Schwinger and Shinichiro Tomonaga (Schweber 1994).

of the original Lagrangian, and those which, like the mass term, allegedly emerged by means of dynamical effects. Thus, the origin of mass could only be understood through following the time-based process of its emergence as expressed in a mixture of formulas and words.

In conclusion, both Heisenberg and Schwinger's models of symmetry reduction could only be understood by following a hybrid, time-based narrative. For Heisenberg it was how symmetric equations gave rise to asymmetric solutions and systems moved form one vacuum to another. For Schwinger it was the dynamical process of mass generation and symmetry breaking leading from the initial to the renormalized Lagrangian. In both cases a historical narrative explanation in Wise's sense was present, yet it is important to note that, at the time, it was not the same narrative in both cases, and the two models were not regarded as equivalent. It was only later on that the two proposals were appropriated and combined by other authors, who transformed both the mathematical and the verbal elements of the narratives.

One of the most popular creations in this direction was the so-called σ-model constructed by Murray Gell-Mann and Maurice Levy (Gell-Mann and Lévy 1960). As we saw above, it was the model which Peskin and Schroeder used as the primary example of spontaneous symmetry breaking in their textbook. In that model, Schwinger's $\Phi_{(0)}$ field, now renamed σ-field, was employed to break a symmetry of strong interactions and, in doing so, mass terms were generated, just as in Schwinger's model. Although Gell-Mann and Lévy had in many ways the same starting and ending formulas as Schwinger's theory, they chose not employ verbal statements to connect them in a narrative of dynamical symmetry breaking, but rather described the passage from the symmetric to the asymmetric model in terms of the real-world activity of the theorists, speaking of "performing a translation of the field variable σ" (Gell-Mann and Lévy 1960, p. 717). Yet their restraint left the question open, why one should perform the translation of variable at all. Here we may think back at what Peskin and Schroeder did in their manual, using the exemplar of ferro-magnetism to present the reshuffling of fields variables as in some (albeit obscure) way linked to a physical transformation in which mass was generated and symmetry spontaneously broke down. Historically, the connection to solid state physics was the crucial step leading to the rise of the notion of spontaneous symmetry breaking as a physical phenomenon. That connection was not yet present when Gell-Mann and Lévy wrote their paper, but was soon brought in by the work of Yoichiro Nambu on superconductivity.

9 Spontaneous symmetry breaking's unfolding II: the connection to solid state physics

Starting point for the analogy between particle phenomena and solid state physics was the so-called BCS-model for superconductivity proposed in 1957 by John Bardeen, Leon Cooper and John Schrieffer (Hoddeson et al. 1992, pp. 560–561; Borrelli 2015d). The phenomenon of superconductivity, in which some metals at very low temperature display almost no resistance to electric current, was known since the early twentieth century, but until the 1950s no satisfactory model for it existed. The BCS-theory proved empirically successful, but was at first met with scepticism because it did not possess the symmetry of electromagnetism which was linked to charge conservation. However, Nicolai Bogoliubov showed how the BCS-theory can be connected to electromagnetism by introducing “quasi-particles” and their “collective excitations”, both of them formal, unobservable constructs (Bogoliubov 1958). All observable predictions of the BCS-theory are symmetric, and asymmetries appear only in descriptions of non-physical quasi-particle and collective excitations.

In 1960, Yoichiro Nambu gave an alternative formulation of Bogoliubov’s model (Nambu 1960). By using methods from quantum field theory, Nambu argued that quasi-particles and their collective excitations were two complementary non-symmetrical manifestations of the fundamental symmetry of electromagnetism. He explained that the symmetrical equations of electromagnetism had both symmetric and asymmetric solutions. The latter could only be computed employing non-perturbative methods and corresponded to quasi-particles and collective excitations. Although both quasi-particles and collective excitations were asymmetric, when they combined to form observable quantities their asymmetrical features mutually compensated to give rise to symmetrical phenomena. Although Nambu’s argument was equivalent to already existing treatments of superconductivity, it was soon regarded as a seminal contribution to a physical understanding of that phenomenon. In his treatment, quasi-particles and collective excitations were presented not as two terms in a mathematical computation, but as two distinct, asymmetric manifestations of hidden (but not broken!) symmetry. Thus, Nambu had framed formal results concerning the theory of superconductivity in terms of apparent loss and recovery of a physically significant symmetry, constructing a hybrid, time-based narrative which, as he soon realized, could be fruitfully employed in the field of particle physics, when linked to the already existing stories of hidden symmetries. One can here use Hartmann’s terminology to claim that Nambu had found a ‘good story’ for the formalism of superconductivity, yet my point is that the narrative was not a crutch or a purely rhetorical device to garner support for the model, but rather a theoretical construct including the formalism and giving rise to new physical meaning.

In 1961 Nambu, together with Giovanni Jona-Lasinio, applied his reflections on hidden symmetry to particle physics. Starting point was the formal similarity between Dirac’s equations for fermions, which describes nucleons, and Bogoliubov’s one for quasi-particles (Nambu and Jona-Lasinio 1961). Nambu and Jona Lasinio assumed that some as-yet-undetected fundamental massless fermions existed, whose Lagrangian possessed a symmetry which was apparently lost in observed phenomena involving massive nucleons and pions. Formally, they explained, nucleons played the role of quasi-particles, while pions were their collective excitations. Nambu and Jona Lasinio referred to Heisenberg, but, while Heisenberg had not been able to deliver computations to support his ideas, they could offer at least a partial analysis of their results using the methods of solid state physics. A key factor supporting Nambu and Jona Lasinio’s reflections was the reference to the case of superconductivity. It was the first step in the establishment of an ambiguous, yet heuristically fruitful analogy between particle physics and solid state physics which would become increasingly elaborate and important in the following decades.

Although from the formal point of view the analogy between nucleons and quasi-particles was rather straightforward, it is important to note that, physically, it implied a radical twist: nucleons were real particles, while quasi-particles were formal constructs that had to be regarded as strictly nonobservable. Electrons in solids, on the other hand, were observable physical entities, but in the analogy they corresponded to hypothetical massless fermions which could probably never be observed. Yet the analogy was very powerful, as it provided an empirically-rooted exemplar to conceive the two levels of the particle world suggested by both Heisenberg and Schwinger: a symmetric, hidden one, and an asymmetric, manifest one. In this sense, the philosophical-historical analysis by Doreen Fraser and Adam Koberinski (2016), which argues that the analogy was purely formal, is factually correct, yet misses an essential epistemic dimension of the process: the construction of new physical meaning through formal analogy and a shared overarching narrative.

Here, too, the vacuum played an important role. Following the formalism developed earlier on by Nambu, the authors noted that the symmetric and asymmetric solutions to the equations of the system were linked respectively to a symmetric vacuum and an asymmetric one:

> The two worlds based on $\Omega^{(0)}$ and $\Omega^{(\mathrm{m})}$ [i.e. the symmetric and asymmetric vacuum] are physically distinct and outside of each other. No interaction or measurement, in the usual sense, can bridge them in finite steps (Nambu and Jona-Lasinio 1961, p. 350).

By the early 1960s a number of hybrid constructs with temporal dimension which narrated different versions of symmetry reduction existed (Borrelli 2015c). A particularly important work for later developments was the one by Jeffrey Goldstone (1961). Goldstone represented the transition from symmetry to asymmetry through a Lagrangian containing a scalar field with a non-zero vacuum expectation value, like Schwinger had done. Although, like Heisenberg and Nambu, he suggested that this field arose from some more fundamental fields, he left the latter undefined. However, around the end of the paper, he tentatively offered a rationale for the existence of the vacuum expectation value by means of the double-well potential in one dimension (Fig. 1), which appeared here for the first time as a representation of symmetry loss. Goldstone offered the same argument found today in standard presentations of spontaneous symmetry breaking: the potential had two minimum energy states and, when quantizing, one of them had to be chosen as representing the vacuum state, breaking the initial symmetry. Goldstone explained: “the theory has two vacuum states, with a complete set of particle states built on each vacuum, but […] there is a superselection rule between these two sets so that it is only necessary to consider one of them” (Goldstone 1961, p. 163).

Thus, the physicists’ choice of one vacuum instead of another was a choice between two physical worlds separated by “superselection rule” forbidding passage from one to the other. The temporal dimension of the relationship between symmetry and asymmetry was superimposed to that of the lived time of the physicist who wrote down the Lagrangian and chose one or the other of its solutions. This is the same narrative we found in Peskin and Schroeder’s discussion. The temporal dimension is necessary to understand the relationship between symmetry and asymmetry. Without the time-based process, one would be left with a lack of symmetry. Knowledge of the origin of asymmetry and mass terms is attained through narrative.

10 Spontaneous symmetry breaking's unfolding III: spontaneous breakdown

In the early 1960s the Higgs mechanism emerged in a process often described in historical literature which need not be discussed here further (Karaca 2013). Here I wish instead to underscore one important factor which further supported the narrative of asymmetry emerging from symmetry: the introduction of the term "spontaneous" and its connection to the so-called bootstrap model of particle interactions, which in the early 1960s dominated high energy theory (Kaiser 2005b, pp. 306–355).

The bootstrap idea, as endorsed especially by Geoffrey Chew, was that all particle masses and couplings emerge in a self-consistent way from (so far unknown) fundamental equations in which all parameters are set equal to zero. The term "self-generation" was often employed to describe the coming-to-be of particles properties. The connection between bootstrap theory and the transition from symmetry to asymmetry was made in a paper by Marshall Baker and Sheldon Glashow entitled "Spontaneous breakdown of particle symmetries" (1962), where symmetry breaking was labelled "spontaneous" for the first time. For Baker and Glashow this term expressed the spontaneous generation of the symmetry breakdown in the spirit of the bootstrap theory. They wrote: "Mass is completely dynamical; mass splittings and 'approximate symmetries' result from nonsymmetric solutions to a fully symmetric Lagrangian theory" (Baker and Glashow 1962, pp. 2462–2463), and concluded the paper stating: "we have shown the possibility that the fundamental interactions can generate themselves from a 'bootstrap mechanism' in a theory where the bare coupling constants vanish" (Baker and Glashow 1962, p. 2470). In Baker and Glashow's narrative, the symmetry explicitly became the agent behind its own demise by spontaneously breaking down, just like in the bootstrap theory charges and masses generated themselves. Later on, the bootstrap idea fell from grace among high energy physicists, yet the term "spontaneous" remained as an important verbal expression of a new, special kind of relationship between symmetry and asymmetry.

In the 1960s the notion of spontaneous symmetry breaking started being extended to phenomena different from mass generation and superconductivity. Solid-state physicist Philip Anderson was among the first ones to point out that the formal analogy between superconductivity and particle theory could be extended also to other systems - notably ferro-magnetism, which would later become the poster child of spontaneous symmetry breaking (Anderson 1963). This and other exemplars were crucial for supporting narratives of dynamical effects and spontaneous breakdown in the absence of full-fledged mathematical models implementing them. Today, they form an essential component of the construct spontaneous symmetry breaking.

In the late 1960s, the powerful narrative of a "third way" between symmetry and asymmetry led both Steven Weinberg and Abdus Salam to suggest that spontaneous symmetry breaking might ensure the renormalizability of a unified theory of electromagnetic and weak interactions (Borrelli 2018). When in 1971 Gerhard 't Hooft actually proved the renormalizability of the Weinberg-Salam model ('t Hooft 1997), this results was seen as supporting both quantum field theories and narratives of hidden or spontaneously broken symmetries of nature. Ironically, though, the success of quantum field theory also meant the final demise of the bootstrap idea which had motivated the narrative of "spontaneity" through the self-generating nature of all particles. With time, the Higgs fields was not regarded any more as a mere effective representation of the dynamical, self-generating workings of nature, but rather as a fundamental physical instance in its own right. Yet at the same time its epistemic significance continued to rest upon the idea that there was behind it a "mechanism" of spontaneous symmetry breaking providing a privileged path to modelling nature. In this context, a reshuffling of variables in the Lagrangian came to be perceived as sufficient to represent mathematically a physical phenomenon of mass generation to be further investigated. Spontaneous symmetry breaking could and still can be understood only by going through the reshuffling of variables as representing a (hidden) process of nature.

11 Spontaneous symmetry breaking's unfolding IV: cosmological epilogue

By the middle of the 1970s the spontaneous breakdown of electroweak symmetry and mass generation had become a cornerstone of particle physics. So far, however, the time dimension in which masses were generated was seen as distinct from lived time, but soon a new version of the narrative came to be which obtained in real time, albeit in a very far past, shortly after the Big Bang. In the 1970s, particle physics and cosmology came nearer to each other because of a series of institutional, pedagogical and theoretical factors (Kaiser 2006). In this context, the "mass generation" through the Higgs came to be conceived as an event which had taken place in the early history of the universe. The earliest suggestions of a cosmic symmetry breaking came from Soviet authors, but the idea was made popular by Steven Weinberg in a paper published in 1974, where he wrote:

> The idea of a broken symmetry was originally brought into elementary-particle physics on the basis of experiments with many-body systems [...]. It is natural to ask whether the broken symmetries of elementary-particle physics would be restored by heating the system to a sufficiently high temperature, in the same way as the rotational invariance of a ferro-magnet is restored by raising its temperature (Weinberg 1974, p. 3357).

Verbally underscoring the similarity between phase transitions and electroweak symmetry breakdown, Weinberg stated that, if the latter, too, were reversible, this would provide evidence that local gauge symmetries were no pure mathematical constructs—an important "philosophical" result (Weinberg 1974, p. 3359). He also speculated that the phase transition in the particle realm might have taken place in the "hot" phase of Big Bang cosmologies, a hypothesis which he included in his widely read popular exposition of cosmology *The first three minutes*, where he compared the symmetry breaking in the cooling universe to the formation of ice crystals in freezing water (Weinberg 1977, pp. 142–146).

In the early 1980s the "electroweak phase transition" of the universe became the key ingredient of Allan Guth's theory of cosmic inflation, and here, too, Weinberg apparently played a role in peddling the idea (Earman and Mostarin 1999). The Higgs phase transition remains today part of standard cosmology, though not necessarily in connection with inflation (Sarkar 2008, pp. 392–394). The mathematical arguments supporting it remain non-rigorous and rely once again on the formal analogy between particle and solid state physics. In the analogy, solid state physics temperature corresponds to the imaginary time-variable of particle physics: the temporal parameter changes, but the narrative stays the same. In his manual of quantum field theory, physicist Anthony Zee describes the status of the analogy in the physical community with these words:

> Surely you would hit it big with mystical types if you were to tell them that temperature is equivalent to cyclic imaginary time [...]. Some physicists, myself included, feel that there may be something profound here that we have not quite understood (Zee 2010, p. 289).

Through my analysis I hope to have demonstrated how important hybrid theoretical constructs are in scientific practice, and in particular how narratives function in that context as epistemically autonomous components occupying a privileged yet rarely acknowledged position. The narratives are not expendable window-dressing, but are necessary to express scientific knowledge. When high energy physicists talk about the Higgs boson, they are not only referring to mathematical formulas and experimental results, but are always also talking about the hybrid narratives expressing their scientific conviction that something profound is linked to those formulas and results, and allows to narratively understand mass as dynamically generated by the Higgs field in a spontaneous symmetry breakdown. As noted above, this conviction often goes hand in hand with a belief that in some future a logical-mathematical theory of spontaneous symmetry breaking may come to be, and that the narrative only constitutes a place-holder for it (Borrelli 2015b, p. 18, p. 21). Yet, as I believe to have shown, the hybrid narrative at present fulfils the function which the (so far non-existent) logical-mathematical construct might take over, and there are also no indication that such a construct may ever emerge.

12 Conclusions

The notion of spontaneous symmetry breaking as a “third way” between symmetry and asymmetry slowly emerged from the late 1950s onward as a hybrid narrative of how asymmetry may arise from symmetry, without the symmetry being lost, but only somehow hidden at a more fundamental level of reality. As I have endeavoured to show, the ambiguous, and somehow even contradictory character of spontaneous symmetry breaking is not due to misleading interpretations of clear-cut mathematical structures, but rather constitutes a primary feature of the notion and is essential for its epistemic status as an explanation for particle masses and many other physical observations. It is a narrative historical explanation in the sense discussed in Sect. 2: knowledge whose acquisition requires physicists to go through the step-by-step mathematical, verbal and visual procedure of transforming a symmetric model into an apparently asymmetric one. Although from a practical point of view it would be just as well to start from the asymmetric model and never consider the allegedly hidden symmetries, in this way the explanatory potential which spontaneous symmetry breaking displays in current scientific practice would be absent.

Today, an overarching narrative of spontaneous symmetry breaking is shared by scientists working in different areas of physics, as well as of other natural sciences. This umbrella notion derives its epistemic potential from simple physical examples, such as falling rods, and mathematical models, like the double-well-potential, which working scientists may connect to the complex phenomena and mathematical constructs they deal with in their research. One implementation of spontaneous symmetry breaking is the spontaneous breakdown of electroweak symmetry in the Standard Model and the relevant generation of particle masses, which I have discussed in some detail above.

The analysis of how electroweak symmetry breaking and mass generation are presented in quantum-field-theory manuals has shown how the hybrid narrative of spontaneous symmetry breaking today provides for the physics community an explanation of mass generation, which in turn motivates physicists to regard the Higgs field as holding the key to the question of the origin of mass. The case of electroweak symmetry breaking is of particular importance not only because it is an instance of spontaneous symmetry breaking which has so far defied philosophers' attempts at an exhaustive and comprehensive logical-mathematical analysis, but especially because it historically played a key role in the formation and establishment of spontaneous symmetry breaking as a physical notion. In particle physics of the late 1950s and '60 s various elements combined into the narrative of spontaneous symmetry breaking linked to the appearance of particle masses, and in the 1970s this construct took centre stage, as theorists came to regard it as a (narrative) explanation of the masses of gauge bosons, as well as of other particles. Following the unfolding in time of spontaneous symmetry breaking provides a historical narrative understanding of its present features which a purely logical-mathematical analysis cannot deliver.

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