More is different: Broken symmetry and the nature of the hierarchical structure of science

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Classical

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P.W. Anderson (with an introduction by Jeffrey A. Goldstein)

Reduction, construction, and emergence in P. W. Anderson's "More is different"

> *The central task of theoretical physics in our time is no longer to write down the ultimate equations but rather to catalogue and understand emergent behavior in its many guises...*
>
> —Laughlin and Pines (2000)

P. W. Anderson's classic paper was selected for republishing in this issue for several reasons. First, because it presages several of the major constructs underlying the contemporary study of complex systems. Second, that the central focus of the paper is on what later became known as "emergence", one of the dominant themes of our classic papers. Third, because Anderson was one of the founders of the Santa Fe Institute in the mid-eighties where his earlier formulation of ideas like spin glasses, complex optimization, simulated annealing, evolution on rugged landscapes, collective excitations, and spontaneous symmetry breaking were taken up by researchers coming from diverse disciplines (see the very informative interview of Anderson conducted by Alexei Kojevnikov, 1999, 2000; and Anderson's webpage at Princeton University where as an nonagenarian, he is still active as a professor emeritus, Anderson, nd).

Although Anderson's ideas on emergence had long been a rich source of inspiration for me, the more I read in preparing this introduction, the more startled I became by the vast breadth, depth, and prescience of his work. The era of neo-emergentism which we are passing through now—*Emergence: Complexity & Organization* being an emblem of the kind of themes explored in contemporary work into complex systems—has been marked by a movement away from the more speculative character of proto- and mid-phase emergentism; a shift largely made possible by innovative tools of empirical research and experimental design, as well an impressive array of sophisticated mathematical and computational perspectives. Anderson's paper "More is different" can be viewed as a primer of what a large part of the study of complex systems would later include.

That his early work extends out beyond partisan issues in solid state physics can be appreciated by considering the fact that Anderson's championing of the notion of spontaneous-symmetry breaking (SBB), although in this paper as a general "mechanism" for the processes of emergence, had originally been offered by Anderson to Peter Higgs and other progenitors of the now notorious Higgs Particle as an explanation for mechanism by which the Higgs particle acquires mass. In fact, many physicists have urged that the name of this momentous discovery at CERN be changed to the "Anderson-Higgs" mechanism, an appellation that can already be found in many influential papers in the field (see Moffat, 2014). Although the idea of SBB has the advantage of being a way of accounting for processes of emergence in a theoretical realm all-too-often neglecting the whole issue of process (see Goldstein, 2013b, 2014), it is not an idea coming without a certain measure of obscurity and even ambiguity as to what it ultimately amounts to explanatorily, a topic I will say more about below.

It is worthwhile to recognize that Anderson's paper was written within the context of an ongoing, and at the time vituperative debate, between particle physicists, on the one hand, with their highly effective Standard Model of the so-called fundamental forces (such as weak, strong, electro-magnetic on up to their final unified "theory of everything") and mostly negative attitude towards emergence in the past, and solid state or condensed matter physics, on the other hand, whose investigations into phenomena such as phase transitions, superconductivity, ferromagnetism and so on required the introduction of constructs and methods pertaining to higher scale dynamics, organizing principles, and emergent collectivities. Two of the chief antagonists in this conceptual battle have been the Nobel Laureate particle physicist Steven Weinberg known for his work on the unification of the electro-magnetic and the weak forces and Anderson who of course is another Nobel Prize winning physicist (on this dispute see Silberstein, 2009). This clash shows itself in this classic paper through Anderson's attack on strident reductionism, of which Weinberg has long been a vigorous proponent, along with Victor Weiskopf whose reductionist stance involving extensive and intensive explanatory strategies Anderson takes on in his paper.

Later, Anderson (2001) looked back and saw those early times as when he had become fed up with the denigration he believed the particle physicists were aiming at solid state and other physicists. He pointed out that most physicists were conducting research in what he considered a harder field than particle physicists; a "frontier between the mysterious and the understood: the frontier of complexity...where the watchword is not reductionism but emergence." Of course I don't know the inside story, but the more I have read about this acrimony the more I see how much ordinary old ego has been involved in these so-called theoretical debates in physics. Perhaps there is a touch of envy on both sides, for example, the SSB notion that Anderson put forward very early had a big influence in Weinberg's later work. And then there's the rancorous story of how Anderson opposed Weinberg's plea for the building of a super-duper collider in Texas before the Large Hadron Collider was built at CERN, with Anderson's side winning-out of course.

In his classic paper, Anderson did not then, nor does he now, completely renounce reductionism as such as if he were calling for an embrace of some kind of "holism". Instead his criticism is of the totalizing type which he describes through his notion of the "constructionist hypothesis": "The ability to reduce everything to simple fundamental laws does not imply the ability to start from those laws and reconstruct the universe". Strident reductionists should give fealty to the contructionist hypothesis since they hold that what the reductionist approach discovers about the foundational dynamics, formulated as foundational equations (e.g., through the formats of canonical Lagrangians and Hamiltonians), are what's ultimately causing the system under scrutiny to be and act as it does. From such a perspective, if you know the foundational equations you certainly should be able to reconstruct the whole thing from the foundation up.

For Anderson, though, the constructionist hypothesis does not and cannot live up to its promise since the reduction on which it is based had not included the equally fundamental fact that "entirely new properties" arise at each new level of complexity and scale (scale here is not simply a synonym for level of resolution). It is these "entirely new properties", which later would be termed "emergent properties", which require the introduction of a new formulation, the order parameter, which is the metric of the new order expressed in the emergent properties. The notion of an order parameter went back to the great Russian physicists Lev Landau and Vitaly Ginzburg in their "phenomenological" models of such emergent phenomena as superconductivity. Later, Hermann Haken, and to a lesser extent Ilya Prigogine, took up the mantle of order parameter in the Synergetics approach and the Far-from-equilibrium approach to understanding collective or coherent phenomena (dissipative or partly ordered structures as one of the prototypes of emergence). The very fact of needing a new variable like an order parameter to formulate these collective phenomena shows that there was something seriously lacking in a strictly reductionist strategy.

By the way, it seems that Anderson was not particularly fond of the work of Prigogine, a sentiment that he was not bashful to frequently and publicly announce. According to Anderson (cited in Hartman, 2000), although Prigogine's dissipative structures did indeed consist of new patterns, Anderson held such patterns to be only temporary modifications that did not possess enough permanence to account for enduring emergent phenomena. Furthermore, Anderson doubted that in the far-from-equilibrium conditions within which dissipative structures arise, there was a well-defined function behaving as an order parameter. One can surmise, however, that besides genuine scientific disagreement, one might see not a little ego involved here as well: they both received Nobel Prizes in 1977 with Anderson in physics and Prigogine in chemistry; some have held that it was not uncommon for Prigogine to strut his ideas around as solving deep issues in quantum mechanics, cosmology, and metaphysics without a great deal of experimental support for their generality; and Anderson was well-known as a curmudgeon whose blunt hammer could land on subjects about which he did not know that much.

Superconductivity and spontaneous symmetry-breaking

Anderson's push for emergence and allied concepts for explaining collective phenomena has had a deep and lasting effect in many fields where complexity constructs have been applicable. Usually, this application of emergence also includes the theoretical framework of spontaneous symmetry breaking as how emergence comes about. In the BCS theory of superconductivity of 1957 which led to the award of a Nobel Prize to its three theorists—John Bardeen, Leon Cooper, and Robert Schrieffer—one does find a micro-level theory on the emergence of the radically novel feature of resistance-free electrical current in a metal taken to a very low temperature, an unexpected micro-level pairing of electrons (called Cooper Pairing). However, the

Cooper Pairing effect on the micro-level is only a doorway to the generation of a macro-level collection action, a macro-level "quantum wave", a surprising collectivity that seems to go against what the foundational equations would suggest since electrons are supposed to repel and not attract each other because they have the same charge.

This puzzle was eventually solved after thirty years of intense investigations by some of the world's most eminent physicists and chemists who already knew most of the foundational equations that would be operative, and one of the keys to this solution would be SBB. Taking a complicated and convoluted story and boiling it down intentionally to a simplistic model: first, the metal has to have a unique constitution whereby at normal temps it is *not* a good conductor of electricity. This necessity means that the mechanism at work in superconductivity cannot be explained as an extension of an already existing metallic property. Second, very low temperatures are required, eventually realized as a necessary way that the expected thermal noise in the system could be diminished to the extent that allowed something unique to take place. Then, once this noise was low enough, electrons could pair up against expectations through the intermediary actions of phonons, quasi-particles or "collective excitations" composed of vibrations of the atoms on the metallic lattice structure. As the thermal noise decreased, the electrons could be attracted to the phonons which played the role as kind of marriage brokers which then passed the attraction on to another electron. Of course, there is a lot more going on here concerning the role of the phonons and the forming of layers of electrical flow and the emptying out of the magnetic field and so forth. What is important for appreciating the role of SBB is that the collective "quantum wave" of the electron pairs became a kind of order parameter representing a breaking of the original gauge symmetry, a feat accomplished by the low temperature.

In two quite illuminating but difficult papers on the SBB in emergent superconductivity, the philosopher of science Margaret Morrison (2006, 2012) has called attention to how it is indeed tempting to interpret the Cooper-pairing scenario as an example of an effective reductive explanation. Yet, Morrison goes on to demonstrate how a close scrutiny of the foundational equations with their accompanying gauge symmetry simply cannot predict the ensuing emergent novelty. One reason has to do with the property of universality, which refers to how a replacement with a completely different metal with its different micro-level, i.e., foundational, composition can yield the same phenomena of superconductivity (for more on universality and this view of emergence, see Batterman, 2005).

According to Morrison, it is because Cooper pairs only manifest at the critical low temperature required, their presence demonstrates that the system has undergone a phase transition which calls into play a novel order parameter (and I might add, not just more criticalizations of any control parameters) measuring the amplitude of this emergent macro-level collective quantum wave. She argues that it is possible to derive the exact, emergent properties of the superconductive phenomena by empirical measure of the ostensive phenomena and not through appeal to the foundational Lagrangian and its symmetry.

It is a general principle in physics that systems seek to be in the most stable state. A simple example is the instability of a pencil balanced on its end. A very slight movement of a table underneath will perturb this instability so the pencil falls down and assumes the much more stable condition of lying horizontally on the table. It would take an appreciably much stronger jolt to get the horizontally lying pencil to move and maybe fall off the table. In a superconducting metal, at low temperatures the Cooper pairing and collective electron flow is an unstable energy condition. The symmetry of the original equations is still being conformed with, but it is now in an unstable state. A more stable state is for the macro-scope wave function of the collective electrons to form. It has been said that the context of the appearance of this emergent phenomena at the low temperature "solves" its governing equations by assuming a more stable dynamics. The stability of the asymmetric emergent phenomena in the system's new context trumps the unstable but symmetric equations it is supposed to follow. As stated by the prominent quantum field theorist and historian of physics, Silvan Schweber (cited in Mainwood, 115) that Anderson's main message with his use of SBB:

> *... it is not enough to know the 'fundamental' laws at a given level. It is the solutions to equations, not the equations themselves, that provide a mathematical description of the physical phenomena. 'Emergence' refers to properties of the solutions in particular, the properties that are not readily apparent from the equations.*

The micro-level explanation utilizing foundational equations with their original symmetry is not wrong—rather the symmetry is "hidden" behind the appearances of the observed non-symmetrical but stable condition. Thus, at higher temps, the stable states show the symmetry of the Hamiltonian, e.g., with no regular spatial arrangements (special spatial arrangements break the symmetry—compare a circle with a circle in which a pod is forming aimed in some preferred direction). To be sure, the construct of SBB has not struck only a few eminent physicists as somehow fishy in the sense of its peculiar ability to ad hoc explain via the difference between equations and their solutions and an appeal to hidden and revealed symmetries. We'll come back to this seemingly explanatory legerdemain later in this introduction.

A helpful discussion for what is going on in the case of this bi-fold explanatory strategy, contrasting equation and solution, can be found in a very accessible paper (Laughlin & Pines, 2000) authored by Robert Laughlin, another Nobel Laureate and David Pines, Anderson's eminent nonagenarian colleague and Santa Fe Institute pioneer (see references for the webpage of the Institute for Complex Adaptive Matter founded by Pines). They distinguish between *knowing the rules operative in the actual, manifested domain* of the emergent phenomena (calling such collectivities "protectorates" because of their independence from micro-level fluctuations) and *knowing the rules of the foundational equations.* A close examination of the emergent protectorates reveals they are governed by emergent rules which cannot be determined by the foundational equations. Rather, one needs experiment, measurement, and how experiment and measurement reveals the emergent context and its new asymmetric rules.

Furthermore, according to Laughlin and Pines, the emergent protectorates require "higher organizing principles" which are not discernible at the level of the foundational equations and are consequently typically downplayed by reductionist scientists:

> *The fact that the essential role played by higher organizing principles in determining emergent behavior continues to be disavowed by so many physical scientists is a poignant comment on the nature of modern science. To solid-state physicists and chemists, who are schooled in quantum mechanics and deal with it every day in the context of unpredictable electronic phenomena such as organogels, Kondo insulators, or cuprate (high temperature) superconductivity, the existence of these principles is so obvious that it is a cliché not discussed in polite company. However, to other kinds of scientist the idea is considered dangerous and ludicrous, for it is fundamentally at odds with the reductionist beliefs central to much of physics. But the safety that comes from acknowledging only the facts one likes is fundamentally incompatible with science...* (Laughlin & Pines, 2000: 30).

Finally, concerning the unpredictability of higher-level emergent collective phenomena from foundational equations, Gu *et al*. (2008) offer a very sophisticated updating of Anderson's early work (using the Ising model formulations of collective phenomena) within the context of findings from mathematical logic and computational complexity theory concerning undecidability in formal systems (in a previous paper, Goldstein, 2014, I tried to show a related way of linking undecidability, uncomputability, and the emergent gap). The Gu *et al.* paper demonstrated how in the field of solid state physics, systems manifesting emergent collectivity that is observable macroscopically, the defining properties or behaviors "cannot be deduced from first principles ...[so that] from knowledge of the lattice Hamiltonian ... any macroscopic law that governs these quantities must be logically independent of the fundamental interactions" (on a closely related connection of physics with undecidabilty see Moore, 1990)

The process of emergence, SBB, and the need for contextual exploration

Recently (Goldstein, 2013a, 2013b, 2014), I have called attention to what I see as a troubling lack of inquiry into how emergence works, i.e., the mechanisms, processes, and operations possessing the requisite potency for generating emergent phenomena with their unique and radical properties. This trend can be noticed not only in critiques of the idea where it might be expected because emergence itself is denied, but also somewhat surprisingly in strong endorsements of the idea. For instance, in off-handed remarks about emergence happening on a higher level out of interactions on a lower level, not much of interest at all is given. Such a deficiency can damage the credibility of the idea which I think has happened in the case of the questionable and strikingly lightweight co-optations of the idea by the particle physics and cosmology community.

Anderson though does offer a "mechanism" or process by which emergents emerge, namely, spontaneous symmetry-breaking as described above in the emergence of superconductivity. To better appreciate what SSB can offer to an understanding of the processes of emergence, it needs to be distinguished from other types of symmetry-breaking. One type, sometimes called "explicit" symmetry breaking (see, Anderson, 1984) involves adding a symmetry-breaking a term that is added to the fundamental equations, e.g., a term representing an operation that leads to a particular spatial direction thereby breaking an initial state when no special spatial direction is chosen. Related is the kind of symmetry breaking associated with bifurcation in a dynamical system occurring when a bifurcation parameter reaches a certain threshold, e.g., a bifurcation parameter which leads to a criticalization so that symmetry breaks in the so-called "one hump" (quadratic) maps studied by May and Feigenbaum and which inspired so many aspiring complexity buffs in the nineteen eighties. It has not been uncommon for approaches to emergence to include the arising of new attractors at bifurcation thresholds.

However, the SBB that Anderson is known for and that he talks about in this classic case is a stranger beast. Above we came across such descriptors as "hidden" and "apparent", equation versus solution, gauge symmetry versus actual ostensive manifestations of emergent phenomena, stable versus unstable, and others. Of course, there is nothing particularly misleading by such ways of interpreting SBB and thereby how emergence works. But what have we really added to our store of understanding through these metaphors? The problem is not that we are resorting to metaphors, since all explanations at some point employ metaphors, a "nucleus" is a metaphor, "electric current" is a metaphor, "string" is a metaphor. Instead, the problem is more like that something has occurred and yet one cannot quite get a conceptual grasp, and what is offered instead is something as vague and non-forthcoming as "hide and seek." In an important sense the supposed symmetry of the foundational symmetries have to break since the apparent symmetry was nothing more than superficial anyway: "a way for nature to say, 'your theory of symmetry is wrong in the first place'" and this is related to kind of epistemological filtering (this way of putting it is thanks to Kurt Richardson, Managing Editor of *E:CO* and complexity-oriented physicist himself). I've had the sense of a kind of conceptual sham being perpetrated, but not intentional, rather out of ignorance and failure to see that at some point the mathematical predictability has to be seen as not the essential fundamental nature of nature.

I propose thinking about the difference between symmetry and the ensuing broken symmetry as like the shift in "aspect seeing" of the famous "duckrabbit" drawing appealed by Wittgenstein in *The Philosophical Investigations*. From one perspective, the drawing appears as a duck's bill with the duck's eye facing to the left, while from the other perspective, the drawing shifts to the duck's bill now having been transposed to a rabbit's long ears and the rabbit's eye (the same eye but direction switched) facing to the right. Does this mean it is all totally arbitrary as to which aspect one is seeing? I suggest no, since the sequence of the aspect-seeing manifests the temporal unfolding of the phase direction from symmetry to symmetry breaking. One starts, say, with the duck and assumes there is the same duck mirrored looking in the opposite direction. But then the aspect shifts and one sees the rabbit thereby realizing there is another perspective, but to see this perspective demands one breaks the symmetry of the presumed mirror image of the duck. In a sense, this new aspect can only be discerned through the recognition of the entirely new properties which is occasioned by experiment, measurement, and the subsequent new context. I believe Anderson would go along with this since he remarks in this classic paper that at some point even symmetry breaking needed to be overtaken by considerations of increasing complexity, since it is complexity involved with entirely new properties that is revealed as we ascend the hierarchy of the special sciences. Each of these new sciences are investigating new levels with their own new foundational stories which underlay that "basically new types of behavior can result."

Much of this, in my opinion, has to do with the explanatory gap that nearly all accounts of emergence claim for emergence. This is the gap of predictability, deductibility, computability. In terms of SBB this is the gap of the symmetry-breaking, this is the gap of not able to go from the foundation to the emergent outcome. As I have pointed out in Goldstein (2014). In fact, upon first coming across it, it can evoke a sense of trickery or sham, that it is postulated to have occurred and yet one cannot quite see how. This sentiment is related to how SBB talks about a hidden symmetry associated with the foundational formulation. At high temperatures, the stable state is the one with the foundational equations symmetries. The strange thing is that the foundational equations, and the symmetries associated with them, remain even with the transition occurring at the very low temperature. At that point, however, for the system to remain stable (which seems to be the stronger pull) these symmetries break, but breaking doesn't mean they are deleted.

The self-transcending construction hypothesis

Anderson, not content to leave his paper with just the negative message of decrying reductionist science, also emphasizes that "at some point we have to stop talking about decreasing symmetry and start calling it increasing complication.. with increasing complication at each stage, we go on up the hierarchy of sciences". Today, of course are more likely to use the term "complexity" for what he meant by "complication". Furthermore, he shifts the concept of fundamental from referring only to one fundamental set of laws at the level of the tiniest micro-scopic to the recognition that each level has its own set of foundational dynamics, behaviors and thereby laws of the new dynamics at that new level.

I propose following this sentiment by relooking at his constructionist hypothesis by means of inverting it and adding to what we normally take as constructions, crucial aspects of the entirely new properties discovered at each new level. In previous work, I have termed these emergent generating constructions "self-transcending constructions", the qualification of "self-transcending" indicating the unique nature of this kind of construction: they must be capable of producing the requisite emergent novelty at each new level. For example, superconductivity, as an actual real world phenomena, results from self-transcending constructional processes. In this perspective, the symmetry breaking of course remains, but the emphasis instead is on how the foundational equations are combined with the numerous other factors in the facilitation of the radical new properties of the ultra-cold metal to the outcome of an STC. Most important is that observation, context, and measurement are coupled with whatever can be gleaned from foundational questions. Insight into what will need to be included in the formulation of the self-transcending construction will require, in each instance of experiment that discovers "new laws, concepts, and generalizations", "inspiration and creativity".

If emergence eludes explanation via strict reductionism, then the specific ways such systems elude reduction makes up the crucial factors that must be added to how the self-transcending constructional process works. This is a call to envision constructional processes that somehow or other manage to incorporate what reduction on its downward trajectory to the foundation has left out, that is, the entirely new properties at each level of scale or complexity. This very different type of construction would need to be able to, *de facto*, contain those operations, processes, and constraints able to construct emergent phenomena with their radically novel properties. Emergence is quite different than ordinary change and the ordinary novelty that results from ordinary change. That is why its construction needs to be radically different than ordinary change processes.

Since processes of constructions are all about the building-up of structure, pattern, organization, ordering, self-transcending construction consist of what possesses the potency for the building-up of *novel* structure, pattern, organization, ordering. This implies that processes with this potency must have a capacity for continually taking extant structure and subjecting it to operations which transform this structure to now have "entirely new properties." This seems a tall-order and, as I have tried to indicate in past work, our imaginations have not been shaped to easily accept its possibility. That is why in previous papers I have offered examples from mathematics that specifically demonstrate in which kinds of operations that self-transcending constructions consist. That was meant to pry open the imagination and not that the self-transcending constructions at work in the instances of emergence all around us must conform to such obscure mathematics. Instead, it is a call to attend to what Laughlin and Pines say in the opening quote to this paper, that it is time to shift our attention away from the foundational equations and focus on observation and context.

In fact, the challenge facing the conceptualization of a self-transcending construction contains something akin to a paradox (as I've said before, a "flirtation with paradox" and not an embrace): what is being constructed via operations on substrates at their own level must at the same time transcend the level of these substrates since the emergent phenomena as "protectorates" being constructed are independent of the lower more micro-scopic level. These emergent protectorates possess what can be taken as the opposite characteristic to that found, e.g., in chaotic attractors with their sensitivity to initial conditions: emergent protectorates must be in an important sense insensitive to initial or micro-level conditions or they would be capable of enduring. One response to this challenge is that even though emergent phenomena are built out of lower level substrates, Ganeri (2011) has pointed out the key operation of transformation, i.e., the substrates or part are so transformed that the resulting emergent is constituted by what are effectively radically novel parts no longer tethered as before to their roots on the original level. The independence of emergent protectorates doesn't happen by magic or creation ex nihilo but by the action of self-transcending constructional operations on phenomena below.

By the way, certain readers might find the working out of similar ideas but in a very different mathematical framework, that of category theory (Ehresmann & Vanbremeersch, 2007). There emergence can be likened to the mathematical object of a "category" on which four prototypes of construction are operated: absorption, elimination, binding, and classification (or association). The self-transcending construction leading to the emergent phenomena of the category is understood as a "complexification" whose formation has been the result of so much intermingling, the substrates of the formation "cannot be untangled", Chapter 4 especially).

Conclusion

The anti-reductionist stance described by Anderson in this classic paper as well as his later work is obviously not some uninformed and poorly thought-out gibberish condemning science that unfortunately one finds too much of these days, even among those who should definitely know better. Rather it an attempt, on the part of a celebrated Nobel Laureate and coming-out of his seven decades of research and theorizing, to lay-out serious limitations in *the thought-numbing variety of strict reductionism.* Furthermore, the position taken in support of the idea of emergence and its application in the sciences did not emanate from any preconceived scientific or philosophical commitment to the idea—Anderson has intimated in interviews that he had not even known of the word "emergence" before he wrote this classic (which is why one cannot find the word used in the paper). It was only later after his paper became more well-known that complexity/emergentist accolytes contacted him, inviting him to conferences and to contribute papers that he felt himself drawn to a complexity perspective. It was only a dozen years later that the Santa Fe Institute was founded for complexity oriented research and theorizing and Anderson was one of its chief intellectual architects.

One can read about Anderson's own work as well as the history of the SFI in many places. Here, I would like to very strongly recommend one of his recent works, *More and Different: Notes from a Thoughtful Curmudgeon* (Anderson, 2011) a fun and enlightening read replete with popular writings, essays, anecdotes, book reviews, and so on covering an incredible and prolific career and life. Anderson was never one to be bashful in expressing his viewpoints, a curmudgeon not afraid to call out when the Emperor is truly not wearing any clothes. Without even knowing it, without even having to struggle with difficult technical ideas, after reading this book I felt that an enormous amount of information was mysteriously transmitted to my brain. I think it had to do with the book being a peek into the thinking of a truly great thinker.

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More Is Different

Broken symmetry and the nature of the hierarchical structure of science.

P. W. Anderson

The reductionist hypothesis may still be a topic for controversy among philosophers, but among the great majority of active scientists I think it is accepted without question. The workings of our minds and bodies, and of all the animate or inanimate matter of which we have any detailed knowledge, are assumed to be controlled by the same set of fundamental laws, which except under certain extreme conditions we feel we know pretty well.

It seems inevitable to go on uncritically to what appears at first sight to be an obvious corollary of reductionism: that if everything obeys the same fundamental laws, then the only scientists who are studying anything really fundamental are those who are working on those laws. In practice, that amounts to some astrophysicists, some elementary particle physicists, some logicians and other mathematicians, and few others. This point of view, which it is the main purpose of this article to oppose, is expressed in a rather well-known passage by Weisskopf (*1*):

> Looking at the development of science in the Twentieth Century one can distinguish two trends, which I will call "intensive" and "extensive" research, lacking a better terminology. In short: intensive research goes for the fundamental laws, extensive research goes for the explanation of phenomena in terms of known fundamental laws. As always, distinctions of this kind are not unambiguous, but they are clear in most cases. Solid state physics, plasma physics, and perhaps also biology are extensive. High energy physics and a good part of nuclear physics are intensive. There is always much less intensive research going on than extensive. Once new fundamental laws are discovered, a large and ever increasing activity begins in order to apply the discoveries to hitherto unexplained phenomena. Thus, there are two dimensions to basic research. The frontier of science extends all along a long line from the newest and most modern intensive research, over the extensive research recently spawned by the intensive research of yesterday, to the broad and well developed web of extensive research activities based on intensive research of past decades.

The effectiveness of this message may be indicated by the fact that I heard it quoted recently by a leader in the field of materials science, who urged the participants at a meeting dedicated to "fundamental problems in condensed matter physics" to accept that there were few or no such problems and that nothing was left but extensive science, which he seemed to equate with device engineering.

The main fallacy in this kind of thinking is that the reductionist hypothesis does not by any means imply a "constructionist" one: The ability to reduce everything to simple fundamental laws does not imply the ability to start from those laws and reconstruct the universe. In fact, the more the elementary particle physicists tell us about the nature of the fundamental laws, the less relevance they seem to have to the very real problems of the rest of science, much less to those of society.

The constructionist hypothesis breaks down when confronted with the twin difficulties of scale and complexity. The behavior of large and complex aggregates of elementary particles, it turns out, is not to be understood in terms of a simple extrapolation of the properties of a few particles. Instead, at each level of complexity entirely new properties appear, and the understanding of the new behaviors requires research which I think is as fundamental in its nature as any other. That is, it seems to me that one may array the sciences roughly linearly in a hierarchy, according to the idea: The elementary entities of science X obey the laws of science Y.

X	Y
solid state or many-body physics	elementary particle physics
chemistry	many-body physics
molecular biology	chemistry
cell biology	molecular biology
•	•
•	•
•	•
psychology	physiology
social sciences	psychology

But this hierarchy does not imply that science X is "just applied Y." At each stage entirely new laws, concepts, and generalizations are necessary, requiring inspiration and creativity to just as great a degree as in the previous one. Psychology is not applied biology, nor is biology applied chemistry.

In my own field of many-body physics, we are, perhaps, closer to our fundamental, intensive underpinnings than in any other science in which non-trivial complexities occur, and as a result we have begun to formulate a general theory of just how this shift from quantitative to qualitative differentiation takes place. This formulation, called the theory of "broken symmetry," may be of help in making more generally clear the breakdown of the constructionist converse of reductionism. I will give an elementary and incomplete explanation of these ideas, and then go on to some more general speculative comments about analogies at

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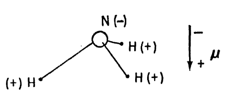
other levels and about similar phenomena.

Before beginning this I wish to sort out two possible sources of misunderstanding. First, when I speak of scale change causing fundamental change I do not mean the rather well-understood idea that phenomena at a new scale may obey actually different fundamental laws—as, for example, general relativity is required on the cosmological scale and quantum mechanics on the atomic. I think it will be accepted that all ordinary matter obeys simple electrodynamics and quantum theory, and that really covers most of what I shall discuss. (As I said, we must all start with reductionism, which I fully accept.) A second source of confusion may be the fact that the concept of broken symmetry has been borrowed by the elementary particle physicists, but their use of the term is strictly an analogy, whether a deep or a specious one remaining to be understood.

Let me then start my discussion with an example on the simplest possible level, a natural one for me because I worked with it when I was a graduate student: the ammonia molecule. At that time everyone knew about ammonia and used it to calibrate his theory or his apparatus, and I was no exception. The chemists will tell you that ammonia "is" a triangular pyramid



with the nitrogen negatively charged and the hydrogens positively charged, so that it has an electric dipole moment (μ), negative toward the apex of the pyramid. Now this seemed very strange to me, because I was just being taught that nothing has an electric dipole moment. The professor was really proving that no nucleus has a dipole moment, because he was teaching nuclear physics, but as his arguments were based on the symmetry of space and time they should have been correct in general.

I soon learned that, in fact, they were correct (or perhaps it would be more accurate to say not incorrect) because he had been careful to say that no stationary state of a system (that is, one which does not change in time) has an electric dipole moment. If ammonia starts out from the above unsymmetrical state, it will not stay in it very long. By means of quantum mechanical tunneling, the nitrogen can leak through the triangle of hydrogens to the other side, turning the pyramid inside out, and, in fact, it can do so very rapidly. This is the so-called "inversion," which occurs at a frequency of about 3×10^{10} per second. A truly stationary state can only be an equal superposition of the unsymmetrical pyramid and its inverse. That mixture does not have a dipole moment. (I warn the reader again that I am greatly oversimplifying and refer him to the textbooks for details.)

I will not go through the proof, but the result is that the state of the system, if it is to be stationary, must always have the same symmetry as the laws of motion which govern it. A reason may be put very simply: In quantum mechanics there is always a way, unless symmetry forbids, to get from one state to another. Thus, if we start from any one unsymmetrical state, the system will make transitions to others, so only by adding up all the possible unsymmetrical states in a symmetrical way can we get a stationary state. The symmetry involved in the case of ammonia is parity, the equivalence of left- and right-handed ways of looking at things. (The elementary particle experimentalists' discovery of certain violations of parity is not relevant to this question; those effects are too weak to affect ordinary matter.)

Having seen how the ammonia molecule satisfies our theorem that there is no dipole moment, we may look into other cases and, in particular, study progressively bigger systems to see whether the state and the symmetry are always related. There are other similar pyramidal molecules, made of heavier atoms. Hydrogen phosphide, PH_3, which is twice as heavy as ammonia, inverts, but at one-tenth the ammonia frequency. Phosphorus trifluoride, PF_3, in which the much heavier fluorine is substituted for hydrogen, is not observed to invert at a measurable rate, although theoretically one can be sure that a state prepared in one orientation would invert in a reasonable time.

We may then go on to more complicated molecules, such as sugar, with about 40 atoms. For these it no longer makes any sense to expect the molecule to invert itself. Every sugar molecule made by a living organism is spiral in the same sense, and they never invert, either by quantum mechanical tunneling or even under thermal agitation at normal temperatures. At this point we must forget about the possibility of inversion and ignore the parity symmetry: the symmetry laws have been, not repealed, but broken.

If, on the other hand, we synthesize our sugar molecules by a chemical reaction more or less in thermal equilibrium, we will find that there are not, on the average, more left- than right-handed ones or vice versa. In the absence of anything more complicated than a collection of free molecules, the symmetry laws are never broken, on the average. We needed living matter to produce an actual unsymmetry in the populations.

In really large, but still inanimate, aggregates of atoms, quite a different kind of broken symmetry can occur, again leading to a net dipole moment or to a net optical rotating power, or both. Many crystals have a net dipole moment in each elementary unit cell (pyroelectricity), and in some this moment can be reversed by an electric field (ferroelectricity). This asymmetry is a spontaneous effect of the crystal's seeking its lowest energy state. Of course, the state with the opposite moment also exists and has, by symmetry, just the same energy, but the system is so large that no thermal or quantum mechanical force can cause a conversion of one to the other in a finite time compared to, say, the age of the universe.

There are at least three inferences to be drawn from this. One is that symmetry is of great importance in physics. By symmetry we mean the existence of different viewpoints from which the system appears the same. It is only slightly overstating the case to say that physics is the study of symmetry. The first demonstration of the power of this idea may have been by Newton, who may have asked himself the question: What if the matter here in my hand obeys the same laws as that up in the sky—that is, what if space and matter are homogeneous and isotropic?

The second inference is that the internal structure of a piece of matter need not be symmetrical even if the total state of it is. I would challenge you to start from the fundamental laws of quantum mechanics and predict the ammonia inversion and its easily observable properties without going through the stage of using the unsymmetrical pyramidal structure, even though no "state" ever has that structure. It is fascinating that it was not until a couple of decades ago (*2*) that nuclear physicists stopped thinking of the nucleus as a featureless, symmetrical little ball and realized that while it really never has a dipole moment, it can become football-shaped or plate-shaped. This has observable consequences in the reactions and excitation spectra that are studied in nuclear physics, even though it is much more difficult to demonstrate directly than the ammonia inversion. In my opinion, whether or not one calls this intensive research, it is as fundamental in nature as many things one might so label. But it needed no new knowledge of fundamental laws and would have been extremely difficult to derive synthetically from those laws; it was simply an inspiration, based, to be sure, on everyday intuition, which suddenly fitted everything together.

The basic reason why this result would have been difficult to derive is an important one for our further thinking. If the nucleus is sufficiently small there is no real way to define its shape rigorously: Three or four or ten particles whirling about each other do not define a rotating "plate" or "football." It is only as the nucleus is considered to be a many-body system—in what is often called the $N \rightarrow \infty$ limit—that such behavior is rigorously definable. We say to ourselves: A macroscopic body of that shape would have such-and-such a spectrum of rotational and vibrational excitations, completely different in nature from those which would characterize a featureless system. When we see such a spectrum, even not so separated, and somewhat imperfect, we recognize that the nucleus is, after all, not macroscopic; it is merely approaching macroscopic behavior. Starting with the fundamental laws and a computer, we would have to do two impossible things—solve a problem with infinitely many bodies, and then apply the result to a finite system—before we synthesized this behavior.

A third insight is that the state of a really big system does not at all have to have the symmetry of the laws which govern it; in fact, it usually has less symmetry. The outstanding example of this is the crystal: Built from a substrate of atoms and space according to laws which express the perfect homogeneity of space, the crystal suddenly and unpredictably displays an entirely new and very beautiful symmetry. The general rule, however, even in the case of the crystal, is that the large system is less symmetrical than the underlying structure would suggest: Symmetrical as it is, a crystal is less symmetrical than perfect homogeneity.

Perhaps in the case of crystals this appears to be merely an exercise in confusion. The regularity of crystals could be deduced semiempirically in the mid-19th century without any complicated reasoning at all. But sometimes, as in the case of superconductivity, the new symmetry—now called broken symmetry because the original symmetry is no longer evident—may be of an entirely unexpected kind and extremely difficult to visualize. In the case of superconductivity, 30 years elapsed between the time when physicists were in possession of every fundamental law necessary for explaining it and the time when it was actually done.

The phenomenon of superconductivity is the most spectacular example of the broken symmetries which ordinary macroscopic bodies undergo, but it is of course not the only one. Antiferromagnets, ferroelectrics, liquid crystals, and matter in many other states obey a certain rather general scheme of rules and ideas, which some many-body theorists refer to under the general heading of broken symmetry. I shall not further discuss the history, but give a bibliography at the end of this article (*3*).

The essential idea is that in the so-called $N \rightarrow \infty$ limit of large systems (on our own, macroscopic scale) it is not only convenient but essential to realize that matter will undergo mathematically sharp, singular "phase transitions" to states in which the microscopic symmetries, and even the microscopic equations of motion, are in a sense violated. The symmetry leaves behind as its expression only certain characteristic behaviors, for instance, long-wavelength vibrations, of which the familiar example is sound waves; or the unusual macroscopic conduction phenomena of the superconductor; or, in a very deep analogy, the very rigidity of crystal lattices, and thus of most solid matter. There is, of course, no question of the system's really violating, as opposed to breaking, the symmetry of space and time, but because its parts find it energetically more favorable to maintain certain fixed relationships with each other, the symmetry allows only the body as a whole to respond to external forces.

This leads to a "rigidity," which is also an apt description of superconductivity and superfluidity in spite of their apparent "fluid" behavior. [In the former case, London noted this aspect very early (*4*).] Actually, for a hypothetical gaseous but intelligent citizen of Jupiter or of a hydrogen cloud somewhere in the galactic center, the properties of ordinary crystals might well be a more baffling and intriguing puzzle than those of superfluid helium.

I do not mean to give the impression that all is settled. For instance, I think there are still fascinating questions of principle about glasses and other amorphous phases, which may reveal even more complex types of behavior. Nevertheless, the role of this type of broken symmetry in the properties of inert but macroscopic material bodies is now understood, at least in principle. In this case we can see how the whole becomes not only more than but very different from the sum of its parts.

The next order of business logically is to ask whether an even more complete destruction of the fundamental symmetries of space and time is possible and whether new phenomena then arise, intrinsically different from the "simple" phase transition representing a condensation into a less symmetric state.

We have already excluded the apparently unsymmetric cases of liquids, gases, and glasses. (In any real sense they are more symmetric.) It seems to me that the next stage is to consider the system which is regular but contains information. That is, it is regular in space in some sense so that it can be "read out," but it contains elements which can be varied from one "cell" to the next. An obvious example is DNA; in everyday life, a line of type or a movie film have the same structure. This type of "information-bearing crystallinity" seems to be essential to life. Whether the development of life requires any further breaking of symmetry is by no means clear.

Keeping on with the attempt to characterize types of broken symmetry which occur in living things, I find that at least one further phenomenon seems to be identifiable and either universal or remarkably common, namely, ordering (regularity or periodicity) in the time dimension. A number of theories of life processes have appeared in which regular pulsing in time plays an important role: theories of development, of growth and growth limitation, and of the memory. Temporal regularity is very commonly observed in living objects. It plays at least two kinds of roles. First, most methods of extracting energy from the environment in order to set up a continuing, quasi-stable process involve time-periodic machines, such as oscillators and generators, and the processes of life work in the same way. Second, temporal regularity is a means of handling information, similar to information-bearing spatial regularity. Human spoken language is an example, and it is noteworthy that all computing machines use temporal pulsing. A possible third role is suggested in some of the theories mentioned above: the use of phase relationships of temporal pulses to handle information and control the growth and development of cells and organisms (*5*).

In some sense, structure—functional structure in a teleological sense, as opposed to mere crystalline shape—must also be considered a stage, possibly intermediate between crystallinity and information strings, in the hierarchy of broken symmetries.

To pile speculation on speculation, I would say that the next stage could be hierarchy or specialization of function, or both. At some point we have to stop talking about decreasing symmetry and start calling it increasing complication. Thus, with increasing complication at each stage, we go on up the hierarchy of the sciences. We expect to encounter fascinating and, I believe, very fundamental questions at each stage in fitting together less complicated pieces into the more complicated system and understanding the basically new types of behavior which can result.

There may well be no useful parallel to be drawn between the way in which complexity appears in the simplest cases of many-body theory and chemistry and the way it appears in the truly complex cultural and biological ones, except perhaps to say that, in general, the relationship between the system and its parts is intellectually a one-way street. Synthesis is expected to be all but impossible; analysis, on the other hand, may be not only possible but fruitful in all kinds of ways: Without an understanding of the broken symmetry in superconductivity, for instance, Josephson would probably not have discovered his effect. [Another name for the Josephson effect is "macroscopic quantum-interference phenomena": interference effects observed between macroscopic wave functions of electrons in superconductors, or of helium atoms in superfluid liquid helium. These phenomena have already enormously extended the accuracy of electromagnetic measurements, and can be expected to play a great role in future computers, among other possibilities, so that in the long run they may lead to some of the major technological achievements of this decade (*6*).] For another example, biology has certainly taken on a whole new aspect from the reduction of genetics to biochemistry and biophysics, which will have untold consequences. So it is not true, as a recent article would have it (*7*), that we each should "cultivate our own valley, and not attempt to build roads over the mountain ranges . . . between the sciences." Rather, we should recognize that such roads, while often the quickest shortcut to another part of our own science, are not visible from the viewpoint of one science alone.

The arrogance of the particle physicist and his intensive research may be behind us (the discoverer of the positron said "the rest is chemistry"), but we have yet to recover from that of some molecular biologists, who seem determined to try to reduce everything about the human organism to "only" chemistry, from the common cold and all mental disease to the religious instinct. Surely there are more levels of organization between human ethology and DNA than there are between DNA and quantum electrodynamics, and each level can require a whole new conceptual structure.

In closing, I offer two examples from economics of what I hope to have said. Marx said that quantitative differences become qualitative ones, but a dialogue in Paris in the 1920's sums it up even more clearly:

FITZGERALD: The rich are different from us.

HEMINGWAY: Yes, they have more money.

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