Levels and reduction

BUNGE, MARIO. *Levels and reduction*. Am. J. Physiol. 233(3): R75–R82, 1977 or Am. J. Physiol.: Regulatory Integrative Comp. Physiol. 2(2): R75–R82, 1977.—This paper addresses the problem of reconciling pluralism with reductionism, i.e., acknowledging both the variety of the world and the need and possibility to explain it. First the various kinds of monism and pluralism that litter the scientific and philosophical literature are examined cursorily. Then certain maligned notions are examined, mainly those of novelty, self-assembly, level, and levels "hierarchy." They are shown to be amenable to analysis and even mathematization. Then the logic of reduction is analyzed. Two kinds of reduction are distinguished: full or straight, and partial or roundabout. And three stands on reduction are examined: anti-, radical, and moderate reductionism. The former is dismissed for being obscurantist and the second for being quixotic. Moderate reductionism, aiming at the (partial) reduction of higher levels to lower ones without skipping any intermediate levels, is adopted. Finally moderate reductionism is found to be consistent with a certain variety of pluralism, characterized as naturalistic.

pluralism; reductionism; hierarchies; physics

1. VARIETIES OF MONISM AND PLURALISM

Scientists and philosophers are aware of the variety and mutability of things, and seek unity in the midst of variety as well as invariance amid change. They seek unity in terms of a few basic substances and invariance in terms of general patterns. In this respect all science and all philosophy are reductionist. However, there are several degrees and kinds of reductionism: there may be unity and invariance in the world, but there is certainly no such thing when it comes to our world views.

The best known world views are monism and dualism. According to monism there is but one basic substance, be it matter, spirit, or some neutral stuff. (Hence the three kinds of monism: materialist, idealist, and neutral, as represented, respectively, by Democritus and Epicurus, by Berkeley and Hegel, and by Ostwald and Whitehead.) Hence variety consists for monism in the different arrangements of bits of the one and sole stuff. In particular, man is a one-level thing: all material, or all spiritual, or else neutral. And everything is ultimately to be explained in terms of the properties and laws of the one substance. Thus whereas the Greek atomists sought to explain everything in terms of moving atoms, Hegel attempted to understand everything in terms of ideas, and Ostwald in terms of energy.

Dualism on the other hand holds that there are two substances, each with its own properties and laws, namely matter and mind (or spirit or soul). Hence while some things are purely material and others purely mental, still others are mixtures of the two. In particular, man is a compound of matter and spirit, or body and mind. And everything is ultimately to be explained in terms of one or the other substance or both of them. There are of course several versions of dualism, from Plato's hylomorphism through Descartes' compromise to contemporary varieties of psychophysical parallelism and interactionism still popular among neurophysiologists.

Dualism is the simplest form of pluralism. It is also the most popular of metaphysics. It has been enshrined by the majority of religions, in fact by all those that draw a sharp line between matter and spirit, the worldly and the unworldly, the lower and the higher, the transient and the eternal, and so on. These differences are so much taken for granted by ordinary knowledge that they have become entrenched in ordinary language and even in medicine, with its talk of mental vs. physical conditions and ailments. Dualism is in short part and parcel of common-sense philosophy, at least in the Western world. It is the easiest to understand and it allows one to perpetrate any atrocity in the name of spiritual values for, after all, bodies are just chunks of matter: what really matters is the spirit, spelled with or without the capital.

However, dualism is not the only form of pluralism. There are others which postulate numerous modes of being, and some perhaps infinitely many. The best known of the pluralist metaphysics are the various ancient and medieval views of the Great Chain of Being. In some cases the chain was thoroughly natural: it consisted of several rungs in the scala naturae, from lowly dust to lofty Man. In other cases – in particular the Pseudo-Areopagite's Celestial Hierarchy – the chain went all the way up to the various categories of celestial beings such as thrones and archangels. Unlike the scala naturae, this one was a genuine hierarchy because the relation among its various rungs was one of rank and domination: the higher the better and more powerful. On the other hand the pluralism of philosophers such as Leibniz, Alexander, Russell, and Hartmann was more sophisticated and usually not part of theodicy.

In short, there is a plurality of pluralisms. However, most if not all of them share one trait, namely the thesis that each kind of substance (or mode of being, or level, or rung in a hierarchy) can be understood only in its own terms, though perhaps not fully. In particular, psychophysical dualism holds the body to be understandable in physical terms only and the mind in mental terms only – which is tantamount to asserting that biology must not encroach on psychology, and the latter must not make any forays into biology. In other words, ontological pluralism usually accompanies epistemological pluralism or antireductionism.

So much, or rather little, for monism and pluralism in philosophy. How about science: which if any of these philosophies does science espouse? I do not mean which philosophy do scientific workers adopt but which one best accords objectively with contemporary science and is best conducive to scientific advancement. I intend to show that none of the above-mentioned philosophies fills the bill of contemporary scientific research. And I shall propose an alternative philosophy that combines ontological pluralism (i.e., the recognition of variety) with epistemological reductionism (i.e., the claim that higher levels can be explained in terms of lower ones). I shall argue that this philosophy is the one best compatible with our present scientific knowledge, the one most likely to stimulate breakthroughs in research into border-line areas such as physiological psychology, and one that can be formulated in precise terms.

Since we shall be concerned throughout with novelty, we had better start by explaining what it is. This is done in the next section. SECTION 3 is devoted to a conspicuous emergence mechanism, namely self-assembly. In SECTION 4 we shall elucidate a concept of level of organization and formalize the hypothesis of the levels "hierarchy." SECTION 5 is devoted to the logic of reduction. The last section dissolves the apparent paradox consisting in holding (ontological) pluralism together with (epistemological) reductionism.

2. NOVELTY

We are all familiar with particular novelties or examples of novelty, but the general (philosophical) concept of novelty has proved a hard nut to crack. So hard in fact that it has suggested to some (the radical reductionists) that novelty is always apparent, and to others (the radical emergentists) that novelty, though real, is unintelligible. Let us try our hand at cracking it.

It has been customary to distinguish superficial or quantitative novelty from radical or qualitative novelty. The former happens if one or more properties of a thing vary in intensity or degree. On the other hand a thing changes qualitatively if it loses or gains new properties. One way of elucidating the latter process is this. Call x a thing and t an instant, and introduce a function p that assigns the ordered couple $\langle x, t\rangle$ the set $p(x, t)$ of all the properties of x at t. That is, p is the function $p\colon S \times T \to \mathscr{P}(\mathbb{P})$, where S is the set of all things, T the set of all instants, and $\mathscr{P}(\mathbb{P})$ the power set of the set $\mathbb{P}$ of all thing properties, i.e., the family of all the subsets of the set $\mathbb{P}$. A change in thing x can be viewed as a certain change of state of x. Since x is held fixed throughout that change of state, we can use the simpler function $p_x\colon T \to \mathscr{P}(\mathbb{P})$ such that $p_x(t) = p(x, t)$. In short, $p_x(t)$ is the collection of properties of thing x at time t.

Now let t and t' be two instants, such that t precedes t'. The corresponding values of p_x are of course $p_x(t)$ and $p_x(t')$. If these two sets of properties of the thing x are the same, then the thing has not changed qualitatively. If they are different, then the thing has gained or lost some properties. If the latter is the case, the newly gained properties are said to be emergent. We can compress the above into the following.

Definition 1. Let x be a thing with properties $p_x(t)$ at time t, and let $t' > t$ be a later instant. Then, *i)* the *total novelty* that occurs in x during the period $[t, t']$ is

$$n_x(t, t') = p_x(t')\Delta p_x(t)$$

where Δ designates the symmetric difference, and *ii)* the *emergent properties* that appear in x during period $[t, t']$ are those in

$$e_x(t, t') = p_x(t') - p_x(t)$$

(Recall that, if A and B are sets, their symmetric difference is defined to be $A\Delta B = (A \cap \bar{B}) \cup (\bar{A} \cap B)$. On the other hand the simple difference between A and B is $A - B = A \cap \bar{B}$.)

In other words, set

$$p_x(t) = \{P_1, P_2, \cdots, P_m\}$$

$$p_x(t') = \{P_1, P_2, \cdots, P_{m-r}, P_{m+1}, P_{m+2}, \cdots, P_{m+s}\}$$

If $r \neq 0$, then x has lost the r properties P_{m-r+1}, P_{m-r+2}, $\cdots$, P_m. And if $s \neq 0$ then x has gained the s properties P_{m+1}, P_{m+2}, $\cdots$, P_{m+s} in the same interval. The latter are of course the emergent properties that x has acquired, whereas the union of this set and the set of lost properties is the total novelty occurring in x during the period of interest.

Another way of elucidating the concept of qualitative novelty is this. The successive states of a changing thing x may be represented in the state space $S(x)$ of x. This is an abstract space constituted by as many coordinates as there are properties possessed by x throughout its entire existence. Suppose, for the sake of simplicity, that x has just two properties during the first half of its history, and at a given instant it loses one of them while gaining a further property (an emergent one). The entire history of x can then be represented as the trajectory of its representative point in a three-dimensional space $S(x)$. During its initial stage the state lies on one of the

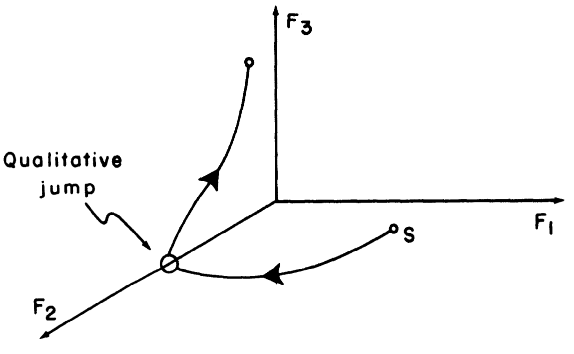

FIG. 1. Representation of a qualitative change of a thing x in its state space $S(x)$. Each coordinate axis represents one property of the thing. During the first part of the existence of x, point s representing its instantaneous state moves on the $F_1 \times F_2$ plane, until it hits the vertical plane $F_2 \times F_3$, where it loses property F_1 and gains property F_3.

coordinate planes, and during its final stage it lies on another plane. See Fig. 1.

There are two conspicuous mechanisms for the rise of radical or qualitative novelty: the assembly and the breakdown of systems. Let us take a look at these mutually dual processes, for they will help explain the concept of level.

3. EMERGENCE THROUGH ASSEMBLY

An assembly process is one in which two or more things join to form a new thing. The process is called *self-assembly* if it is spontaneous rather than brought about by man. There are many kinds of self-assembly processes, from mere clumping through the synthesis of molecules and the aggregation of cells to the merging of social organizations. The simplest self-assembly process is the accretion of similar things such as specks of cosmic dust. Mere accretion may lead to a heap or end up in an emergent such as a star or a planet, a coral reef or a multinational organization.

The simplest way to represent an assembly process is this. Let S be a set of concrete things (atoms, cells, persons, and what have you). Suppose any two things in S can join to form a third member of S. Write $a \dotplus b = c$, where a, b, and c are things in S, for the process of joining or assembling a and b to form c. Assume that the binary operation $\dotplus$ is associative, i.e., that $(a \dotplus b) \dotplus c = a \dotplus (b \dotplus c)$. And add the null thing $\square$, i.e., the element of S such that $\square \dotplus x = x \dotplus \square = x$ for every x in S. Then the conceptual system $\mathscr{S} = \langle S, \dotplus, \square \rangle$ is called the *thing monoid*.

This concept allows us to define the notions of part and composition. We stipulate that, if a and b are things (i.e., members of S), then b is a *part* of a iff b adds nothing to a. That is, $b \sqsubset a$ iff $a \dotplus b = a$. The collection of parts of a thing is called the *composition* of the thing. In symbols: If $x \in S$, then $\mathscr{C}(x) = \{y \in S | y \sqsubset x\}$.

These are the bare bones of association theory. This theory does not tell us whether or not the thing resulting from the assembly of two or more things has any emergent properties: so far as this theory is concerned, $c = a + b$ may be either a heap or an emergent whole (or system). However, association theory does facilitate the investigation of this problem if only because it makes exact the notions of part and composition, which will be taken for granted in the sequel.

To begin with we need a definition of a system. Here is one.

Definition 2. A thing σ is a *concrete system* iff *i)* σ has a nontrivial composition $\mathscr{C}(\sigma)$ = The set of parts or components of σ; *ii)* σ has an *environment* $\mathscr{E}(\sigma)$ = The set of things other than the components of σ, and which act on them or are acted upon by them; *iii)* σ has a *structure* $\mathscr{S}(\sigma)$ = The set of relations among the components of σ, in particular the connections or couplings among them.

We are now in a position to frame a more useful definition of self-assembly than that suggested by association theory. It is this:

Definition 3. Let x be an aggregate of things in a certain environment. Then *i)* the parts of x *assemble* iff x turns into a system σ with the same composition and the same environment as x; *ii)* the assembly process is one of *self-assembly* iff x turns by itself into σ; *iii)* the self-assembly process is one of *self-organization* iff the resulting system has subsystems [not just parts].

The formal apparatus developed so far accounts for the general traits of self-assembly and makes room for emergence but does not enable us to identify the emergents. The latter task is performed by another theory: the general theory of discrete change, which is a generalization of the basic theory of chemical reactions. Here one starts from things endowed with definite properties and ends up with compounds of those things, possessing their own definite properties, some of which are by hypothesis emergent relative to the former. In other words, in this theory one is concerned with definite species of things even though, for the sake of generality, one need not specify which species they are: they may be species of elementary particles, atoms, molecules, cells, organisms, or what have you – in short all kinds of things capable of assembling to form further things. Let us catch a glimpse of this theory.

Let A and B be two species of thing and suppose that their members can join to form things of a third kind C. This process, whether or not it is a chemical one, may be called a *reaction* and it may be represented by the equation: $A + B \rightharpoonup C$, or, equivalently, $A + B - C = \phi$, where ϕ is the empty set. A and B are called the *reactants* and C the *reaction product*. Needless to say, neither of these need be simple. For example, we may suppose that B is composed of D and E, so that the reaction is actually $A + D + E - C = \phi$. If in turn the reaction product C is composed of E and F, then the overall reaction is $A + D + E - E - F = \phi$, which boils down to $A + D - F = \phi$. This is of course the case of a catalyzed reaction, E being the catalyzer and $A + D$ the substrate.

In general there will be a finite though possibly very numerous family (or genus) of species: $G = \{A, B, \cdots, N\}$, the members of which can assemble to form further systems of kinds belonging to G. (Therefore G is not just the set of actual species but that of all really possible species, some of which may not yet have emerged.) We can assume that G is closed under the operation $+$ of combination as well as under the operation − that transforms a thing into a reaction product. With these assumptions, the conceptual system $\mathscr{G} = \langle G, +, -, \phi \rangle$ is a group. Actually this formalism covers not only the buildup or self-assembly processes such as $A + B - C = \phi$, but also the breakdown or self-dismantling processes such as $A - B - C = \phi$, and the substitution or reorganization processes such as $A + B - C - D = \phi$. This is just as well since in reality processes of all three kinds intertwine or succeed one another, whether at the nuclear, chemical, biological, or social levels. And, needless to say, the processes of combination of like with like – such as the synthesis of an oxygen molecule out of two oxygen atoms – are covered as well by the above formalism, since they correspond to the case when the reactants belong to the same species, as in $A + A - C = \phi$. (This shows that the members of G are not idempotents.)

The point of summarizing the theory of discrete change was to exhibit a theory representing emergence through self-assembly. Indeed, if A and B combine to form C, then A and B are the *precursors* of the *emergent* C. That C is indeed emergent relative to A and B, even if we know not precisely in what ways, is a consequence of the assumption that the species C differs from the species A and B.

Finally, the reasons for having spent time with formalizations are these. First, that the emergence concept can be elucidated in mathematical terms refutes the contention of both holists and mechanists that it is an obscure notion, therefore one that must be either accepted on faith (holism) or rejected with contempt (reductionism). Second, the notion of emergence is ontological, not epistemological: it has nothing to do with explanation or prediction. In other words, *a*) emergence is not definable in terms of either explanation or prediction, and *b*) the explanation and the prediction of emergence do not eliminate it. In sum, epistemological reductionism is compatible with ontological emergentism. Thus the way to a rational version of pluralism is open.

Let us turn to a peculiarity of this pluralism, namely the levels hypothesis.

4. LEVELS

Talk of levels of organization (or complexity or integration or evolution) and of a hierarchy of such is rampant in contemporary science, particularly in biology. Unfortunately there is no consensus on the significance of the terms "level" and "hierarchy," which are used in a variety of ways and seldom if ever defined. This fuzziness must be blamed not only on the biologists but also on the philosophers – on the inexact or woolly ones who despise clarity and on the exact ones who are unwilling to solve the philosophical problems of science. Let us attempt to remedy this situation by clarifying what seem to be the most important concepts of level and hierarchy occurring in the recent biological literature.

Many contemporary biologists hold that the biosphere has a hierarchical or level structure. It would seem that this thesis can be split into the following two propositions.

i) The biosphere is composed of ecosystems, which in turn are composed of populations, the components of which are organisms, some of which are composed of organs, which in turn are composed of cells.

ii) The totality of cells constitutes the cellular level; that of organs, the organ level; that of organisms, the organismic level; that of populations, the population level; that of ecosystems, the ecosystem level; and that of biospheres (on all inhabited planets), the biosphere level.

Let us proceed to analyze these concepts in a leisurely manner, so not to become confused. And let us keep our attention focused on the biotic levels, leaving aside the prebiotic as well as the suprabiotic levels. The levels mentioned in proposition *ii* are

B_1 = cell level = the set of all cells
B_2 = organ level = the set of all organs
B_3 = organismic level = the set of all organisms
B_4 = population level = the set of all populations
B_5 = ecosystem level = the set of all ecosystems
B_6 = biosphere level = the set of all biospheres

Levels are then *classes* or sets, hence concepts rather than things. (However they are not arbitrary concepts but represent something real.) Therefore the belonging of something to a given level is the belonging of an individual thing to a set. For example, the sentence "c is a cell" is shortened to: $c \in B_1$ (c is in B_1), not $c \sqsubset B_1$ (c is a part of B_1).

The components of a biolevel are things and moreover things of a special kind, to wit, systems. Moreover, the things belonging to adjoining levels are related in a very special way, namely thus: *the components of a system belonging to a given level are in the immediately preceding level*. For example, the nervous system of an animal belongs to level B_2 and is composed of members of B_1 (neurons, glial cells, etc.). In general, if x is an organ (or member of B_2), then the composition of x is a subset of B_1. This is what it means to say that B_1 *precedes* (or *is lower level than*) B_2. The general concept of the relation of precedence between levels is elucidated by:

Definition 4. If B_i and B_j are two levels, then B_i *precedes* B_j iff the components of members of B_j belong to B_i. That is

$$B_i < B_j =_{df} \forall x(x \in B_j \Rightarrow \mathscr{C}(x) \subset B_i)$$

Note the following points about the preceding convention. First, though motivated by biological considerations, it is not limited to biolevels. Second, there is nothing obscure about the notion of level precedence as long as one sticks to *definition 4* instead of construing $B_i < B_j$ as "the B_i's are inferior to the B_j's" or something of the sort. Third, we have not defined separately the notions of level and level precedence but have defined them both in a single stroke. This may not be completely satisfying but it is all a philosopher can do: it is up to the scientist to decide what things belong to which level.

Let us now tackle the proposition that the entire biosphere, or perhaps life, has a hierarchical structure. Call

$$B = \{B_1, B_2 \cdots, B_6\}$$

the set of all biotic levels. This set is ordered by the relation $<$ of level precedence. (On the other hand B is not ordered by the relation $\subset$ of set inclusion, for it is not true that every cell is an organ, or that every population is an ecosystem, and so on.) In other words the set B of levels together with the relation $<$ of level precedence constitutes a partially ordered set. And it deserves a name of its own:

Definition 5. The set B of biolevels together with the level precedence relation $<$, i.e., $\mathcal{B} = \langle B, <\rangle$, is called the *biolevel structure*.

What we have called, for want of a better name, the *biolevel structure*, is what other authors have called either the scala naturae or the *hierarchy of life*. I submit that the latter are misnomers: a ladder proper should lead somewhere, while a hierarchy proper involves a subordination or dominance relation.

So far we have merely defined the notion of biolevel structure. We now stick our neck out and claim that whatever is alive or composed of living beings is in the biolevel structure:

Postulate 1. Every biosystem and every system composed of biosystems belongs in some level of the biolevel structure.

This version of the "hierarchy" of life is static: it talks about levels and their order but not about their origin. Many contemporary biologists would claim not just that there are levels and that these are ordered, but also that the biolevels are so many stages of an evolutionary process. More precisely, the following hypothesis often occurs explicitly or tacitly.

iii) Every biolevel has emerged spontaneously from the preceding (prebiotic or biotic) level.

This hypothesis is as suggestive as it is fuzzy. In fact since levels are sets they cannot emerge from one another. Fortunately the notion of self-assembly, elucidated in the previous section, allows us to reformulate *iii* in exact terms, namely thus:

Postulate 2. Every concrete system belonging to a given level has self-assembled from things at the preceding level.

An immediate consequence of his hypothesis is:

Corollary 1. Every system (at a given biolevel) is preceded in time by its components or precursors.

In short, level precedence and time precedence, though not cointensive, are coextensive: all components are precursors and conversely. This seems to be the hypothesis that lurks behind the usage of the term precursor in molecular biology.

The scala naturae or "hierarchy" of life is no longer static: it has become part and parcel of an ontology that is not only pluralistic but also evolutionary. The levels are not static layers that happen to be piled atop one another. They succeed each other in time (metaphorically speaking) and they do so by virtue of a definite and pervasive mechanism, namely the self-assembly of things. And they are not rungs in a hierarchy leading from lowly atom through middling man to the Supreme Being: they are but stages in a natural evolutionary process that may have occurred and indeed may be occurring at various places and epochs in the history of the world, though not twice in the same manner.

So much for a quick exposé of a pluralistic, naturalistic and rationalist ontology or world view. (For details see Bunge (3, 4).) Let us now face the problem of reconciling pluralism with the need to explain novelty by reducing higher levels to lower ones. That is, let us examine the logic of reduction and see whether reduction compels us to give up the hypothesis that the world has a level structure.

5. REDUCTION WITHOUT LEVELING

A length of copper wire is an assembly of copper atoms but one that has bulk properties such as high electrical conductivity and brilliance. These are emergent properties since they are not possessed by the constituent atoms. And these properties are explained by solid-state physics in terms of the copper crystal lattice and the electrons wandering through it. In a sense then the physics of copper bodies has been reduced to quantum mechanics, the basis of solid-state physics. Likewise the capacity to perceive parts of the external world, the ability to move about it, and to react upon it are emergent properties of an organism endowed with a nervous system, for no individual neuron possesses them. The hope is that one day physiological psychology will explain such properties in terms of systems of neurons. If this happens we shall be able to say that psychology has been reduced to neurophysiology.

Obviously such reductions, being conceptual operations, do not alter one bit the fact that our copper wire is a good conductor or that a fly perching on it is quick to perceive the motion of a swatter. Explanation has not eliminated whatever emergent properties copper bodies and flies have. In particular, it has not eliminated the emergent laws characterizing such systems: indeed, such molar laws are invariant relations among emergent properties, and emergence does not go away when explained. In other words, reduction does not imply leveling: it relates levels instead of denying that they exist.

Reduction, then, is a theoretical operation that does not alter the level structure of the world. Because it is often a misunderstood operation, we proceed to analyze it. We shall distinguish two sorts of reduction: full (or strong) and partial (or weak). We mean by full reduction sheer deduction without further ado. For instance, optics is deducible from electromagnetic theory without the addition of any new premises. Another example: the diffusion of a chemical through the cytoplasm is reducible to (or an application of) the general diffusion one learns in physics.

On the other hand partial or weak reduction consists in *a)* enriching a hypothesis, or a theory, with a set of premises compatible with it but not contained in it, and *b)* deducing the desired consequence (whatever is to be explained) from the enlarged set of premises. For instance, solid-state physics explains the emergent properties of metallic bodies by adjoining to the general principles of quantum mechanics certain hypotheses concerning the crystal lattice and the interactions among the ions and the electrons in the lattice. Another example: it is likely that a neurophysiological explanation of memory will consist not in assigning individual neurons the recall capacity but rather in attributing this property to neuron assemblies or neural circuits organized in unsuspected ways. This will call for enriching the general principles of neurophysiology with specific assumptions concerning the composition and structure of such subsystems, and so it will be a partial or weak reduction.

We can summarize the preceding in the following:

Definition 6. Let T_1 and T_2 be two theories or hypotheses and let S be a nonempty set of assumptions not contained in either T_1 or T_2. Then *i)* T_2 is *fully reducible* to T_1 if and only if T_1 entails T_2 (i.e., T_2 follows logically from T_1); and *ii)* T_2 is *partially reducible* to T_1 if and only if T_1 jointly with S entails T_2 (i.e., T_2 follows logically from the union of T_1 and S).

Whereas full reduction is straightforward (and infrequent), partial reduction is roundabout (and more common). The latter requires inventing the suitable additional hypotheses that will mesh with a general theory, or hypothesis, to produce the desired explanation. Therefore whereas full reduction can be accomplished by a pure mathematician, partial reduction cannot, because it requires additional factual knowledge and often also great imagination.

How far can or should reduction be pushed? Three different answers to this question have been proposed.

1) Antireductionism, or the rejection of any attempt to understand facts on one level in terms of hypotheses and data concerning some other level(s).

2) Radical reductionism, or the claim that all of the concepts, hypotheses, and theories concerning things at a given level can in principle be reduced to those referring to things belonging to some other level(s).

3) Moderate reductionism, or the strategy consisting in reducing whatever can be reduced without however either ignoring emergence or persisting in reducing the irreducible.

Antireductionism à outrance can still be found in the backwaters of biology, particularly among those who extol the virtues of the study of the whole organism and decry the achievements of molecular biology. We need not waste any ammunition on radical antireductionism because it is refuted every time a biological function is explained in biophysical, biochemical, or control-theoretical terms.

Radical reductionism, on the other hand, is sometimes heuristically fertile, since it stimulates the search for profound explanations, in particular explanations in terms of adjacent levels. However, at other times it can block research by its obstinate refusal to recognize the emergent properties and laws peculiar to every level, and by encouraging unrealistic research programs, such as the reduction of history to thermodynamics. More on this topic shortly.

Finally moderate reductionism, by eschewing the two extremes we have just described, seems to be the most reasonable and practical strategy. It boils down to the following two rules.

Rule 1. Start by studying every system at its own level. Once you have described it and found its patterns of behavior, try to explain the latter in terms of the components of the system and the mutual actions among them.

Rule 2. Look for relations among theories, and particularly for relations among theories concerning different levels. Never skip any levels. If reduction (full or partial) fails, give up at least pro tempore.

Radical reductionists accept the first rule but reject the second. They preach the full (not just the partial or weak) reduction of sociology to biology, of biology to chemistry, and chemistry to physics. (Even the full reduction of all sciences to physics has at different times been proposed, e.g., by the Vienna Circle. Ostwald went farther by claiming that all sciences were reducible to thermodynamics. And Mach claimed that every science should be reduced to psychology.) One can confidently assert that such attempts are bound to fail. First, because full reduction is possible only when the reduced theory or hypothesis describes things with the same or fewer properties (hence also laws) than those possessed by the things described by the reducing theory or hypothesis. (Thus optics is reducible to electromagnetic fields.) Second, because most reductions effectively accomplished have been partial not full. (Even the reduction of astronomy to mechanics and gravitation theory is partial because it cannot be effected unless one adds special hypotheses concerning the mass distribution and spin of planets.) Third, because not even in physics has (partial) reduction been accomplished everywhere. This point merits some attention.

As we all know, mechanism (or the program of reducing the whole of physics to mechanics) was remarkably successful between 1600 and 1800. Only one field resisted its lure, namely gravitation. The latter was joined, a century later, by the electromagnetic field, one more substance devoid of mechanical properties and therefore immune to the encroachment of mechanics. Surely there were attempts to reduce both gravitational and electromagnetic fields to mechanical systems, but such attempts are by now historical curiosities: we now accept the respective field theories. The success of the latter was so great that at the turn of the century some physicists tried to reverse the trend and reduce mechanics to electromagnetism. They too failed. Just as electrical fields and charges are not reducible to mechanical entities, so bodies are not reducible to electromagnetic fields.

Physicists currently admit that there are three fundamental theories, none of which is reducible to the other – and this simply because they deal with things of radically different kinds. These theories are quantum electrodynamics, quantum mechanics, and the relativistic theory of gravitation. For strong electromagnetic fields the former theory goes over into the classical electromagnetic theory, and for weak gravitational fields the relativistic theory of gravitation reduces to the classical theory of gravitation. On the other hand classical mechanics has not yet been successfully reduced to quantum mechanics: it is not known which are the

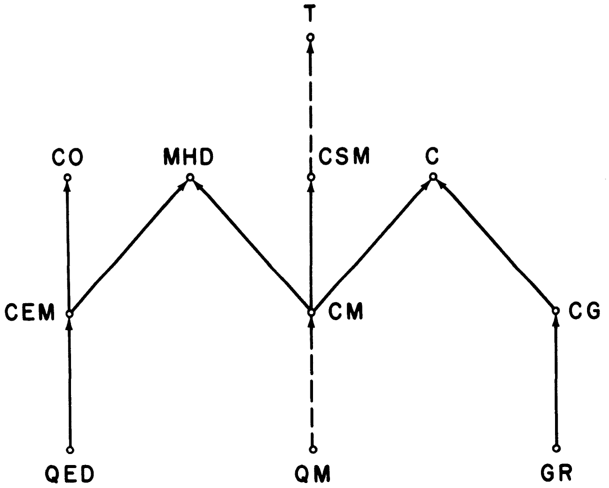

FIG. 2. Three basic physical theories of the day: quantum electrodynamics (QED), quantum mechanics (QM), and general relativity or the theory of gravitation (GR). Arrows designate reduction, still incomplete in the case of dashed lines. Classical optics (CO) reduces to classical electromagnetism (CEM), which in turn reduces to quantum electrodynamics (QED). As for QM, one hopes it will be shown to entail classical mechanics (CM), which in turn yields classical statistical mechanics (CSM), which, suitably enriched, should eventually yield thermodynamics (T). Relativistic theory of gravitation (GR) entails the classical theory of gravitation (CG). The union of CEM and CM entails magnetohydrodynamics (MHD), and the union of CM and CG entails celestial mechanics (C).

suitable subsidiary hypotheses to be adjoined to quantum mechanics in order to obtain the full theory of extended bodies. But classical statistical mechanics follows from classical mechanics when suitably enriched with statistical assumptions. However, the full thermodynamics has yet to be reduced to classical statistical mechanics: hence the lines in Fig. 2. Still, there are three basic physical theories which are not mutually reducible. Yet, there are relations between these. For example, the theory of gravitation borrows from other theories whatever it needs to describe the sources of the gravitational field. (For details on intertheory relations in physics, see Bunge (2).)

What holds for physics holds a fortiori for the whole of science. Thus it is not true that chemistry has been reduced to physics: it has laws of its own, in fact as many as there are chemical reactions, i.e., millions of them. If chemistry were a straightforward application of physics then all of the interesting molecules would have been determined long ago; likewise, all of the reaction formulas and the formulas of chemical kinetics would have been deduced from the principles of quantum mechanics. In fact such reductions are slow in coming, so the most one can assert is that *in principle* chemistry is (partially, weakly) reducible to physics. Likewise it is not true that the whole of biology follows from chemistry and physics.

Surely physiology presupposes physics and molecular biology presupposes chemistry. In other words, physics and chemistry are the *bases* of biology. But they are not sufficient. For example, biophysics can explain the physical aspects of the circulation of blood, the diffusion of chemicals through tissues, and the transmission of neural messages. But it does not explain these processes in their entirety; e.g., it does not explain why such processes emerged and were kept in certain lineages. Likewise biochemistry can explain the chemical aspects of certain processes, such as those of metabolism and mitosis, but it does not explain them in their entirety; e.g., it does not explain why evolution favored certain metabolic pathways or why sexual reproduction is advantageous. In short, while there is no modern biology without physics and chemistry, no amount of physics and chemistry is sufficient to account for biology. This is why we have biophysics but not physical biology, biochemistry but not chemical biology, and sociobiology but not biological sociology—let alone social chemistry or social physics.

The upshot of the foregoing considerations is that the social sciences presuppose the life sciences without being special cases of the latter; likewise biology presupposes chemistry although it is not just applied chemistry, and chemistry presupposes physics without being a mere application of physics. (We can say that a construct B *presupposes* construct A if and only if A is necessary but not sufficient for the meaning or the truth of B; e.g., because B contains A or part of A.) The reason for the incomplete reducibility of the higher level sciences is that they have to cope with the genuine novelties peculiar to those levels. Surely we all hope for a stepwise reduction, i.e., a reduction not missing any intermediate levels, of the higher level sciences to the lower level ones. But such reduction, to be legitimate, must account for emergence and not deny it. In particular, even if we succeed in explaining life in chemical terms, and thought in biological terms, we want to stay alive and to think rather than die or be mindless. In short, we want *reduction without leveling*.

So much for the problem of explanation in general, and that of explaining in depth without denying novelty and levels. (For details see Bunge (1).) It is now time to conclude.

6. CONCLUSION: ONTOLOGICAL PLURALISM CUM EPISTEMOLOGICAL REDUCTIONISM

We have defended both ontological pluralism and a moderate version of reductionism. There is no contradiction here, for the former is an ontological doctrine whereas the latter is an epistemological one. Of course pluralism can be paired to irrationalism. But this we do not here, for our concern has been elucidating the notions of novelty and of emergence and building a theory of the formation of levels.

We have adopted and clarified the levels hypothesis. Levels, though distinct, have been assumed to emerge, metaphorically speaking, through processes of self-assembly. Atoms self-assemble to constitute molecules, which self-assemble to constitute biomolecules, which self-assemble to constitute organelles, and so on. Self-assembly is the thread that runs through the various levels of the "hierarchy" of being. Thus the plurality of levels is consistent with the concrete or material character of their members. In other words the various levels of organization are distinct but they are all levels of organization of matter. There is no room for disembodied spirits in this system.

The material unity of the level structure of the world is what renders it intelligible, i.e., explainable, to us members of the organismic level. We understand a system at a given level in terms of its composition and its mode of composition. This is how science has succeeded in understanding the formation of a number of systems possessing new properties. This procedure is called reduction. However, it is epistemological not ontological reduction. To explain novelty is not to explain it away; to explain levels is not to level them down (or up) to a single level. In short, *epistemological reductionism* (of the moderate sort) *is compatible with ontological pluralism*. This is a fancy way of saying that science can cope with the variety and changeability of the world.

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