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ORIGINAL PAPER

Hierarchical Structures

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Abstract This paper compares the two known logical forms of hierarchy, both of which have been used in models of natural phenomena, including the biological. I contrast their general properties, internal formal relations, modes of growth (emergence) in applications to the natural world, criteria for applying them, the complexities that they embody, their dynamical relations in applied models, and their informational relations and semiotic aspects.

Keywords Change · Composition · Development · Emergence · Heterarchy · Levels · Meronomy · Process · Semiosis · Subsumption · Taxonomy

1 Introduction

Hierarchical models have been appearing in increasing numbers in scientific papers in recent years (see the Further Readings below), but without any fully developed reference on these forms. In this paper I aim to remedy this lacuna. My focus is on biology, where both forms of hierarchy have been used, but I have included references from all fields where I have discovered attempts to use these forms.

Simpson (1961) noted that particularly influential relationships among objects have been 'association by similarity' and 'association by contiguity'. These conceptual modes have come to be utilized in biology as hierarchical forms in connection with, respectively, biological classification (Rieppel 2010), and physiological—ecological

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structure (Salthe 1985; Ahl and Allen 1996). Stanley (1979) and Eldredge (1985) enlisted association by contiguity to enlarge the scope of biological evolution discourse beyond the population, and this form also contextualized the ‘levels of selection’ discourse (Price 1970; Wilson and Dugatkin 1997; Gould 2002). Additionally, in 1993, I enlisted association by similarity to serve as a format for modeling development.

This paper presents my understanding of the nature and uses of the known hierarchical forms. I attempt to clarify, and distinguish between, the structures and implications of the two known logical forms of hierarchy. This seems timely in view of the fact that there has currently been a resurgence of interest in hierarchies (see the post 1990 instances in many fields shown in the Further Readings). As well, and despite their structural differences, these forms are sometimes conflated, presumably as a result of a common lack of explicit knowledge about hierarchical structures, which this paper attempts to remedy. Despite hierarchy’s presence in many discourses, a focus on biology seems especially appropriate because both forms have been used in that discourse (e.g., see above). As this paper is a distillation and consilience of what is found scattered throughout the literature, I will not make specific citations in the body of the text, which represents my own summary. The references in the Further Readings indicate which papers, chapters and books discuss or utilize which form of hierarchy.

2 Two Known Logical Forms of Hierarchy

(a) The compositional hierarchy (including a synchronic map of the command hierarchy), which in applications, for reasons given below, I have labeled the ‘scale hierarchy’. The picture of macromolecules inside living cells inside an organism is a familiar image of an important application. This modular form is suited to the synchronic modeling of systems as they are at any given moment, focusing on dynamic energy transactions and ongoing processes.

(b) The subsumption hierarchy (including a diachronic model of the trajectory of a given command), which I have called the ‘specification hierarchy’. The familiar Linnaean hierarchy as embodied in the cladograms and phylogenies of biological systematics has this structure, which is suitable as well to modeling the diachronic emergence of forms as stages in a developmental process of acquisition of new informational constraints.

Cliff Joslyn (personal communication) has provided the following comparison of the logical properties of the two kinds of hierarchy:

Meronomy	Taxonomy
Whole/part	General/specific
is-a-part-of	is-a-kind-of
Composition	Subsumption
Containment	Inheritance
Modularity	Specification

Using my representations: [whole [part]] and {general {specific}}

Some situations and relations can be interpreted either way. Consider the well-known ‘control hierarchy’ in the example of a corporation, with a CEO at the top and a series of managers at several levels between him/her and various workers. In the subsumption hierarchy, a suggestion from the top becomes an ever more specific command as it approaches the workers, with more particulars added at each intervening level, delivering a pattern of ‘coarse-to-fine’ control. In the compositional perspective, we see that the social role of the CEO—the sphere of interest and influence,—is geographically much greater than that of others in a firm. A CEO’s interests span an entire business, or even an entire continent and beyond, and so involve a much larger scope than that of any of the subordinates, while a worker at a station at the bottom of the hierarchy would be concerned only with his or her current immediate transactions. So the social role of a CEO actually encompasses those of lower level workers, whose roles are contained within it, even though the workers’ bodies are not contained within the CEO’s body. This principle emerges from the role of money in society as well; wealth generally signifies the social status and personal power of an individual.

3 General Philosophical Outlook of Hierarchy

Ontologically, any hierarchy presupposes that the world is in some ways discontinuous. The compositional hierarchy assumes that it is a whole made up of parts, and also that it just keeps getting larger and larger the further one looks outward, or, going inward from an observer’s location, smaller and smaller. So, there would formally be no ‘edge’ to the world in either direction. The subsumptive hierarchy assumes that every dynamical object is supported by all aspects of the world, and that it will have developed from earlier, simpler conditions, and so might be part of a developmental trajectory or evolutionary history.

Epistemologically, the compositional hierarchy presupposes critical knowledge to be derivable by means of subdivision of a system (the traditional ‘biological reductionist’ view), while the subsumptive hierarchy implies that in order to understand a system it would be necessary to look for its sources in prior systems.

Methodologically, the compositional hierarchy presupposes that systems can be conceptually divided into parts, while the subsumptive hierarchy implies that important information about a system would be obtained from seeking antecedent—perhaps ancestral—conditions, the development out of which could usefully be cut up into discrete stages, or series of ancestral kinds.

4 General Properties

Hierarchies are conceptual tools rather than theories. They are methods of ‘cutting (a seemingly continuous) Nature at its joints’. They are examples of ‘partial ordering’ in logic. That is, the items being ordered could be ordered in other ways as well. Hierarchies order entities, processes or realms into a system of levels. The ordering principle (‘is-a-part-of’ or ‘is-a-kind-of’) is transitive across levels. In both of these hierarchies, when used to model actual systems, higher levels control (regulate, interpret, harness) lower levels, whose behaviors are made possible by properties generated at still lower levels (see below for the usage of ‘higher’ and ‘lower’). Higher levels function as formal causes, providing boundary conditions (in some cases, order parameters) on the behaviors of lower levels. This is the meaning of the term ‘downward causation’ in the hierarchy context.

It is important to realize that only some users of hierarchical forms would insist that particular levels actually exist as such in natural systems. Levels are discerned from hierarchical analysis, aimed at constructing/discovering Nature’s ‘joints’ with respect to given projects. Hierarchies thus provide models of any systems that may be susceptible to analysis into levels. If a system appears to be susceptible, then the logic of the hierarchy model used, as outlined in this paper, is imputed to the actual system being modeled—science discourse must of course first be logical. In this way the model serves as an exploratory highway in search for corroboration.

The magnitudes or frequencies of many aspects of the world (words in texts, earthquakes) can be mapped to power laws, ranging over many orders of magnitude. It is possible that levels in compositional hierarchies might also be susceptible to such a mapping, but it is worth noting that the ‘fractal ideology’ here is implicitly continuous rather than discontinuous, as with hierarchies.

(a) To use the compositional hierarchy to model a natural system we need to stipulate a focal level, as well as a lower and a higher, making up a ‘basic triadic system’—as, e.g., when the behavior of living cells is initiated by chemical events, and controlled by internal organismic events. The three level format models stability because with it in place a third level always anchors relations between the other two, and so the middle, focal level cannot be reduced either upward or downward by assimilation into a contiguous level. Here we should note that this hierarchy has been invoked to explain how the world manages to be as stable as it is, by avoiding tight coupling among components of complicated systems. A material system with this structure would be ‘nearly decomposable’, but not fully so. The triadic form also reflects the putative way in which levels would have emerged, by interpolation between primal highest and lowest ones, as when biology would have emerged as organizational forms of chemical activities occurring within an environmental energy-dissipative configuration. The question might arise as to why one could not make a two level version of this hierarchy. The answer is that there are always both material and formal causes bearing upon any material system. A third level will always be implicitly in play, even if not explicitly modeled.

(b) In the subsumption hierarchy the highest level is always the one in focus, with all lower levels subtending it and providing cumulative initiating conditions simultaneously upon it. The focal level supervenes upon all the other, supporting ones. Thus, biological configurations harness both physical forces and chemical potentialities. This dominance of the highest level being considered reflects the fact that this hierarchy is implicitly directional—in applications that would be evolutionary or developmental—with the levels being viewed as having emerged consecutively from the lowest, or most general (or most generally present in the world), up—as with, e.g., biology being emergent from physics as mediated by chemistry, both historically and also at any given moment at some locale. Thus the system has dynamically a two-level form (highest and all lower), which is formally unstable, allowing new levels to emerge at the top of the hierarchy. Use of this form provides us with a model representing emergent changes in the world, as when hominids evolved from African apes, or when a gastrula develops from a blastula—in both cases by the emergence of new informational constraints, logically a process of refinement.

Hierarchical analysis is always driven by a given problem or project, located at the focal level in a compositional hierarchy or at the highest level in a subsumptive hierarchy.

5 Formal Relations Between Levels

(a) The compositional hierarchy is one of parts nested within wholes, as, e.g., [… [species [population [organism [cell […]]]]]], where [higher level [focal level [lower level]]], hence the term 'inclusion hierarchy' is sometimes used. Nested processes or influences would not necessarily be reflected in actual nested things (recall the example of the CEO above, who does not contain the bodies of those subordinate to his wishes). The logic reflects Russell's logical types. In principle the levels just keep going, receding at both ends from any chosen focal level. If the parts of a modeled system are functional in some given analysis, they are referred to as components (of a 'dynamical hierarchy'), if not they would be constituents. As one goes down the hierarchy, the relative number of constituents per level increases, providing a measure of the 'span' of the hierarchy, which may be 'shallow', with few levels, or 'steep', with many.

(b) The subsumption hierarchy is one of classes and subclasses, as, e.g., {material world {biological world (social world)}}, where {lower levels {highest level}}. It should be noted that this use of 'higher' differs from the usage in logic discourse, where the outermost class or set is traditionally labeled the highest level. This reversal is rhetorically necessary in scientific applications to prevent taking, e.g., the physical realm to be 'higher' than the biological realm. The focus of analysis in applications is always the highest level, which is the innermost level of the hierarchy. The logic reflects Ryle's categories. Higher levels inherit all the properties of the lower levels.

Given {A {B}}, the following interpretations can be made:

Logically: B is a kind of A; B instantiates A; B generalizes to A; B is implicit in A

Functionally in an application: B regulates A; B harnesses A; B conceptually subordinates A

Semiotically: B Interprets A

Developmentally in an application: A gives rise to B; B supervenes upon A; B is a later stage of development than A; A is a material cause of B; A is vaguer than B with respect to properties of B that are immanent in A.

Here it will be useful to examine in detail the application of these subsumptive hierarchy principles to a characteristic biological developmental trajectory—

embryonic development. Referring to the basic properties of this hierarchy as enumerated above:

(1) Is an embryo more general than an adult? *Yes, as von Baer showed, earlier embryos (or those at the phylotypic stage) are common to many species, and become gradually more different as development proceeds.*
(2) Is an adult a kind of embryo? *Seemingly not; "kind of" requires further study here.*
(3) Do embryonic traits subsume those of the adult? *Yes, from the epigenetic perspective, they are prior temporally and provide material causes. Adult properties cannot transcend embryonic ones; a later stage is* more than *an earlier one, but it is not* other than *it. Adult features are refinements of embryonic ones.*
(4) Do adults inherit embryonic features? *Genetically, yes; anatomically, (for example, bilaterality; dorso-ventral and antero-posterior differentiation) by direct material derivation from them.*
(5) Are adults more highly specified than embryos? *Presumably so, as one would need to deploy more information to describe them, minimally because the system has during development acquired structure at more scales.*
(6) Does an adult instantiate an embryo? *Seemingly not.*
(7) Does an adult integrate or regulate the embryo? *Yes, insofar as, if the adult fails to breed, its embryonic precursor has failed to give rise to a fertile adult—the selection principle.*
(8) Does the adult interpret the embryo? *Yes,* via *epigenetic refinement.*
(9) Does the adult supervene upon the embryo. *Yes, it emerges out of it.*
(10) Does the adult harness the embryo to its needs? *Yes, by utilizing the precursor embryonic material and information storage*.
(11) Does the adult conceptually subordinate the embryo? *Yes. Given what the adult has become, the embryo had to have been as it was.*
(12) Is the embryo a material cause of the adult. *Clearly yes. This is not gainsaid by noting that the adult might be taken (*via *reproduction) as also being a material cause of the embryo!*
(13) Is the embryo vaguer than the adult? *Yes. Embryonic anlage are only gradually refined into the definitive adult condition.*

We must note the two exceptions here—numbers 2 and 6. The world is one thing, while models are another. It seems to me that with the other eleven queries being convincingly fulfilled, one might be justified in suggesting that the meanings of 'being a kind of' and 'instantiate' are really broader than we might suppose. I am suggesting that models can lead us toward further understandings that we would not have reached without them.

It might be objected that I am here making a tendentious use of the set theory format by modeling a dynamical process using it. The answer to this is clear enough; I am here modeling *successive stages* in a trajectory as classes and subclasses, not the process itself.

Then, it might seem that I am here denying that new forms can emerge during ontogeny, thereby going back to a kind of preformationism. But if we keep in mind the general process of moving from vague embodiment toward more definite expression, we can see that I am here emphasizing that the new, whatever it is, must logically be a refinement of a previous condition, This amounts to, in this format, not privileging the new as such, but treating it as an emergent from its material prior form. No model can emphasize everything. For example, no model and maximize all three of realism, precision and generality. Here I am emphasizing generality. We use different models as probes for different purposes.

(c) A note on levels terminology: The levels in a subsumption hierarchy have been referred to as 'integrative levels' inasmuch as the higher levels (as here defined) integrate the lower levels' properties and dynamics under their own rules. 'Levels of reality' and 'ontological levels' have been used in subsumption as well. One sees other labels, such as 'levels of organization, levels of complexity, or 'levels of observation' used for either kind of hierarchy. I have used 'scalar levels' or 'levels of scale' when applying the compositional hierarchy to material systems for dynamical reasons (see below under 'Criteria').

6 Mode of Growth of the Hierarchy

Biological systems grow, basically by way of cell division. This might result in an actual growth in size or scale, or the growth may be by intussusception (e.g., invagination, involution). The two hierarchies differ logically in the required way to visualize or model growth, or the emergence of new levels.

(a) In applications, a compositional hierarchy would need to add levels by interpolation between existing ones. For this to happen materially, the system must be an expanding one. Therefore, an assumption required for application of this hierarchy would be, e.g., the Big Bang, or other expanding system, like a growing population, or embryo, or phylogeny. The actual process of formation, or emergence, of a level would involve the cohesion of entities generated out of potential configurations of cooperating lower level components, as guided by a scaffolding of higher level boundary conditions, or as harnessed by order parameters imposed by the higher level. This would be a process that is therefore both bottom-up 'causal' and, simultaneously, top-down constrained (downward causation). This process is little understood since this hierarchy has largely been used for synchronic analyses. Some recent works on 'emergence' have been developing relevant viewpoints on this process. Given the reductionist orientation of most scientists, it is not surprising to find that in studies of the incorporation of individuals into a collective the individual properties (which I have called 'initiating conditions) are emphasized rather than any properties of the collective itself, which would be acting as boundary conditions.

It may be noted that the obligatory triadic form, surrounding the emergent focal level by higher and lower ones, implies that this hierarchy must be unbounded both above and below, even if, in applications, practicality or evidence requires cutoffs, such as, in cosmology, at the Planck scale below and the 'event horizon' above. Given today's knowledge about it, the cosmologist's universe could not, therefore, be taken as a focal level as nothing is known about its environment. In biology we find always a bottom limit to populations or individuals, as well as a genetically imposed rather fuzzy upper limit for individuals.

(b) In the subsumption hierarchy new levels in applications would emerge from the current highest one. So this system too can grow—but not in space. Growth here is by the accumulation of informational constraints, modeled logically as a process of refinement by way of adding specification as those constraints become fixed. Perhaps ‘growth by intussusception’ would be an adequate label in some cases. New levels, marked in the model as added subclasses, reflect thresholds of system structural reorganization under the guidance of emerging upper level boundary conditions or order parameters. A new innermost (highest) level emerges when added information results in a reorganization delivering configurations that require new descriptors, as when biological form supervenes upon the products of chemical interactions, or a new subspecies is discovered in systematics. This process does not require, but may be accompanied by, system growth. This hierarchy is open at the top; the innermost, highest, level is unbounded above, and so is free to give rise to ever higher, more highly specified, levels. There are reasons, however (see below) to doubt that an embodied hierarchy of this kind could keep extending indefinitely. The system here is formally a tree (see below), and so growth is in principle accompanied by branching possibilities.

7 Criteria for Application

(a) In order to apply the compositional hierarchy to actual natural systems or locales, components and/or the rates of change at the different levels must differ in size or magnitude roughly by at least an order of magnitude. As a result, entities at any level interact more frequently or more intensely with others at that level than—if at all—with entities at other levels. Failing this, components at different levels would directly interact dynamically, in which case there would not be different levels functionally. Compositional levels transact indirectly, by reciprocally supplying relatively stable conditions above and, e.g., reliable substrate concentrations, genotype proportions, species compositions, etc. (all ensemble properties) below. The principal result is that no information can transit unmediated across levels of scale. In physiology, for example, the organism controls cells by way of broadcast hormones, but individual cells are screened off from the state of the organism as a whole. Thus, I cannot directly affect any particular cell in my body, and it cannot have, as an individual, any effect upon me. A related, possibly derived, criterion is frequency and strength of interactions. Nuclear forces are much larger than covalent bonds, which are larger than hydrogen bonds, which are larger than van der Waals interactions. This scaling by magnitudes would presumably continue with cells, organs, biological individuals, communities, as well as with solar system, galaxy, and clusters of galaxies.

(b) Levels in a subsumptive hierarchy mark the qualitative differences of various realms of being, as in ‘physical realm’ versus ‘biological realm’.

Some might argue that levels like ‘biological’ versus ‘physical’ were constructed by human discourses, and may not have the kind of ‘objectivity’ felt to inhere in applications of the compositional hierarchy, as, for example, in physiology or ecology. I think a reasonable rejoinder would be that measured variables as used in compositional hierarchies are themselves products of discourse.

It is worth noting that in the realm of linguistic thought processes, the process of generalizing moves from particulars to generals, as in the reconstruction of putative ancestral forms in biological systematics. My use here, however, tracing emergent properties or systems from precursors, relates to ontology, where development moves from vaguer toward more fully explicit realization of the highest level. What appears as a general condition when looking 'backwards' would have been derived from a vaguer, precursor possibility during evolution at an earlier period or during development at an earlier stage. In evolution, for example, the gill arches of early fishes would only vaguely portend the later evolution of ear ossicles based on the redeployment of developmental processes, while during ontogeny the ear ossicles only gradually become refined into their definitive form during a 'coarse to fine' series of changes.

8 Complexity in Applications

(a) An application of the compositional hierarchy provides a model of what I have labeled 'extensional complexity', a sign of which would be nonlinear and chaotic dynamics, allowed for by the fact that at any locale at any level in this hierarchy there could be a mixture of different kinds of information coming from different levels (e.g., genetic, cellular, organismic) constraining the dynamics. These could be various relations, rates of activity, constant properties of different kinds, and attractors, which are not fully co-determined by organizing principles from the overall structure itself. The result is that any material system organized this way will have many non-directly interacting, but yet mutually constraining, systems occupying the same locale. This would result in concatenations of contingencies at several levels. Note that it would not be the case that a higher level would be more complex than a lower one since 'higher' and 'lower' are relative relations transitive throughout the hierarchy. It is useful here to contrast complexity with complication. A flat hierarchy with few levels could tend to show more complicated behavior at any given level than a hierarchy with more levels, which would have more constraints imposed top-down. Thus, a prebiotic ocean will have chemical properties and physical forces in interaction, giving rise to a very complicated, quickly changing scene. This system today would have become more stabilized by the addition of constraints from cells, populations and species.

(b) A subsumption hierarchy embodies what I have termed 'intensional complexity', which characterizes a system to the degree that it is susceptible to many different kinds (physical, biological) of analyses. No one approach could exhaust what might be learned from investigating objects at any given level in such a system, except, arguably, the lowest. To this we might also add the several potential new levels presumably hovering just liminal above the highest level; for example: will a Noosphere emerge from the current global domination of the earth by the human species?

9 Dynamical Relations in Applications

(a) Typically, a compositional hierarchy represents a single moment at one locale, so its dynamics represent homeostasis, not change. Emergent levels are already present, having emerged, and are being maintained by a combination of constraints and dynamics. Large scale moments ‘contain’ many small scale moments. It is often suggested that levels differing in scale fundamentally signal rate differences rather than component size differences. We may note that the two most often do go together; relatively big things are usually relatively slow to change or accelerate. Comparison of, e.g., slow chameleons with fast anoles suggests that we might best use average rates of change per size range since there will be a range of rates at any scale. A problem appears in cases that are said to be non-nested, where, e.g., a much slower rate in a component of a cycle would regulate the rate of an entire cycle. It would be rare, however, for such rates to differ by orders of magnitude in any cycle, and so many such putative examples likely are not hierarchical in a functional sense at all. If we allowed mere size differences rather than scale differences to be the criterion, then the constraint of nestedness would be lifted.

Because of the order of magnitude difference criterion between levels in applications of the compositional hierarchy, dynamics at different levels would not directly interact or exchange energy, but would transact by way of mutual constraint (i.e., via informational connections—e.g., order parameters imposed from above). The levels are screened off from each other dynamically. Because of this dynamical separation, informational exchanges between levels are non-transitive, requiring interpretation at the boundaries between levels. While the mereological logic itself is transitive throughout a meronomy, facts as such do not transit across levels separated by scale in applications. For example, while metabolism in a cell involves oxidation, oxidation is not a cogent phenomenon at the level of cells themselves; the results of oxidation would impact a cell as, e.g., molar gradients of ATP. As well, organisms may die, but they do not (functionally in ecology) oxidize. And, while organisms can die, they cannot become extinct, while populations cannot die, but may become extinct. Ontologically, each level requires its own lexicon, which would not make sense applied at other levels. So, levels communicate by transforming information at their boundaries. Generally, because of the dynamical screening off between levels, a higher level entity ‘reads’ a statistical/macroscopic summary of ensemble, microscopic, behaviors at the next lower level, and, facing the other way, ‘reads’ a higher level as being an unchanging, or periodically changing (long period cyclic), set of boundary conditions.

If focal level dynamics were represented by variables in an equation, then the results of dynamics at contiguous levels would be represented by (nonrecursive) constants. Larger scale dynamics are so slow with respect to those at the focal level, that the current value of their momentary result appears relatively unchanging with respect to processes at the focal level. Cumulated results of lower scale dynamics also appear—in this case statistically—unchanging at the focal level, as it takes a very long time for activities taking place in lower scale moments to effect a macroscopic change detectable at the focal level—these points are the essence of the dynamical ‘screening off’ between levels in material applications of the compositional hierarchy model.

Note that, because of these relations, thermodynamic equilibria would be more rapidly achieved per unit volume at a lower scalar level, delivering an adiabatic principle relating to screening off. While change of any kind (development, acceleration, diffusion) is relatively more rapid at lower levels, absolute translational motion can be more rapid at higher levels. Thus, higher levels provide modes of convection—dissipative structures—for the dissipation of energy gradients, which would otherwise proceed only by slow conduction at the lowest level instead. Related to these matters, we should note that metabolic rates and development are absolutely faster in smaller dissipative structures (organisms, fluid vortices, etc.), and that their natural life spans are on average comparatively shorter than would be the case for larger scale ones.

Related to this line of thought is the ‘Price equation’ in evolutionary biology, which models relations between selective pressures at multiple levels in the relevant biological hierarchy—[[[[genetic] organismic] trait group] population]. On the hierarchical principle here stated, rates of change at the lower levels would be faster than at the upper levels. This fact was used to argue against the efficacy of ‘group selection’ between populations because natural selection within populations would eliminate any altruistic genetic predispositions before these could be decisive in competition between populations. However, if the different populations do not lose their altruistic types at the same rates, maintaining a ‘variance in fitness’ between them, then if a large scale, catastrophic, selection pressure (unusual environmental change) descends upon all the populations, those with a critical number of altruists might survive better than the others, keeping the altruists well represented in the species. Thus, while rates of change would be faster at lower levels, comparatively more massive effects at slower rates in higher levels could be decisive in the longer run.

One sometimes sees the term ‘heterarchy’, posed in opposition to the compositional hierarchy model because of supposed failures of actual systems to conform to hierarchical constraints. One needs to recall here again that hierarchy is a conceptual construction, an analytical tool, and use of it does not imply that the world itself is actually hierarchically organized. It does seem to be so in many ways, but to suppose that this logical principle is actually embodied in the world would be naive. Hierarchy is one conceptual tool among many. The heterarchy dissent needs to focus upon what some take to be the true basis of material applications of the scale hierarchy—the order of magnitude separation of rates of change among levels separated by scale. If we have a heterogeneous field of systems of different sizes and rates, with no obvious separations between them, we would assign levels solely on the basis of this rate difference criterion. If no order of magnitude rate differences are found between entities, then the system would be judged to not be differentiated hierarchically. If we have a network of variably connected nodes, where contact between some are strongly lagged compared to most, then the systemic information flows might be hierarchically organized.

In the heterarchy perspective, it could also be the case that higher level entities might have several alternative lower level components among which they could switch their regulatory influence. Thus, in one situation a higher level, A, might regulate x, y, and z, while in another context it would regulate a, b, x and z. This is fully consistent with the principles of compositional hierarchies, even in cases that are not nested.

Often the ‘hetero’ opposition to hierarchy is based merely on faulty understanding (sometimes politically motivated!). For example, the tides are affected (partially controlled) by gravitational effects associated with the moon; yet the oceans are not nested inside the moon. As in classical thermodynamics, it is important to see the whole system appropriately. The oceans are nested, along with the earth itself, within the solar system, and from the hierarchical point of view, these effects on the tides emanate from the level of the solar system, not merely from the moon.

Another point concerning heterarchy is that the basic three-level scale hierarchy represents a system in a steady state configuration. Systems in transit may be highly turbulent, with episodic direct communications between levels distant in scale. Some systems that we can observe, like the surface of Jupiter, may be turbulent at a time scale very much slower than our own observational scale, and they might seem to be in a steady state on that account. But they should not be expected to display scale separated levels. Many systems we might observe would be in transit, but our models of things in the world tend to make the assumption of a tractable steady state, or at least momentary, conditions.

As we descend in applications to the realm of fundamental particles, it may be that some of these rules would break down, via, e.g., quantum nonlocality. Compositional hierarchical models represent events and transactions in the material world—a realm of friction and lag in the affairs of chemical elements and their compositions. From the scale hierarchy perspective, the quantum world could conveniently be viewed as in the quantum wave function—an electron would be ‘everywhere’ at once because its accelerated motion would be so relatively fast as to create a blur for a macroscopic observer.

(b) Dynamics in applications of the subsumption hierarchy are entrained by development, which is modeled as the process of refinement of a class, or increased specification of a category. It is important to note that this process is open-ended in the sense that there could be many coordinate subclasses of a given class, since the subsumptive hierarchy forms a tree. Thus, the potentials arising within any class form a tree. In the hierarchy, {physical realm {material realm {biological realm}}}, or in {mammal {primate {human}}} each of these hierarchies follows just one branch of an implied tree. Rylean categories can branch into new distinctions (and this forms a link with the scalar hierarchy because this process would give rise as well to new logical types). Evolution (unpredictable change) is one →many, and thus we have been able to picture the results of biological evolution using the Linnaean hierarchy. Currently biological evolution is not viewed as having developmental aspects, but that does not vitiate use of the subsumptive model to track its changes because in a material world any change is necessarily launched upon previous forms. This allows a degree of predictability to evolution; for example, predictions of active flight in vertebrates would plausibly be focused upon the forelimbs (true even for flying fishes!).

The fact that this is functionally a two-level hierarchy makes it susceptible to emergent evolution, because, without the anchoring provided by a third level, it can be, in a sense, reduced functionally to a single, newly emergent level subsuming all the previous levels. How is its direction of change into new subclasses insured, giving rise to the hierarchy? In models of the material world this is afforded by the fact that information, once in place (or once having had an effect), marks a system irrevocably. Marks in natural material systems are permanent, usually leaving traces even if subsequently obliterated. If a material system continues to exist, it must march forward if it changes; there can be no ‘reversal of evolution’. Its physical basis is spontaneously irreversible. Since change in the material world is entrained by the Second Law of thermodynamics, we would have here a link between material examples of the two hierarchy models because the Second Law can be seen to be a result of the expansion of the universe being too rapid to allow for the global equilibration of matter. As noted above, this expansion is also what affords the interpolation of new levels in examples of the compositional hierarchy.

So, development in a subsumptive hierarchy model requires a two-level basic form. Yet such hierarchies typically involve more than just two levels. Why do not the more general levels prevent change, as by the weight of their accumulated information at some locale or in some system or entity? Here we are led to note another aspect of development, which is perfectly general. The amount of change (effort, energy) required to launch a new level is ever smaller as a material subsumptive hierarchy develops—refinements are just that. This is also a materialist principle. The more general levels continue to exert their influence; thus, e.g., biology is mostly a kind of chemistry, and humans are mostly a kind of mammal. The key to understanding this situation is that in a subsumptive hierarchy informational relations between levels are transitive. Thus, physical dynamics are fully active players in a biological system. This means that we can sufficiently understand developmental change in this hierarchical model using only two contiguous integrative levels, since all prior levels would be active together in the emergence of a new level.

New levels may branch off anywhere in a subsumptive hierarchy, potentially giving rise to collections of coordinate subclasses. This raises in our minds, e.g., the possibility of other kinds of life, or of other chemistries in other universes.

Regarding causal relations in applications of either hierarchy, more work needs to be done. It has seemed to me that a systems approach like the Aristotelian causal categories could be a useful starting point in this regard. In applications of the compositional hierarchy, representing some ongoing process, my sketch would suggest material causes in the lowest of the three levels, efficient causes in the focal level, and both formal and final causes in the upper level. The subsumptive hierarchy representing development, would have final causes entraining the development in the innermost (highest or emerging) level, with mixtures of material and efficient causes in the lower levels, and with formal causes embodied in the current configurations of a ‘pregnant’ level.

10 Informational Relations and Semiotics

(a) As noted above, informational relations between levels in a compositional hierarchy are non-transitive. The levels are screened off from each other dynamically, and influence each other only indirectly, via transformed informational constraints. Impacts and perturbations moving from one level to another are transformed into signs at boundaries between the levels, as, for example, when the results of biosyntheses in cells have an effect on an organism only if, and after, a certain concentration is reached. When this constraint is not the case, as when a signal from a higher level occasionally transits directly to a much lower level, that level may suffer damage (as when an organism is hit by lightning, or, going the other way, when a particular cell affects the whole organism, this could come about only when and if its effect is promoted by cancerous growth). Here we can note again the idea that levels differing in the scale of their dynamics deliver stability to a system, via the screening-off effect. Unstable systems, e.g., turbulent ones, are not well represented using a compositional hierarchy.

The interpolation of an emergent level between two others can be viewed as involving the appearance of a capability in the uppermost level (via fluctuation, self-organization and/or selection) for making a significant (to it) interpretation of events at what then becomes relegated to being the lowermost level of three. The upper level effectively disposes—facilitates cohesion among—some of what is then the lowest level proposes. As the arena of the upper level's interpretations, causal relations at the new level act as a filter or buffer between the now upper and lower levels bracketing it. This allows us to see levels emerging between each other by way of a classification procedure whereby relatively microscopic topological difference information (say, in chemical mixtures) is converted to, or coheres macroscopically as typological distinction information located in the new middle level as interpreted by the upper level, in an essentially top-down semiotic procedure. Thus, chemical concentrations may be detected at the upper level only when they reach some threshold effect in the middle level.

In the absence of classification by an upper level, communication between levels cannot occur directly, as the 'moments' of levels separated by scale—their 'cogent moments'—would differ by order(s) of magnitude. For example, an upper level could not perceive individual actions at the lowest level, and would synthesize them as a blur, detecting only ensemble effects. So then, we could never communicate our intentions, as such, to, e.g., Gaia! But she might interpret the cumulating results of our activities, like the production of carbon dioxide from our technologies, as calling for the generation of massive fluid vortices like hurricanes.

I note again that the 'languages' at different levels in a compositional hierarchy would be different. The way molecules combine to form a cell differs from the way cells combine to form organs or organisms, or from the way organisms form family groups. The statistical properties of compositional hierarchies are transitive across the whole, but meanings do not transcend particular levels, as such, remaining unique to each level. It is worth noting here that there have been attempts to locate isomorphic forms at different levels, partly in hopes of getting some initial leverage on forms at levels very far from our own in scale. The presence of such isomorphies would not invalidate the non-translatability of meanings across levels, but would raise interesting questions as to their interpretation by the outside observer using this model.

(b) In a subsumptive hierarchy the lower levels also make possible the emergence of a new realm, in an epigenetic (building-upon) process. And here too the process is top-down, but in a different sense, involving finality. Thus, e.g., we can see that organism sociality implies biology in the sense of material implication or conceptual subordination. Then, as organism sociality implies biology, biology implies chemistry, and so, because these relations will have come about as a process of refinement, only a relatively narrow set of possibilities could imply organism sociality. That is, chemistry could give rise to many kinds of subsystems, biology to fewer, and sociality to even fewer as the overall material system—as an epigenetic system—develops. Developments (in contrast to evolution) are entrained by final causes, and approach them asymptotically with each emergence of a new condition. Involved here as well, as in all developments, is the process of senescence, a condition of information overload. Recall that information in this hierarchy is transitive across levels, leading in the higher levels toward a condition of overconnectivity, leading in turn to functional underconnectivity, leading in its turn to inflexibility and habit driven responses (loss of requisite variety), leading ultimately to loss of adaptability. From this viewpoint, the number of realms (chemical, biological, etc.) in the world would likely be quite limited. Thus, even though new higher levels could occasionally arise above the sociocultural level among humans (e.g., a Noosphere), they could be predicted, using the subsumptive hierarchy model, to have a difficult time maintaining themselves for very long, even as does a senescent organism.

Evolutionary biologists might object to the role assigned here to finality, given that there is no evidence of final causes in observations of the fossil record, or any conscious use of it in the neoDarwinian theory of evolution. I note again that the subsumptive hierarchy is one where lower levels subsume the higher. Then we might note that the Second Law of thermodynamics at the lowest, physical, integrative level entrains all changes finalistically toward thermodynamic equilibration of the global system of the universe. At the chemical integrative level this is seen as changes directed toward the condition of least free energy locally. These directed changes are subtending biological changes, where we observe the activities of living dissipative structures. Given the inheritance of properties from lower integrative levels, these too could be supposed to be working to dissipate their supporting energy gradients as rapidly as possible—short of damaging the system. We can note, for example, that the transcription of genetic information into protein products—a central biological image—depends upon the dissipation of energy stored in ATP, which would occur under the constraint of lowering the available free energy as expeditiously as possible locally. Here we face the possibility that a finalistic tendency subtending a higher integrative level must be being promoted at that highest level. It then becomes plausible that the expansion of biological systems, as represented in the Linnaean hierarchy, can be viewed overall as a process of promoting access to increasing numbers of as yet untapped energy gradients.

From the currently ascendant perspective on organic evolution, adaptation would be entrained by no final causes. If that is the case, then the overall evolutionary phenomenon, as a series of happenstances that can be modeled in the subsumptive format merely because of material inheritance, would formally be a degenerate application, with no theoretical implications. I merely point out here that the Linnaean model, being in the subsumptive format, therefore generates a sense of conceptual unease. Models normally exemplify a theory, but it would not be surprising if they also implied one that is as yet unformulated. We know that developments are entrained by finalistic tendencies and can be modeled by a subsumptive hierarchy (as demonstrated above in the formal relations section), and so the question may arise as to whether that which is modeled in the Linnaean hierarchy might also be so entrained. Since science is mediated by logical discourse, might it not also on occasion be entrained by it?

Considering semiotics, it has been suggested that higher integrative levels would have greater ‘semiotic freedom’. This would be a result of the greater elaboration of forms at these levels, allowing greater precision of interpretation, as well as reactions to finer distinctions. That is, reaction to (or interpretation of) a stimulus would at higher levels be more underdetermined by the actual physical interactions taking place in the lower integrative levels. In this way, e.g., the result of a light ray impacting the retina of, say, a fish could not be predicted without knowing further what species of fish the retina is part of and what its current context is. Thus, the hierarchy:

$$\{\text{physiosemiosis } \{\text{chemosemiosis } \{\text{biosemiosis } \{\text{anthroposemiosis}\}\}\}\}$$

models an increase in semiotic freedom. As one moves into the higher levels, there would be an increasing burden of informational constraints bounding the behavior of individuals (e.g., mice can neither divide mitotically nor fly), but some of these are enabling constraints, allowing definite choices in the more detailed, as well as more limited, world of an individual in the innermost, upper, level. Thus, mice might reasonably be supposed to have the possibly of evolving flight. Languages, at the highest known (socio-cultural) integrative level can represent very many quite particular relations, but each language has its own realm, with none encompassing all possible linguistic references (viz. the Whorffian hypothesis). The more you can say in detail, the more (as located on another branch of the hierarchy) you cannot say!

(c) Relations between the compositional and subsumptive hierarchies are only now beginning to be examined using abstract tools, like hyperstructures. One possible approach already suggested could be to see applications of these forms as being orthogonally related, with the subsumptive hierarchy tracing change, while at any instant or stage the trajectory would be in the form of a compositional hierarchy. The diagram in Fig. 1 shows these relations as seen from the point of view of an observer located as simultaneously at the top of a subsumptive hierarchy and in the middle of a compositional hierarchy.

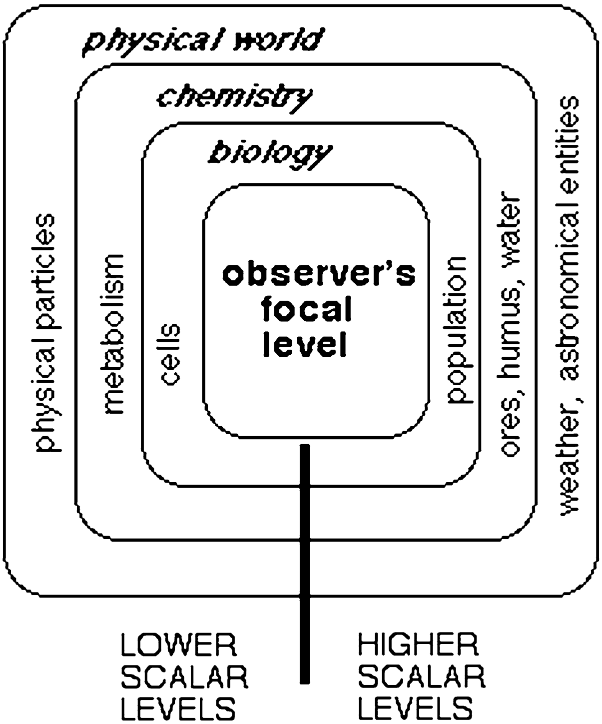

Fig. 1 The subsumptive hierarchy is shown as a pyramid surrounding the observer located at the highest level, with its levels listed *horizontally*. The compositional hierarchy is not shown, but is listed from *left* to *right horizontally* extending from the smallest scale at the *left* to the largest at the *right*, with the observer in the center. The levels on the *left* are contained within the observer, those on the *right* contain him/her

11 Conclusion

In view of the completely different organization of compositional and subsumptive hierarchies, users ought to become familiar enough with these forms and their possible uses so that choice of hierarchical structure for modeling will be informed rather than haphazard. Many natural systems can support either kind of model, and the choice would be made according to the nature of the investigation.

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Appendix: Further Readings

The following sources emphasize the historically important and logically basic, as well as recent (post 1990) references that seem to me to bring in new departures and interesting applications, which could have implications for the principles. These latter also show some of the recent diversity of approaches, usually made in ignorance of principles or of each other's efforts. The presence of a post-1990 paper here does not indicate endorsement by me of all of these works.

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