Chapter 24
Hierarchy Theory: An Overview

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Abstract In both the natural and the artificial worlds, complex systems are often hierarchically organized. In other words, they tend to be structured in layers or levels. The rates of interaction within components at any hierarchical level are much faster than the rates of interaction among components. Also, higher levels tend to be larger and slower whereas lower levels tend to be smaller and faster. This fundamental property of complex systems is called near-decomposability. Hierarchy theory is a general theory that aims to simplify the description, and thus improve the comprehensibility, of complexity by taking advantage of near-decomposability. In this chapter, I provide an overview of the theory, focusing on its core concepts and tenets. These include the following topics: definitions of hierarchy, hierarchical levels, ordering of hierarchical levels, vertical and horizontal structures, near-decomposability and the empty world hypothesis, the basic triadic structure, hierarchy and scale, the observer's role. I also discuss some common criticisms on hierarchy theory, and conclude with some comments on the nature and future of the theory.

Keywords Complexity • Near-decomposability • Loose coupling • Levels • Scale • The Basic triadic structure • Hierarchy-scale correspondence • Space-time correspondence • The Observer's role

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> *Scientific knowledge is organized in levels, not because reduction in principle is impossible, but because nature is organized in levels, and the pattern at each level is most clearly discerned by abstracting from the detail of the levels far below. …… And nature is organized in levels because hierarchic structures – systems of Chinese boxes – provide the most viable form for any system of even moderate complexity.*
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> – H. A. Simon (1973, pp. 26–27)

24.1 Introduction

Many modern scientific marvels, from biology to medicine and from physics to engineering, have been achieved through reductionist approaches that treat a complex system as something no more than the sum of its parts. At the same time, however, increasingly challenging environmental and socioeconomic problems on broad scales seem to have defied the power of reductionism, demanding more comprehensive and integrative perspectives. Even on micro-scales with an individual organism, it has become increasingly clear that the meticulously detailed inventory of genes, proteins, and metabolites is not even sufficient to understand the complexity of a cell, much less the behavior of an organism (Hartwell et al. 1999; Oltvai and Barabasi 2002). Complexity makes wonders, but challenges understanding.

Both natural and artificial (man-made) systems can be complex when the number of components is large and when their interactions are nonlinear. For example, ecosystems are complex when one considers the large number of species interacting with each other and with their ever-changing environment. Socioeconomic systems are complex as their dynamics are determined by myriad factors involving government, society, and institutions from the local to the global scale. In general, coupled human-environmental systems may be even more complex because they encompass both natural and anthropogenic entities as well as the diverse interactions among them. To cope with complexity, the guidance of theory is often indispensable.

Great efforts have been made to develop theories and methods to deal with complexity during the past several decades. According to Herbert A. Simon, a polymath and a Nobel Laureate in economics, since the twentieth century there have been three "recurrent bursts of interest in complexity and complex systems" (Simon 1996). The first burst took place after World War I, and had a strong anti-reductionist flavor, as suggested by the terms of "holism," "Gestalts," and "creative evolution" (Simon 1996). The second burst occurred after World War II as systems science began to take shape. Research during this period was characterized by such terms as "general systems," "information," "cybernetics," and "feedback," focusing primarily on the roles of feedback and homeostasis in maintaining system stability (Simon 1996). Since then, systems theories and methodologies have continued to develop and been widely used in both sciences and engineering fields. The third burst probably started in the late 1970s or the early 1980s, characterized by terms such as "chaos," "catastrophe," "fractals," "cellular automata," and "genetic algorithms," "criticality," "adaptive systems," and "hierarchy," with a research focus on mechanisms that create and sustain complexity and on methods that describe and analyze complexity (Simon 1996). Hierarchy theory is an alternative and a complement to the other existing approaches to complexity, which is based on the premise that "complexity frequently takes the form of hierarchy" (Simon 1962, p. 468). In his epochal paper on the subject, Simon (1962, p. 481) argued that "one path to the construction of a nontrivial theory of complex systems is by way of a theory of hierarchy."

Although the concepts of hierarchy and levels of organization have long been used since ancient times, not until the early 1960s did hierarchy theory begin to emerge. As an offshoot of general systems theory, hierarchy theory was developed from a cross-disciplinary perspective, with important contributions from management sciences, economics, psychology, biology, and mathematics. The most important founder of the theory was Herbert A. Simon, whose series of writings not only laid the foundation of hierarchy theory, but also have continued to influence its further development ever since (Simon and Ando 1961; Simon 1962, 1969, 1973, 1976, 1981, 1995, 1996, 2000) (Table 24.1). Other important earlier contributions include Koestler (1967), Whyte et al. (1969), Weiss (1971), and Pattee (1973) (Fig. 24.1). Since the early 1980s, hierarchy theory has been further elaborated and expanded, with a distinctly biological and ecological emphasis, through several influential books, including Allen and Starr (1982), Eldredge (1985), Salthe (1985), O'Neill et al. (1986), Allen and Hoekstra (1992), and Ahl and Allen (1996) (Fig. 24.1). Particularly in ecology, the influences of hierarchy theory became pervasive and prominent between the 1980s and the early 2000s, contributing to the new ecological paradigm that centers on pattern-process-scale relationships (Wu and Loucks 1995; O'Neill 1996).

The objective of this chapter is to provide an overview of hierarchy theory, focusing on its key concepts and tenets that are particularly relevant to ecological and human-environmental systems. This is not an easy task because hierarchy theory is not a formal theory, meaning that it lacks clearly-defined terms, well-developed methodologies, and unambiguous predictions. Different versions of hierarchy theory exist. While I discuss some of the different perspectives when necessary, this is not intended to be an inclusive treatment of the subject in terms of its developmental history or diverse viewpoints.

24.2 Hierarchy: A Word with Many Meanings

24.2.1 What Is Hierarchy?

The online Merriam-Webster Dictionary (http://www.merriam-webster.com) defines the word "hierarchy" as follows:

> (1) a division of angels; (2a) a ruling body of clergy organized into orders or ranks each subordinate to the one above it; especially: the bishops of a province or nation; (2b) church government by a hierarchy; (3) a body of persons in authority; (4) the classification of a

Table 24.1 The architect of simplifying complexity – Herbert A. Simon – and his seminal publications on hierarchy theory (Photos from http://www.techcn.com.cn/). The number of citations to his publications was obtained from Scholar.Google.com (May 10, 2013)

Herbert A. Simon (1916–2001): *Economist, psychologist, political scientist, sociologist, and computer scientist; Nobel Laureate in economics in 1978*	Number of citations
Some publications on hierarchy	
Simon, H. A. and A. Ando. 1961. Aggregation of variables in dynamic systems. Econometrica 29:111–138	628
Simon, H. A. 1962. The architecture of complexity. Proceedings of the American Philosophical Society 106:467–482	3,997
Simon, H. A. 1969, 1981, 1996. The Sciences of the Artificial. 1st, 2nd, and 3rd edition. The MIT Press, Cambridge	14,607
Simon, H. A. 1973. The organization of complex systems. Pages 1–27 in H. H. Pattee, editor. Hierarchy Theory: The Challenge of Complex Systems. George Braziller, New York	650
Simon, H. A. 1976. How complex are complex systems? Pages 507–522 *in* PSA: Proceedings of the Biennial Meeting of the Philosophy of Science Association	48
Simon, H. A. 1995. Near decomposability and complexity: How a mind resides in a brain. Pages 25–44 *in* H. Morowitz and J. Singer, editors. Mind, the Brain, and Complex Adaptive Systems, Santa Fe Institute Studies in the Sciences of Complexity. Addison-Wesley, Reading, MA	50

group of people according to ability or to economic, social, or professional standing; also: the group so classified; (5) a graded or ranked series <a hierarchy of values>.

[Origin: Middle English *ierarchie* rank or order of holy beings, from Anglo-French *jerarchie*, from Medieval Latin *hierarchia*, from Late Greek, from Greek *hierarches;* First Known Use: 14th century.]

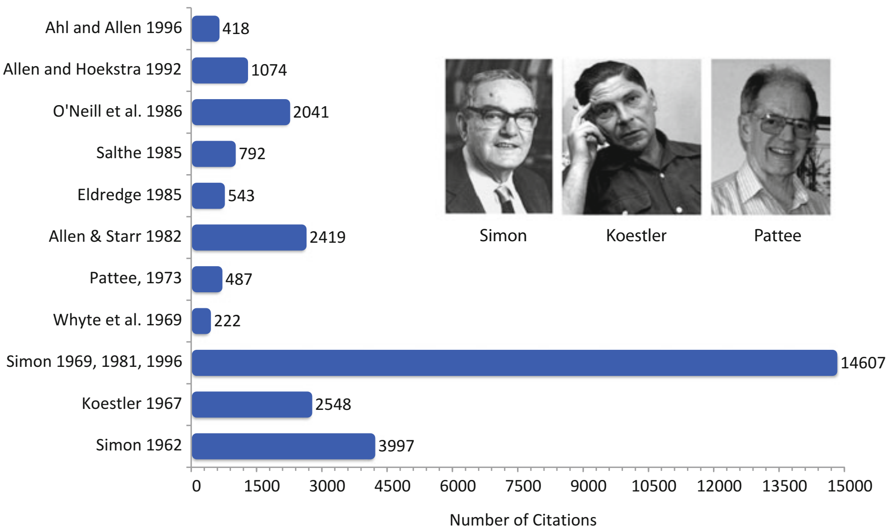


Fig. 24.1 Some key works on hierarchy theory. Information on citations to the publications was obtained from Scholar.Google.com (May 10, 2013)

The above definitions indicate that hierarchy originated in a religious context, and that its connotations are often human-centered, with a strong sense of authority, dominance, or ruling power. However, none of these definitions adequately captures the breadth of modern-day use of the term.

In general, a hierarchy simply refers to a system that is structured in layers or levels that have asymmetric relations. From a systems perspective, Simon (1962, p. 468) defined hierarchy as "a system that is composed of interrelated subsystems, each of the latter being, in turn, hierarchic in structure until we reach some lowest level of elementary subsystem." Simon (1962) further noted that determining the level of elementary components in a hierarchy is somewhat arbitrary. Mathematically, a hierarchy is a partially ordered set or poset in which not all elements are related (e.g., the set of all plant species in an area ordered by their phylogenetic relationship, or the set of postal codes for a country).

Hierarchy has much broader meanings than an authoritarian system or a pecking order. Chinese boxes, Russian dolls (also known as Matryoshka dolls), trees, and pyramids of sorts are common analogies of hierarchy. As Simon (1973) pointed out, however, a set of Chinese boxes (or Russian dolls) is a complete ordering, whereas a hierarchy is a partial ordering which is structurally more similar to a tree. The concept of hierarchy is closely related to "levels" of organization, dating back to ancient times (Wilson 1969). In biology and ecology, for example, the hierarchy of life and the spatial hierarchy have long been used in the classic and modern literature (Tansley 1935; MacArthur 1972; Odum and Barrett 2005). For example, when Arthur G. Tansley (1935, p. 299) coined the term "ecosystem," he apparently envisioned it as a level of a grand hierarchy of the universe: "These ecosystems … form one category of the multitudinous physical systems of the universe, which range from the universe as a whole down to the atom."

24.2.2 What Kinds of Hierarchy Are There?

Hierarchy is ubiquitous in both the natural and artificial worlds (Simon 1962, 1996). For example, the universe consists of galaxies that in turn consist of planetary systems that in turn consist of satellite systems (Shapley 1958; Simon 1962, 1976; Wilson 1969). Biological systems, classification schemes of all kinds, governments, postal codes, software packages, and social, economic, and scientific organizations are structured in levels, i.e., hierarchical. Ecological organizations (e.g., organisms-populations-communities-ecosystems-landscapes), food webs, and pyramids of numbers, biomass, and energy are familiar examples of hierarchy to ecologists. Even human aspirations can be organized hierarchically according to prepotency, as shown in the Maslow's hierarchy of needs (Maslow 1954).

Hierarchies can be classified into different kinds based on various criteria. For example, in terms of their content and dimensions, we may have spatial versus non-spatial hierarchies, structural versus functional hierarchies, living versus nonliving hierarchies, and political, social, religious, economic, ecological, and physical hierarchies. Wilson (1969) identified three broad categories of hierarchy: "hierarchy as concept" (mental models), "hierarchy in nature" (from elemental particles to the universe), and "hierarchy in artifact" (from computers to human organizations). From a different perspective, Salthe (1991) recognized two forms of hierarchy: scalar hierarchies are organized by spatio-temporal scales (e.g., atom-molecule-cell-organ-organism-population), whereas specification hierarchies are composed of nested "integrative levels" or stages of development (e.g., physics-chemistry-biology-sociology-psychology). Similarly, Ahl and Allen (1996) distinguished scalar hierarchies that are composed of "levels of observation" (empirically derived) from definitional hierarchies that consist of "levels of organization" (stipulated by the observer). The levels in conventional ecological organizational hierarchies from organisms to the biosphere are definitional, and do not necessarily meet scalar criteria (Allen and Starr 1982; Ahl and Allen 1996; O'Neill and King 1998).

Another classification, which is important in hierarchy theory, is the dichotomy of nested versus non-nested hierarchies (Allen and Starr 1982; Ahl and Allen 1996). Many natural, social, and organizational hierarchies are nested hierarchies in which higher levels contain, or are composed of, lower levels. Familiar examples of nested hierarchies include the compositional hierarchy that connects the nonliving and living systems (i.e., elementary particles-electrons + nuclei-atoms-molecules-cells-tissues-organs-organisms-populations-communities-biomes-the biosphere) and the biological taxonomic hierarchy (i.e., species-genus-family-order-class-phylum-kingdom). Systems made up of spatial units of different sizes are nested hierarchies (e.g., the world map, a photo mosaic, and a Russian doll set). Non-nested

Table 24.2 Comparison between non-nested and nested hierarchies (Based on Allen and Starr 1982; Ahl and Allen 1996)

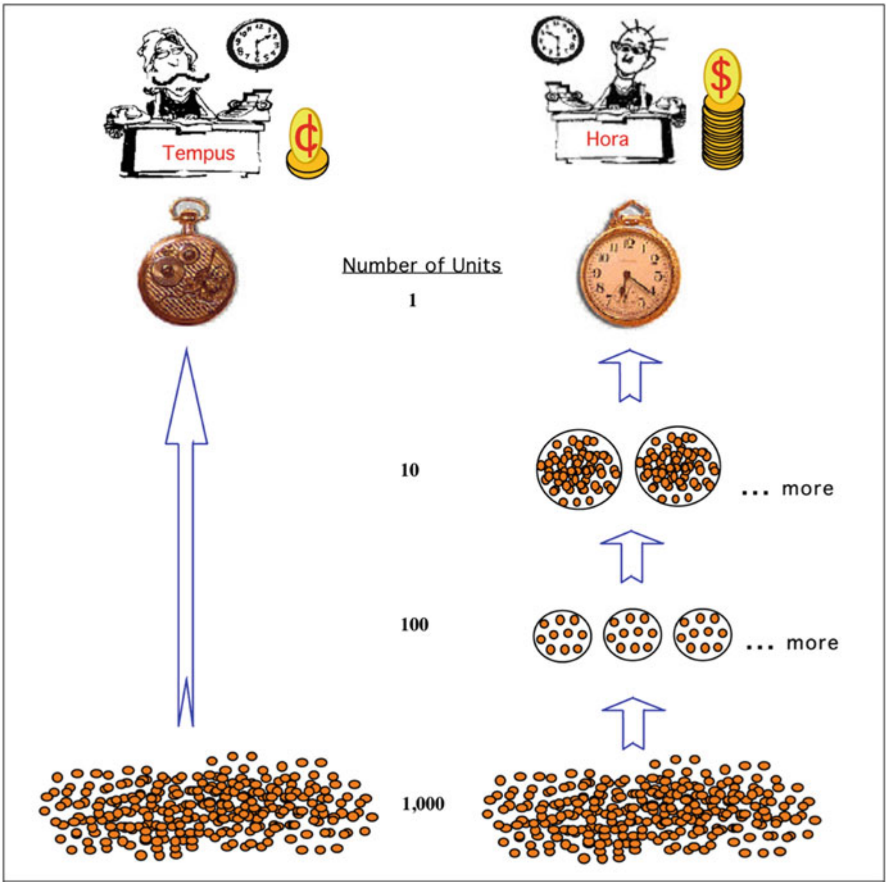
Non-nested hierarchies	Nested hierarchies
Examples: the military command hierarchy; food webs	Examples: the army consisting of soldiers of all ranks; taxonomic systems
Not suitable for exploration	Suitable for exploration
Same criteria (or measurement units) pressing across all levels	Different criteria (or measurement units) at different levels
Comparison between hierarchies is more feasible	Comparison between hierarchies is less feasible
System-level understanding can not be obtained by knowledge of parts	System-level understanding can be obtained by knowledge of parts

hierarchies may have all other asymmetric between-level relations, but not the one of containment (e.g., the trophic hierarchy, the army command hierarchy, and the Maslow's hierarchy of human needs). Although the general concepts and principles of hierarchy theory apply to both types of hierarchies, they differ in several ways (see Table 24.2).

24.2.3 Why Is Hierarchy So Common?

Simon (1962, 1973) answered this question by telling his favorite "watchmaker parable" (Fig. 24.2). The parable started with two fine watchmakers who made equally fine watches consisting of the same number of basic parts. Both attracted many phone calls from customers which interrupted their work. Such interruptions forced both men to let the unfinished watch at hand fall apart. The fate of the two watchmakers, however, was quite different: one became rich and the other went bankrupt. The structure of the watch (i.e., the organization of parts) turned out to be the difference maker. The winner's watch was structured hierarchically or modularly, whereas the loser attempted to assemble his watch directly from the parts without any intermediate assemblies (Fig. 24.2). The parable suggests that "hierarchies will evolve much more rapidly from elementary constituents than will non-hierarchic systems containing the same number of elements" (Simon 1973, p. 8). In general, a non-hierarchical complex system is less likely to evolve; if it does exist, it can not be fully described; if it could, it would be hardly comprehensible (Simon 1962, 1973, 1995).

In the artificial world, a hierarchical architecture is often advantageous. It is hard to think of any complex human-made system – from brick buildings to software systems, societies, and institutions – that does not have a hierarchical structure. The watchmaker parable suggests that a system with a large number of components is unlikely to be efficient and stable if it is not hierarchically organized. Of course, this does not mean that hierarchy guarantees efficiency and stability. When a hierarchical



- **Two fine watchmakers**: Hora and Tempus, who were making equally fine watches, each consisting of 1000 parts. Their popularity attracted many phone calls from customers, interrupting their work and making the partly assembled watch at hand fall apart.
- **The math**: Assuming that the probability of an interrupton occurring while a part is being added to an assembly is 0.01, Hora made 111 times as many complete assemblies per watch as Tempus; Tempus had to make 20,000 as many attempts per completed assembly as Hora.
- **The outcome**: Hora became a rich man, but Tempus went bankrupt.

Fig. 24.2 Illustration of the watchmaker parable (Based on the description in Simon 1962)

system is too deep (too many levels) and too rigid (too strong top-down controls), its performance is doomed because of low efficiency and low adaptability.

From a thermodynamics perspective, dissipative structures and stratified stability theory have also been invoked to explain why physical and biological systems are hierarchically organized. Dissipative structures help explain how ordered structures emerge hierarchically in open systems, while stratified stability provides a description of how such structures persist and form building blocks for higher levels of organization (O'Neill et al. 1986; Wu 1991). For example, functional groups or guilds in ecological systems are more stable and enduring than their component species, and thus serve as building blocks for ecosystems (O'Neill et al. 1986). On micro-scales, interacting molecules of different types make up functional modules who carry out various cellular functions (Hartwell et al. 1999).

Furthermore, from a spatial perspective, dividing a geographic region into subregions and further into smaller areas, according to either natural or human criteria, always results in a spatially nested hierarchy. The eminent ecologist, Robert H. MacArthur (1972, p. 186) described the nested-hierarchical structure of the environment quite nicely:

> A real environment has a hierarchical structure. That is to say, it is like a checkerboard of habitats, each square of which has, on closer examination, its own checkerboard structure of component subhabitats. And even the tiny squares of these component checkerboards are revealed as themselves checkerboards, and so on. All environments have this kind of complexity, but not all have equal amounts of it.

Thus, maps are the most common way of showing spatial hierarchies of different kinds. Maps of the world, nations, and administrative units are familiar examples. Maps of climate, soils, vegetation, ecosystems, and land use are routinely used in ecological studies. Spatial hierarchies are always nested, and they may or may not correspond exactly to rate hierarchies that are defined for the same systems (O'Neill et al. 1986).

24.2.4 Is Hierarchy Real?

Do hierarchies exist in reality external to the observer, or are they merely the observer's mental models that do not necessarily correspond to the real world? These are ontological questions, begetting philosophical and epistemological arguments. Allen and Starr's (1982) version of hierarchy theory advocates a "process-oriented" framework, in which the ontology of entities is considered unimportant. These authors are clearly in favor of the view that hierarchies are observer-imposed constructs which may or may not correspond to reality (Allen and Starr 1982; Ahl and Allen 1996). Subscribing to Allen and Starr (1982) version of hierarchy theory, Wilby (1994, p. 657) claimed that "It is the content of the hierarchies that is the reality, not the organization framework we call 'hierarchy' that is real." This suggests that hierarchies constructed in studies, influenced or even determined by the observer's epistemology, are never real. On the other hand, Salthe's (1985) version of hierarchy theory is based on a "thing-oriented" framework in which entities or objects are not only real but also essential for describing and understanding hierarchical structuring. The fact that organisms are composed of organs that are further composed of tissues, cells, molecules… exists independent of the observer's epistemological stance. Explicitly recognizing and relating these levels has contributed significantly to advances in modern biology.

Although not discussing the ontological issue explicitly, most other authors seem to assume that many physical, biological, and organizational hierarchies exist in reality, admitting that some conceptual hierarchies may be constructed without realism. As Tansley (1935, p. 300) stated, “The mental isolates we make are by no means all coincident with physical systems, though many of them are, and the ecosystems among them.” Simon (1962, p. 468) asserted that “hierarchy … is one of the central structural schemes that the architect of complexity uses.” This implies that hierarchy exists in real-world complex systems although the observer or investigator may inevitably play a role in the process of observing and constructing the hierarchy. In other words, “complexity may lie in the structure of a system, but it may also lie in the eye of a beholder of that system” (Simon 1976, p. 508).

In scientific studies, therefore, hierarchies neither are absolutely the reality nor merely the perception of the observer; but rather, they are the products of the interactions between the reality and the observer. The degree of “realness” of hierarchy not only depends on the nature of the real system, but also the observer’s abilities, including the theoretical framework, methods, and data used to discover the hierarchy. Although sometimes it is relevant to know whether hierarchies are real or whether they are at least reflective of reality, hierarchy theory can be, and has often been, used without explicitly addressing the issue of ontological reality. In most cases, one may simply take “an epistemological stance in a utilitarian philosophy” as Allen and Starr (1982) preferred.

24.3 Main Tenets in Hierarchy Theory

24.3.1 Hierarchical Levels

Hierarchies are characterized by layered structures, and the discrete layers are also called levels. A hierarchical system is composed of multiple levels, each consisting of one or more components or subsystems (Fig. 24.3a, b). The nature and characteristics of components comprising levels vary with the type of hierarchies. For example, a *scalar hierarchy* is composed of empirically-based levels of observation, while a *definitional hierarchy* is comprised of the observer-defined levels of organization (Ahl and Allen 1996; Allen 2009). Although Simon (1962, p. 468) noted that “hierarchic systems have certain common properties independent of their specific content,” hierarchy theory does not apply to all kinds of hierarchies mentioned so far. The power of hierarchy theory usually resides with scalar hierarchies, both nested and non-nested.

The components or subsystems that make up a hierarchical level are called “holons” (from the Greek word *holos* = whole and the suffix *on* = part or particle as in proton or neutron), a term coined by Koestler (1967). A holon is like a “Janus-faced” entity with a dual nature, acting as a whole when facing downwards and

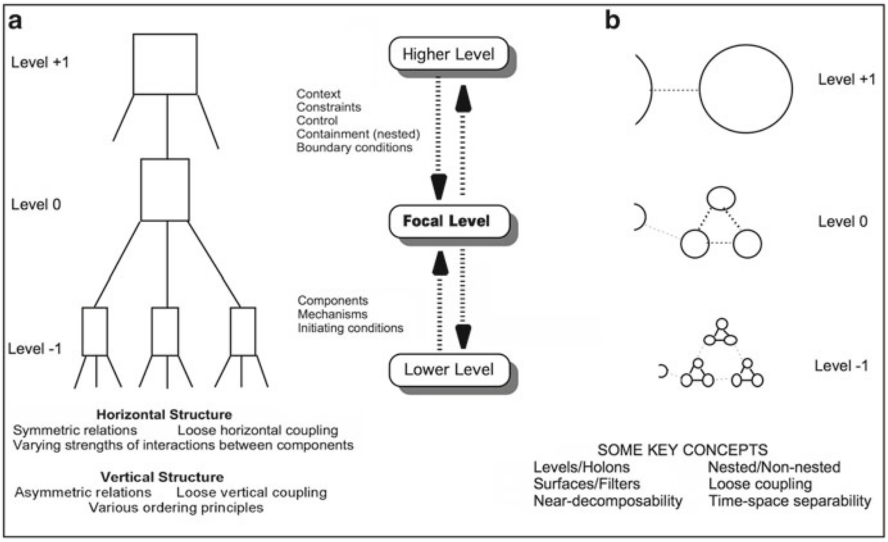


Fig. 24.3 Illustration of key terms and concepts of hierarchy theory, in which (*A*) and (*B*) are two schematic representations of a hierarchy (*A* redrawn from O'Neill 1988 and *B* redrawn from Urban et al. 1987)

as a part when facing upwards (Koestler 1967). The boundaries between levels and holons are also termed "surfaces," which correspond to places exhibiting the highest variability in interaction strength (Allen and Starr 1982; Ahl and Allen 1996). Surfaces sift the flows of matter, energy, and information crossing them, and thus can also be perceived as "filters" (Allen and Starr 1982; Ahl and Allen 1996).

In applying hierarchy theory, it is desirable to derive hierarchical levels from data using quantitative methods. For example, in the recent decades, remote sensing, geospatial analysis tools, and computing capacities have enabled ecologists and geographers to quantify spatial structures from the local ecosystem to the globe. Such studies have repeatedly shown that hierarchical structures exist, external to the observer, in both natural and human-dominated systems, which can be revealed through spatial pattern analysis regardless of the observer's perception. Also, recent studies in systems biology and network analysis have shown that "network motifs" or modular structures (e.g., small subgraphs-significance profiles-superfamilies-networks) exist in biological, sociological, and technological networks, ranging from protein signaling networks to power grids, World Wide Web links, and word-adjacency networks in different languages (Oltzvai and Barabasi 2002; Milo et al. 2004). These hierarchical modular structures now can be detected using new methods with increasing efficacy and objectivity (Oltvai and Barabasi 2002; Milo et al. 2004; Itzkovitz et al. 2005; Zhou et al. 2006; Sales-Pardo et al. 2007).

24.3.2 Ordering of Hierarchical Levels

Central to hierarchy theory is the ordering of hierarchical levels. Simon (1962, 1973, 1976, 1996) emphasized that process rates and the frequency and strength of interactions among components are the fundamentally important criteria for the ordering of hierarchical levels. He indicated that, in both social and physical systems, faster and higher frequency dynamics are associated with lower levels, whereas slower and lower frequency dynamics are related to higher levels (Simon 1962, 1973, 1996). Pattee (1991) noted that there are numerous criteria for ordering hierarchical levels, including scalings of time, rate, space, number, and connectivity. Allen (2009) summarized five general principles for ordering levels in ecological hierarchies:

1. higher levels operate more slowly and at a lower frequency than lower levels;
2. higher levels exert constraints on lower levels;
3. higher levels function as a context to lower levels;
4. higher levels have weaker bond strengths between holons and thus lower integrity than lower levels;
5. in the case of nested hierarchies, higher levels contain or consist of lower levels.

While different hierarchical ordering criteria may suit with different purposes, process rates-related measures (e.g., behavioral frequencies, relaxation time, cycle time, and response time) are considered the most general and fundamental criteria, and that levels in biological and ecological hierarchies can most easily be characterized by response time. Hierarchical levels can also be identified or defined in terms of tangible boundaries (e.g., spatial hierarchies), but such hierarchies may differ from rate-based hierarchies although they share many properties (O'Neill et al. 1986; Urban et al. 1987).

The process of identifying and ordering hierarchical levels is a critical step in simplifying a complex system using hierarchy theory. After a large number of components are organized into a much smaller number of levels and holons, the dimension of the system is greatly reduced, the problem at hand becomes much more tractable, and the comprehensibility of the system is substantially enhanced.

24.3.3 Vertical and Horizontal Structures

From a process perspective, complex systems often have a number of different processes operating over a wide range of time scales. If a systems is hierarchical, a certain number of levels can be extracted from observation data. Components with similar process rates will be grouped into the same level. These different levels form the vertical structure of the hierarchy which is a simpler but accurate representation of the original complex system. The asymmetrical relationship between levels is the most salient characteristic of the vertical structure of hierarchies. The number of levels in a hierarchy represents its depth. The deeper a hierarchy is, the more elaborated its hierarchical structure tends to be. Natural and human systems may differ in both the number of levels and the strength of top-down constraints and bottom-up initiating forces. For example, industrial sectors are often hierarchically organized with different number of administrative layers, and the "degree of hierarchy" (a transaction network-based measure) of the automotive sector is higher than that of the electronics sector (Luo 2010). On a general level, this pattern also exists in biological and ecological hierarchies (e.g., food webs of different habitat types). An extremely shallow hierarchy with only two levels and with the lower level populated by a huge number of components is called a "flat hierarchy" (e.g., a crystal or a volume of gas) (Simon 1962). Such systems may seem quite complicated, but are not really complex (Ahl and Allen 1996).

On the other hand, the relationships among holons at the same level are symmetric, and can be characterized by interaction strength. In general, interactions among components within a holon are much stronger and more frequent than those among holons. It is the stronger and more frequent inter-component interactions, and it gives rise to the apparent identity and integrity of holons at each level. For example, the strength of interactions between subatomic components is much stronger than that between atoms, which is in turn stronger than that between molecules (Simon 1962, 1973). Also, both the strength and frequency of between-component interactions decrease from the level of organisms to the levels of local populations and metapopulations.

The above discussion indicates that components in a hierarchical system are only "loosely" coupled in both the vertical and horizontal directions: the "loose vertical coupling" enables and maintains the separation between levels, whereas the "loose horizontal coupling" allows for each holon to operate dynamically in independence of the details of the other holons (Simon 1973). The loose coupling of system components provides a fundamental basis for the near-decomposability of complex systems, a key concept in hierarchy theory which is discussed below.

24.3.4 Near-Decomposability and the "Empty World Hypothesis"

"Near-decomposability," or "nearly complete decomposability," refers to a central property of hierarchical complex systems: *rates of interaction within components at any level are much higher than rates of interaction between components* (Simon 1962, 1973). Complete decomposability occurs only when system components are completely decoupled from each other. Clearly, this is not the case for complex systems. If the components are strongly coupled, the system cannot be "decomposed" and then its description requires the consideration of all components – no matter how many of them. As mentioned earlier, hierarchical systems consist of components that are loosely coupled, and thus they are near-decomposable. It is this near-decomposability that permits simplification necessary for clearly describing and adequately understanding complexity (Simon 1962, 1973, 1976, 1996). To explain near-decomposability, Simon (1973, p. 10) provided the following example:

> If we now observe the behavior of the system over a total time span, T, and our observational techniques do not allow us to detect changes during time intervals shorter than τ, we can break the sequence of characteristic frequencies into three parts: (1) low frequencies, much less than 1/T; (2) middle-range frequencies; and (3) high frequencies, greater than $1/\tau$. Motions of the system determined by the low frequency modes will be so slow that we will not observe them – they will be replaced by constants. Motions of the system determined by the high frequency modes … will be so rapid that the corresponding subsystems will appear always to be in equilibrium … The middle band of frequencies, which remains after we have eliminated the very high and very low frequencies, will determine the observable dynamics of the system under study…

In brief, to describe the dynamics of a hierarchical system parsimoniously and adequately, select a focal level, treat slow behaviors at the higher levels as constants and fast behaviors at the lower levels as averages or equilibrium values. For a specific problem, it is not only possible but also wise to "scale off" the relevant levels from those above and below, thus achieving a greater simplification and better understanding (Simon 1962, 1973, 1996).

Although the degree of decomposability varies among different systems or even among different processes of the same system, the principle is generally applicable. For example, hydraulic and aerodynamic systems are full of turbulence and thus chaotic and unpredictable in detail, but they become "manageable" when they are dealt with as aggregate phenomena (Simon 1996). The principle of near-decomposability has been demonstrated mathematically for both linear and nonlinear dynamic systems in economics (Simon and Ando 1961; Ando and Fisher 1963) and ecology (Overton 1975a; Cale and Odell 1979; O'Neill and Rust 1979; Gardner et al. 1982; Iwasa et al. 1987, 1989). Simon (2000, p. 753) pointed out that "Near-decomposability is a means of securing the benefits of coordination while holding down its costs by an appropriate division of labor among subunits. So, if we design complex systems to operate efficiently, we must incorporate near-decomposability in the design." Thus, organizations are often hierarchically structured, and serve as the most powerful tools to cope with the problem of "bounded rationality" by combining people's thinking powers (Simon 1996, 2000).

Simon (1962, p. 478) stated that "A generalization of the notion of near-decomposability might be called the 'empty world hypothesis' – most things are only weakly connected with most other things; for a tolerable description of reality only a tiny fraction of all possible interactions needs to be taken into account." Apparently, the statement that "everything is connected to everything else," often encountered in the ecological literature, is not helpful or even may be misleading, in dealing with complex problems.

24.3.5 The Basic Triadic Structure

Conceptually linked to the principle of near-decomposability, Salthe (1985) proposed the basic triadic structure for studying complex systems. While near-decomposability focuses on rate differences, the basic triadic structure is based explicitly on the structural levels of a hierarchy. Specifically, it states that three adjacent hierarchical levels need to be considered for both a parsimonious and sufficient description of the behavior of the focal level in the middle (Salthe 1985). This assumes that the dynamics of the focal level is determined primarily by the initiating processes at the level below and the boundary conditions and constraints at the level above. Also, the significance of the focal-level dynamics is understood at the higher level, where as the mechanistic explanations of the focal-level dynamics comes from the lower level.

The basic triadic structure can be linked to process rates based on form-function and space-time relationships (Salthe 1985; Wu 1999). So, it is not just a "structural" approach. As a heuristic guide, it has been widely used in natural and social sciences. Exceptions to the basic triadic structure rule exist when certain nonlinear effects penetrate through several levels above or below (e.g., O'Neill et al. 1991a), which are referred to as "perturbing transitivities" by Salthe (1991). Also, three here is not a magic number, and some studies may need to consider four or five adjacent hierarchical levels, depending on the nature of the phenomena and the research objectives. So, the basic triadic structure should be considered the minimal hierarchical structure for dealing with complex systems.

24.3.6 Hierarchy and Scale

Hierarchy theory provides a powerful framework for understanding scales in time and space. Recent developments in hierarchy theory have made increasingly explicit the relationship between hierarchical levels and scales. Hierarchical levels, which are inherently related to temporal and spatial scales, become more useful when this relationship is quantitatively expressed. This is especially true for relating patterns to processes and for translating information across scales or scaling. Hierarchy theory suggests that the characteristic scales of patterns and process in a complex system should change discontinuously in correspondence to hierarchical levels. When hierarchical levels are defined based on "scale breaks" using statistical methods, a marriage between hierarchy and scale is made (O'Neill 1989, 1996; O'Neill et al. 1991b; Levin 1992; Wu 1999; Wu and Li 2006). This may be called the hierarchy-scale correspondence principle.

Closely related to the hierarchy-scale principle is the time-space correspondence principle: the characteristic scales of complex systems in space and time are related in such a way that the ratio between the two (the so-called characteristic velocity) tends to be relatively invariant over a range of scales (Blöschl and Sivapalan 1995;

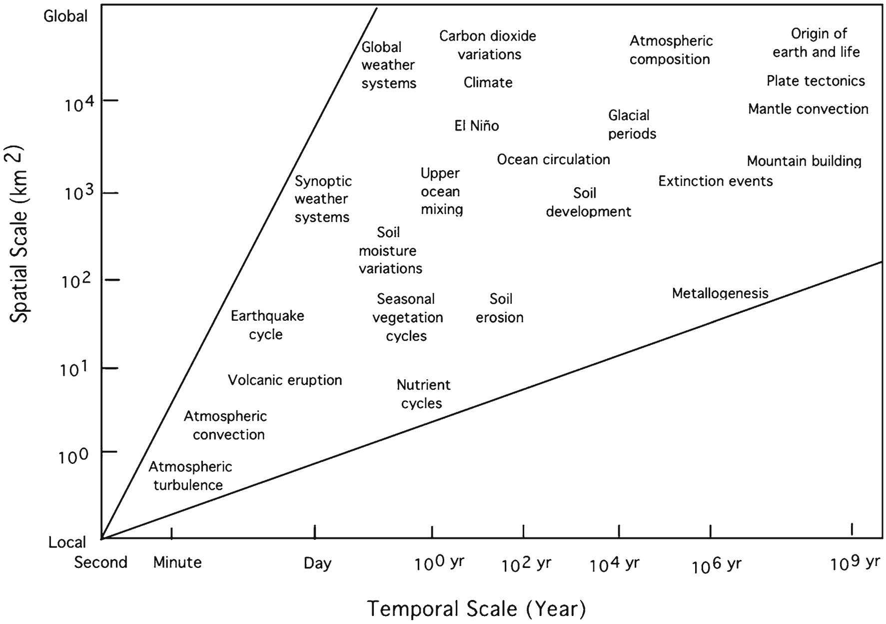


Fig. 24.4 An illustration of the space-time scale correspondence principle. Physical and ecological phenomena tend to line up, approximately, along the diagonal direction in the space-time scale diagram although variations increase with scales (From Wu 1999 and references therein)

Wu 1999). In the parlance of hierarchy, higher levels tend to be slower in time and larger in size, whereas lower levels faster in time and smaller in size (O'Neill et al. 1986, 1991b; Urban et al. 1987; Wu 1999). The space-time correspondence principle is often illustrated by space-time scale diagrams or "Stommel diagrams" (Stommel 1963; Urban et al. 1987; Levin 1992), indicating that hierarchical complex systems can be decomposed in time and space simultaneously (Fig. 24.4). The hierarchy-scale correspondence principle and the space-time correspondence principle provide an essential conceptual foundation for the hierarchical patch dynamics paradigm that links pattern, process, scale, and hierarchy in ecological systems (Wu and Loucks 1995; Wu 1999; Wu and David 2002).

24.3.7 The Observer's Role

In hierarchy theory, the importance of the observer's role in understanding complex systems is generally recognized. When the observer is considered as part of the study hierarchical system, his or her exact position relative to levels (below, on, or above) and holons (within or outside) greatly influences what is to be observed because of the functioning of surfaces and filters (Allen et al. 1984). In this sense, hierarchy theory is sometimes viewed as a "theory of observation" that emphasizes the paramount importance of the role of the observer (Allen and Starr 1982; Allen et al. 1984; Ahl and Allen 1996).

The observer-within-the-hierarchy analogy illustrates nicely why changing the scale of observation and analysis often leads to different results when studying complex systems. But when the role of the observer is over-emphasized, everything that comes out of the study at the end would appear subjective or arbitrary. In this case, the scientific value of hierarchy theory may be compromised. While there is no absolute objectivity, how closely a constructed hierarchy corresponds to the structure of the real system significantly and how the hierarchy is analyzed would undoubtedly affect the usefulness and power of a hierarchical approach (Wu 1999; Wu and David 2002).

24.4 Critiques on Hierarchy Theory

Hierarchy theory has been criticized on several grounds. Some of them are due to misinterpretation, and others are mostly related to the immaturity of the theory. For example, in social sciences, hierarchy is still often perceived as "a top down, authoritarian, if not dictatorial, systems design" (Wilby 1994, p. 665). Thus, "the very word 'hierarchy' grates for a sociologist, as it smacks of an endorsement of domination, whether intended or not" (Bell 2005, p. 474). This is unfortunate because the theory is quite relevant to a broad range of problems with social systems (Simon 1962, 2000; Giampietro 1994; Warren 2005). Control or dominance hierarchies do exist in both the natural (e.g., pecking orders or dominance hierarchies of animals) and artificial worlds (e.g., totalitarian regimes and human-engineered modularly-structured control systems). However, as Simon (1973, p. 5) observed long ago, hierarchy is a general term that is "divorced from its original denotation in human organizations of a vertical authority structure." In fact, hierarchies can be constructed and interpreted from both an authoritative and emancipatory perspective (Wilby 1994).

In a critical review of the theory, Wilby (1994, p. 653) pointed out that "hierarchy theory has been deemed successful in the systems field." She went on identifying several difficulties with hierarchy theory, including: (1) the lack of a single, coherent set of definitions and principles for all variants of the theory, (2) the lack of a specific, systematic methodology for the application of the theory, and (3) the lack of a precise and capable mathematical framework. While these criticisms are helpful for further developing hierarchy theory, much of the relevance depends on how the word "theory" is interpreted here. For example, Allen et al. (Allen et al. 2009, p. 2939) stated:

> Hierarchy theory is a special sort of theory that may not meet criteria for what many would have theory be, because of its relationship to hypotheses and predictions. It does not make predictions per se, but rather explicitly extracts the functional structure of the system from the data, rather than relying on an arbitrary designation of components.

If hierarchy theory is taken as a general theory, which it is, developing a single set of precise and coherent definitions and mathematical frameworks may just be a desirable but unachievable goal. Does systems theory have such a set? On the other hand, as hierarchy theory is used in a more specific problem setting, be it ecological, economic, or social, the terms have assumed unambiguous meanings, testable hypotheses have been formulated, and appropriate mathematical frameworks have been developed. In fact, this has been happening since the seminal work by Herbert A. Simon (e.g., Simon and Ando 1961; Simon 1962, 1976, 1995, 1996). During the past few decades, the further development and application of hierarchy theory in ecology have resulted in a large number of such examples in diverse research areas, including ecosystem modeling, species-habitat relations, ecological succession, animal foraging behavior, habitat fragmentation, and patch dynamics of sorts (Overton 1975b; McIntire and Colby 1978; O'Neill et al. 1986; Senft et al. 1987; O'Neill 1988, 1996; Kolasa 1989; Pickett et al. 1989; Waltho and Kolasa 1994; Wu and Levin 1994, 1997; Yarrow and Salthe 2008). Undoubtedly, hierarchy theory will continue to develop as a general theory and, at the same time, produce specific principles pertaining to problems in diverse fields in natural and social sciences.

24.5 Conclusion

Complex systems are perceived by people as complex because their large number of interacting components resists easy description and understanding. Then, how do we approach such systems. One approach would be to treat them as "black boxes" – try to understand them by knocking on their walls and corners from the outside and then interpreting their responses without knowing anything inside. This would be an extremely holistic approach, which has proven to be of limited value. Another approach would be to treat them as nothing but the sum of their parts – an extreme reductionist perspective. Newly-developed computationally intensive approaches, such as cellular automata and genetic algorithms, assuming that complexity is only generated by iterating simple rules or that complex patterns can be derived solely from interactions of local processes, represent improved but still fundamentally reductionist methodologies. If the complex world is hierarchically or modularly structured, which seems true in many situations, none of the above-mentioned approaches should work. In these cases, hierarchy theory has proven useful and effective.

Several key elements of hierarchy theory can be identified, and most of them have originated in the work of Herbert A. Simon in the 1960s–1970s. Among the most essential are the observation that hierarchy is a central architecture of complexity, the generality and fundamental importance of rate-based ordering of levels, the loose coupling of system components, and near-decomposability of hierarchical systems. The theory has been further developed and applied rather extensively during the 1980s, most noticeably in the fields of biology and ecology through a series of books. Today, hierarchy theory has pervasive influences in ecology and also broad applications in a number of other fields, including geophysical, computer, economic, psychological, and management sciences.

To conclude, hierarchy theory is a general theory of simplifying complexity by taking advantage of the fundamental property of many complex systems – near-decomposability. From a philosophical perspective, it integrates reductionism and holism, as Simon (1962, p. 468) pointed out: "In the face of complexity, an in-principle reductionist may be at the same time a pragmatic holist." Hierarchy theory considers both top-down influences and bottom-up processes as important, and provides a theoretical basis for multiple-scale analysis and synthesis. In fact, hierarchy theory suggests that a proper balance between top-down constraints and bottom-up processes is key to the performance and persistence of most complex systems. Hierarchy theory neither implies inflexibility nor a lack of diversity and creativity. On the contrary, an appropriate hierarchical, dynamic structure provides opportunities for diversity, flexibility, and creativity, as well as higher efficiency and stability that are difficult to obtain in non-hierarchical complex systems.

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